CO_2 2.Low carbon

Structural engineering innovation for a zero-carbon world: an R&D agenda to match the carbon budget

Pete Winslow, Mike Sefton and Will Arnold set out a vision for a net-zero structural engineering sector and the R&D that we as a profession need to tackle to get there.

Introduction

The IPCC *Special Report on Global Warming of 1.5°C*[1] shows the importance to our planet and society of limiting further global temperature increases and of the emissions reductions required to achieve this. Reaching net zero by 2050 is the headline target, but it is also critical to reduce carbon dioxide (CO_2) emissions by 45% by 2030 compared with 2010 levels[2], and to keep total greenhouse gas emissions below the global 440GtCO_2e 'budget' (for the period 2021–50, derived from IPCC data[1]). As discussed by Arnold *et al*.[3], this means we need to make significant annual emissions reductions of around 10% per year, year on year, starting now.

This article considers these reductions within construction split into 'now and next' **(Figure 1)**. The 'now' harnesses a cultural shift in design using existing technology to reduce emissions in the immediate years ahead. In the past year, the Institution of Structural Engineers has published significant amounts of guidance to support this. However, at some point we will reach the limit of emissions reductions through this approach. At which time the 'next' phase will need to be ready to provide further reduction opportunities.

The 'next' phase relies on technology which currently requires either new fundamental research or, more realistically within the timeframe required, the scaling-up of existing technology and the development and implementation of emerging technology. It is imperative to boost this research, development and innovation work now in order that, as the gains of the 'now' phase lose pace, we have new approaches to continue making carbon reductions year on year over the coming decades.

This article sets out a research, development and innovation agenda, aiming to promote, inform and steer the collective effort – of both practising engineers and researchers – to rapidly and coherently transition to a zero-carbon world. No single initiative identified is a 'silver bullet' and simply waiting for new technologies is not a viable pathway to keep warming within 1.5°C. While this portfolio of needed technologies and approaches is in development, we still need to take as much action as possible on today's projects, to enable optimal outcomes within current parameters.

Although the primary focus of this article is greenhouse gas emissions reductions, the importance of biodiversity cannot be overstated. This has been reinforced by the recent publication of *The Economics of Biodiversity: The Dasgupta Review*[4], which promotes nature-based solutions to enhance biodiversity and is also a key part of the 'UK Structural Engineers Declare Climate & Biodiversity Emergency' movement. Low-carbon construction has little meaning without the biodiversity needed to sustain life, fertilise crops, etc., and so a key tenet flowing through all R&D – from industrial ecology of timber to novel structural manufacturing processes – will be the need to consider and improve biodiversity; a critical topic for many future articles.

Challenges of today

The agenda set out in this article reflects the orders of magnitude of emissions that the structure contributes at each stage of an asset's lifecycle.

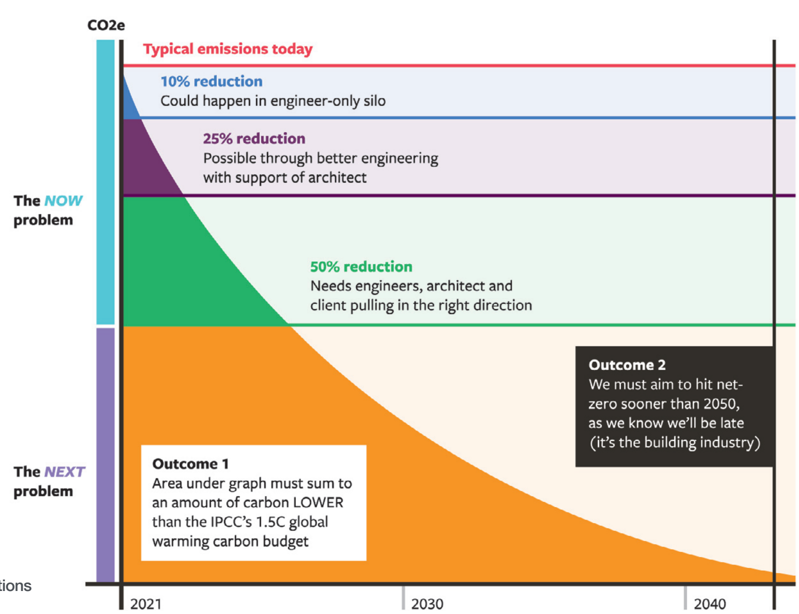

FIGURE 1: Carbon reductions 'now and next'

		Strategies	
Circular economy ↑	Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product.
		R1 Rethink	Make product use more intensive (e.g. by sharing product).
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fufils its original function.
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function.
Increasing Circularity		R5 Refurbish	Restore an old product and bring it up to date.
		R6 Remanufacture	Use parts of discarded product in a new with the same direction.
	Useful application of materials	R7 Repurpose	Use discarded product or its parts in a new product with a different function.
		R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.
↓ Linear economy		R9 Recover	Incineration of material with energy recovery.

