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The greenhouse gas emissions and mitigation options for materials used in UK construction

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Abstract

The UK construction industry faces the daunting task of replacing and extending a significant proportion of UK infrastructure, meeting a growing housing shortage and retrofitting millions of homes whilst achieving greenhouse gas (GHG) emission reductions compatible with the UK's legally binding target of an 80% reduction by 2050. This paper presents a detailed time series of embodied GHG emissions from the construction sector for 1997-2011. This data is used to demonstrate that strategies which focus solely on improving operational performance of buildings and the production efficiencies of domestic material producers will be insufficient to meet sector emission reduction targets. Reductions in the order of 80% will require a substantial decline in the use of materials with carbon-intensive supply chains. A variety of alternative materials, technologies and practices are available and the common barriers to their use are presented based upon an extensive literature survey. Key gaps in qualitative research, data and modelling approaches are also identified. Subsequent discussion highlights the lack of client and regulatory drivers for uptake of alternatives and the ineffective allocation of responsibility for emissions reduction within the industry. Only by addressing and overcoming all these challenges in combination can the construction sector achieve drastic emissions reduction.

Keywords
Building materials; climate change mitigation; construction; embodied emissions; Input-Output Analysis;

1. Introduction

The evidence of climate change is now “unequivocal” [1] and the anticipated increases in the frequency of extreme weather events, threats to water and food security and the massive loss of biodiversity represent a fundamental risk to the health and livelihoods of a large portion of the global population. The extensive and growing evidence base suggests that it is “extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century” [2], principally through the extraction and burning of fossil fuels alongside changes to land use. Humans have already significantly altered three quarters of the world’s terrestrial habitats and continue to extract 60 billion tonnes of raw materials each year [3,4]. The construction sector is the largest user of these materials [4]. Buildings are the sector with the largest single energy use worldwide and are responsible for approximately a third of global carbon emissions [5,6].

In the UK, the volume of carbon dioxide emissions that the construction sector influences is significant, accounting for an estimated 47% of total UK CO_2 emissions [7]. In a typical year, the UK construction industry requires over 420 million tonnes of material resources, energy equivalent to just under 8 million tonnes of oil, and is responsible for over 90% of non-energy mineral extraction [8,9]. The construction sector is also the largest generator of waste, at over 100 million tonnes per year in 2008 [10]. Furthermore, every year the construction industry uses 6500 ha of land and is responsible for a third of all industry-related pollution incidents [11]. In addition to direct environmental impacts from its activities, the sector also has a critical role to play in enabling the supply of clean energy and facilitating sustainable practices in other areas of the economy. The impending transition to a low carbon economy represents a sizeable package of works for the construction industry. Indeed, the influential 2010 UK Innovation and Growth Team (IGT) report concluded that “over the next 40 years, the transition to low carbon can almost be read as a business plan for construction” [12].

The UK is facing a sizeable housing shortfall, the imminent replacement of the majority of its electricity generating plant, and intends to increase public investment in many pieces of large-scale infrastructure (such as high speed rail and highway networks) [13]. In addition, the sector faces the challenging task of retrofitting millions of ‘non-decent’ domestic properties that are responsible for high levels of fuel poverty and operational greenhouse gas (GHG) emissions [14]. The production of these new structures and the retrofit of existing stock will require a considerable volume of construction materials over the coming decades. Over this same period, to meet legally binding targets, the UK must make reductions in GHG emissions of 80% relative to 1990 levels. Reducing the emissions associated with the production of these materials and structures could play a significant role in meeting this target [15].

The carbon emissions associated with construction are typically distinguished as either *embodied* or *operational* emissions. Embodied emissions (sometimes called capital carbon) are those associated with the initial production of a structure. Typically this includes emissions from: raw material acquisition, transport, processing and manufacturing of building materials; distribution of materials to site; and energy used on-site in assembly. A comprehensive definition would also include indirect emissions associated with supporting activities such as design, project financing, legal support and other professional services. For most projects the embodied emissions are dominated by emissions associated with the extraction and processing of materials [7,16]. Meanwhile operational emissions are those associated with the operation and maintenance of a structure. This typically includes activities such as space heating, lighting, and air conditioning. Emissions associated with the deconstruction and disposal of a structure can also be considerable, though the method of estimation and documentation varies between studies.

Studies based around Life Cycle Assessment (LCA) methods have found the ratio of embodied to operational emissions varies considerably by structure type and from project to project [17]. Academic studies have most frequently found operational emissions to constitute 70-80% of life cycle emissions associated with a variety of structures [18]. Non-academic studies have also arrived at comparable estimates [12,19]. However, many of these studies have suffered from a number of crude assumptions [17]. Common simplifications include the omission of emissions from on-site activity, personnel transport, material transport and material wastage. End of life considerations, for example deconstruction and recycling or disposal of key materials, are frequently excluded. A number of studies are also predicated on the assumption that there will be no further decarbonisation of the electricity supply over the lifetime of the structure [e.g. 113] – resulting in a likely overestimation of operational emissions. For these reasons the ratio of operational to embodied emissions is often overstated.

The last decade has also seen an increased emphasis on improving building fabric to achieve better thermal performance. This has necessitated an increased use in materials, as better performing wall systems are typically thicker and more complex [20]. A study of homes built in recent years found embodied emissions now typically make up 31-42% of total life cycle emissions [21]. New regulations and increasing construction activity are expected to continue this trend towards increasing embodied emissions and reduced operational emissions [17].

These trends have led authors to conclude that "as gains in operational energy reduction are realised, embodied energy of the construction, maintenance, refurbishment and disposal cycle will become increasingly important in making further progress" [22]. Recent industry publications have also identified the need to address embodied carbon in tandem with operational carbon. For example, the authors of the Green Construction Board (GCB) Low Carbon Routemap for the Built Environment estimated that capital carbon reductions of 21% by 2022 and 39% by 2050 relative to a 2010 baseline will be needed, alongside reductions in operational emissions of 85% (for domestic properties) and 77% (for non-domestic properties), to meet sector targets [19].

This paper provides an improved estimate of the total embodied emissions associated with construction and presents a range of mitigation options that focus on reducing the use of materials with carbon-intensive supply chains. The barriers to uptake of these alternatives are presented and the subsequent discussion highlights the lack of client and regulatory drivers for their adoption. Key gaps in existing qualitative research, data and modelling approaches are also identified.

2. **Quantifying the embodied emissions of the construction sector**

2.1 Previous estimates and their limitations

At least two recent attempts, summarised in Table 1, have been made to estimate the emissions that fall within the influence of the UK construction sector [7,19]. Both of these concluded that operational emissions are the dominant component and thus warrant the principal attention of policy makers. However, the means by which embodied emissions are computed remains a subject of much debate [17]. Owing to the poor granularity of data currently gathered for the UK's territorial and consumption-based emissions accounts[1], it remains exceptionally difficult to swiftly and accurately distinguish the true embodied impacts of the construction sector.

