Circular construction: building for a greener UK economy

Methodology

This analysis calculates the amount of raw, primary materials needed to build the houses, commercial buildings and infrastructure needed in the UK out to 2035 based on predicted household numbers, commercial building demand and infrastructure spending. There are two pathways:

1) Business as usual: no improvements in resource efficiency in construction.
2) Circular scenario: making better use of existing buildings and reducing demolition rates, as well as reaching the technical potential for resource efficiency by 2035, ie fully implementing measures to reduce the amount of raw material needed per building or project.

Baseline material use in construction

Baseline material use in the UK construction sector in 2018 is taken from M Drewniok, et al (preprint).[1]

A summary of material use and upfront carbon emissions associated with each material included in the study is presented in the table below.

Concrete and other cementitious materials, such as plaster and mortar, were responsible for 89 per cent of materials used and 62 per cent of emissions. Metals such as aluminium and steel made up just three per cent of material use but contributed 27 per cent of emissions. Construction of domestic buildings consumed the most materials and emitted most carbon, at 41 and 38 per cent respectively. Non-domestic building construction consumed 20 per cent of the materials, but emitted 30 per cent of the carbon, reflecting the greater proportion of high carbon materials such as concrete and steel used in non-domestic buildings.

Summary of materials used in UK construction in 2018, according to M Drewniok et al (preprint)

Material	Material used		Upfront carbon emissions	
	Million tonnes (Mt)	Per cent of total	Million tonnes (Mt)	Per cent of total
Ready mix concrete	54.7	55.5	7.5	29.8
Precast concrete	25.6	26.0	4.8	19.3
Other cementitious	7.1	7.2	3.2	12.6
Clay products	5.8	5.9	1.8	7.3
Steel reinforcement	1.1	1.1	2.4	9.5
Steel sections	1.1	1.1	1.9	7.6
Steel sheets	0.3	0.3	1.3	5.2
Timber	0.7	0.8	0.4	1.7
Natural stone	0.5	0.5	0.05	0.2
Gypsum products	0.9	0.9	0.2	1.0
Glass	0.1	0.1	0.2	0.8
Aluminium	0.08	0.1	1.1	4.4
Plastic (PVC)	0.04	0.04	0.1	0.6
Total	**98.6**		**25.0**	

Model building typologies used in M Drewniok et al (preprint)

Sector	Model building typologies
Domestic	End terrace
	Mid terrace
	Semi-detached
	Detached
	Bungalow
	Converted flats
	Low rise flats, less than four storeys
	Low rise flats, between four and six storeys
	High rise flats, between seven and ten storeys
	High rise flats, over ten storeys
Non-domestic	Low rise office building
	High rise office building
	Small industrial building
	Medium industrial building
	Large industrial building

M Drewniok, et al (preprint) takes a bottom-up approach to estimating material flow in the construction sector, based on ten model building typologies for domestic and five for non-domestic buildings (see above) and representative material intensity for each typology.

Infrastructure was modelled based on a top down approach, due to data limitations, that includes data for concrete, steel and steel reinforcement only.

Business as usual (BAU)

Material demand out to 2035 is projected by scaling up the baseline in line with construction demand for housing, commercial buildings and infrastructure, based on the UKGBC *Whole life carbon net zero roadmap*.[2] For housing, this is based on Office for National Statistics household projections.[3] For commercial buildings and infrastructure, projections include the infrastructure required for net zero, such as in the power system. Power system modelling is based on National Infrastructure Commission analysis of needs for net zero.[4]

Current recycling and reuse rates are used to calculate raw material demand for BAU (see below). Reuse rates are converted into reductions in raw material use by applying reuse rates to the amount of material coming from demolitions in the baseline, to calculate a percentage reduction in demand due to current reuse rates.

Recycled content and reuse rates assumed for BAU

Material	Recycled content (per cent)	Reuse rate (per cent)
Concrete	28[5]	0
Steel sections	42[6]	6[7]
Steel rebar		1[8]
Steel sheets		12.5[9]
Timber	0	2.5[10]
Glass	25 [11]	0
Aluminium	56 [12]	0
Plastic	15[13]	0

Circular scenario

This applies interventions from 2025, to give time for government to implement supporting policy, and scales them up linearly to reach technical potential in 2035. Interventions are based on academic literature and expert judgement, and technologies available today. All are applicable to the UK context. Interventions are grouped into five categories: design, demand reduction, reuse, material substitution and modern methods of construction, and recycling (see below).