FIGURE 2: 10 Rs and circularity[13]

The upfront embodied carbon (modules A1–A5) of a building can account for as much as 55% of the whole-life emissions for an ultra-low-energy build[5] (and a higher percentage for non-building structures). It is therefore clear that tackling upfront emissions with full force is a priority due to their relative magnitude and also the immediacy of their impact in reducing carbon emissions. However, in the future, as we reach closer to net-zero emissions, we will need to look beyond upfront embodied carbon alone to eliminate greenhouse gas emissions and waste at all stages in a structure's life.

The in-use embodied carbon (modules B1–B5) associated with building maintenance, repair and replacement, etc. has been estimated to be as much as 20% of whole-life emissions[5]. Much of this may be fitout and facades, but structure and its relation on these elements can influence the environmental demand. This provides opportunity for development and normalisation in practice of methods to reduce embodied use emissions in current building stock and to design for minimisation of these in future construction. Operational carbon (modules B6–B7) is estimated to be around a further 23%, with the typical contribution of the structure being the impact of thermal mass.

The actual processes in the end-of-life stages (modules C1–C4) may be only 2% of the whole-life emissions[5] but, crucially, these stages provide significant potential for reducing the upfront emissions for subsequent structures. Challenges lie both in designing new buildings for reuse in years to come (after a long life), but also in enabling the reuse of existing structures (in their entirety or their constituent parts) with as a high a value as possible.

Visions of net zero 2050

Several institutions and organisations have produced route maps which build possible pictures of 2050, and the challenges that will need to be tackled to reach net zero. These include the International Energy Agency (IEA)[6,7], the UK's Sixth Carbon Budget[8], industry roadmaps from the Mineral Products Association and UK Concrete[9], the British Constructional Steelwork Association[10], and the European Ceramic Industry Association[11]. The UK FIRES report, *Absolute Zero*[12], provides a broad cross-sector position and is recommended reading to all IStructE members.

The R&D areas defined in the next section draw on the key route maps referenced above and many other articles from a range of institutions and bodies, as well as extensive formal and informal discussions (both specifically in the course of preparing this article and the authors' other work). Nevertheless, they have been developed and written from a pragmatic standpoint through the lens of the structural engineering profession. This R&D agenda is considered appropriate for a future industry/ profession in which the following principles are already established and in operation as the de facto norm:

- Mandatory universal and coherent carbon assessment and reporting with high-quality digital information throughout all stages of a structure's lifecycle.
- A planning and design process which enforces the 10 Rs **(Figure 2)**[13], maximises circularity, and represents a paradigm shift in terms of when we build (if it all) and what we build (and its functionality).
- Implementation of all the easy wins, low-hanging gains and aggregated marginal gains[14], including those set out in the 'Climate emergency' series of articles in *The Structural Engineer* through 2020 and 2021, reducing demand for materials which can in turn support new paradigms and opportunities in industrial ecologies (with a system-based approach to material stocks/flows).
- Carbon pricing/shadow carbon pricing implemented industry-wide, e.g. building on and implementing BEIS figures[15].
- A documentation and record system to provide a whole picture of 'structures/ buildings as material banks'.
- Zero non-reusable waste enforced at all stages of production, fabrication and construction.

On carbon capture utilisation and/or storage (CCUS)

Several of the industry route maps referenced above (and that of the IEA) include CCUS as a major source of emissions reduction. This may transpire to be the case and, given the scale and importance of global decarbonisation, the material-production foundation industries will need to continue to develop CCUS technology and should be supported in doing so **(Figure 3)**. However, just as the UK COVID-19 Vaccine Taskforce did not rely on a single vaccine programme/ technology platform (any one of which had a significant risk of low effectiveness or delays during development and upscaling), we should not rely on CCUS preventing the majority of carbon emissions.

