Construction Sector Innovation within Absolute Zero




Business growth in a transformative journey to zero emissions

UK FIRES

Construction

UK FIRES is a 5-year research programme funded by £5m of UKRI support and the subscriptions of an active and growing industrial consortium. With academics from six universities spanning from materials engineering through data science to economics, corporate strategy and policy and an industry consortium spanning from mining through construction and manufacturing to final goods.

UK FIRES stands for placing Resource Efficiency at the heart of the UK's Future Industrial Strategy. When we proposed UK FIRES, it was to focus on Resource Efficiency as the key means to reduce industrial emissions. However, in 2019, both houses of Parliament unanimously approved a change to the UK's climate change act to target zero emissions in 2050. This has been reinforced by recent Government targets for 2030 and 2035.

So, although we haven't changed our name to UK FIZES, our focus is now on placing Zero Emissions at the heart of the UK's Future Industrial Strategy.

UK FIRES takes a pragmatic approach: we focus only on technologies that are available to us today and exclude those that have yet to be proven at meaningful scale, since they simply may not be ready in time. In 2050 we aim to meet the energy demand of UK society by non-emitting electricity generation.

In December 2019, UK FIRES released the "Absolute Zero" report, a ground-breaking description of the operation of the UK with zero emissions by 2050, without relying on as-yet un-scaled energy sector or negative emissions technologies. This pragmatic but striking view of the journey to zero emissions has attracted widespread interest including a full debate in the House of Lords in February 2020.

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Authors: Hawkins, W., Drewniok, MP., Dunant, C., Horton, PM., Romain, P., Stephenson, S., Sergent, F., Allwood, JM.

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Contact details: UK FIRES is led by Professor Julian M. Allwood FREng who can be contacted via our website, www.ukfires.org.

Executive Summary

£74bn

total annual UK construction output

££

billions growth opportunity in material restraint

The construction industry will be transformed in a zero-emission society; from the choice of materials, their production and the design of structures, to the organisation of towns and cities. The built environment is a great enabler of other transformations in the way we work, play and live, and in transportation and energy.

Today, the built environment produces significant emissions both from its operation – heating, lighting and cooling – and embodied in the production, construction, maintenance and demolition of its constituent materials and components. Eliminating both forms of emission requires transformative change, yet the pathway for operational emissions is, whilst requiring major investment and labour mobilisation, relatively clear: grid decarbonisation, electrification and mass retrofit of buildings for energy-efficiency. For new buildings, modern standards such as PassivHaus allow the virtual elimination of operational energy.

Eliminating embodied emissions will bring far more fundamental changes. There is great potential to use less material without compromising functionality. However, while being essential, transformative, and creating vast potential for innovation, efficiency alone is not enough to reach zero emissions. The shape of the urban environment will also change, allowing for denser living and reduced transport needs and energy consumption. Yet this is still not enough.

To bridge the gap, the pallete of available construction materials must also transform, eliminating those with inherently emitting process and bringing forward non-emitting alternatives. These will include: naturally low-energy materials such as stone, earth and timber; components reused and repurposed from demolition; and electrified supplies of recycled steel, cement and bricks, albeit limited by a constrained supply of non-emitting electricity under high demand.

For the transition to occur at the required speed, the shape of the built environment must be designed to allow innovation to accelerate. This great transformation is also a great opportunity to improve the design of houses, the quality of life of all, and to enable a myriad of businesses capable of providing the know-how to meet the needs of the future. In this report, we present some of the needs, and the opportunities which will arise from them, and show how a zero-carbon construction industry can thrive.

Key Messages

Delivering zero emissions in UK construction by 2050 will lead to substantial business growth across the full construction supply chain:

- **For material suppliers:** Because some processes, such as cement kilns or blast furnaces, inevitably cause emissions, they will have to close. This will restrict the supply of common construction materials, leading to growth in zero-emission materials with minimal process requirements such as those from natural or waste sources. All remaining processes will be electrified;

- **For manufacturers:** Materially-efficient products and processes will become increasingly competitive, whilst a greater emphasis on maintenance, repair and refurbishment will open up new business models;

- **For builders and contractors:** The electrification of site activities will lead to investment in new plant and equipment, and the growth of low-carbon construction materials and products will create new demand for specialist skills and knowledge;

- **For designers:** A constrained inventory of materials and components will foster new approaches to design, requiring broad knowledge of materials, new software tools, creative reuse and adaptation, and a greater emphasis on resource efficiency;

- **For policy-makers and planners:** Transitioning to low-carbon lifestyles will require new, joined-up, high-density urban infrastructure, with the existing building stock adapted and extended to minimise new construction.

Background

Concrete

Abating cement emissions is most easily achieved by replacing Portland cement with greater quantities of supplementary cementitious materials (SCMs). Today's SCMs are typically by-products of blast furnaces (GGBS) or coal-fired power stations (fly ash - FA); both sources which are already limited and incompatible with a zero-carbon economy. Alternatives will therefore be required, the most promising of which are calcined clays, created through the calcination of kaolinite which, although energy-intensive, can be electrified. Domestic supplies of kaolinite clays are plentiful, however calcined clay can only replace up to 50% of Portland cement. As a result, the mass low-cost consumption of concrete will no longer exist in 2050, since the unavoidable emissions will require genuine, expensive and limited offsetting to match. Currently, the UK consumes 90Mt of concrete each year, with a value of £9.2bn.

Steel

To have zero emissions, smelting of iron ore relies on energy-intensive carbon capture and storage (CCS) technology which is unlikely to be economical by 2050. However, it is possible to make zero-carbon steel without CCS in a renewably-powered electric arc furnace (EAF) with 100% recycled feedstock. Considerable investment is required to prepare the UK's steel manufacturing capabilities to EAFs, which currently produce only 22% of steel in the UK (compared with 40% in the EU). Although 85% of waste steel is already recycled, this transition will increase the demand for scrap, incentivising the exploitation of new sources and UK-based metal sorting and processing facilities, whilst still heavily restricting the total supply of steel. Today, two million tonnes of steel are used in UK construction each year, with a value of £1.7bn.

Timber

Today, timber construction produces considerable carbon emissions; however, none of these are 'locked-in' by chemical processes, making decarbonisation relatively straightforward. Kiln-drying is commonly powered by natural gas or biofuel, but may be decarbonised through solar heating or electrification in the future. Forestry, limbing, debarking, sawing and transportation must also be electrified to make a zero-emission product. The sustainable supply of timber is limited by the annual increment of forests. Although this is increasing in the UK and Europe, supply cannot rapidly match increased demand; a typical rotation period for UK-grown timber is 35-45 years, and considerably longer at the higher latitudes and altitudes from which the majority of the UK's timber is imported.

Clay products

Bricks are typically used in a non-structural capacity, yet we still produce over 2bn annually in the UK with a value of £1.2bn. Bricks have a high embodied carbon due to high firing temperatures, a process which can be electrified - albeit at a very high energy cost. Today, over 70% of the UK's housing stock features a brick outer layer, yet this is likely to become an increasingly costly option as non-emitting energy comes under increasing demand from other decarbonising sectors.

Glass

Primary glass making requires temperatures of 1700°C, currently achieved typically using natural gas, and produces additional process emissions which cannot be avoided through electrification. As a result, zero-emissions glass must utilise recycled feedstock, for which supply and processing infrastructure are already well-established. This need for complete circularity will somewhat constrain the supply of glass, and the energy-intensive recycling process will encourage direct re-use and reconditioning of glass panels from demolition sites.

Aluminium

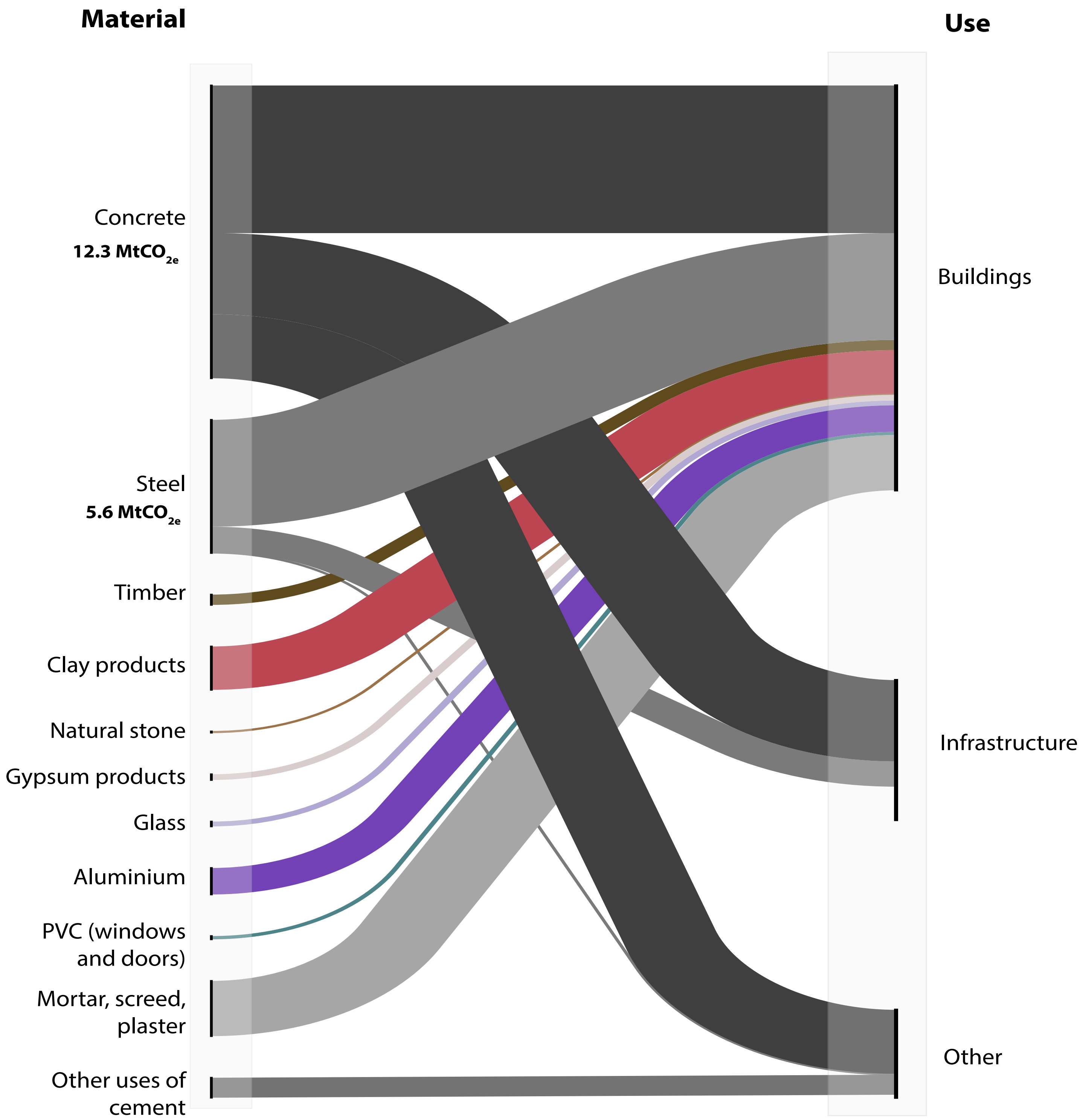
Aluminium is typically found in building cladding systems. Its primary production has high embodied carbon emissions due to both the release of CO_2 from electrolysis and the large amount of electricity required. Although the latter will decrease due to grid decarbonisation, process emissions are unavoidable, making re-melting of recycled material the preferred zero-emission compatible pathway. As for steel, this will lead to increased demand for scrap, and higher prices due to a restricted supply of the material