Interventions modelled

Design	– Reducing overspecification of materials in infrastructure reduces demand by 25 per cent[14] – Optimising design of buildings through digital tools reduces demand for materials by 7 per cent[15] – Flexible formwork technology to create more complex structures that minimise the use of concrete[16] – Optimising reinforcement of concrete[17] – Optimising use of structural steel[18] – Post-tensioning concrete floor slabs, to reinforce them while requiring less material[19] – Increasing use of precast concrete elements[20]
Demand reduction	– Triple the numbers of homes delivered by converting commercial buildings into flats, reducing demand for other housing types by 24 per cent and demolition of commercial buildings by 57 per cent.[21]
Reuse	– Reusing structural and sheet steel reduces demand by 40 per cent, structural timber by 18 per cent, and bricks by 30 per cent[22] – Repurposing entire foundations in 5 per cent of new buildings[23] – Increasing reuse of stone, glass, aluminium, and plastic by five per cent[24]
Material substitution and Modern Methods of Construction (MMC)	– Increasing use of timber in structural elements of low and mid-rise buildings reduces demand for steel, cement and bricks.[25] – MMC increases to 30 per cent of building stock by 2035. Wastage rate is halved for all materials in these buildings.[26]
Recycling	– Increasing recycled content of steel, aluminium, glass and plastic to 95 per cent[27]

To account for the potential for demolition rates to be reduced and building lifetimes extended, this pathway delivers more housing through change-of-use from commercial properties to domestic.

The baseline study includes a domestic housing typology called 'converted flats' which represents change of use from commercial to domestic. This typology assumes the structure of the building, including foundation, frame and external walls are retained, but all other elements are replaced. It therefore assumes that internal walls, doors, and windows can all be reconfigured to provide a residential space.

In the circular scenario, the number of homes delivered as 'converted flats' is tripled by 2035, compared to the baseline, and demand for all other housing types is reduced by 24 per cent to maintain overall housing delivery. This reduces the demolition of commercial buildings by 57 per cent.

For infrastructure, spending has been reduced to account for only maintenance of existing roads, with no money spent on new roads. A 51 per cent reduction is applied to road spending projections and material use, based on previous Green Alliance analysis on road spending commitments in the March 2020 spring budget.[28]

Carbon emissions calculations

The upfront carbon emissions associated with UK construction in the baseline year of 2018 is taken from M Drewniok, et al (preprint).[29] For construction, upfront emissions include emissions from extraction and processing of materials (modules A1-3), transport to site (A4) and construction processes (A5). Carbon intensity of materials are given in Table 32 of the supplementary information for M Drewniok, et al (preprint).

The carbon intensity of material production and construction activity is assumed to be constant, to demonstrate the potential for circularity to reduce emissions from construction independent of efforts to decarbonise industrial production of materials such as steel and concrete.

In the circular scenario, upfront carbon emissions are reduced by taking into account the reduced amounts of raw primary material required, and the emissions from secondary materials. To account for reuse, emissions from modules A1-3 (extraction, processing, etc) are removed but transport and construction process emissions (A4 and A5) are retained. To account for recycling, emissions from modules A1-3 are adjusted to reflect the lower carbon intensity of recycling compared to primary extraction (Table 5). Transport and construction process emissions (A4 and A5) are retained.

Carbon emissions reduction due to recycling

Material	Carbon emissions reduction due to recycling
Steel	62-90 (average 76) per cent reduction kg CO_2e/kg from cradle-to-gate[30]
PVC	2 tonnes CO_2e reduction per tonne recycled[31]
Glass	300kg CO_2e reduction per tonne of flat glass remelted[32]
Aluminium	80-96.5 (average 88.25) per cent reduction kg CO_2e/kg from cradle-to-gate[33]

The environmental impacts of common UK construction materials and best practice potential

The table below provides the reasoning behind our assessment of the environmental impacts of construction materials, on page 27 of *Circular construction: building for a greener UK economy*.