Installed CCUS capacity is currently equivalent to just 0.1% of global emissions[16] and there is significant future cost and technological uncertainty[17]. It is thus essential to also pursue other approaches, especially within one's engineering sphere of influence, that can minimise emissions much further in the first instance. Furthermore, a focus on regenerative, nature-based solutions which promote biodiversity while reducing greenhouse gas production can have multiple benefits, as opposed to CCUS solely engaged to capture emissions from current processes.

UK FIRES[12] states that 'until we face up to the fact that breakthrough technologies won't arrive fast enough, we can't even begin having the right discussion' and rules out reliance on CCUS. The authors of the current article have endeavoured to focus the R&D agenda on adjacent, rather than radical breakthrough, technologies, but do not take such a black-and-white view on CCUS. It is therefore assumed here that some CCUS capacity will be available towards 2050 as needed to tackle the last stubborn emissions to get us to net zero.

Today's research, development and innovation challenge areas to help reach zero carbon

In this section, we consider areas of construction which can contribute in the shift to a net-zero future, and identify research, development and innovation needs which could facilitate this **(Table 1)**. These areas of R&D require urgent attention within the next few years, if the structural design community is to increase its range of low-carbon options in time for the 'next' phase starting in 2029 **(Fig. 1)**.

Design and process

1) Transform normal construction typologies. To reach net zero, current standard construction responses to typical building challenges will be completely transformed, prioritising net-zero emissions. Current structural typologies have developed over a long period of time and are engrained in culture, code and supply chains. Research needs to overcome this inertia and drive change quickly to enable carbon-optimal approaches which respond to local material supplies and needs with net-zero emissions. Critically, this also means reconsidering the levels of functionality provided: everything from m^2/desk to presumed optimal height for building, to structural performance and reliability levels.

2) Balancing a circular and sustainable supply chain will be a characteristic feature of a sustainable future with more considered use of materials. The assumption of an infinite global material supply chain will not be valid. The concept of waste will be eliminated and we will have grown databases of available materials (prioritising those stored in existing buildings over new) that form a platform to balance use against availability within regions to achieve zero emissions across the industry. Design will start from available materials, so procurement and early linking-in of the supply chain will become an integral part of concepts.

3) Data-driven automated calculations and decision-support tools. Design calculation will be based around automatic material optimisation with solutions predicated on off-site construction typologies, using accurate carbon intensity data for manufacture and transport, underpinned by more effective use of data-rich building information models (BIM) running through a structure's lifespan. These principles of design are essential to take advantage of reused steel, cost-effective timber, and productised novel cements. Design calculation and analysis will be truly statistically based; not using historical (often empirical) partial factors, material grades, loads, etc. Software will have reliability analysis embedded to ensure appropriate performance; no more no less.

4) New approaches to design concept and scheming will work with modern methods of manufacture (beyond 'modern methods of construction') to drive new carbon-optimal typologies, saving cost and time, and enabling project teams to continue honing down carbon and resource use. Structures made from specific advanced manufacturing processes, becoming certified products and assembled as part of a fully integrated considered off-site system, will be the norm.

Materials

5) Natural materials (timber, biobased materials, stone, low-impact blocks/bricks) are typically already the most carbon-efficient option for the construction of short- to medium-span above-ground structures, bridges and buildings, and there is no reason to assume that this won't continue to be the case. Prioritising lower-embodied-carbon materials for these uses will reserve the limited (by carbon budget) steel and concrete quantities for applications where only they will do: wind turbine towers, high-load foundations, low-carbon transport infrastructure, etc. (which may see substantial growth in volumes if society is to decarbonise sufficiently quickly).

Truly rapidly renewable, low-carbon, natural materials will be preferred to those extracted from finite resources. The production methods of these materials will still need to decarbonise over coming years, and these industrialised production processes will need to find balance with the ecological need of the environment that they are being taken from. A better understanding of the wider industrial ecology will be achieved; understanding material stocks, flows, impacts, abilities to meet supply and demand and whole-life/whole-system impacts at national and international levels.

Case study 1. Ultra-low-carbon precast concrete

Network Rail's low-carbon platform components project, a national programme running in the UK from 2020–28, is reducing embodied carbon of precast concrete elements by up to 80% by using lower-carbon novel cements and reinforcement, and optimised design approaches. The project team includes Expedition Engineering, Amcrete, Studio One, Gtech, BRE, the National Composites Centre and the University of Cambridge.