Table 1 – Estimates of GHG emissions attributable to the built environment

Estimate	Innovation and Growth Team [7]	Green Construction Board [19]
Total emissions attributable to the built environment	298.4 $MtCO_2$ in 2008 Of which 51.9 $MtCO_2$ embodied	190 $MtCO_2e$ in 2010 Of which 33.6 $MtCO_2e$ embodied
Ratio of operational:embodied emissions	17:83	18:82
Breakdown of embodied emissions	Product manufacture: 45.2 $MtCO_2$ Distribution: 2.8 $MtCO_2$ Operations on-site: 2.6 $MtCO_2$ Design: 1.3 $MtCO_2$ Refurb/demolition: 1.3 $MtCO_2$	Materials extraction, manufacturing and production: 18.1 $MtCO_2e$ Distribution: 3.4 $MtCO_2e$ On-site activities: 6.7 $MtCO_2e$ Design services: 1.7 $MtCO_2e$ Other: 3.7 $MtCO_2e$
Methodology	Domestic: sum of emissions attributable to the domestic production of 'Wood and wood products', 'Paints, varnishes, printing ink etc.', 'Rubber products', 'Plastic products', 'Glass and glass products', 'Structural clay products, cement, lime and plaster', 'Articles of concrete, stone etc.', 'Metal products', plus 28% of the total for 'Iron and steel, non-ferrous metals, metal castings' based on figures from the Environmental Accounts. Imports: 2004 embodied emissions from imports from Sector 88: 'Construction' of the University of Leeds and CenSA two region MRIO model[2].	The entire capital carbon allocation is extracted solely from Sector 88: 'Construction' of the two region University of Leeds and CenSA MRIO model for the period 1990-2009. This is then apportioned into 'Infrastructure', 'Non-domestic buildings', and 'Domestic buildings' based on the financial value of construction output during this period [19, pp. 22–24]

[1] Territorial emissions loosely refer to emissions of GHG within national borders whilst consumption based emissions are allocated according to final consumption irrespective of the location of GHG emission. For a more detailed description see [137].

[2] See Supporting Information for a description of the model and its coverage.

The first attempt, made in support of the 2010 IGT report: Low Carbon Construction [12], estimated that construction could influence around 47% of the total CO_2 emissions of the UK. Of this total an estimated 17% were attributable to embodied emissions, of which 87% came from the manufacture of materials [7]. However the approach suffered from two important deficiencies. Firstly, no attempt was made to update the 2004 figure for imported emissions to the 2008 base year adopted in the report, despite the fact that this figure had grown by 49% in the preceding 4 years [24]. Secondly, the assumption that 100% of domestic material production from some of the sectors included is used exclusively for construction in the UK is highly questionable, and the means by which the figures were aggregated will inevitably result in some degree of double counting. This would suggest an overestimate in the total figure for domestic emissions. However, this is likely counterbalanced to a significant extent by the underestimate in the figure attributable to imports due to the use of 2004 instead of 2008 data. Retrospectively comparing the data for these years shows a nearly 20% increase in emissions attributable to imports between 2004 and 2008. Once emissions attributed to design, distribution and operations on site were included, total embodied emissions for 2008 were estimated in the IGT report to be 51.9 $MtCO_2$.

The Green Construction Board (GCB) chose to adopt an alternate approach for their estimation of 'capital carbon'[3] within the 2013 Low Carbon Routemap for the Built Environment [19]. The approach implicitly assumes the same material intensity across all construction sectors throughout the analysis period. Does a bridge really produce the same emissions per £ of output as a house? Was the material intensity of producing a house the same in 1990 as in 2009? This simplistic assumption has the potential to significantly undermine the subsequent scenario analysis. This means of estimation also resulted in total embodied emissions of less than 39 $MtCO_2e$ in 2008 compared with the IGT estimate of 51.9 $MtCO_2$. Clearly, the assumptions made in allocating embodied emissions to construction can result in a considerable difference in the calculated figure (of the order of 33%). Whilst it would initially appear probable that the IGT figure was an overestimate, the GCB figure was likely an underestimate due to its exclusion of emissions attributable to direct transactions between material producers and households. This discrepancy is discussed in further detail in the Supporting Information. Ultimately, the GCB estimated that the built environment accounted for 210 $MtCO_2e$ in 1990 and just over 190 $MtCO_2e$ in 2010.

The GCB report also outlined future projections of emissions under a number of routemap scenarios. In the '80% Carbon Reduction Scenario', the authors projected a reduction in total emissions to 42 $MtCO_2e$ by 2050. This required capital carbon reductions of 39% by 2050 relative to a 2010 baseline alongside reductions in operational emissions of 85% for domestic properties and 77% for non-domestic properties. This resulted in an overall shift to 60% operational and 40% embodied emissions by 2050. The authors described this scenario as "challenging" and suggested it "would

[3] The GCB definition of capital carbon included "direct process emissions and indirect emissions from the manufacture and production of UK and imported construction materials and products, emissions from the transport of materials, emissions associated with professional services in support of construction, and all construction and demolition works on site".

require maximum uptake of technically viable solutions in all sectors, including implementation of technologies that at present do not have a financial return on investment over their lifetime" [19, p. 2]. However, owing to the means by which capital carbon was initially established and distributed, alongside a number of additional assumptions, it is likely that the authors significantly underestimated the required reductions in capital carbon emissions.

In the case of domestic and non-domestic building stock, the GCB '80% Carbon Reduction Scenario' assumes that building performance will improve drastically over time with the use of better building fabrics without any corresponding increase in embodied emissions. Improved building performance (and reduced operational emissions) is typically achieved through the use of thicker and more complex building fabrics [20]. This additional material represents an increase in the capital carbon of the structure. Therefore the implicit assumption in the GCB scenarios that new structures with improved performance will be produced with the same capital carbon input as current structures is almost certainly incorrect. Furthermore, the report's assumed growth in infrastructure spending is minimal and predicated largely on historical trends from 1980-2011 not current considerations. This includes assumptions of no change from current road investment levels and increases of 1.7% in railways and 9% in electricity to 2017 with only 1.2% thereafter [19, p. 35]. These figures fall below levels already set out for 2011-2015 in the National Infrastructure Plan and Infrastructure Investment Pipeline [13].

Even under these optimistic assumptions the scenario that achieves 2050 targets assumes Carbon Capture and Storage (CCS) will contribute in the materials industry within the next 7 years and will be universally deployed by 2050. At the time of writing, CCS has not yet been fitted on any materials production facility in the world. It appears highly unlikely that this will change in the near future [23]. The scenario also envisages improvements in material production efficiencies of 43% for metals, 31% for concrete, 61% for brick and 30% for glass by 2050. The opinion of the authors of this paper is that improvements of this magnitude are currently inconceivable. Consequently, there is good reason to believe the situation is even more desperate than suggested by the already "challenging" 80% reduction scenario.