The colour grading is as follows:

(red)	Large environmental impact
(yellow)	Medium environmental impact
(green)	Minimal environmental impact
(grey)	Lack of clear data

Concrete[34]	**Typical performance**	**Best practice**
Carbon	Upfront carbon emissions from concrete production: 133kg CO_2e/tonne.[35] The production of clinker used in cement, is energy intensive, needing rotating kilns the length of two football pitches heated to 1,500 degrees.[36] For every tonne of cement produced, it is estimated that 600kg CO_2e is released.[37] Whilst the upfront carbon per tonne of final concrete is lower than other materials, the amount used in UK construction results in a carbon footprint twice as large as steel, ten times greater than brick and 50 times greater than timber.[38]	Increasing the proportion of slag in cement can decrease energy consumption and embodied carbon and the industry had a 2020 target to reach 35 per cent (which it missed).[39] In addition, the availability of secondary slag and fly ash is declining as coal plants and blast furnaces close.[40] Decarbonising cement and concrete production is also difficult as 50 to 60 per cent of emissions derive from the chemical decomposition of raw materials which contain carbon.[41] Alternative non-carbon compounds are being piloted, such as calcium silicates which sequester carbon, but these lack robust life cycle assessments that can point to their impact and viability.[42]
Extraction and waste	For every tonne of clinker produced (a key ingredient in cement used for concrete) 1.55 tonnes of raw material are used.[43] UK mine and quarry waste was 20Mt in 2019, of which aggregates had the largest share, alongside china clay waste.[44] Waste to landfill from production is low, at only 0.3kg/tonne of concrete.[45]	Quarry waste could be better used as fine aggregate in construction, rather than as backfill.[47] In production, waste to landfill is low, at only 0.3kg per tonne of concrete.[48] Increasing the recycled content of aggregate in concrete is problematic, as strength and workability concerns have resulted

	However, virgin material use is dominant, as concrete only uses five per cent recycled aggregates, although cement is currently made of 26 per cent industry by-products (such as slag, fly ash etc).[46]	in the British Standard for Concrete limiting recycled content to 20 per cent, which can be adjusted slightly depending on the type of recycled aggregate and the purpose of the final product.[49] In Europe, it is expected that cement paste will be separated from aggregate and sand waste by 2030, giving rise to opportunities for reuse within concrete production, but research is still ongoing.[50]
Biodiversity and land impact	Mining can impact local ecosystems and the UK sources up to a quarter of its sand through marine dredging, which can degrade sea floor ecosystems and contribute to coastal erosion.[51] In the UK, 39 per cent of aggregate reserves with extraction permits are in areas of protected land.[52] However, in general, mining for non-metallic minerals (such as sand, gravel and limestone), accounts for less than two per cent of resource impacts, as considered by the UN, which include impacts related to climate, health, water stress and land use.[53]	Using more secondary materials in cement (such as slag) can considerably reduce the depletion of non-living resources and impact on land use potential (by 72 and 41 per cent respectively), which will, in turn, create more favourable conditions for biodiverse ecosystems.[54] However, the availability of slag and fly ash is declining as coal fired power plants and blast furnaces close.[55]
Water	Portland cement, used in concrete, has a blue water footprint (fresh surface water or groundwater) of 680 litres per tonne, excluding water used indirectly through energy for production.[56] Potable water is then used to mix dried cement with aggregates and in 2019, the UK concrete industry consumed 78.2 litres of mains water per tonne of performance concrete.[57]	Further water reduction can be achieved through the use of harvested rainwater and recycled production water, where recent developments in water reducers (the chemicals added before concrete is poured) allow residues to be treated and reused.[58] Progress is also needed in consistent data monitoring to set a baseline for a water reduction target.
Pollution	Quarrying for aggregates, used in concrete, affects the local environment. In 2020, aggregate mining in the UK produced 18,000 tonnes of particulate matter – 2,000 tonnes higher than passenger cars for the same year –which has health	For quarries over 25 hectares, pollution to water and air has to be recorded.[61] While there are industry standards for quarrying, there are no clear targets for mitigation and a lack of data as to whether standards are commonly upheld.

	consequences for the lungs and heart, as well as environmental impacts on nutrient health.[59] Quarrying for aggregates was also responsible for 22 tonnes of sodium pollution, which can negatively impact marine ecosystems if leaked into freshwater.[60]	
End of life	Most concrete recycling is in the form of low grade aggregate, with 75 to 80 per cent of recycled aggregate ending up in sub-base fill.[62] Some forms of concrete are reusable at the end of life, largely from prefabricated structures and larger concrete blocks, but reuse is difficult and not integrated into the industry, with rates being even lower than steel.[63]	Direct reuse could deliver a primary raw material saving of over 1000kg/m^3 of concrete compared to its recycled equivalent.[64] However, there are only limited opportunities for concrete reuse, mostly with precast elements and through foundations which can be reused in situ.[65] In general, aggregates recycling is now reaching its 'upper limit', according to the Mineral Products Association, with 70 per cent virgin aggregates still needed to meet the overall demand.[66]