Plastics

The production of plastics is currently carbon-intensive, particularly when produced from virgin fossil fuels. Today's low rates of plastic recycling will need to increase dramatically in the zero-carbon transition, although this will require the currently extensive range of available polymers to reduce. As a result, plastics will become increasingly constrained and expensive to produce, and bioplastics will take the place of oil-derived virgin materials. Today, the construction sector accounts for a seventh of all plastic used in the UK annually, with 68kt of plastic packaging film waste also arising from the sector.

Today's construction industry is reliant on a small number of key materials, of which concrete is most dominant. With distinct production processes and technology options, each material is more or less suited to the constraints of a zero-emission economy. The diagram opposite shows how material use is currently distributed across the main construction sectors.

Embodied CO_{2e} emissions in UK construction by material - 2018



Total emissions: 25$MtCO_{2e}$

A vision for the future of the built environment in a zero-carbon world

A reducing supply of emitting construction materials

Decarbonisation will drive a transformative change for the UK's construction industry. Most of today's construction materials cannot be made without emissions, so construction in 2050 must operate with a highly restricted set of resources. This is likely to include recycled steel, sustainably-harvested natural materials, recycled glass and aluminium, and a limited amount of zero-carbon concrete. These will be augmented by modules and components re-used from previous structures. In the decades to 2050, and beyond, it will drive changes from high-level planning decisions right down to the way materials are produced, and everything in between. This creates wide-ranging innovation opportunities.

Overall demand reduction with expanded supply of non-emitting materials

The graph below shows how a zero-carbon UK construction industry can arise, based on the volume of emitting and non-emitting materials. The underlying assumptions are described in the 'How we Created this Report' section.

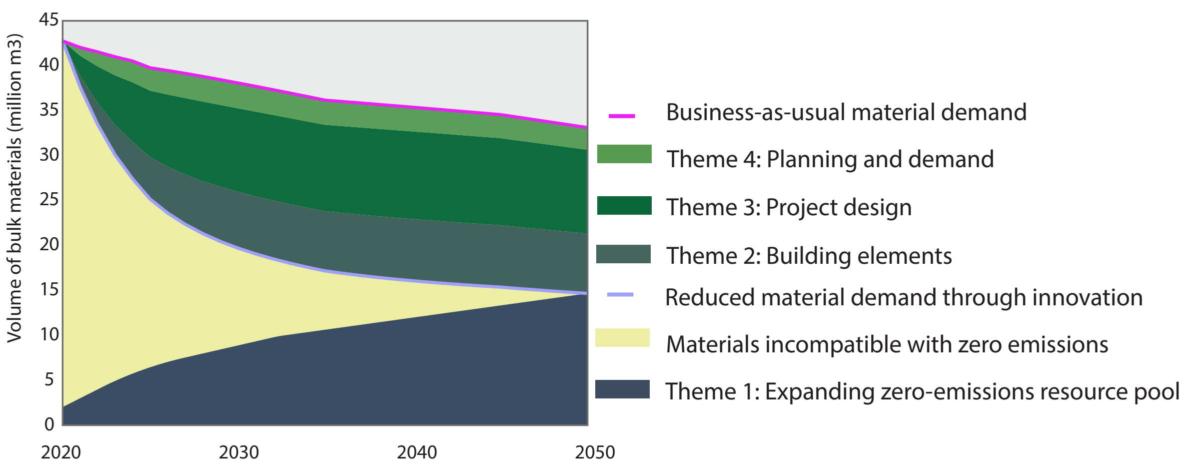
Many of today's production processes inevitably release carbon emissions, making them incompatible at-scale with a decarbonised economy. Although the overall demand for construction materials in the UK will already decrease under a 'business-as-usual' scenario' as population growth slows, the phase-out of emitting materials will necessitate an additional drop in material consumption, increasing the demand for materially-efficient technologies and designs. Nonetheless, a rise in living standards and continued maintenance of infrastructure will still require vast amounts of structural materials, and these must be replaced by an increasing supply of non-emitting equivalents.

This report describes the innovation opportunities created by a transition to zero emission construction. It is split into four themes which consider the full construction supply chain, starting by **Expanding the zero-emission resource pool** (*Theme 1*) to create a decarbonised material supply, then considering the implications for downstream **Building elements** (*Theme 2*), the role of **Project design** (*Theme 3*), and changes to **Planning and demand** (*Theme 4*) which will together drive the scale of change needed for a zero carbon transition.

Policy Support

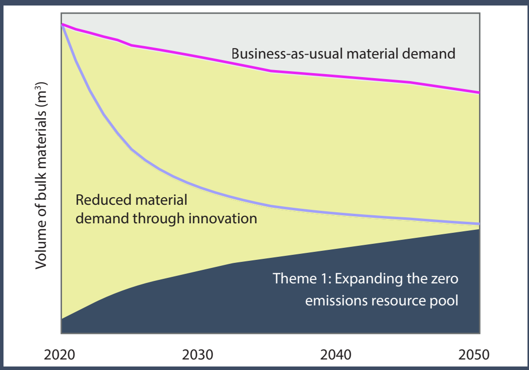
Current and proposed construction regulations do not recognise the incompatibility of typical building practices with net zero targets, whilst some policies actively disincentivise sustainable practice, such as VAT exemption for new construction but not retrofit and refurbishment.

Public policy that works to support and not hinder innovation is crucial to its success. Opposite, we highlight the key policy changes to kickstart innovation in response to the opportunities identified across the four themes of this report. By recognising the responsible actors in each case, the need for a cross-sectoral and cross-departmental effort is highlighted.



Challenge	Policy approaches	Actor
	Theme 1: Expanding the ZE resource pool - *What we use to build*	
The vast majority of the materials used today are incompatible with a zero emissions economy, we therefore need policies to support the growth of zero carbon resources to meet demand.	Supporting the development of new standards and guidelines for low-carbon building materials; Tax incentives to better exploit waste streams, encouraging direct reuse and high-value, low-energy recycling.	BSI HM Treasury HM Government (The Building Regulations) Infrastructure and Projects Authority NHBC
	Theme 2: Building elements - *How we build*	
Greater efficiency and reduced material use in buildings is achievable with existing construction techniques. New policies to direct best practice towards these more efficient approaches are required.	Embed environmental assessment within existing construction product regulations to encourage manufacturers to publish high-quality environmental data; Create an open, transparent and official national database of material and product life cycle assessment information; Tighten planning regulation around wasteful or carbon-intensive features, such as deep basements. Facilitate direct re-use of building components by modifying regulatory barriers intended for new products.	BRE Group NHBC BRE Group / UKGBC / GCB / IStructE / ICE / RIBA Planning inspectorate / government departments Infrastructure and Projects Authority
	Theme 3: Project design - *What we build*	
Early stage design choices can dramatically reduce embodied carbon, but this is rarely considered alongside competing design features. Centring these concerns would change the structure of buildings without necessarily impacting functionality	Endorse an official, standardised national methodology for life cycle impact assessments; Mandate life cycle carbon assessments for all construction projects, enforced through planning or building regulation 'Approved Documents', and ratchet down targets in line with wider climate pledges; Remove VAT on retrofitting and refurbishment of buildings; Stricter regulation against the demolition of safe buildings.	Department for Levelling Up, Housing & Communities (DLUHC) Local planning authorities DLUHC HM Treasury Local planning authorities
	Theme 4: Planning and demand - *Why we build*	
Post-COVID, net zero compliant thinking of how we use our built space, must occur at a centralised planning level. Creating the right infrastructure and ensuring the best utilisation for existing buildings is essential to reducing aggregate emissions.	Large scale up-skilling and training of workforce for retrofit, low-carbon materials, carbon assessment and lean design; Reduce private transport dependency through holistic planning decisions and '15 minute cities'.	Department for Education Local planning authorities, Infrastructure and Projects Authority

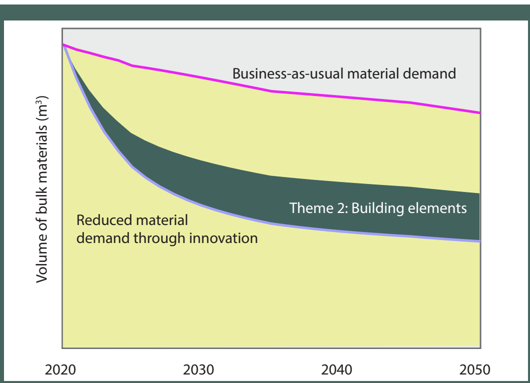
Innovation themes and opportunities



Theme 1

Expanding the zero-emissions resource pool

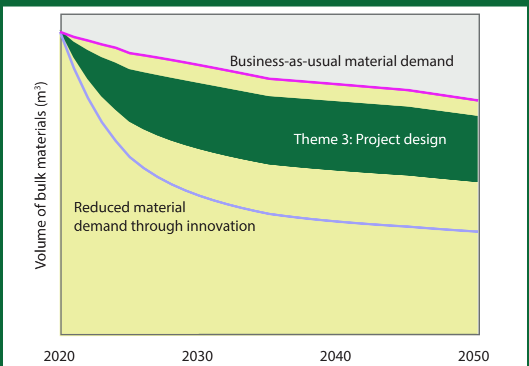
What we use to build



Theme 2

Building elements

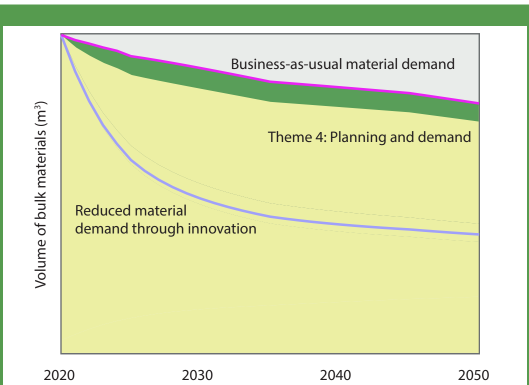
How we build



Theme 3

Project design

What we build



Theme 4

Planning and demand

Why we build

Opportunities

Waste as material supply
Plant-based materials
Stone and earth
Plastics
Decarbonising on-site activities