2.2 New estimate

In this section an improved estimate of the embodied emissions associated with construction is presented, which makes a number of corrections to the IGT and GCB approaches. The model used is an updated version of the UK MRIO model developed at the University of Leeds for DEFRA [24]. The model is a multi-region Environmentally Extended Input-Output model based upon multiple data sources. Four regions are considered: the UK, EU, China and Rest of the World (ROW). Whilst the sector classifications are similar to those adopted for the GCB estimate, the core figures for the construction sector benefit from a number of model refinements. Additional figures have also been added to the original sector total to correct for an accounting anomaly whereby transactions made directly between material producers and households do not appear within the influence of the construction sector. A detailed description of the model can be found in the Supporting Information.

Figure 1 shows that total embodied emissions associated with the construction sector in 1997 were approximately 56.2 $MtCO_2e$. This figure grew to 62.6 $MtCO_2e$ by 2007. Over the following years the global financial crisis and the corresponding UK recession resulted in an unprecedented drop in construction output. This resulted in embodied emissions falling to only 42.6 $MtCO_2e$ by 2011. Throughout the analysis period total emissions generally tracked increases and decreases in construction activity.

Figure 2 presents a decomposition of the total embodied emissions of construction, which shows that in a typical year around half of embodied emissions are attributable to material producing sectors. The proportions attributable to each activity remain similar throughout the analysis period[4]. These results are consistent with past publications [12, p. 23], [19, p. 15] which demonstrated that the production of materials is responsible for the majority of embodied emissions from construction. This is not surprising as the construction industry consumes around 6 tonnes of materials every year on behalf of each UK resident [9]. Most of the associated emissions are attributable to a small number of materials, principally steel and cement, which together contribute 44% of industrial carbon emissions in the UK [16, p. 13]. Owing to the high costs of energy, material producers have long been strongly incentivised to improve production efficiencies. Consequently, many of the available improvements have been exploited and new production is slowly approaching practical thermodynamic limits [16, pp. 99–113]. Unavoidable emissions associated with key chemical processes, such as the calcination of limestone in cement manufacture and the reduction of iron ore by coke and oxygen in steel manufacture, now dominate [16, p. 99]. Without CCS these process emissions are unlikely to be reduced. Widespread CCS is unlikely to occur within the timescale required [23] to achieve embodied emissions reductions of the order of 21% by 2022, as suggested by the GCB [19]. Consequently, reductions of the order of magnitude required are unlikely to be met through improvements in material production methods alone [6]. If substantial reductions are to be made in embodied emissions, then reducing the use of these carbon-intensive materials will need to play a significant role.

Figure 3 reveals that throughout the analysis period around half of total supply chain emissions (between 48 and 58%) occurred outside UK borders. Whilst in the years prior to the recession (2000-2007) there was a small rise in emissions attributable to imports from China, largely the emissions attributable to imports followed trends in total construction output with the majority of emissions attributable to imports from the EU or Rest of World regions. This reflects a consistently strong dependence in recent decades upon imported materials (such as wood, steel and aluminium) which limits the scope of influence of UK territorial policies in achieving radical emissions reduction in the construction sector. Even combined UK and EU policies only govern around 65% of the current total. Consequently, policies directed solely at UK or EU material producers are highly unlikely to achieve sufficient reductions in embodied emissions to achieve sector targets.

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[4] Materials extraction, manufacturing and production (50.8-53.4%); construction activities (18.6-23.2%); transport of people, plant and materials (8.2-10.3%) and all other activities (16.1-19.8%).

2.3 Anticipated growth in embodied emissions

It is also important to remember that the current embodied emissions of around 42.6 MtCO_2e represent the sector during a period of historically low construction output. The sector was hit exceptionally hard by the recession which resulted in the worst downturn in construction activity since the Second World War [25]. Quarter2 2008 to Quarter2 2009 featured the largest annual drop in construction output on record, with Quarter3 2011 to Quarter3 2012 being the fourth largest [26]. In Quarter2 2013 industry output still remained 15.8% below the 2008 peak [27]. Construction sported the highest redundancy rates of any sector throughout the recession, and along with manufacturing accounted for a third of total redundancies between 2008 and 2012 (more than double the combined share of these sectors in total employment) [25]. From the sector's peak in September 2008 employment fell by 428,000 (roughly 17% of the total workforce). Private commercial output also reduced by a third between 2008 and 2012 [26]. It has been projected that output may not return to 2007 levels until 2022, leaving the construction sector preparing for a "decade of pain" [28]. However, this still represents gradual growth on current levels in the short term, with a number of demographic and structural changes expected to drive significant activity in the medium term in key areas such as infrastructure and housing.

Population growth, and the increasing prevalence of one-person households, is expected to drive an increase of 5.8 million households in England by 2033. These projections look set to exacerbate the on-going housing crisis, with a projected shortfall of 1.7 million houses by 2029 if current trends continue [29]. In spite of this, the UK is currently experiencing the "lowest level of house building in peacetime since 1923" [30]. In addition, it has been estimated that the UK must retrofit 13,000 homes per week until 2050 if emission reduction targets are to be met [14]. This represents a rate of more than a home every minute for the next forty years. This includes 8 million 'non-decent' homes, which either pose a serious health hazard to occupants or provide inadequate thermal comfort [14]. With a raft of Government policies introduced to encourage greater house building and retrofit it seems certain that higher rates of construction will be observed in coming decades. Infrastructure expenditure is also set to expand with the Government's National Infrastructure Plan setting out 550 projects valued at over £330 billion to 2015 and beyond [13,31]. Rail construction is set to rise by more than one third by 2015 and energy construction is set to double by 2016 [32]. This combination of ambitious retrofit targets, replacement and expansion of infrastructure, and development of new low energy domestic and non-domestic buildings has the potential to increase absolute material requirements and embodied emissions. As shown in Figure 1, the embodied emissions associated with current levels of construction are already higher than the suggested GCB combined target for embodied and operational emissions of 42 MtCO_2e by 2050. Therefore it is essential to reduce the embodied emissions associated with construction if an 80% reduction in total emissions is to be achieved.

Aside from being necessary, strategies that target reductions in embodied emissions may also be preferable to reductions in operational emissions, as they offer more immediate and predictable savings [17]. The current focus on the occupancy phase leaves strategies more susceptible to widely documented performance gap problems [33]. Ongoing work from the Technology Strategy Board Building Performance Evaluation Programme shows that even in recently built structures actual operational emissions are still typically 2 to 6 times the anticipated design values [34]. The benefits of lower carbon material choices can be readily quantified at the design stage and are less dependent on unpredictable factors, such as future building occupancy and use. Building life expectancies, particularly for commercial structures, are frequently overestimated. This results in predicted savings in operational emissions, which notionally offset increased embodied emissions decades into occupancy, never being realised in practice.