Steel	**Typical performance**	**Best practice**
Carbon	Upfront carbon emissions for steel production for UK construction: 2,084kg CO_2e/tonne.[67] Steelmaking is energy intensive, accounting for a quarter of global industrial carbon emissions and 15 per cent of UK industrial emissions.[68,69]	The manufacturing process can be decarbonised through a combination of electric arc furnaces and hydrogen direct reduction processes, which would reduce the UK's CO_2 emissions from steel production by 87 per cent by 2035.[70] Scrap-electric arc furnace production currently accounts for 21 per cent of the UK's overall steel production, with direct CO_2 emissions from the furnace coming to 100kg CO_2e per tonne of steel, compared to 1,900kg for traditional blast furnaces.[71]
Extraction and waste	For every tonne of virgin steel produced, the industry requires 2.4 tonnes of raw material (iron ore, coal and limestone) and 0.13 tonnes of scrap steel.[72] Once in manufacturing, the material efficiency rate for the sector is high – at 97.6 per cent – as waste and by-products, such as slag and ferrous	Reducing waste from mining is heavily dependent on the location and quality of iron ore. Rich iron ores have better material efficiency and deep ores allow for underground mining, producing less waste rock.

	scrap, have broader uses and value in industry.[73]	Waste can be managed through treatment to prevent acidic sludge and, if not suitable for production, used as backfill in mines.[74] When scrap steel is used in production, raw material savings for every tonne produced are 1,400kg for iron ore, 740kg for coal and 120kg for limestone.[75] Using electric arc furnaces also reduces the production of slag by-products by around 200kg per tonne of steel produced compared to blast furnaces.[76] Whilst recovery rates for slag are high, from 80 to 100 per cent, the ratio can be improved in many regions.[77]
Biodiversity and land impact	Ecosystem impacts from raw material extraction vary but can be considerable. In 2019, 75 per cent of iron ore extraction occurred in three species-rich and critical biomes, and around 1,000Mt iron ore was originated from within 20km of a protected area boundary.[78] In general, mining for metals within protected areas has surged, increasing from 225Mt extracted metal ores to 480 Mt from2000 to 2019, with iron ore accounting for over half of this extraction in 2019.[79]	The Responsible Steel Standard requires sites to take stock of what risk they pose and impact they have on biodiversity and to implement a plan to manage them. The standard also expects sites to safeguard areas identified as being important for biodiversity.[80] Best practice for mining, in general, recommends minimising the activity in space and time, eg to avoid seasonal migration routes of important species.[81] However, reporting is still not consistent or transparent.
Water	The blue water footprint from processing virgin steel is around 8,000 litres per tonne.[82] Over 90 per cent of water used in UK steel production is returned to source, meaning only a little is lost (mainly to evaporation). However, discharge of cooling water can significantly raise the temperature of the receiving water body and affect the aquatic ecosystems if not treated properly.[83]	Electric arc furnaces (EAFs) use similarly high levels of water to blast furnaces, but return slightly more to source (94 per cent), but there is a lack of independent assessment for the water footprint of EAFs.[85] Water pollution, however, can be mitigated by treating water before returning it to source, which is commonplace in the UK. Where mining remains necessary, increasing global demand for metals