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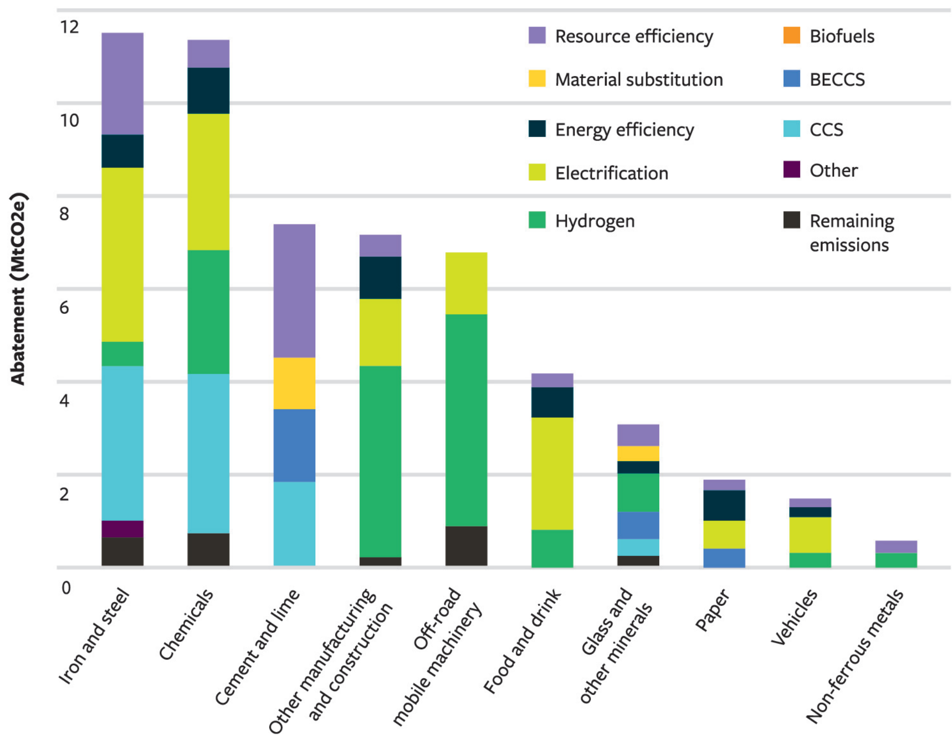

↑FIGURE 3: Abatement and remaining emissions for manufacturing and construction subsectors in 2050[8]

TABLE 1: Research, development and innovation challenge areas

Theme	Challenge area	Research, development and innovation need
Design and process	**1) Transform normal construction typologies**	Develop new construction typologies that can truly respond to locally available materials and minimise transport energy demands.
		Develop building systems and typologies that provide alternatives to those currently dependent on wet on-site OPC, e.g. screeds. Consider benefits of off-site manufacture including carbon, cost and speed drivers.
		Reimagine foundations; with timber and stone superstructures in 2050, by far the largest remaining embodied carbon would be in concrete foundations and substructures requiring research into alternative zero-carbon approaches/norms.
		Develop and nurture alternative zero-carbon construction systems for building typologies currently dependent on traditional brick – be it future-generation straw-bale SIPPS for non-structural partitions or prefabricated ultra-low-carbon brick slip panels.
	2) Balancing a circular and sustainable supply chain	Develop effective ways to store the right BIM information in a common open-source accessible manner to support best high-value ongoing use of structural materials. To facilitate extended lifespans, refurbishment, structures as material banks and maximise end-of-life value in terms of carbon emissions.
		Reimagining the design process with material sourcing and early supply chain data/input as a critical part of concept development.
		Research to define where, in a 2050 resource-critical world, each high-impact material should be used (and not used) so that it plays to its strength and best complements overall industrial ecologies.
		Develop smarter, quicker structural surveys, assessments and re-justification of existing structures aided by new digital tools and performance-based approaches. Understand the limits of existing assessment and re-justification techniques, i.e. what types/classes of structure are currently just on the wrong side of the reuse-refurb vs demolish equation.
	3) Data-driven automated calculations and decision-support tools	Development of software tools that optimise materials and construction process for carbon emissions that are no harder to use than traditional ones and link in with resource availability data.
		Harness big data to gather true statistical models for all code parameters (in place of pre-prescribed characteristic strengths, partial factors, characteristics loads, etc).
	4) New approaches to design concept and scheming, working with modern methods of manufacture	Identify and develop products and systems which implement a true industrialisation of construction which is driven by and enables a sustainable-first approach.
		Harness the best aspects of current construction approaches that have been honed over many years, e.g. lean fast-to erect steel frames, and ensure these are not lost with the push to platform builds/modular/off-site systems, etc.
Materials	**5) Natural materials –** timber, biobased materials, stone, low impact blocks/bricks	Understand how to balance industrialisation and optimisation of material production processes with the ecological need of the environment that they are being taken from.
		Develop construction norms (inc. design guides and accessible codes) for timber, stone and other natural materials, particularly in all types of short- or medium-span/rise superstructure, including off-site innovations and industrialisations to drive cost competitiveness.
		Reimagine low-cost, low-tech, flexible (in supply chain), historical forms of construction that are much more accessible to the layperson for appropriate forms of construction.
		Overcome fire considerations to make timber viable against steel at mid-rise.
		Reach consensus on, and 'solve' end-of-life carbon release challenge for timber and other biobased materials.
		R&D to bring step-change reductions in drying energy and/or novel timber-based materials/elements with reduced need for drying[18].
		Connect construction to forestry, develop local supply chains which promote biodiverse forestry increase in harmony with construction harvesting.
		Develop local-first sustainable sourcing of stone, with consideration to a finite supply source, positive social impact and promotion of biodiversity during extraction and after.
		Develop low-carbon, renewable block-type, brick replacement materials.