The benefits of lower carbon material choices can also be harnessed immediately and represent a swift response to a time-sensitive issue. The majority of GHGs exhibit long atmospheric lifetimes (30-95 years in the case of CO_2, the most abundant GHG). Thus, cumulative carbon emissions not annual emissions are the critical component in preventing unacceptable levels of climate change [35]. For this reason it has been suggested that a significantly heavier weight should be attached to current rather than future emissions savings [36]. Meanwhile current policy has taken the reverse approach, basing evaluations on anticipated rises in the value of carbon in coming decades, essentially devaluing the benefits of early action [37]. The prevailing advice of climate scientists is that the world must act in the next two decades to prevent dangerous levels of change [2]. Savings projected decades into the future may already come too late to prevent catastrophic changes associated with global temperature rises over 2°C, a target many climate scientists predict will be exceeded [38]. Indeed, when viewed through the lens of cumulative carbon emissions, it becomes clear that demand for infrastructure development will inevitably account for a considerable portion of remaining cumulative carbon budgets [39]. Therefore it is imperative to make reductions in the emissions associated with the construction of new infrastructure and maintenance of the existing stock. Both of these activities require vast volumes of materials.

Therefore, as other authors have identified [40], it becomes necessary to limit the use of carbon-intensive materials. Though the term 'carbon-intensive materials' is used throughout this paper, the authors do not seek to suggest that any individual material is a universally unsustainable choice. In certain cases the use of materials such as steel and concrete represent the most sustainable option for a given project. However, what is immediately apparent from consideration of cumulative material production and emissions statistics is that the current material mix and consumption rate must change if emission reduction targets are to be met. The UK construction sector cannot continue using such volumes of these carbon-intensive materials and achieve an 80% reduction in GHG emissions.

With limited scope for further reducing key material production emissions the sector must adopt alternative approaches that seek to minimize the use of carbon-intensive materials.

3. **Options for reducing the use of carbon-intensive materials**

Fortunately, there is a wealth of on-going research into alternative construction materials, technologies and practices that could help limit required volumes of carbon-intensive materials. These include: using alternative materials;

substitution of unconventional materials, such as wastes, into material production streams; applying technological and design solutions to minimise extraneous material use; increased re-use and recycling of materials; and minimising demand for new structures through refurbishment and adaptive re-use of existing structures. Within these five broad strategies there are numerous specific materials, technologies and practices that can be employed (see Table 2 for a selection). A brief summary of these follows.

It should be noted that this summary focusses on alternative structural and functional elements of the building fabric, and does not consider fixtures and finishes. Though in many building studies a notable proportion of the total life cycle emissions are attributable to non-structural materials, it seems self-evident that, where emissions reduction is considered a key criterion at the design stage, finishes with minimal environmental impacts should be preferred by designers and specifiers.

Table 2 - Summary of options for reducing the use of carbon-intensive materials in the UK construction sector

Alternative Materials	Substitution in the Production of Common Materials	Minimising Excess Through Improved Design and Manufacture	Re-use, Recycling and Leasing of Components	Adaptive Re-use and Life Extension of Existing Stock
Timber (traditional forms, SIPs, Brettstapel and CLT) Plastic (FRP, ETFE) Straw-bale (infill, load-bearing or composite panels e.g. Modcell®) Earth (rammed earth, unfired brick, cob, wattle and daub, and adobe) Geopolymer concrete Hemp (hemcrete and hemp-lime blocks) Limecrete Tyres Bamboo (laminated or unprocessed) Cardboard (tubing or panels)	*Alternative cementitious materials or aggregate substitutes* GGBS Fly Ash Agricultural wastes (rice husks, corn cobs, vegetable fibres, nut shells) Consumer waste (plastics, glass, ceramics, tyres, carpets) Construction and demolition waste Industrial wastes (pulp and paper mill residuals, coarse steel slag, silica fume, cotton waste, sewage sludge ash) *Waste-derived fuels* Agricultural wastes (wheat straw, rice husks, nut shells) Non-agricultural biomass (sewage sludge, paper sludge, animal bone and fat) Consumer Waste (carpets and textiles, plastics, tyres, municipal solid waste)	Optimised carpet/roll-out reinforcement Mesh reinforcement Hollowcore slabs Precast sections Modern methods of construction Variable depth structural members Selective use of higher grade materials	Increased dismantling and re-use of members Leasing of structural components (e.g. roofs) More use of recycled aggregates Improved recycling practices on site	Increased redevelopment and adaptive re-use Refurbishment of existing structures Adaptive design of future structures

3.1 Alternative Materials

The majority of structures in the UK are currently built using steel, concrete and masonry but similar structures can be produced using a variety of traditional and modern building materials with lower environmental impacts. Many examples already exist in the commercial and housing sectors of structures produced using natural materials such as straw, hemp and earth [41]. Indeed, the UK sports numerous examples of buildings dating back to the 19th century made from these traditional materials [42]. There has been a small scale renaissance in these longstanding techniques, with a raft of projects completed in the last decade [43]. Movements to combine traditional materials with modern methods of construction have also resulted in increased uptake. For example, the use of panellised prefabricated timber and straw bale systems such as ModCell [44] and ecofab [45]. There are now several hundred recently completed straw bale structures in the UK [43,46] including three storey load bearing homes [47]. Traditional alternatives to cement plasters such as lime and gypsum are also increasing in popularity, as are natural insulation materials such as sheep's wool.

Wood has seen a resurgence in recent years perhaps attributable to a combination of effective campaigning from expanded advocacy groups and the use of modern methods of construction such as Structural Insulated Panels (SIPs) and Cross-Laminated Timber (CLT). Developments, such as the expansion of Brettstapel production and increasing use of timber in hybrid timber/steel structures, also offer opportunities to further expand the use of timber.

Technological developments have also yielded a multitude of novel plastics with structural applications. These not only offer opportunities in housing and commercial sectors but can be used in infrastructure projects, for example in railway sleepers and lightweight bridge construction [48]. Extended service lifetimes, reduced weight, reduced maintenance requirements and the potential for incorporating recycled content can lead to reduced emissions using these materials [49].

Many of these novel and traditional materials are increasing in use and offer great potential to displace steel, concrete and masonry principally in the housing and commercial sectors. Certain opportunities also exist for displacement of these materials in infrastructure projects.

3.2 Substitution in the Production of Common Materials

Direct replacement of certain materials with lower carbon alternatives is not always possible due to particular functional requirements. For example, concrete is the predominant material used in foundations with alternatives only suitable for low loads across a limited range of ground conditions. However, concrete is the second most consumed material in the world, and cement production is one of the key contributors to GHG emissions [50]. Therefore minimising the need for carbon-intensive cement production is an essential part of reducing the embodied emissions of construction. Fortunately, where there are no opportunities to directly replace a material in use, there are often opportunities to replace carbon-intensive elements of the material production process. For example, over past decades a number of high volume waste streams have emerged that produce materials with useful properties. These can either be incorporated into material production as raw materials or used as alternative fuel sources, displacing current carbon-intensive sources. Significant opportunities exist for waste utilisation to reduce the carbon intensity of production processes for cement, concrete, asphalt, brick and blockwork [51].