	Iron ore mining also often takes place in desert environments, including in Australia, the world's largest producer of iron ore, where water availability can be problematic.[84]	and the declining quality of ore could increase water use.[86]
Pollution	Iron mining results in the most tailings of any metal.[87] Some tailings dams have failed in recent years. These store hazardous waste from iron ore mining operations and can release toxic sludge, as well as posing environmental risk in use due to contaminants spread through dust and seepage.[88,89] Steel mining can also harm human health through exposure to particulate matter (PM) and other toxins.[90] In general, metals were responsible for 39 per cent of global PM health impacts, mostly deriving from iron and steel.[91] In 2020, UK blast furnace steel production also produced 43,000 tonnes of poisonous carbon monoxide gas.[92]	At an EU level, pollution is managed through environmental management systems which require the monitoring of chemicals used and wastewater and waste gas streams produced, with policies and technologies to reduce the consumption and consequent risks of these products.[93] Mining is more difficult to regulate, and increased demand for metals combined with declining ore quality, mean that mines will need to use more energy, more water and create more waste, which has knock-on polluting effects.[94]
End of life	As a 'permanent material', steel has the potential for nearly 100 per cent recyclability, and can be converted to the same (or higher or lower) grade product depending on the initial usage and metallurgy.[95,96] In the UK, the steel recycling rate is around 95 per cent, but reuse is only five per cent. [97]	Whilst steel recycling rates are very high, there is potential for reuse to be much higher and to deliver significant environmental savings compared to recycling.[98] For example, reusing steel could offer a carbon saving of over 2,000 kg CO_2e/tonne of reused product. It is estimated that 40 per cent of UK construction demand could be met by reused steel.[99]

Timber	**Typical performance**	**Best practice**
Carbon	Upfront carbon emissions for timber production: 293kg CO_2e/tonne.	Timber can be carbon negative over its whole lifecycle, if forests are managed sustainably.[103]

	This does not account for its carbon storage potential.[100] Timber can be carbon negative from cradle to gate if carbon storage is included, and a typical three-bedroom semi-detached timber frame house can lock up around four tonnes of atmospheric CO_2, with variations depending on timber species.[101] However, the forestry sector and deforestation contribute up to 17 per cent of global greenhouse gas emissions.[102]	Energy-consuming drying processes have the potential to use 60 per cent less heat, when using best available technologies in drying kilns.[104] (See page 28 of our report *Circular construction: building for a greener UK economy*. There are questions about how much timber can be sustainably sourced, given other pressures on global forestry and land use.)
Extraction and waste	For every metre cubed of tree cut in a forest, half goes to waste in the form of damaged residuals, abandoned logs, stumps, branches and trimmings.[105] This waste is often used in production (such as for steam production boilers for drying wood products), but can be left on site.[106]	New technologies have been developed to allow for the use of low quality logs, but these production methods are not transformative nor are they widely used.[107] Technological changes can reduce waste, as well, but not to a great extent: waste from plywood production can be reduced by six per cent, for instance.[108] For some products, the amount of secondary content can be increased, but virgin timber is often still preferred to ensure consistent quality: recycled content in wood boards can be above 70 per cent in one company, but only 40 per cent in another.[109] The price of recovered wood can be high, due to government incentives for biomass as fuel, limiting its reuse.[110]
Biodiversity and land impact	Unlike extraction methods for rocks and ores, timber harvesting requires topsoil to remain intact, causing less disruption to wildlife habitats.[111] Globally, there are pressures on sustainable forestry, with estimations suggesting paper and timber sourcing combined are responsible for 13 per cent of deforestation and suggestions that forestry involving clear cutting or slashing and burning, which largely occurs outside Europe, causes a loss	Sustainably managed, regenerative forests protect biodiversity and can improve the condition of native woodlands.[115] According to the forestry industry, the expansion and maturing of existing forests for wood production has demonstrably increased levels of biodiversity and ecological restoration.[116] (See page 28 of our report *Circular construction: building for a greener UK economy*, as there are questions about how

	of up to 50 per cent of local species.[112,113] The global picture is an important aspect of UK timber demand as most wood for the UK market – 81 per cent – is imported, although this is mostly from FSC-certified EU sources.[114]	much timber can be sustainably sourced, given other pressures on global forestry and land use.)
Water	Healthy forests filter water, reduce erosion and recharge groundwater tables, which ensures safe water quality.[117] However, if managed unsustainably and deforested, water quality is compromised and there is an increased risk of floods and drought, triggering a host of additional environmental problems.[118] In comparison with other materials, timber pollutes water less, with estimations that steel and concrete pollute 300 per cent and 225 per cent more water resources respectively.[119]	Sustainably managed forests protect water supplies, improve water security and overall water quality.[120]
Pollution	Forest felling and restocking can increase acidification and the likelihood of soil nitrate leaching, but the extent of the impact varies depending on forest type, rate of revegetation and broader pollution levels.[121] Diversified second and subsequent rotations have marginal impacts on surface acidity.[122]	By identifying vulnerable areas, establishing buffer zones and closely managing the type and longevity of forest cover and revegetation, forestry has a marginal impact on acidification.[123,124]
End of life	Wood products are often easier to deconstruct and reuse than concrete, especially when connections are nailed or screwed.[125] However, this has not been mainstreamed and half of wood waste is burnt as biomass, which releases carbon that would be stored if material were reused or recycled. Low grade recycling (estimated at 30 per cent) is the next most common destination, with only 2.5 per cent	There is potential for greater reuse of timber, exemplified by the National Community Wood Recycling Project who reused 44 per cent of wood waste in 2017.[129] Reuse will continue to be limited by demand for the growing biomass energy sector, though, which is being encouraged by government policy. Recycling cross laminated timber provides a carbon benefit of 364kg CO_2e/m^2, though there is limited research on how to improve its recyclability.[130]