TABLE 1: Research, development and innovation challenge areas (continued)

	6) Steel	Develop industry-wide databanks for fabrication models without barrier to entry/access.
		Enable easy application of leaner structural elements types (fish belly, intermediate catalogue sizes, roll to order).
		Investigate the viability of impurity tolerance metallurgies (one of the downsides of closed-loop EAF/low-grade scrap inputs) for different structural applications, together with scrap processing routes to ensure low-impurity steels (e.g. rail sections, structural sections) remain high-value not mixing with low-grade scrap.
		Development of zero-carbon fire protection options which are essential for much steel use.
	7) Brick	Develop design standards and guidance for low-carbon bricks/blocks; essential to drive widespread use.
	8) Concrete	Research and develop second-generation AACMS/novel cements that do not use PFA or GGBS.
		Research and develop long-term supplementary cementing materials (eg LC3, calcined clays, due to limited PFA and GGBS).
		Develop and implement approaches to reduce quantities and carbon intensity of rebar, e.g. higher-strength/more widespread high-spec fibre-reinforced concrete/use much less rebar/basalt (to improve overall steel industrial ecology situation as well as making direct carbon reductions).
		Develop a suite of carbon-optimal local specifications in response to available proximity of material supply and environmental conditions for durability.
Construction, maintenance and deconstruction	9) Site and transport emissions	Develop new approaches to information systems (in the broadest sense) to ensure the right information is readily available when choices are being made, e.g. currently a designer specifies a material but rarely has the detailed travel distance/mode – yet this data could exist – and should become more possible to access easily with the rise of end-to-end cloud quality assurance systems collating big data across the sector.
		Democratising high-tech production/fabrication vs centralised approaches with greater transport distances to consider which is better in terms of carbon is still an open question. It will rise in importance as certain forms of transport rapidly decarbonise while others don't, and researching the benefits of each is key to achieving the lowest-carbon project for many materials, structural typologies and projects.
	10) Understanding and eliminating the performance gap	Develop a standardised measuring, collation and reporting approach for upfront carbon in construction for comparison to predictions in design to feed back to wider industry is to be developed.
	11) Design for low embodied carbon during maintenance and refurbishment	Find new forms of maintenance/recoating/reconditioning/replacement that are very low/zero carbon. The structures built today, in 2021, will typically have an expected life to first major maintenance of 20–25 years, taking us to 2045–50; the moment at which we as an industry need to be hitting zero carbon.
		Forensic research is needed to better understand which aspects/components/constituent parts of structures are causing limits on real lifespan, and develop 'failure mode, effects and criticality analysis'-type approaches to systematically design out the weak links.
	12) Maximising the value of demolished materials	Find new ways to reuse each and every system/element/component/material at its highest value and biggest net carbon benefit; taking account of practical construction considerations in addition to theoretical material properties.
		Ensure high value from end-of-life concrete either via smart crushing-type approaches (applied to structures that have already been built) or by reimagining reinforced concrete as something which can be demounted and reconditioned/reused (for structures not yet built).