Many supplementary cementitious materials (SCM) with reduced embodied emissions and lower unit cost are commonplace in UK designs [52]. Extensively researched industrial wastes such as Ground Granulated Blast-furnace Slag (GGBS) and fly ash have been used for decades as partial substitutes to clinker. GGBS is already present in half of UK ready-mix deliveries because it improves workability and durability. However, at times of high demand, UK supplies of GGBS have been exceeded and demand has depended upon German imports [53]. Globally supplies of conventional SCMs are estimated to total less than 30% of global cement production [16, p. 284], so there is a limit to the volume of cement these materials could realistically displace (in addition to the obvious performance limitations). However, further industrial wastes such as steel slag [54] and sewage sludge ashes [55] do not suffer from such restricted supply. Consumer wastes such as plastic, glass and ceramics can also be used as secondary aggregates in concrete production [56]. The wastes are typically used in the form of granules, fibres or powders and can improve workability, permeability and strength. Waste carpets and PET can also be used effectively in fibre-reinforced concretes [57]. Experiments are increasingly incorporating agricultural wastes in lightweight concretes, though much research is still needed to assess their suitability for a range of applications. Construction and demolition waste can be recycled as aggregate in concrete, subject to the limits of BS 8500-2 [58]. However, the emissions reductions in this case are highly dependent on material transport considerations [59]. Combinations of these waste streams are also being used by researchers to produce an assortment of masonry units [60]. Some of which, such as Encobricks™ [61], are entering commercial production.

Many of these wastes can also be utilised as alternative fuels in cement production. At least 5 plants in the UK now use significant quantities of wastes such as: wheat straw, rice husks and nut shells; sewage sludge; paper sludge; carpet and textiles waste; waste tyres; and waste plastics (see [62] for a comprehensive list). There is scope for increased exploitation of many of these resources, though some are limited by supply.

The role of careful mix design is also critical [63] and the prudent use of admixtures can yield significant reductions in embodied emissions [64].

Geopolymer concretes also offer an outright alternative to OPC. However, despite decades of research, regulatory limits, a lack of long-term performance data and practitioner knowledge still restrict use to certain niche applications [65,66]. Only one UK company currently produces commercial geopolymer concrete products, though Australian examples such as Zeobond are more established (producing E-Crete™ since 2007). Significant material resources exist in the UK for producing geopolymer concrete, including large stockpiles of PFA [67]. This could yield reductions in embodied emissions of 36-56% compared with OPC[5] [68]. However, it will likely be decades before production reaches a substantial scale [66]. Consequently, the expanded use of SCMs remains the principal opportunity for displacing OPC production in the near term.

3.3 Eliminating Excess Through Improved Design and Manufacture

In many structures up to a third of the material used can be excess to design requirements [16,69]. This is usually a result of either:

- rationalisation – a process whereby a variety of component sizes are simplified to a smaller set of sizes to simplify site work
- cheaper manufacture of standard parts – many of the processes whereby typical components, such as I-beams, are manufactured are cheaper for members with a constant section along their length. It is also often cheaper to purchase the most readily available off-the-shelf sizes.
- over-specified components copied across projects to minimise costly design time
- higher specifications required for the construction phase that are surplus to in-use requirements
- overly conservative regulatory requirements

Over recent decades terms such as 'lightweighting' and 'member optimisation' have arisen to describe fields that essentially endeavour to minimise this excess. Generally this requires changes in design practice or novel manufacturing processes. Computational optimisation has helped reduce the weight, cost and emissions associated with many structures, and continues to provide further scope for improvements. Meanwhile, innovative manufacturing processes have led to new products that offer a greater control of section size and reduced need for rationalisation. All of these options reduce the weight of key elements which can also lead to further reductions in the supporting structure, notably in foundation sizes.

Many of these alternatives also have practical advantages, such as quicker installation without skilled workers. For example, lightweight stock meshes and computationally optimised roll-out reinforcement carpets can save time fixing rebar on site whilst significantly reducing the amount of rebar needed in floor slabs by eliminating rationalisation losses [71,72]. Alternatively, traditional rebar can be disposed of altogether in cases where fibre-reinforced concrete can meet functional requirements. Lighter concretes with pockets of air or additives are also becoming increasingly commonplace. The increased use of pre-stressed and precast sections can also minimise the volumes of concrete that are needed on site and reduce material wastage. Though, such potential savings must be carefully balanced against increased transport emissions.

In the case of steel, many structural members, such as beams, are produced with a uniform cross-section for ease of manufacturing, not to meet a structural need. The use of optimised members with varying cross-sections could

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[5] It should be noted that these figures were calculated for an Australian product and would likely differ for the UK. Unfortunately, to this author's knowledge, no figure has yet been estimated for UK production.

significantly reduce material requirements. Current methods of manufacture are prohibitively expensive; however, cheaper production methods are in development [73].

In many cases, using higher grades of concrete and steel can significantly reduce the required volume and self-weight of a structure [74]. This in turn can lead to reductions in the size of foundations, leading to overall reductions in the associated environmental impacts. With the rise of BIM and holistic evaluation tools for estimating the embodied emissions associated with an entire structure, such as BRE IMPACT [75], Butterfly [76] and Rapiere [70], it will become easier for designers to calculate and realise these benefits.

3.4 Increased Re-use, Recycling and Leasing of Components

Demolition has become increasingly preferred to deconstruction due to time constraints, health and safety concerns and financial considerations. This has resulted in increased volumes of construction waste. These volumes have been partially mitigated by the increased use of on and off-site recycling plant. However, whilst recycling of construction materials has increased, re-use has declined substantially in the last decade [77]. For example, of the one million tonnes of steel arising from UK demolition in 2007, only 30,000 tonnes were reclaimed for re-use (3%). Meanwhile, only 1.5% of 2007 new build steel demand was met by reclaimed steel [77, p. 15]. Other estimates have suggested that across the EU between 10 and 37% of steel is re-used, depending on section type [78]. Allwood and Cooper have suggested that up to 50% of many common steel and aluminium construction products could be re-used [79]. It is clear that significant potential exists for greater re-use of this high value and carbon-intensive material. This argument also extends beyond steel, with an estimated 10 million tonnes of construction materials that could be re-used each year [77, p. 6]. This could significantly reduce demand for new material production.

Motivating increased re-use of materials may require promotion of principals such as design for disassembly and an increased focus on the end of life project stage during design. Considered design, appropriate building documentation, labelling of structural members, and improved site management can all improve recovery of key materials. Increased testing and re-conditioning facilities and standards may also be needed to provide surety for engineers and insurers. Suitable financial incentives must also exist, which may necessitate high landfill taxes, tax incentives for recovered materials or similar policy interventions.