Opportunities

Reused components
Materially efficient floor systems
Foundations
Exploiting geometry for material efficiency

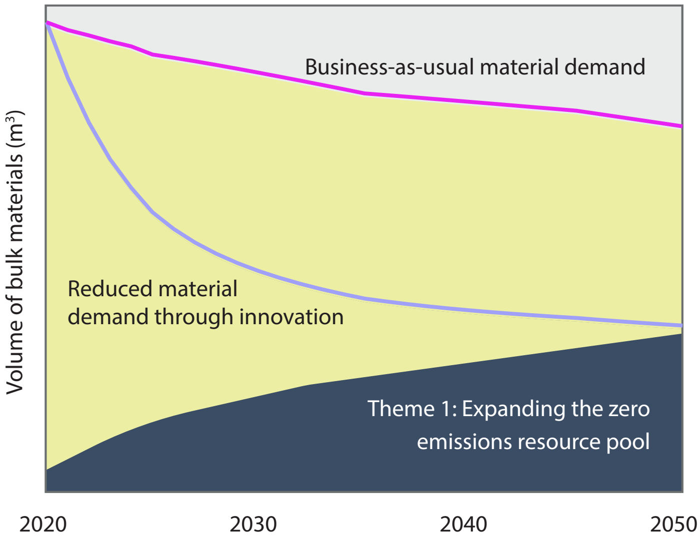
Opportunities

Life extension and adaptation
Questioning the brief
Changes to fee structures
Maximising operational efficiency
Carbon accounting

Opportunities

Minimising new construction
Reassessing our building footprint
Leasing buildings as services
Urban planning for zero emissions
District/centralised heating
Education and training

Expanding the zero-emission resource pool: *What we use to build*



Traditional materials such as concrete, steel, aluminium and brick will require fundamental changes to production methods to decarbonise, significantly impacting their availability and cost. As a result, the many natural materials currently considered 'alternative' will be increasingly sought after, and the value of waste materials which can be reused will increase. These changes will bring a diverse range of opportunities for new business innovations.

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Opportunities

Waste as material supply

Construction and demolition produces half of the UK's total waste. For many materials, the quantity of waste is at a similar magnitude to consumption of new materials: we dispose of 1Mt structural steel, 0.6Mt reinforcing bar, 24 Mt hardcore and 0.2Mt structural timber, compared to 0.8 Mt steel sections, 1.2 Mt reinforcing bar, 54Mt concrete, 5Mt bricks and 0.6Mt timber consumed.

In 2019, UK firms paid £683m in landfill tax.

£683m

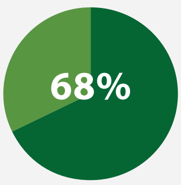
At present, the amount of construction waste generated in the UK is comparable to, or even exceeds, the materials consumed.

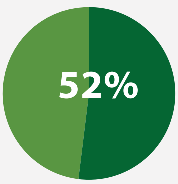
Although 92% of waste is currently recycled, much of this is crushed to produce low-value aggregates and hardcore. Direct re-use of components should be prioritised over recycling: for steel, the energy savings are significant; for concrete, we avoid emissions from cement production and for timber, we prolong lifespan and delay re-release of stored carbon.

Preserving the value of waste materials using zero emission methods will bring a range of new business opportunities:

- Domestic recycling facilities will be increasingly viable in response to growing raw material costs. These will also avoid the need for international shipping, which is hard to decarbonise. Today, 77% of the UK's steel scrap is exported overseas;
- Specialist assessors will be able to determine the reuse potential of structural elements. They will identify which part of the structures can be resold at a profit, and establish demolition plans which will maximise this;
- Demolition contractors will take on the role of stockists as they will have prime access to components for reuse. They will add reconditioning to their portfolio of know-how and will partner with fabricators;
- New synergies between industries will be exploited, such as the ability to turn concrete waste into new cement via the steel recycling process - Cambridge Electric Cement.

Plant-based materials





££ x2

The UK imports 68% of its sawn timber and 52% of its wood-based panels. The total timber imports value in 2021 was £1.7bn, a 62% rise from 2015.

The price of imported timber has more than doubled since 2015.

The production of timber can be feasibly made zero carbon through electrification, and it will therefore play a major role in the decarbonisation of construction. The key challenges are to keep timber cost-competitive in the face of rising demand, maximise potential applications and expand the sustainable supply:

- Electrification of the timber production process will require new logging, sawing, kiln-drying and transportation equipment;
- New bio-based adhesives with zero emissions will be required to replace those currently used in the production of engineered timber products;
- Structural timber from domestic supplies will increase in response to rising global demand and the carbon cost of shipping. This will require increased forest planting and management, new sawmills and manufacturing facilities;
- Timber piled foundations are a proven low-carbon solution in many applications;
- Durability and fire resistance remain key concerns for timber buildings, creating a strong demand for new solutions such as coatings;
- New manufacturing processes for low value timber, currently used for fuel, pulp, packaging or panels, will enable this to be used in construction, adding value and meeting an ever-increasing demand.

Fast-growing plants such as bamboo, straw, and hemp sequester carbon more quickly than trees, and can meet rising demand more rapidly. Bamboo, both in the round and engineered into panels and beams, is likely to see increased use, as are established plant-based construction materials such as straw bale and hempcrete.

Stone and earth

£1.1bn

Concrete blocks dominate todays masonry wall construction, a market worth around £1.1bn each year.

4.7M m^3

4.7Mm³ of concrete is used annually in the UK to make shallow foundations for low-rise domestic buildings.

Natural stone masonry is currently expensive and labour-intensive. Nonetheless, in a zero-carbon world, it could see a revival: the cutting and transportation of stone can be feasibly made fully-electric. Foundations made using masonry blocks underpin all our historic tall buildings, and opportunities to re-discover these technologies and apply them to modern construction could yield significant carbon savings where conditions allow, as well as giving unparalleled levels of durability.

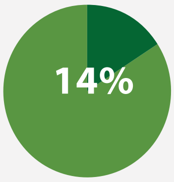
- New markets for zero-carbon blocks and foundations will lead to a revival of quarrying and stone cutting in the UK;
- Rammed earth is a proven and potentially zero-emission alternative which can utilise abundant local materials and improve the energy performance of buildings. Innovations which reduce its high labour requirements could unlock this technology;
- Pad foundations using gravel confined by used car tyres have also been proven to be effective and highly economical (see case study);
- In certain soil conditions, an adequate shallow foundation can be formed using rubble-filled trenches, a simple, low-cost and very low-energy alternative to a concrete strip;
- Floor screeds currently use 800,000 m^3 of concrete per year. Alternatives such as cement-free dry screeds or those using calcium sulphate as a binder will become increasingly attractive.

Source: The School of Natural Building

CASE STUDY

The Tulse Hill Neighbourhood Hub, constructed between 2017 and 2021, was designed to be built entirely by non-professionals and completely eliminates concrete. This is achieved using a timber frame, straw bale walls, and innovative pad foundations with car tyres and gravel. This structure is highly cost-effective, has a 200-year design life, and won two gold awards at the National Building & Construction Awards 2021.

Plastics



Construction accounts for 14% of UK plastic consumption.

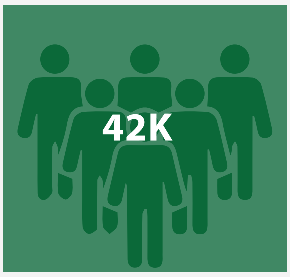
3Mt

3Mt of UK plastic each year is landfilled, incinerated or exported overseas, 90% of the total waste stream.

Plastics have a high embodied energy and carbon through their production via the petro-chemical industry. Yet they are a key material group for construction with a diverse range of applications: surface treatments, membranes, windows, packaging, pipework and many, many more. With their embodied emissions likely to remain stubbornly high, a move away from our current approach to plastics will require broad innovation.

- With their renowned durability, direct reuse of plastic components represents a considerable opportunity to reduce primary production. New business models based on collection, refurbishment and sale of used plastic elements will emerge;
- Bioplastics typically have a considerably lower embodied carbon than petroleum-based alternatives, and will also biodegrade when disposed of;
- Repairs, maintenance and refurbishment currently account for 15% of the UK's cement consumption, and are unavoidable for ageing infrastructure. Alternatives which avoid Portland cement, such as polymers or geopolymers, are likely to become more popular as embodied carbon becomes increasingly important.

Decarbonising on-site construction activities



Total UK revenue in construction equipment was £13bn in 2018, employing over 42k people.

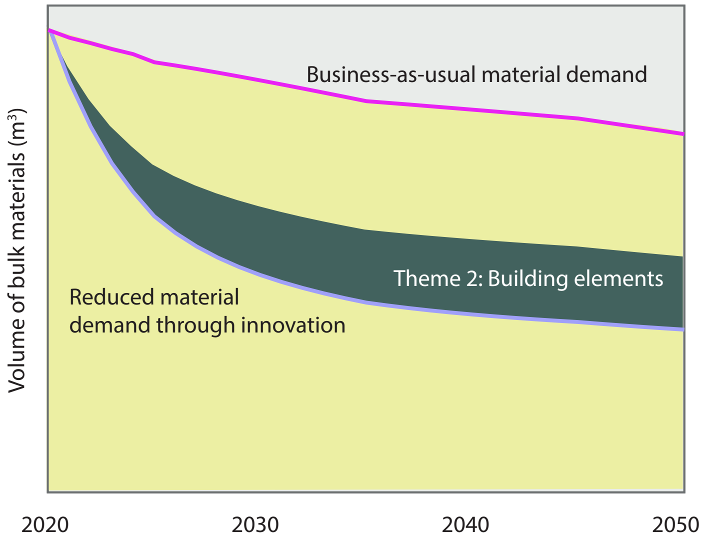
13.4Mt CO_{2e}

Construction activities in the UK emit 13.4MtCO_{2e} each year, 3% of territorial GHG emissions.