6) Steel – steel in developed countries (with a mature built environment) will have full circularity in 2050; the demand for new will be limited to the tonnage of scrap arisings. All steel could then, in principle, be reused or recycled by renewables-powered electric arc furnaces (EAF). This will be enabled through reduced demand for steel, with structural engineers using efficient design, optimisation and aggregating all possible marginal gains[14] alongside the increase in market share for natural materials in superstructures.

Developed countries will target the provision of a net export of recycled, EAF steel to countries with expanding built environments to reduce the reliance of the rest of the world on basic oxygen steel (with/without CCUS). Specific categories of steel structure will be reused without remelting, enabled by digital systems which better retain smart fabrication models and match supply to demand.

7) Brick – existing bricks will be reused, and new bricks will be made via non-fossil furnaces – be they electric or hydrogen-powered. This will also be accompanied by increased use of alternative low-impact bricks.

8) Concrete – concrete will not be reliant entirely on ordinary Portland cement (OPC) chemistry. Rather there will be many more classes of novel cement and cement replacement in use depending on specific applications, including second-generation alkali-activated cementitious materials (AACMs) (which don't rely on pulverised fuel ash (PFA) and ground granulated blast-furnace slag (GGBS) as their already limited supply will diminish), calcined clays and other cements such as magnesium oxide-based chemistries.

New chemistries and placing, curing and testing requirements will mean a very large proportion of concrete is precast, and likely 'certified products' underpinned by broader performance requirements (in future editions of PAS 8820).

Construction, maintenance and deconstruction

9) Site and transport emissions will be reduced through universal use of electric and hydrogen-powered transport and site-plant. Combined with increased off-site construction, this will eliminate construction-phase emissions. Long-distance shipping, especially by sea, will remain a challenge to decarbonise, so prioritising semi-local sourcing will be important.

10) Understanding and eliminating the performance gap will be required to ensure that the embodied carbon calculated in design is producing intended results.

11) Design for low embodied carbon during maintenance and refurbishment will be normal in 2050 to maximise structural life, but not at the expense of upfront embodied carbon, as research into improving future technologies will continue to boost the ability to extend life with low-carbon interventions. Circular economy principles will be critical to achieving this, e.g. design for easy separation of layers, use of reversible fixings.

12) Maximising the value of deconstructed materials from existing structures that need to be demolished will be essential. For example, concrete will be smart-crushed to extract clean aggregate, clean sand and, via chemical processing, ensure full carbonation of all the cement paste to absorb CO_2. Steel reuse will be maximised via retention of fabrication models and by smart sensing – big data which captures the actual loading through the life of the material, enabling calculation of the residual fatigue life for that component.

Bringing research into practice

A viable net-zero future needs research and development to provide fresh opportunity for developing a truly sustainable construction industry. It needs to do this at a fast pace, in a not-done-before, joined-up manner between academics, designers and contractors, such that:

- research starts now and is carried out at a fast enough pace and a large enough scale to respond to the emergency
- research is focused on areas with real-world application and viability
- engagement ensures that construction avoids the 'valley of death' between proving a technology/approach in the lab (or a one-off trial) and it becoming usable at scale across the industry
- industry and academia are able to work effectively together end-to-end through research, development, and delivery; enabled by appropriately configured bodies and institutions and innovative funding mechanisms.

“2050 IS TOO SOON TO WAIT AND HOPE FOR RADICAL BREAKTHROUGH TECHNOLOGIES TO DELIVER NET-ZERO EMISSIONS

The key challenge areas set out in the agenda above show there is much work to be done across the structural engineering profession and the construction industry more widely. 2050 is too soon to wait and hope for radical breakthrough technologies to deliver net-zero emissions and tackle the biodiversity emergency, so the focus is necessarily on today's current and adjacent technology and approaches; developing, scaling, endeavouring to make them business as usual for the whole sector via innovation acceleration.