Opportunities also exist to improve re-use and recycling through new ownership structures. For example, the leasing of major structural components such as roofs. In such a scheme, occupiers would lease out the roof for a long period corresponding to the anticipated structure life (such as 40 years) after which time the roof owners and installers would dismantle and reclaim the materials for re-use on a similar project. This model could potentially be applied to many commercial and industrial structures (e.g. warehouses) with short anticipated lifespans and standardised designs. The first tentative steps have been taken towards this in the aluminium industry, with large players such as Tata Steel perceiving a potential major market for steel leasing. Precedents already exist in established take back schemes for plasterboard and PVC windows.

Significant opportunities also exist for greater re-use of foundations. Foundations are often responsible for the largest environmental impacts of a structure, requiring high volumes of concrete and steel. A wide range of reasons restrict their re-use in practice but many of these can be overcome [78, pp. 89–93]. An estimated fifth of global steel production is used in foundation rebar [79]. Simply leaving this material in the ground at the end of a structure's life is a tremendous waste. The development of technologies that enable effective recovery of this steel could significantly reduce new material demand.

3.5 Adaptive Re-use and Life Extension of Existing Structures

Demand for additional structures can be reduced through increased adaptation and refurbishment of the existing building stock. Currently many structures are demolished before the end of their design life for reasons that are unrelated to structural performance [80]. Extending the lives of these structures through effective redevelopment could significantly reduce the demand for core structural materials. This requires effective adaptation of old structures to meet new client needs and modern performance standards. This poses a significant challenge to designers, but not an insurmountable one. This practice is increasingly common and banks of successful case studies are steadily becoming available [81,82]. However, further research is required to understand the barriers to adaptive re-use and the influence of building and component service lives on cumulative life cycle impacts [83].

The need for widespread refurbishment of existing structures, including 8 million 'non-decent' homes [14], is also commonly acknowledged. In many past cases demolition has been the preferred option, even where opportunities for refurbishment exist. Currently around 25,000 homes are demolished in the UK every year [69, p. 35] and influential studies have advocated a several fold increase in this rate [84]. Other studies have disputed the benefits of demolition, and advocated refurbishment wherever possible [85,86]. A better understanding of the financial, temporal and design barriers that lead to demolition being preferred to refurbishment could lead to savings in total life cycle emissions. There are a wealth of additional social and economic benefits to refurbishment as compared to demolition, and a great opportunity to preserve the historic, cultural and community value of the existing building stock [86].

Future benefits could also be realised by incorporating the principles of adaptable design in new buildings [22]. As Mackay points out, "the most valuable buildings are those that are adaptable during their life, enabling effective changes of use to take place, but are also easily dismantled into components that can be recycled or reused with minimal energy expenditure" [87]. Embedding these values in current designs could have significant long term benefits, and is equally important as reducing current operational requirements.

4. **Discussion**

As shown in Section 2, embodied emissions are a considerable and growing proportion of the total attributable to the built environment. The majority of embodied emissions are associated with the production of materials. Changes in building fabric, combined with increased construction activity, are expected to drive further increases in material consumption and total embodied emissions. Limited scope remains for significant reductions in emissions associated with material manufacture due to the already highly efficient nature of domestic production processes and the UK's dependence upon imported materials. Therefore drastic reductions in embodied emissions can only be achieved through a reduction in the total use of carbon-intensive materials and the adoption of a range of alternative materials, technologies and practices highlighted in Section 3.

Though a multitude of potential alternatives exist many are not yet widely accepted or utilised. The conservative, cost-driven, and risk-averse nature of the construction industry is well documented [88,89] and research has demonstrated that stakeholders are reluctant to use new sustainable materials or technologies where they stand to suffer the consequences of any failures [90]. Consequently, new materials, technologies or practices are often faced with significant barriers to market entry and expansion. Though isolated studies have started to appear [89,91] the need for greater work identifying the barriers to uptake of new construction materials and technologies has been widely acknowledged by academics, policy-makers and practitioners [12,15,19,92,93]. A preliminary analysis of over 1000 publications[6] gathered for an intended systematic review of alternative materials, technologies and practices reveals a common set of barriers to uptake (see Table 3).

The general diffusion of innovations is well understood in theoretical terms (see [94, pp. 10–12] for an excellent summary). It depends upon a number of technological, institutional, economic and social factors, and is strongly influenced by the interaction of key stakeholders. The institutional framework, established culture and historical events all affect the uptake of a new technology or practice. Old technologies are often 'locked-in' by market feedbacks, a focus on short-term advantages or sunk capital. Initially new technologies must exploit niche markets that afford opportunities to develop the technology through 'learning by doing, using and interacting', as well as time to establish supply chains and user-producer relationships. Growth beyond this phase typically necessitates institutional changes, entry of new firms and formation of advocacy groups. This requires engagement of a variety of stakeholders, including AEC professionals, material suppliers, and regulators. Knowledge and skills take time to develop and it is clear that lack of experience undermines confidence and hinders the diffusion of innovations in the construction sector [95]. Unfortunately this well understood diffusion theory has rarely been applied to construction research.

Whilst a plethora of publications investigate and document the technical minutiae of material performance there is a noticeable dearth of corresponding research assessing the barriers to uptake amongst construction professionals. Qualitative research in this area is limited to a handful of materials and applications, for example the use of timber in

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[6] See Supporting Information.

multi-storey construction [95–99]. Minimal qualitative evidence exists on the common factors affecting uptake of novel materials and practices amongst construction professionals.

Table 3 – Common barriers to the uptake of lower embodied carbon materials, technologies and practices in the construction industry

Institutional and Habitual	Economic	Technical and Performance-related	Knowledge and Perceptions
Institutional culture and established practice promotes preferred material palette Focussed training and recruitment results in departmental lock in to familiar materials Time constraints incentivise familiar ‘copy-paste’ designs Lack of established advocacy groups Lack of effective marketing from producers Lack of user-producer relationships Influence of industry trends Habitual specification and historic practice of individual practitioners Viewed as outwith responsibility or remit of any individual High level of design inconvenience	High cost of new products Market externalises cost of embedded emissions Uncertainty premium placed on novel options High transaction costs of additional professional training and research Money sunk in existing materials (in terms of training, establishing relations with supply chains etc.) Lower design:fee ratio because of increased detailing Insufficient comparative information on costs Unwillingness to accept risk Project financing incompatible with time constraints Anticipated increase in lead times Small industries producing alternatives cannot compete against established industries’ economies of scale	Lack of established standards, design guides and tools, and standardised details Lack of material performance data Lack of full-scale demonstration projects Policy and regulatory limitations and restrictions Lack of confidence in contractor ability and availability of skilled labour prevents inclusion in design Shortage of specialist skills prevents installation Insufficiently developed supply chains Local availability of materials and technologies	Lack of awareness and practical knowledge of alternatives amongst practitioners Lack of client knowledge of alternatives Negative perceptions amongst practitioners based on past experiences Negative perceptions held by clients Insufficient fit with the culture of the clients/inhabitants Perceived unreliability or risk of new alternatives Perceived concerns about material sourcing prevent selection Policy uncertainty Regarded as low priority and other considerations take precedence