While material production currently accounts for the bulk of construction emissions, a significant minority is produced during the construction process itself through energy consumption and direct fuel use. The route to decarbonised construction sites brings a number of growth opportunities for the sector, since it requires full electrification, maximum energy efficiency and the minimisation of material waste.

- Manufacturers of electric plant and machinery will capture the full market;
- New processes for utilising site waste will offer significant cost savings to both demolition contractors and recycling businesses;
- Repair and refurbishment of existing equipment will be vital due to resource constraints;
- A constrained and fluctuating emissions-free electricity supply will require new approaches to on-site energy management and storage to minimise costs.

Building elements: *How we build*



The UK's ambitious target of a 45% reduction in emissions from 2018 to 2030 can only be achieved through reduced material demand – transformative changes in material production methods will take longer to achieve. This means that construction will operate within an increasingly constrained supply of newly produced materials. Thankfully, there are many existing technologies, either in development or currently in-use, which can offer significant reductions in material consumption today, and others which are also compatible with a zero-carbon future.

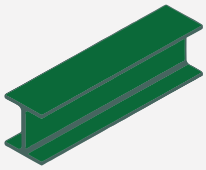
Emily Tolan / Shutterstock.com

Opportunities

Designing with reused components

12.5M m^3

A non-domestic floor area of 12.5Mm^3 is demolished in the UK each year.



New steel components are over six times more valuable than scrap, creating a large potential profit margin for direct reuse.

The energy-saving benefits of directly reusing building components without recycling will create additional innovation opportunities for designers. Many building elements are far more durable than the buildings of which they are part. For new buildings, designing components such that they can be later disassembled and reused will become standard practice. For demolition, new methods and business models will arise to enable components to be reused.

- Inventory constrained design approaches, and enabling software, will streamline the use of existing components in a radical departure from today's default 'bespoke' approach;
- New, durable, proprietary systems which allow simple deconstruction and re-use will capture increased market share. As a co-benefit, easily demountable buildings can be more easily adapted to suit changing needs;
- New equipment will be needed to cut out reusable sections of masonry or concrete from existing buildings;
- New ownership models, with building elements leased from suppliers rather than owned, will unlock a circular approach to design, as well as reducing initial capital barriers to construction, incentivising durability and creating a business model for component reuse.

Materially-efficient floor systems

£74 bn

The total floor area of new buildings constructed annually in the UK is 43Mm^2, with a value (output) of £74bn.

14.4 Mt

14.4Mt of ready-mix concrete, prefabricated concrete and concrete blocks are used for ground floors each year.

£700 m

16.4Mm^2 of upper floors in buildings in the UK are concrete with an approximate material value of materials £700m.

£56 m

Cross-laminated timber (CLT) has emerged as a low-carbon alternative to concrete floors, with a market now worth £56m per year.

The majority of a building's structural material typically exists within its floors. These are also the least materially-efficient, where the desire to minimise total thickness, and therefore overall building height, conflicts with the improved efficiency offered by deeper, stiffer structural sections. The least structurally-efficient floor system is also currently one of the most popular: the reinforced concrete flat slab. As embodied carbon becomes increasingly prioritised, more efficient systems will become necessary, whatever the material.

- A simple switch away from concrete slabs to steel composite decking can save approximately 20% of the upfront embodied carbon on an average office building;
- Significant savings can also be achieved using pre-tensioned hollow-core concrete slabs in place of traditional slabs;
- Deep flooring systems with service integration allow increased structural efficiency without adding to a building's total height;
- As the global demand for forest products grows, timber construction systems which maximise efficiency will come to dominate the market. This might incorporate additional ribs, carefully positioned voids, or mitigate vibration or deflection issues through active damping or displacement control;
- Hybrid floor systems, combining steel, timber and even bulk materials, are also zero carbon compatible and can offer benefits in many applications;
- Vaulted floor systems have been shown to offer dramatic reductions in material consumption over even the most efficient slab and beam systems, and could be constructed using masonry blocks, tiles, or even timber with minimal material.

Foundations

2.5Mt CO_{2e}

Foundations account for nearly half of ready-mix concrete consumption in the UK with an emission of 2.5 $MtCO_{2e}$.

Concrete dominates foundation construction at all scales, from single-storey dwellings and sheds through to the tallest towers and largest infrastructure projects. For many applications, alternatives are less obvious than they might be for above-ground structures. However, the increasing cost of concrete, and acknowledgement of its associated emissions, will create a multitude of innovation opportunities; firstly for construction techniques which maximise material efficiency, and secondly for those which use alternative zero-emission compatible materials. The best choice of foundation technology depends on many factors, including construction methods and ground conditions, but there is a stark difference in material efficiency between options.

- Steel screw piles can be used for low-rise applications and are have a long history of use with temporary structures. Being quick to both install and remove, steel screw piles offer an ability to form a foundation without concrete and with limited excavation. As we move to a low-carbon economy, this will become a key advantage alongside their ease of re-use;
- Hollow piles can save considerable quantities of material without sacrificing geotechnical strength, and will require new construction methods;
- Shallow foundations which are cement-free and practical, perhaps using stone, timber or recycled material, will replace concrete strips and pads;
- New systems for ground-bearing slabs will be required, which can both avoid the use of cement and enable deconstruction and reuse without wet trades;
- Ground improvement techniques which operate in-situ, such as using lime to stabilise clays, are another solution which can minimise or eliminate the need for concrete.

Exploiting geometry for material efficiency

Over half the material and embodied carbon in a typical concrete floor can be eliminated through re-shaping.

Long-span structures such as roof canopies can become materially-intensive due to the large bending forces which they attract. As more material is added to give strength, so the self-weight increases. However, more elegant systems which act purely in tension or compression (membrane action) can be orders of magnitude more efficient. This is particularly effective for long-span structures which principally support their own self-weight.

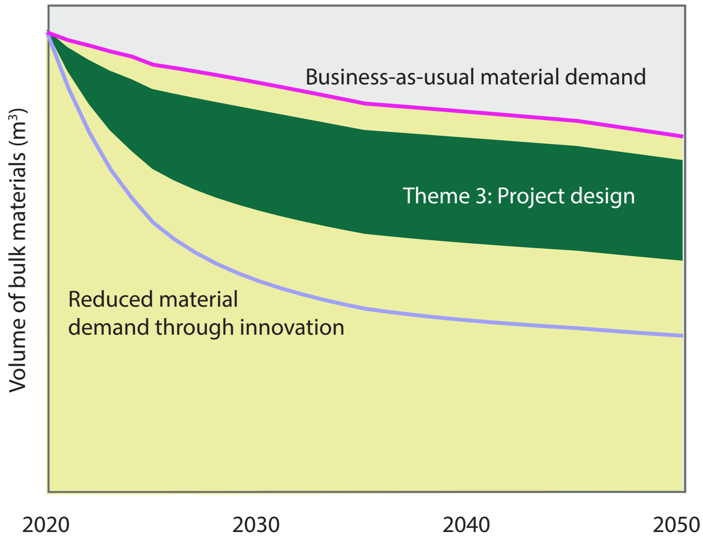
- Steel cable-nets, high performance tensile fabrics or combinations of both can be orders of magnitude more efficient than rigid structures. Currently requiring specialist knowledge and equipment to design and install, the high efficiencies of these systems are likely to lead to increasing popularity as carbon cost penalises bulkier systems. As a result, those who can will have access to a growing market including stadia, public transport infrastructure, retail and cultural sectors;
- New software will bring niche optimisation methods to everyday projects, as the need for material efficiency grows ;
- Similarly, the refurbishment and reuse of dismantled fabric structures will provide an effective potential zero-emission pathway.

CASE STUDY

Designed by Expedition Engineers, the London Olympic Velodrome is often cited as an example of both efficient engineering and architecture. Moving from a flat, rigid roof to a tensile system comprised of steel cables reduced overall material consumption by more than 35%, saving 3000 tonnes of embodied carbon. This also gives the building its distinctive profile, and minimised the internal volume of air to be heated and cooled, improving operational efficiency.

Artur Salisz / CC

Project Design:
What we build



Designers are increasingly quantifying the carbon emissions associated with projects, and this will likely soon become a requirement at city and national scales, leading eventually towards carbon targets or quotas. Indeed, campaigns to introduce life cycle carbon accounting, and later limits, into UK building regulations are supported by an increasing number of architects, engineers, contractors and developers alike. This section details opportunities for reducing emissions through early-stage design choices. Firms which adopt these practices will gain a measurable advantage as allowable emissions are reduced.

Akira Kaelyn / Shutterstock.com

Opportunities

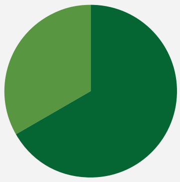
Life Extension and Adaptation

7.5M m^2

Every year, 7.5Mm^2 of buildings in the UK are demolished.

£744 m

The cost of demolition in the UK was £744m in 2020.



Two-thirds of new projects in London by floor area are refurbishments.

For projects with existing structures on site, retaining and reusing these should be a first priority wherever this reduces the need for new materials. Existing foundations and basements are particularly valuable, since these are both materially-intensive and represent the most difficult parts of a building to construct without concrete.

With demolition becoming less common, the need to design long-lasting, future-proof buildings will be ever more essential. Design details are key to longevity, particularly for timber, where waterproofing and drainage are key considerations. Buildings will also need to be reconfigurable, repairable and upgradable to truly achieve a 'forever' lifespan.

- Repair and strengthening is already common practice for bridge structures, but will increasingly be applied to buildings, generating increased demand for building surveys and specialist design and historical knowledge;
- Firms which specialise in the surveying, refurbishment and analysis of existing substructures will offer time, cost and carbon savings to clients;
- New services will offer continual repair and maintenance, particularly where zero emission materials such as earth and straw require this.

Questioning the brief

CO_2 **££**

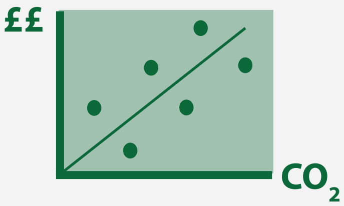
Making the right early stage design decisions can reduce the embodied carbon of a building structure by typically 50% and its cost by 40%.