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Case study 2. Low-carbon bricks from natural materials

Strocks are an ultra-low-carbon block/brick made by H.G. Matthews from natural materials – unfired clay and straw. A testing and development programme is currently under way, towards more widespread use as a viable alternative to conventional loadbearing brickwork while saving over 50% of the embodied carbon.

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REFERENCES

1) Intergovernmental Panel on Climate Change (2019) *Special Report on Global Warming of 1.5°C* [Online] Available at: www.ipcc.ch/sr15/ (Accessed: January 2021)

2) UN Environment Programme (2019) *Making Peace with Nature* [Online] Available at: www.unep.org/resources/making-peace-nature (Accessed: March 2021)

3) Arnold W., Cook M., Cox D., Gibbons O. and Orr J. (2020) 'Setting carbon targets: an introduction to the proposed SCORS rating scheme', *The Structural Engineer*, 98 (10), pp. 8–12

4) HM Treasury (2021) *The Economics of Biodiversity: The Dasgupta Review – Abridged Version* [Online] Available at: www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review (Accessed: February 2021)

5) Gibbons O.P. and Orr J.J. (2020) *How to calculate embodied carbon* [Online] Available at: www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/ (Accessed: January 2021)

6) International Energy Agency (2020) *Cement Tracking Report* [Online] Available at: www.iea.org/reports/cement (Accessed: January 2021)

7) International Energy Agency (2020) *Iron and Steel Technology Roadmap* [Online] Available at: www.iea.org/reports/iron-and-steel-technology-roadmap (Accessed: January 2021)

8) Committee on Climate Change (2020) *The Sixth Carbon Budget: The UK's Path to Net Zero* [Online] Available at: www.theccc.org.uk/publication/sixth-carbon-budget/ (Accessed: March 2021)

9) Mineral Products Association, UK Concrete (2020) *UK Concrete and Cement Industry Roadmap to Beyond Net Zero* [Online] Available at: www.thisisukconcrete.co.uk/TIC/media/root/Perspectives/MPA-UKC-Roadmap-to-Beyond-Net-Zero_October-2020.pdf (Accessed: March 2021)

10) British Constructional Steelwork Association (2020) *Steel Construction: Carbon Credentials* [Online] Available at: www.steelconstruction.info/images/d/df/Steel_construction_-_Carbon_Credentials.pdf (Accessed: March 2021)

11) European Ceramic Industry Association (2012) *Paving the way to 2050: The ceramic industry roadmap* [Online] Available at: http://cerameunie.eu/topics/cerame-unie-sectors/cerame-unie/ceramic-industry-roadmap-paving-the-way-to-2050/ (Accessed: March 2021)

12) UK FIRES (2020) *Absolute Zero: Delivering the UK's climate change commitment with incremental changes to today's technologies* [Online] Available at: https://ukfires.org/absolute-zero/ (Accessed: March 2021)

13) Image adapted from **Ellen Macarthur Foundation (2017)** based on **Cramer J. (2014)** 'Moving Towards a Circular Economy in the Netherlands: Challenges and Directions', *Proc. HKIE Environmental Division Annual Forum: The Future Directions and Breakthroughs of Hong Kong's Environmental Industry*, Hong Kong, 17 April, pp. 1–9 [Online] Available at: https://wp.hum.uu.nl/wp-content/uploads/sites/32/2015/04/Paper-HongKong-JC-april-2014.pdf (Accessed: March 2021)

14) Wise C. (2018) 'MaGIC: Marginal Gains in Construction – a UK industry strategy to deliver more value with less cost', Plenary Lecture, UK Steel Construction Day, SCI, 8 November

15) Department for Business, Energy & Industrial Strategy (2020) *Valuation of Energy Use and Greenhouse Gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government*, Table 3, 19 March [Online] Available at: www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal (Accessed: January 2021)

16) Global CCS Institute (2020) *Global Status of CCS 2020* [Online] Available at: www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf (Accessed: January 2021)

17) Pamenter S., Myers R.J. (2021) 'Decarbonizing the cementitious materials cycle: A whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts', *J. Indust. Ecol*., pp. 1–18; doi: https://doi.org/10.1111/jiec.13105

18) Ramage M.H., Burridge H., Busse-Wicher M. *et al*. (2017) 'The wood from the trees: The use of timber in construction', *Renew. Sustain. Energy Rev*., 68 (1), pp. 333–359; doi: https://doi.org/10.1016/j.rser.2016.09.107