From the limited available studies it is clear that ‘culture’ and established practice are significant institutional barriers. In construction, the adoption of systematic innovations is generally impeded by the decentralized nature of the industry, and varies both regionally and across firms of different sizes [100]. Consequently, individual firms or sub-sectors often establish particular work flows and material palettes which are used across all projects. This can engrain a culture of building in certain materials and prevent construction professionals from seeking or experimenting with new materials or practices. Change in established cultures can only be achieved through effective knowledge sharing. Broader research in this area is essential as ultimately it is the beliefs, perceptions, knowledge and skills of AEC professionals that will influence uptake. Often these perceptions may differ from the reality, but the perceptions and attitudes rather than reality determine behaviours [99]. Critical to bridging the gap between perceptions and knowledge is the effective synthesis and dissemination of information on alternative materials, technologies and practices. This information is often scattered across many publications and online sources and is rarely coherently synthesised and presented to practitioners and policy makers. The effective transfer of research from academia to industry, alongside the formation of effective industry advocacy groups (such as The Alliance for Sustainable Building Products) and knowledge hubs (such as the UK Green Building Council's online Pinpoint platform) is critical in encouraging uptake. The high level of redundancies throughout the recession has also undoubtedly weakened the industry's knowledge and skills base. A shortage of training and skills had already been repeatedly identified as a concern, with research suggesting a "quantum leap" in the industry's response is needed [101]. The recession has also resulted in restricted access to finance and weakened the financial position of many companies in the construction industry [102]. This has served to increase anxieties about cost, and force sustainability concerns down the priority list [103].

In addition to the identified barriers there is a fundamental lack of drivers for change. In recent years, the industry has consistently expressed a desire for regulatory and financial drivers, and though significant policy steps have been taken to minimise operational emissions, no effective regulation exists to motivate reductions in embodied emissions [17]. Substantive regulation on embodied emissions is unlikely to be enacted until the next decade, but reductions in the order of 21% will need to be made by 2022 [104]. Where embodied impacts of materials are considered in current environmental assessment schemes (such as BREEAM and the Code for Sustainable Homes), they represent a small, and often isolated, component of a larger appraisal framework incorporating a wide range of environmental factors [105]. Even where headline targets for regulation have been forthcoming, much of the policy detail, such as the definition of 'zero carbon' and changes to Part L, have either been slowly released or repeatedly revised [102]. It is clear that hesitancy and mixed messages from policy makers has undermined industry confidence and delayed investment [106]. Clear, structured and timely legislation in this sector is essential, as where regulatory obligations do not exist sustainability objectives are often ignored [90].

Other than increasing landfill charges, significant financial drivers have yet to appear. The costs of carbon emissions are still not effectively absorbed by the emitter or consumer. There also remains scant evidence of a premium for 'green' properties in either the residential or commercial markets [106,107,108]. Furthermore, there is limited client demand for change. Whilst there have been isolated examples of eco-conscious clients provoking exemplary design, for the majority of clients environmental impacts remain a secondary concern. Project cost, timescales, functionality and aesthetics remain the principal client priorities [109]. There is thus a dilemma. It is clear that the embodied emissions associated with construction must reduce, but no strong regulatory, financial, or client drivers exist.

Underlying this dilemma is a fundamental question of responsibility. Whilst many stakeholders recognise the need for change, few are willing to adopt the associated financial or reputational risk [90]. Furthermore, given the salami-sliced nature of the design, procurement, construction and operation of a structure it is often hard for an individual stakeholder to exert a strong influence. Stakeholders often feel unable to enforce sustainable solutions 'down the line', just ensuring minimum standards are met is difficult enough, let alone the adoption of best practice solutions [90]. This problem was one of the key challenges identified in the GCB Routemap which concluded that "taking responsibility for carbon reduction at an industry level is essential to driving uptake and delivering results as quickly as possible. There are many sectors where no industry body "owns" the carbon and no plans have been developed to manage carbon reduction" [19, p. 3]. This question of responsibility urgently needs to be addressed, as it is only through effective allocation of collective and individual responsibility that progress will be made in translating headline targets into decisions at a project level.

It is also, as yet, unclear what order of emission reductions exploiting the presented options could yield. Whilst recent years have seen a profusion of product LCAs, many of these are based on simple process-based analyses (PA-LCA) that suffer from limited system boundaries that do not encompass the full direct and indirect impacts of the product [110]. This systematic truncation error, the magnitude of which will vary from product to product, can typically be of the order of 20-60% [111,112]. It is clear that the LCA process, originally developed for manufactured products, has still yet to be effectively adapted for large, complex structures that are unique in nature and construction [113]. Many aspects of the life cycle are context specific and the service lives of materials are often long, highly variable or difficult to estimate [114]. Often these aspects of the life cycle have to be assumed and can be determinant in the outcome and product selection. The increasing dependence upon generic LCI datasets such as ICE [115] and Ecoinvent [116] also increases the susceptibility of PA-LCAs to several sources of error. The data contained in generic databases are often based upon production methods from firms operating in other regions, using different technology, during different time periods [117]. In addition, some sectors are often sparsely represented in databases, resulting in skewed distribution of process detail by sector that can lead to 'aggregation by proxy' and 'sectoral background truncation' [112]. Consequently, whilst judicious use of such generic datasets can ease calculation, the data contained therein should be used with caution.

Alternative approaches based upon Environmentally-extended Input-Output Analyses (EIO-LCA) provide a top-down alternative. EIO-LCA considers the whole economy as a system boundary and thus avoids truncation errors whilst providing a boundary that is consistent across analyses [118]. This makes it more suitable for comparison of options, particularly at the macro-scale. However, whilst it mitigates the principle problems of PA-LCA it suffers unique errors that stem from the underlying proportionality assumption, aggregation uncertainties, and allocation uncertainties [111]. The data, whilst more systematically gathered and more complete than process-based data sets, is still of dubious quality and often represents sectors at a very coarse resolution [110]. It is also uncommon for imported products to be represented in detail and is therefore inappropriate for sectors or products with a high dependence on imports (e.g. aluminium). This is a particular concern for the UK construction industry where the sector resolution of available data is much too coarse.

Hybrid approaches combining PA-LCA and EIO-LCA remain in their infancy and are typically very data and time-intensive to assemble [117]. All approaches are highly dependent on the quality of input data, which is still sparse and infrequently updated for many regions and applications. This gives rise to the common view that LCA is “a flawed tool that cannot deliver what it promises” [118]. Furthermore, this combination of truncation errors, mismatched boundaries, and source data uncertainty are often masked in the presentation of LCA results. Commonly only headline figures are available to decision-makers with the consequence that product selections are often made with incomplete, inaccurate or incomparable information.