	reused or reprocessed as a higher value product.[126] Cross-laminated timber is difficult to recycle due to the glues used, which could prove problematic as the global market for this is expected to triple by 2030.[127] Around 26 per cent UK wood waste is from construction, which matches the amount of wood waste generated through demolition.[128]	

Brick	Typical performance	Best practice
Carbon	Upfront carbon emissions for brick production: 213kg CO_2e/tonne.[131] Although the efficiency of manufacturing kilns has generally improved, the process is energy intensive and is still reliant on fossil fuels, with just five per cent of electricity derived from on site renewables.[132]	The industry is beginning to investigate the feasibility of replacing natural gas with low carbon fuels such as hydrogen, and electric-firing.[133] There are also improvements which could be made in efficiency, which worsened during the Covid-19 pandemic due to decreased demand.[134] With current technology, using reclaimed materials can reduce embodied carbon by 16kg per tonne of recycled content included, which is a reduction of seven per cent.[135]
Extraction and waste	For every tonne of brick produced, approximately 1.2 tonnes of raw material are needed.[136] The volume of waste generated in manufacturing is low, with around 0.5kg sent to landfill per tonne of brick produced.[137] However, only six per cent of the materials used in brick production are from alternative, recycled or secondary sources.[138] This figure is around half of that reported a decade ago.[139]	The volume of waste generated in manufacturing is low, with around 0.5kg sent to landfill per tonne of brick produced.[140] Though they are still in their infancy and have very limited market share, innovations, such as the K-Briq and ECO brick strips in the Netherlands, demonstrate that it is possible to produce bricks with a minimum 90 per cent recycled content, equivalent strength, high thermal mass and at comparable price points to conventional bricks.[141,142]
Biodiversity and land impact	As with cement and concrete, mining can impact local ecosystems.	There is no clear reporting on the interim impact on biodiversity of quarrying for bricks.

	Clay mining can contribute towards topsoil erosion and remove the natural protection that clay provides in aquifers.[143] Currently, 88 per cent of UK production sites are covered by a site specific biodiversity restoration plan, but the interim impact on local ecosystems is not clearly reported.[144]	Whilst there are 'Nature after minerals' parks largely focused on biodiversity restoration once quarries are closed, this covers only 80 out of 2,000+ quarries in the UK and the lead times to these restoration plans and the interim impacts on biodiversity are unclear.[145] Best practice can be attributed to the quarries within these parks that begin restoration while still active, reducing intermediary impacts.
Water	There is a lack of transparent data about absolute water consumption in UK brick manufacturing. Estimates suggest around 54 to 350 litres of water are needed per tonne of bricks, depending on the product type (with facing bricks needing the most water and bricks for walls needing the least).[146] In 2019, most water used was derived from rainwater collected from clay quarries, which improves water efficiency per tonne by 14 per cent.[147]	Whilst the use of mains water versus harvested water is being monitored, and minimising water use is mentioned in the sector's water policy, absolute targets for water consumption or efficiency have not yet been established.[148,149]
Pollution	Brick production in the UK was responsible for 1,700 tonnes of PM pollution in 2020, which can negatively impact human health and the local environment.[150] In 2020, UK brick production generated around 4,700 tonnes of additional air pollutants such as sulphur dioxide and carbon monoxide, which are dangerous for human health and, in the case of sulphur dioxide, contribute to acid rain.[151]	For quarries over 25 hectares, pollution to water and air has to be recorded.[152] While there are industry standards for quarrying, there are no clear targets for mitigation and a lack of data as to whether standards are commonly upheld.
End of life	Bricks often go to landfill, as high-strength mortars limiting reclamation.[153] Approximately 2.5 million bricks are released from buildings via demolition annually in the UK, with a reuse reclamation rate of less than five per cent.[154] For bricks that are	The Demolition Protocol suggests that the recovery potential for clay bricks could be as high as 100 per cent in some buildings, especially where lime-based mortar is used, which aids disassembly.[156] However, lime-based mortar was mostly used in historic buildings: Portland cement has a higher bond strength