Large material savings can be made through simple changes to a building's design, and design teams which can capture these and promote them will not only add value for clients, but also be able to anticipate future legislation restricting embodied carbon. Software which can help designers quickly explore design options and estimate cost and embodied carbon will become a critical early-stage design tool.

Key features of low-carbon buildings include:

- Simple massing – Avoiding wasteful overhangs or cantilevers and enabling the use of regular grids, is a significant means of reducing material consumption and enhancing future adaptability;
- Short spans - Floor structures are the primary consumers of material in buildings, and span is the key parameter dictating their depth. Avoiding long spans is also especially important for timber, which suffers from a low inherent stiffness. Architects must therefore become more adept at designing spaces without the long, clear spans typical of modern office design;
- Moderate height - Around 4-10 storeys is the most materially efficient per unit floor area, since the roof construction as a proportion of the total is reduced, foundations are moderate, and costly high-rise stability systems are avoided;
- Minimalistic foundations - Basements are a common feature of high-rises, providing parking space, storage, space for utilities, particularly where building height is restricted. However, the additional retaining structures required are considerable, and nearly always in concrete. As a result, basements will increasingly come to dominate embodied carbon, becoming more difficult to justify;
- Realistic design criteria – Loading and serviceability requirements are often unrealistic and excessive today, leading to unnecessary strong and heavy structures.

Changes to fee structures



In general, cost and embodied carbon are correlated: a structure which is cheaper to build also has a lower carbon footprint.

The fees charged by building designers are typically specified as a percentage of the total build cost, which can vary depending on project specifics but is generally agreed at the outset. For a new build contract value of £4m, architects' fees ranges between 3.6%-5.0%, Structural Engineering services, 2.5-2.9% This creates a perverse incentive in terms of sustainability, where designers stand to gain by making projects larger and less efficient. To drive down embodied carbon this must be reversed - the best designers should be rewarded for saving cost and carbon.

- New fee structures where design teams are paid a proportion of cost savings have the potential to benefit both clients and designers while reducing carbon;
- This will require new contractual arrangements and project management structures, both of which are opportunities for forward-thinking and sustainability-driven companies.

CASE STUDY

Developed in a collaboration between engineers Price & Myers and the University of Cambridge, PANDA informs early-stage decision making in the design of buildings. Once the basic building dimensions and design requirements are entered, PANDA automatically generates many thousands of viable, buildable and code-compliant structural designs and calculates both the cost and embodied carbon of each. This level of design exploration would simply not be possible to do manually, and enables the project team to make quick, reliable and informed decisions which greatly improve material efficiency.

Maximising operational efficiency

£55 bn

The UK government's Climate Change Committee estimates that £55bn of investment in home energy efficiency is required to achieve a 'balanced net zero pathway' to 2050.

25 m

Today, 25m UK homes are heated by gas boilers, all of which will be replaced by 2050. For new build, gas boilers will be banned by 2035.

To decarbonise the operation of buildings, all burning of oil and gas for heat must end. The most efficient way of replacing these functions will be through electrification, and the high demand for this emissions-free energy will make efficiency paramount. Whilst relatively simple in principle, the scale of this transformation is unprecedented, and will create huge new markets and business opportunities.

- Heat pumps will become the most common means of heating both homes and larger buildings, requiring both installation, and the removal of existing gas or oil boilers;
- Airtightness and insulation must be upgraded in many buildings for these to be effective;
- Adaptable, mass-produced products for building retrofit will quickly and cheaply improve operational efficiency with minimal disturbance;
- New buildings will be designed around energy efficiency, with greater design emphasis on ventilation, insulation and solar gain.

Carbon accounting

£27 bn

The UK construction management sector is currently worth £27bn a year.

£68 bn

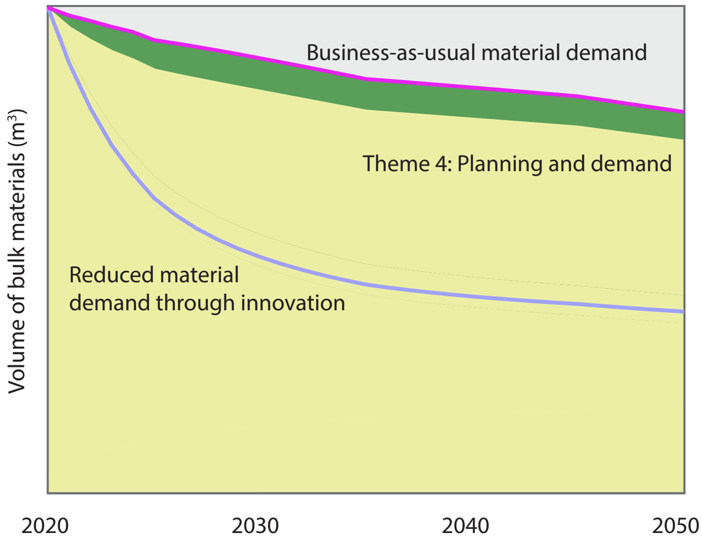
The UK's Architecture, Engineering Consultants and Related Services' market is valued at £68bn, the third largest in the world.

The Greater London Authority's London Plan, launched in March 2021, requires many larger projects to undertake whole life cycle carbon assessment. It likely that other regions will follow suit, with emissions targets and limits a next step.

Measuring and managing embodied carbon will become a standard part of construction project management, and is likely to be a key component of planning applications, creating vital new roles for specialist managers and carbon accountants. Efficient designs usually come about when clients, designers, fabricators and builders work closely together.

- Independent carbon assessors will be needed on both the design and planning sides to ensure compliance;
- The value of coordinating and managing large numbers of firms from the project outset will grow;
- Companies who are more open and willing to collaborate and share data will have competitive advantage;
- Growing specialist knowledge of low-carbon materials and minimising carbon in design will give specialist consultants and contractors the edge.

Planning and Development:
Why we build



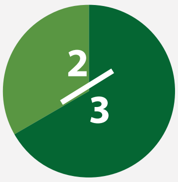
The greatest savings in material-use and embodied carbon are likely to come from high-level planning decisions. After all, avoiding new construction altogether is perhaps the simplest and most effective zero-carbon strategy: restraint is key in a world of constraints. However, reduced building will nonetheless create a multitude of new opportunities.

This section outlines the opportunities created by the changes in planning and demand driven by emission reductions. These may arise in a top-down manner, from local or national planning strategies, or from the bottom-up due to increased raw material and energy costs. Of course, the success of the measures previously outlined in this report will dictate the extent to which demand reduction is required to achieve absolute zero.

Britain from Above / Shutterstock.com

Opportunities

Minimising New Construction



For non-residential buildings, the industry is already shifting away from new builds: Two-thirds of current building projects in Central London by volume are refurbishments, and rising.

Most building structures are considerably over-designed, leaving spare capacity for vertical extensions without strengthening.
In 2018 there were 750,000 vacant dwellings and 588,000 second homes in the UK.

With a restricted zero-carbon material supply, it is likely that entirely new buildings will become more difficult to fund. Because of this, clients will look for alternative means of meeting their objectives, and this will bring new creative consultancy opportunities.

Most demolitions are unnecessary from a structural safety perspective, being driven instead by economic factors. The practice of demolition and rebuild is increasingly considered wasteful, and the resource cost of this will become ever more apparent towards 2050. It is likely that planning policy will restrict demolition, accelerating the market for renovating, modifying, extending existing structures. Adding additional storeys to existing buildings is very often feasible, due to historical over-design and modern, lightweight construction methods using timber, and there is a growing precedent for both large and small vertical extensions projects.

- New consultancies which can creatively avoid or minimise construction will be of increasing value to clients;
- Councils with zero-carbon ambitions will require high-level analysis to determine how their building stock can be best adapted and repurposed to minimise new construction;
- Structural design firms who can assess existing frames and foundations will capitalise on a growing market, alongside construction firms specialising in working above existing structures;
- New lightweight construction systems will be specifically designed for quick erection above, and interfaces to, existing building typologies.

Reassessing our building footprint

25M m^2

Each year, the UK housing stock grows by approximately $25Mm^2$.

63%

In 2020 tenant demand in office market reduced by 63%...

£12.8 bn

A post-covid occupancy reduction means that the majority of desks in London offices are only occupied 28% of the time representing a significant cost to businesses.

52%

... while availability of offices grew 52%.

Each of us has a 'building footprint' measured in square metres per capita. This not only includes houses, but also workplaces and a share of hospitals, schools, warehouses, shops and many others.

The COVID-19 pandemic has shown how dramatic shifts in building use are possible - large-scale working from home has led to a demand shift from office to living spaces. This vast reorganisation of how we live and work is an amazing opportunity for designers and architects to rethink the way we live and work.

- Building footprints could be substantially reduced by creating adaptable buildings which are occupied for more time, leading to increased revenue. These might include reconfigurable partitions or transformable interiors;
- Unused space, from temporarily vacant offices to bedrooms, could be better utilised through new peer to peer apps, linking supply to demand;
- New letting agencies will link those who have spare capacity to those who require it.

Lease model – buildings and components as services

65%

Home ownership in the UK has fallen considerably in the past two decades, with a corresponding increase in rental markets. 65% of households in England are homeowners.

A building's fundamental purpose is to provide services – shelter, heat, comfort, light, water, sanitation, entertainment. Companies leasing these services, rather than the buildings themselves, will be incentivised to provide efficient, durable products, and will reap the financial benefits of doing so as both materials and energy costs increase. Philips, for example, can be contracted to provide lighting in offices, rather than lights. This model could be extended to a much larger range of systems, including the building fabric itself.

- Office furniture can be leased rather than owned, enabling cost savings through reuse and refurbishment;
- A lease model for domestic heating could unlock the mass adoption of low-energy heat pumps, by eliminating upfront costs for homeowners, as well as incentivising retrofit. What if installation companies sold heat, rather than heat-pumps?

Urban planning for zero emissions

£210 m pa

The urban planning consultancy market is worth £210m / year in the UK.

£1.1 bn

Annual expenditure on planning by local authorities approximately £1.1bn.

Bungalows have a 62% higher carbon footprint per square metre than medium-rise flats.

A greater focus on energy efficiency in a zero-carbon economy will change the way urban spaces are organised. Walkable or cyclable cities require a higher density than car-oriented ones, yet many suburbs are still built around the car. Low-rise buildings are also more materially intensive, while very tall buildings also waste space and material on lifts and lateral stability systems. The optimal building height for material consumption is in the middle, around 4-10 storeys. Since these also create a high urban density, mid-rise buildings are the natural low-carbon choice, and will be central to the reconfiguration of cities required for the zero-carbon transition.