It is also as yet unclear how the sum of individual product selections based on limited information could yield savings in capital carbon emissions of the order required (e.g. 21% by 2022 and 39% by 2050, as identified in the GCB Routemap project). A dearth of quantitative evidence exists, not only in assessing the environmental impacts of individual construction materials and products, but in evaluating the cumulative sector wide changes that may be necessary to meet emissions reduction targets [12,15,19]. Further research is required to develop a means for translating sector wide targets to specific structure types and individual projects. Additional data gathering is also required to establish suitable benchmarks for design teams. Industry or regulatory strategies that focus on material efficiency or substitution can also result in unforeseen macroeconomic impacts and affect significant structural change in an economy [40,119]. Such potential secondary impacts have yet to be evaluated.

It is clear that further research is needed to estimate the scope for emission reductions from these alternatives, and to identify and overcome the barriers to their uptake. Only once these issues are better understood, will it be possible to form a credible routemap for the construction sector that could achieve the requisite embodied emission reductions.

5. Conclusions

The UK construction industry faces the daunting task of replacing and extending a significant proportion of UK infrastructure, meeting a growing housing shortage and retrofitting millions of homes whilst achieving emissions reductions compatible with the UK’s target of an 80% reduction in GHG emissions by 2050. Data representing the carbon footprint of UK construction shows that, aside from the fall attributable to the global financial crisis, GHG emissions associated with construction are significant and growing.

Embodied emissions are a considerable and growing proportion of the total attributable to the built environment. The majority of embodied emissions are associated with the production of materials. Changes in building fabric, alongside an anticipated increase in construction activity are expected to drive further increases in material consumption and total embodied emissions. Many key materials, such as steel and cement, are produced by highly efficient processes with limited scope for radical improvements as unavoidable emissions from fundamental chemical processes now dominate. Over recent decades an increasing proportion of UK material demand has been met by overseas supply chains. Therefore the opportunity to drive emission reductions from interventions targeting UK material manufacturers is extremely limited. Consequently, the construction sector’s challenging emission reduction targets will only be met through a reduction in the total throughput of carbon-intensive materials. This will require the uptake of a combination of alternative materials, technologies and practices.

Whilst a variety of alternatives exist, greater research is needed to characterise and overcome the barriers to widespread uptake amongst construction professionals. Synthesis of existing research is also required to inform practitioners and policy makers and to identify the most viable combinations of options for the UK. The modelling approaches that could support a robust assessment of these options are still in their infancy, and the requisite data is in many cases insufficiently granular. Further progress in data gathering schemes and development of robust building level LCAs is essential. However, improvements in data quality, design aids and practitioner knowledge will not stimulate use of these alternatives without additional drivers for uptake and effective allocation of responsibility for emissions reduction along the supply chain. In the event that client demand for structures with low embodied carbon does not materialise swiftly enough, additional policy drivers will almost certainly be required to spur demand. Only once all these problems are addressed in tandem will it be possible to form a coherent and credible forward plan for the UK construction industry.

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Figures

Figure 1 – Embodied GHG emissions of the UK construction sector 1997-2011

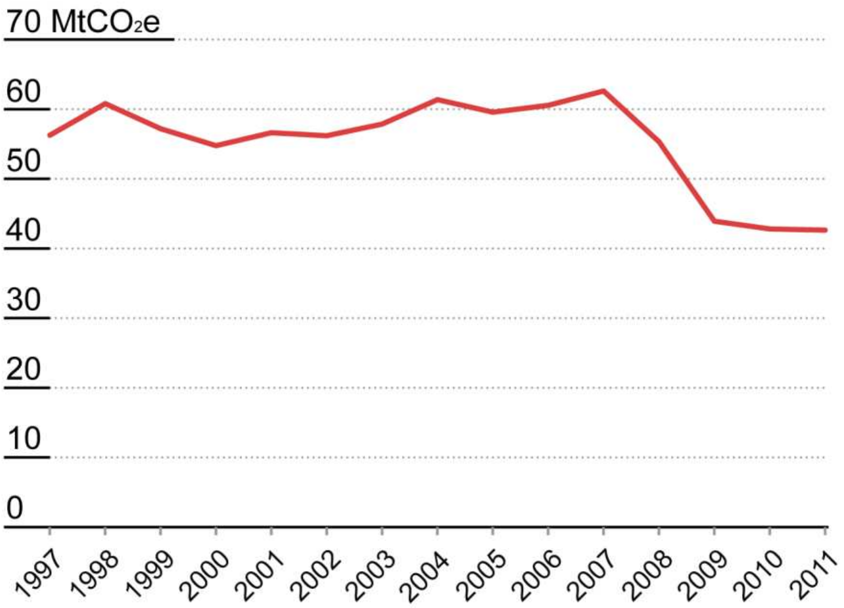

Figure 2 – GHG emissions of the UK construction supply chain by activity

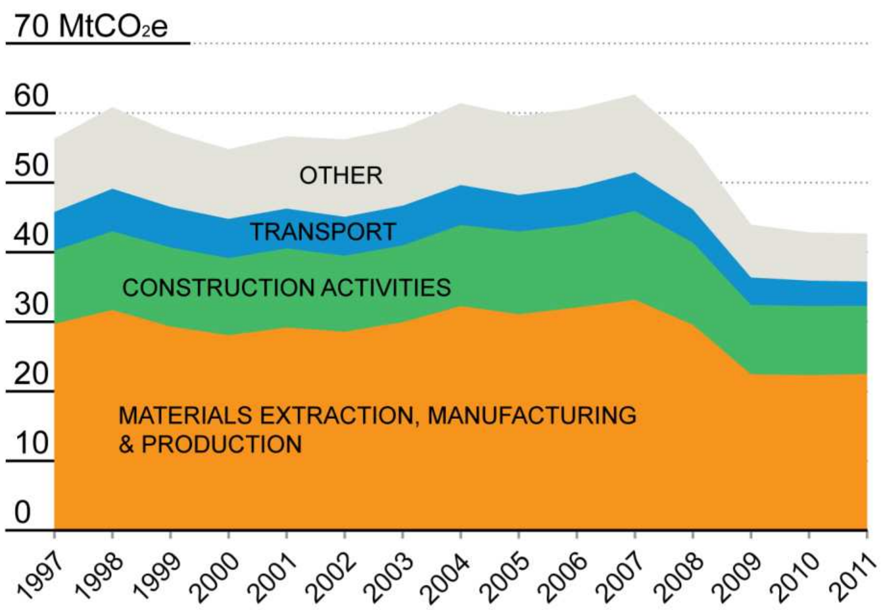

Figure 3 – GHG emissions of the UK construction supply chain by region