- Denser cities are well suited to low-carbon transport, leading to growth in cycle routes, personal mobility, and light rail, for example;
- Vertical extensions can be used to increase the urban density of today's car-oriented suburbs, as well as saving on the embodied carbon of new foundations, and should therefore be prioritised through planning and legislation;
- Localised amenities such as co-working spaces will become more widespread, as long-distance commuting becomes less favourable.

District/centralised heating

20%

Heat networks have the potential to supply up to 20% of the UK's total heating demand.

£17.5 bn

The Climate Change Committee estimates a £17.5bn investment in heat networks is needed to meet their balanced decarbonisation pathway.

Heating in 2050 will be powered by a zero-carbon electricity grid under very high demand. As such, efficiency will be paramount. With the supply dominated by wind and solar energy, daily, weekly and yearly fluctuations in supply will become larger and more problematic, creating new demand for energy storage systems.

- An increased uptake of district heating systems for new developments will require more specialist designers, installers and manufacturers;
- Large, ground-source heat pumps are typically more efficient but expensive than smaller air-source alternatives. Used communally, they can offer valuable cost savings for housing developments, flats or office complexes;
- Energy storage through battery or thermal systems will be built into both large and small developments, and added to existing buildings, creating new markets for innovative products.

Planning for change – education and training

Decarbonisation will drive fundamental changes to the construction industry at an unprecedented pace. As this report shows, the technologies to achieve this already exist; it's the scale of their implementation which is the primary challenge. This will require upskilling on a massive scale, creating additional jobs and business opportunities for those who can provide this.

- University curricula will change to make sustainability central to engineering education. Concrete design will be taught in a historical context, for building adaptation and reuse, for example;
- Retrofitting millions of homes, each with bespoke requirements, will require the training of a massive workforce;
- Experienced engineers and architects will need to understand the fundamentals of carbon assessment, gain knowledge for a 'reuse first' approach, and learn how to design with low-carbon materials, opening a large market for training providers and educational materials';
- New building assessors, reuse experts and carbon accountants will require up-skilling and retraining.

The UK construction sector employs 3.1 million people – over 9% of the total workforce.

CASE STUDY - London and Scottish. Crown House, Sheffield

This project in Sheffield took an existing office building and adapted it for a new demand for student housing, adding three storeys above the existing structure.

How We Created This Report

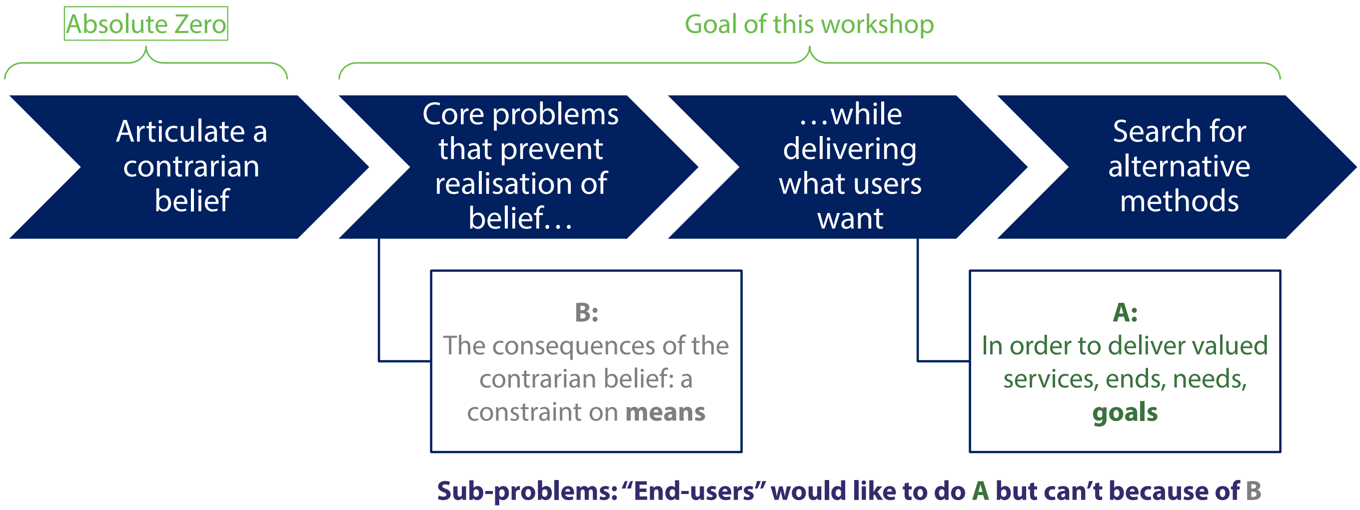
This report draws on various research activities from across UK FIRES, providing both background numerical analysis and the generation of growth opportunities. This section details these research methodologies and their underlying assumptions.

Construction Innovation workshop

The four decarbonisation themes outlined in this report (expanding the zero-emissions resource pool, building elements, project design, planning and demand) were developed from a comprehensive list of opportunities identified in the Construction Innovation Workshop, which was hosted by UK FIRES in October 2020 and attended by over 60 construction professionals across both research and industry.

The workshop was structured around the 'Value-lab' framework proposed by Felin et al. (2021), which uses a contrarian belief to identify business opportunities. In this case, the contrarian belief was that set out in the UK FIRES Absolute Zero Report (Allwood et al., 2019), which proposes that the UK will reach zero emissions by 2050 using today's technologies, meaning that any product or process which cannot be electrified or has associated process emissions must cease.

The essential services provided by a sector are then defined (A), along with a list of constraints (B) which arise from the contrarian belief, as summarised in the figure below. Both lists were devised prior to the workshop, although an opportunity to add to these was given. In groups, the participants were then presented with various combinations of service-constraint pairings to stimulate a discussion of possible solutions and opportunities. For example, combining service A1 (foundations) with constraint B1 (no clinker-based cement) led to opportunities for foundation re-use and refurbishment, steel piles, and stone footings being identified. The full list of solutions was then reviewed by the UK FIRES team, before being grouped into the four themes presented in this report.



The Construction Innovation Workshop used pairs of services and constraints to identify innovation opportunities

Services	Constraints
A1: Attaching buildings and infrastructure to the ground (foundations)	B1: There will be no clinker-based cement in 2050
A2: Providing floors and supports at ground level	B2: Blast furnace steel production will end
A3: Providing floors and supports for upper levels	B3: The closure of trans-ocean freight will constrain material supply including critical metals, minerals and metallic ores
A4: Delivering insulation and thermal mass	B4: The supply of non-emitting heat and electrical power will be less than total demand, and this will limit the availability of steel, glass, aluminium and plastic
A5: Providing impermeable surfaces to contain and direct water (tiles, culverts, dykes, dams walls, pipes)	B5: There is limited local production capacity for zero emissions materials such as wood, hemp and straw
A6: Providing load-bearing supports for transport and other infrastructure systems (tunnels, bridges, railway track, road paving, utilities, sea defences…)	B6: Local timber production is less than current consumption
A7: Joining blocks together (bricks, blocks, tiles, prefab elements)	B7: We lack a nationally agreed method for certifying emissions-free materials
A8: Providing load-bearing hard-wearing floor coverings (screeds)	B8: Demand for recycled materials will rise, but:- existing buildings have not been designed for ease of disassembly; the UK construction supply chain lacks recycling capabilities

Modelling current and future construction emissions in the UK

The Sankey diagram on page 3 of this report shows the current material consumption and associated emissions in UK construction for 2018, based on an analysis detailed by Drewniok et al. (2022).

The results from this analysis also underpin the decarbonisation curves introduced on page 4, which show a reduction in demand (Themes 2, 3 and 4) coupled with growth of a zero-emission compatible material supply (Theme 1). A slowing of anticipated population growth in the UK is responsible for the fall in business-as-usual material demand. Various measures related to each theme were then modelled to deduce the effect on total demand, with measures using technologies which are already commercially available assumed to be phased in over a 15 year period, and those that are currently still being deployed phased in over 25 years. Further, we have used the findings of Dunant et al. (2021) to estimate the potential saving in structural design. The growth of low-carbon material supply was assumed to match the reduced demand.

Opportunity evaluation

The following table details the underlying assumptions and background data behind the opportunities described across the four themes of this report.

Background: Defining the zero-emissions resource pool		
	Value	**Notes**
Embodied carbon from construction, UK, 2018	44 $MtCO_{2e}$ 25 $MtCO_{2e}$	(Green et al., 2021), cradle-to-practical completion including design; all materials, (M. P. Drewniok et al., 2022), cradle-to-practical completion, materials: concrete, steel, timber, clay products, natural stone, gypsum products, glass, aluminium PVC (windows and doors), mortar, screed, plaster.
Concrete		
2018 cement consumption / sales in the UK	11.7 Mt	MPA – Annual Cementitious Statistics (Annual Cementitious Statistics, 2022)
Value of cement sales	£1.5bn	2018 cement price £119.3 / t (Spon's Architects' and Builders' Price Book 2018, 2018) 2018-2020 price change 5.7% (Monthly Statistics of Building Materials and Components, 2022) 11.7 Mt x £119.3 / t x 1.057 = £1.47bn
2050 cement consumption / sales in the UK	9.5 Mt	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
2018 UK concrete production (site mixed and precast)	90 Mt	37 Mm^3 (Ready-mixed concrete industry statistics - Year 2018, 2019) Concrete density – 2.4t/m^3 37 Mm^3 x 2.4 t/m^3 = 88.8 Mt
2018 UK ready mix-concrete production (RMC)	54 Mt	22.5 Mm^3 (Ready-mixed concrete industry statistics - Year 2018, 2019) Concrete density – 2.4t/m^3 22.5 Mm3 x 2.4 t/m3 = 54.0 Mt
2018 cement used in RMC	6.3 Mt	278 kg/m^3 - Average cement content in (Ready-mixed concrete industry statistics - Year 2018, 2019)

2018 value of RMC	£3.5bn	£96.1/m^3 – weighted average of RMC price (Spon's Architects' and Builders' Price Book 2018, 2018) Weights (Ready-mixed concrete industry statistics - Year 2018, 2019): GEN0-GEN3 – 11%; RC20/25 – 25%, RC25/30 – 27%; RC30/37 – 27%; RC35/45 – 5%; RC40/50 – 3%; RC50/60 – 2% 2018-2020 price change -1.5% (Monthly Statistics of Building Materials and Components, 2022)
2050 UK ready mix-concrete use (RMC)	47.0 Mt	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
2050 cement used in RMC	5.3 Mt	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
2018 value of precast concrete (structural and non-structural)	£5.7bn	Non-RMC – 37- 22.5 Mm^3 = 14.5 Mm^3 (Ready-mixed concrete industry statistics - Year 2018, 2019) UK concrete blocks deliveries in 2018 – 713,080 thousand m^2 (Monthly Statistics of Building Materials and Components, 2022) , 10 m^2 per 1 m^3; 7.1 Mm3; £25/m2 (Spon's Architects' and Builders' Price Book 2018, 2018); 2018-2020 change – 4.8% (Monthly Statistics of Building Materials and Components, 2022), £1.9 bn Rest (7.4Mm^3) assumed as structural concrete (precast); £62.88 /m^2 (floor span 7.5-9.5m, 1200x250mm) (Spon's Architects' and Builders' Price Book 2018, 2018), 320 kg/m^2; £470/m^3; 2018-2020 change – 7.1% (Monthly Statistics of Building Materials and Components, 2022), £3.8 bn
Steel		
UK EAF steel production route	22%	World Steel Association, Steel Statistical Yearbooks (Steel Statistical Yearbooks, WSA, 2020)

EU average EAF steel production route	40%	World Steel Association, Steel Statistical Yearbooks (Steel Statistical Yearbooks, WSA, 2020)
Steel recycling rate	85%	worldsteel (Broadbent, 2018)
Steel used in UK construction, 2018	2,000,000 t	879kt of constructional steelwork consumption in construction ("BCSA Annual Review 2017-2018," 2021); 1,200 kt rebar consumption ("Liberty Steel enters rebar market," 2020)
Value of structural steel used in construction	£1.7bn	£1020/t of constructional steelwork (average) (Spon's Architects' and Builders' Price Book 2018, 2018), 2018-2020 change – 6.5% (Monthly Statistics of Building Materials and Components, 2022); £0.84bn £881/t of rebar (average) (Spon's Architects' and Builders' Price Book 2018, 2018), 2018-2020 change – 13.4% (Monthly Statistics of Building Materials and Components, 2022); £0.92bn
Share of constructional steelwork consumption by sector	48% - Industrial 12% - Offices 9% - Power sector 8% - Education 4% - Bridges 4% - Leisure 4% - Other infrastructure 11% - Retail, Health, Domestic, Agriculture	Annual Review 2020/21, BCSA ("BCSA Annual Review 2017-2018," 2021)
Timber		
Apparent consumption of sawnwood	10.4Mm^3	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)
Import of sawnwood	7.2Mm^3	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)
Sawnwood import value	£1.7 bn	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)
Apparent consumption of wood-based panels	5.8Mm^3	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)

Wood-based panels value	£1.2 bn	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)
Import of wood-based panels	3.3Mm^3	UK Wood Production and Trade (UK Wood Production and Trade, 2020 Provisional Figures, 2021)
Timber Consumption is in Construction & Ancillary Products	75% of 2018 timber consumption (sawnwood + wood-based panels)	Global Timber Outlook, Gresham House (Global Timber Outlook, 2020)
Structural timber, joists, plywood and veneers	26% of 2018 timber consumption (sawnwood + wood-based panels)	Global Timber Outlook, Gresham House (Global Timber Outlook, 2020)
Timber consumption by 2050	3% per annum	Global Timber Outlook, Gresham House (Global Timber Outlook, 2020)
Clay products		
2018 UK brick consumption	2,025m	Monthly Statistics of Building Materials and Components, BEIS (Monthly Statistics of Building Materials and Components, 2022)
Value of brick consumption	£1.2bn	£0.54/brick (Spon's Architects' and Builders' Price Book 2018, 2018) – 2018; 2018-2020 price change – 10% (assumed)
A number of houses with cavity walls in UK	70%	English Housing Survey, 2019 to 2020: energy (English Housing Survey, Energy report, 2019-20, 2021), Annex Table 1.12: Construction type, by tenure, 2019 In 2019, 16.8 mln of the 24.4 mln dwellings in England were built with cavity walls, in GB in 2020, 20.4 mln were cavity (Household Energy Efficiency detailed release: Great Britain Data to December 2020, 2021). There is correlation between population and number of dwellings (Piddington, Nicol, Garrett, & Custard, 2020) and thus UK housing stock in 2019 represent approximate 29,974,000 of which 20,981,800 was cavity walls.
Glass		
Glass production in UK for construction and automotive industries	0.9 Mt	The UK glass sector produces over 3 million tonnes of glass per year, 30% is used for glazing for the construction and automotive industries (Glass Sector. Joint Industry - Government Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan, 2017)
Alluminium		
Primary aluminium production	223 kt	Primary Aluminium Production (Primary Aluminium Production, UK Aluminium Industry Fact Sheet 17, 2020)
Gross Value Added (GVA) to the UK economy	£2.97bn	The Aluminium Industry in the UK (The Aluminium Industry in the UK, 2021)

Plastics		
Plastic used in the construction sector every year	1 Mt	THE 'P' WORD – Plastic in the UK: practical and pervasive … but problematic (Cullen J.M., Drewniok M.P., & Cabrera Serrenho A., 2020)
Annual UK plastics consumption	6.4 Mt	THE 'P' WORD – Plastic in the UK: practical and pervasive … but problematic (Cullen J.M., Drewniok M.P., & Cabrera Serrenho A., 2020)
Plastic packaging film waste from Construction and Demolition	68 kt	PackFlow Covid-19 Phase I: Plastic (Johnson, 2020)

Theme 1: Expanding the zero-emission resource pool: What we use to build		
	Value	**Notes**
Waste as material supply		
Construction and demolition waste (2018)	Total waste pro-duction: 222 Mt C&D waste pro-duction: 67.8 Mt Waste from demolition: 30 Mt C&D recovery rate: 92%	UK Statistics on Waste (UK Statistics on Waste, 2021) UK Statistics on Waste (UK Statistics on Waste, 2021) NFDC Survey (NFDC waste survey, 2021) UK Statistics on Waste (UK Statistics on Waste, 2021)
Structural steel scrap (Grade OA) (2018)	1 Mt	Domestic Scrap Steel Recycling – Economic, Environ-mental and Social Opportunities (Hall, Zhang, & Li, 2021)
Steel reinforcing bar scrap (2018)	0.6 Mt	24Mt of hardcore from demolition in 2018 was sent for recycling or reuse (NFDC waste survey, 2021) Assumed that 80% of hardcore was reinforced concrete Assumed average reinforcement 70kg/m3 (29kg/t)
Structural timber waste (2018)	0.2 Mt	0.3Mt of timber was send for recycling or reuse (NFDC waste survey, 2021) Assumed that 70% of waste was structural timber
Landfil Tax receipt in 2018	£683m	HM Revenue and Customs (HMRC Tax Receipts and National Insurance Contributions for the UK, 2021)
UK's steel scrap exported overseas	77%	Domestic Scrap Steel Recycling – Economic, Environ-mental and Social Opportunities (Hall et al., 2021)

Plant-based materials		
The UK imports and import value		See: Background: Defining the zero-emissions resource pool / Timber
The price of imported timber	2015 = 100 Dec 2021 = 208	Monthly Bulletin of Building Materials and Component (Monthly Statistics of Building Materials and Components, 2022);
Stone and earth		
2018 concrete blocks market for low-rise domestic buildings	£1.1bn	UK FIRES modelling, based on (M. P. Drewniok et al., 2022) 9.9 Mt of concrete blocks used in low-rise domestic buildings Weight of one block – 19 kg/piece; 522m blocks; £2.0/piece (Spon's Architects' and Builders' Price Book 2018, 2018) 2018-2020 price change 5.0% (Monthly Statistics of Building Materials and Components, 2022)
RMC used for shallow pad and strip foundations for low-rise domestic buildings.	4.7 Mm^3	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
Floor screeds used on buildings	800,000 m^3	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
Plastics		
Share of plastics used in construction, UK pa	14%	THE 'P' WORD – Plastic in the UK: practical and perva-sive … but problematic (Cullen J.M. et al., 2020)
Plastic waste treatment in the UK	30% - landfill 38% - incineration 21% - export 11% - UK recycling	THE 'P' WORD – Plastic in the UK: practical and perva-sive … but problematic (Cullen J.M. et al., 2020)
Share of cement used for repairs, maintenance and refurbishment in construction in UK	15%	How much cement can we do without? Lessons from cement material flows in the UK (Shanks et al., 2019)
Decarbonising on-site construction activities		
The total UK revenue in construction equipment and employment (2018)	Revenue: £13bn Employment: 42,000 people	The UK's construction equipment sector report 2019 (Dorling & Woodrow, 2019)

Construction activities (2018)	Buildings and building con-struction works: 2.4 $MtCO_{2e}$ Constructions and construction works for civil engineering: 5.7 $MtCO_{2e}$ Specialised con-struction works: 5.3 $MtCO_{2e}$	UK greenhouse gas emissions by Standard Industrial Classification (SIC) 1990-2018 (UK greenhouse gas emissions by Standard Industrial Classification (SIC) 1990-2018, 2022)
Theme 2: Building elements: How we build		
Designing with reused components		
Demolition of non-domestic buildings in 2018 in UK	12.5 Mm^2	(M. P. Drewniok et al., 2022)
New structural steel and steel scrap price	£995/t of constructional steel-work (average) £105/t - £190/t of OA plate & girder scrap	£1020/t of constructional steelwork (average) (Spon's Architects' and Builders' Price Book 2018, 2018), 2018-2020 change – - 6.5% (Monthly Statistics of Building Materials and Components, 2022); OA plate & girder scrap ("Ferrous scrap metal prices 2020," 2022)
Materially-efficient floor systems		
The total floor area of new buildings constructed in 2018 in UK and a value (output)	43.4 Mm^2 (domestic and non-domestic buildings) £74bn	(M. P. Drewniok et al., 2022) Construction output (GB) - housing and private com-mercial and public other - £72.3 bn (Construction statistics, Great Britain: 2020, 2021); scale by popula-tion to get UK

Area of upper floors in buildings in the UK and a value of materials	16.4Mm^2 of up-per floors in buildings £700m	(M. P. Drewniok et al., 2022) 4.2Mt of RMC concrete used for upper floors slabs (1.75 Mm^3); assumed RC30/37; £98.5/m3 (Spon's Architects' and Builders' Price Book 2018, 2018), 2018-2020 price change 5.7% (Monthly Statistics of Building Materials and Components, 2022); £182m 1.8Mt of precast floor planks used for upper floors slabs; 235 kg/m^2 of precast floor planks; 7.66 Mm2; £62.88/m2 (Spon's Architects' and Builders' Price Book 2018, 2018); 2018-2020 price change 7% (Monthly Statistics of Building Materials and Components, 2022); £515m
Concrete use for ground floors	14.3 Mt	(M. P. Drewniok et al., 2022)
Cross-laminated timber (CLT) market (material)	£56m	UK consumption of CLT in 2020 - 70,000m3 (Hyams, Watts, Sweet, & Swinburne, 2020) CLT price £800/m^3 (Shann, 2020)
Foundations		
Ready-mix concrete consumption in foundation in buildings in the UK (2018)	14.6 Mt	Total RMC use in buildings – 29.5Mt (M. P. Drewniok et al., 2022) (Ready-mixed concrete industry statistics - Year 2018, 2019) 14.6 Mt of RMC is used in buildings foundations (49%) (M. P. Drewniok et al., 2022)
Ready-mix concrete used in foundation in buildings in the UK (2018) - GHG	2.5 $MtCO_{2e}$	Upfront embodied carbon in UK construction in 2018, 25 $MtCO_{2e}$ (M. P. Drewniok et al., 2022) 2.5 $MtCO_{2e}$ of RMC is used in buildings foundations (10%) (M. P. Drewniok et al., 2022)
Exploiting geometry for material efficiency		
The material and embodied carbon in a typical concrete floor savings	53–58% embod-ied carbon reduc-tion compared to an equivalent flat slab	A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors (Hawkins, Orr, Ibell, & Shepherd, 2020) (M. Drewniok, 2021)

Theme 3: Project design: How we build		
	Value	**Notes**
Life extension and adaptation		
Demolition of non-domestic buildings in 2018 in UK	12.5 Mm^2	UK FIRES modelling, based on (M. P. Drewniok et al., 2022)
The cost of demolishing buildings in the UK (2020)	£744m	Construction statistics annual tables (Construction statistics annual tables, 2021)
New builds vs refurbishments in London (2020)	Two-thirds of new starts are refurbishment, indicating refurbishments are on the rise	A state of suspension. London Office Crane Survey (A state of suspension. London Office Crane Survey, 2020)
Embodied carbon savings making the right early stage design decisions Cost savings from making the right early stage design decisions	50% 40%	(Dunant, Drewniok, Orr, & Allwood, 2021), (M. Drewniok, 2021) (Dunant et al., 2021)
Changes to fee structures		
Fees for professional services	Quantity Surveying Services: 2% Architects Service: 3.6 – 5.0% Structural Engineering Service, Services Engineering: 2.5 – 2.9%	(mean, % for a contract value of £4,000,000, new build, excl. VAT) SPON'S, Architects' and Builders' Price Book 2018 (Spon's Architects' and Builders' Price Book 2018, 2018)
Maximising operational efficiency		
Investment in home energy to achieve a 'balanced net zero pathway' to 2050.	£55bn	Total investment in the programme of efficiency in existing homes in The Balanced Pathway is around £45 billion to 2035 with a total spend of £55 billion by 2050 (The Sixth Carbon Budget Buildings - Sector summary, 2020)
UK homes are heated by gas	25m	84% of domestic buildings in England (21m out of 24.4m) have gas heating (English Housing Survey, Energy report, 2019-20, 2021) To cover UK, this figure was scaled by population
Natural gas boilers replacement end date (Natural gas phase out) in the Balanced Net Zero Pathway	Date: Residential: 2033 Commercial: 2033 Public: 2030	The Sixth Carbon Budget Buildings (The Sixth Carbon Budget Buildings - Sector summary, 2020) Heat and Buildings Strategy (Heat and Buildings Strategy (CP 388), 2021)

Carbon accounting		
The value of the UK construction management sector	£27bn	All project management sector contributes £156.5 bn of annual value added (GVA), project management in construction, £27bn ("Project management industry adds £156 billion of value to UK economy," 2019)
The UK Architecture, Engineering Consultants and Other Related Services market	£67.5bn	$90 billion in 2016 (Global Architecture, Engineering Consultants And Other Related Services Market Report 2017 - Research and Markets, 2017) Exchange rate 0.75
A whole life cycle carbon assessment in construction	Requirement from March 2021 in London for larger projects	The London Plan - The spatial development strategy for Greater London (The London Plan - The spatial development strategy for Greater London, 2021)

Theme 4: Planning and Development: Why we build		
	Value	**Notes**
Minimising New Construction		
New builds vs refurbishments in London (2020)	Two thirds of new starts are refurbishment, indicating refurbishments are on the rise	A state of suspension. London Office Crane Survey (A state of suspension. London Office Crane Survey, 2020)
Vacant buildings and second homes in the UK (2018)	750,000 vacant dwellings 588,000 second homes in the UK	In 2018 there were 634,000 vacant dwellings in England (English Housing Survey, Household Data. [data collection]. UK Data Service. SN: 8669, 2020). This figure was scaled by population to get UK vacant dwellings. In 2018, 772,000 households in England had in total 783,000 owned second homes. Of these, 495,000 were in the UK (English Housing Survey, Household Data. [data collection]. UK Data Service. SN: 8669, 2020). This figure was scaled by population to get UK second homes.
Reassessing our building footprint		
UK domestic stock net addition	25 Mm^2	In 2018 and 2019 net additions to domestic building stock in England was 237 and 243 thousand respectively (English Housing Survey, Household Data. [data collection]. UK Data Service. SN: 8669, 2020). These figures were scaled by population to get UK net additions – 280 and 282 thousand. An average floor area per a dwelling is 90 m^2. Net change in the UK domestic building stock in 2018 and 2019 was 25.2 Mm2 and 25.4 Mm^2

Cost of unused desks in office buildings in London after Covid-19 restrictions are lifted	cost businesses £12.84bn	"London office workers want to spend an average of 2.7 days per week back in the office once all coronavirus restrictions are lifted, as long as they have the resources to work from home comfortably" (Clark, 2020)
In 2020 tenant demand and availability in office market in the UK	Tenant demand reduction by 63%, availability grew 52%.	Widening disparity between strong industrial sector performance and struggling office and retail markets. Q4 2020: UK Commercial Property Market Survey (Widening disparity between strong industrial sector performance and struggling office and retail markets. Q4 2020: UK Commercial Property Market Survey, 2020)
Building over-design	30%-40% materi-al savings in structural concrete 30 to 45% of the steel in steel framed buildings is unnecessary (40–60% less embodied carbon)	(J. J. Orr, Darby, Ibell, Evernden, & Otlet, 2011) (Moynihan & Allwood, 2014) (Dunant et al., 2021) (M. P. Drewniok, Campbell, & Orr, 2020) (J. Orr et al., 2019)
Lease model – buildings and components as services		
Home ownership in the UK	70.9% in 2003 63.9% in 2018	Homeownership has been in decline in the United Kingdom, falling from an all-time high of 70.9% in 2003 to 63.9% in 2018 (English Housing Survey, Household Data. [data collection]. UK Data Service. SN: 8669, 2020)
Urban planning for zero emissions		
The urban planning consultancy market (2019)	£210m/year	Planning consultants: Market Report 2019: Overview (Branson, 2019)
Expenditure on planning by local planning authorities	£1.1bn	Total expenditure on planning by local planning authorities is £900 million a year across England. This figure was scaled by population to get UK value (£1.1bn) (Resourcing Public Planning - RTPI Research Paper, 2019)
Embodied carbon per square metre for different domestic buildings typologies (max and min)	Bungalows – 520 kgCO2e/m^2 4-6 storey flats – 322 gCO2e/m^2	(M. P. Drewniok et al., 2022)
District/centralised heating		
Heat networks (all buildings)	£17.5bn in total	The Sixth Carbon Budget - Investment costs to 2030 in the Balanced Pathway (The Sixth Carbon Budget, The UK's path to Net Zero, 2020)

Heat networks (all buildings)	20%	"(…) the economic potential for heat networks as as-sessed by the spatial model is fully met by 2050 i.e. that 20% of UK heat demand is met by heat networks by 2050." (Opportunity areas for district heating networks in the UK. National Comprehensive Assessment of the potential for efficient heating and cooling, 2021)
A heat network solution against individual building counterfactual where gas continues to be the main fuel source 2020-2050	Savings: 113 $MtCO_{2e}$ social costs (loss): £52bn financial costs (savings): + £4bn	For the UK as a whole. The lower carbon emissions would arise due to the use of waste heat and heat pumps in the heat network solu-tion, while the higher costs are due mainly to the higher capital costs of installing a heat network compared with the low capital cost of single building gas boilers using existing gas infrastructure. The discounted financial costs of the networked solu-tion in contrast are lower than those of the counterfac-tual; this is due to the inclusion of electricity sales from gas CHP in the networked option (Opportunity areas for district heating networks in the UK. National Comprehensive Assessment of the potential for efficient heating and cooling, 2021).
A heat network solution against individual building counterfactual where dominant energy pathway is electrification.2020-2050	Savings: 3 $MtCO_{2e}$ social costs (sav-ings): + £18bn financial costs (savings): + £12bn	For the UK as a whole. Both approaches use electricity and heat pumps as the primary heating source hence the similarity in emissions, however the heat network option does mar-ginally improve heat pump efficiency through the use of waste heat; this also accounts for the fuel savings of around 2TWh/yr. The costs of the heat network solution are lower than those of the individual building solution in both social and financial terms (i.e. social costs are £18bn less and financial costs are £12bn less) (Opportunity areas for district heating networks in the UK. National Comprehensive Assessment of the potential for efficient heating and cooling, 2021)
Planning for change – education and training		
Employment in the UK construction sector	3.1m people – over 9% of the total workforce	Construction Sector Deal (Construction Sector Deal - Policy paper, 2019)

Glossary

CO_{2e} – Carbon dioxide equivalent emissions

GHG – greenhouse gas

SCM – supplementary cementitious materials

GGBS - ground granulated blast-furnace slag

FA – fly ash from coal-fired power stations

RMC – ready mix-concrete

BOF – basic oxygen furnace

EAE – electric arc furnace

Constructional steelwork – structural steel including: rolled sections, fabricated sections made from plates, and also hollow sections

C&D – construction and demolition

Scrap Grade OA - plate and structural scrap consists of cut structural and plate arisings, predominantly 6mm thick

MMC – modern methods of construction

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