	recycled, it is often low grade: around 50 per cent of bricks are under hybrid recycling, which means they are crushed alongside other materials and used in hardcore and underground fill for pavements and roads.[155]	and is consequently primarily used in modern masonry.[157] Reclaiming bricks with cement-based mortar is much more difficult, but it is technically possible through techniques such as saw-cutting and punching, and could become more feasible if aspects of the process are automated.[158]

Glass	**Typical performance**	**Best practice**
Carbon	Upfront carbon emissions for glass production: 1,627kg CO_2e/tonne.[159] Glass manufacturing is energy intensive, requiring very high furnace temperatures of around 1,600°C for the soda-lime-silica flat glass sheets most commonly used in construction.[160] Typically, over 80 per cent of fuel consumed on UK glass sites is natural gas.[161]	Traditional furnaces are about as efficient as technically possible. Some new technologies are being explored, such as all-electric melting, hybrid furnaces and hydrogen), but these are not yet well established and can be unsuitable for the technical production of flat glass.[162] A key facet of decarbonising glass production is to increase the use of cullet which refers to recycled glass that can be used in production. A ten per cent increase in the content of cullet reduces energy consumption by approximately three per cent.[163]
Extraction and waste	For every tonne of flat glass produced, 1.4 tonnes of raw material are used.[164] Production waste can be recycled internally, as glass offcuts can be reprocessed as 'cullet', ie recycled glass that is used in manufacturing. Up to 15 per cent of manufactured glass is collected and used as internal cullet.[165] Glass lost in downstream fabrication requires careful sorting to be remelted, and breakages often make the glass unusable.[166] As of 2008, the recycled content from external sources (eg end of life waste) was thought to be between 20 and 30 per cent.[167]	Fine aggregate waste generated through sand extraction can also be used in construction, but there are suggestions that ore-based sands, referring to the tailings from mining for ores, can be used to replace the amount of virgin material needed.[168] However, this would be highly dependent on the physical properties and silica content of tailings, and impurities need to be closely monitored. Every tonne of cullet remelted into new glass saves 1.2 tonnes of raw materials.[169] Production of cullet waste can already be entirely recycled internally in the melting furnace.

		There are not many further improvements to be made in material efficiency, as flat glass is already close to its minimum thickness.[170] There is technical potential to produce flat glass derived entirely from secondary material. This has not yet been extensively tested, though, and there may be quality issues for certain products, as well as problems with the availability of waste input. [171]
Biodiversity and land impact	Like other non-metals, mining for silica sand, limestone and soda ash affects local ecosystems, but has a relatively low impact overall. There is, however, uncertainty regarding the long term security of silica sand supply to make clear glass, putting pressure on already fragile ecosystems.[172,173]	There is no clear reporting on the interim impact on biodiversity of quarrying for limestone or mining silica sand. Whilst there are 'Nature after minerals' parks focused on biodiversity restoration once quarries are closed, this covers only 80 out of 2000+ quarries in the UK, few of which are silica sand mines, and the lead times to these restoration plans and the interim impacts on biodiversity are unclear.[174] Best practice can be attributed to the quarries within these parks that begin restoration while still active, reducing intermediary impacts.
Water	The blue water footprint of glass is around 3,200 litres per tonne of soda-lime float glass, largely deriving from the Solvay process, which produces soda ash.[175] Glass extraction and production also generates sediments which are critical pollutants when leaked into water bodies.[176] Water usage is not transparently monitored in UK industry.	There are alternative production possibilities for float glass, but the potential water reduction achieved through them has not been quantified. For instance, there have been suggestions that seawater, rather than freshwater, could be used in the Solvay process, which would lower the industry's blue water footprint.[177] In addition, alternative dry lime processes require less water than liquid lime, which is conventionally used.[178]
Pollution	The polluting impact of glass production is relatively low,	According to the glass industry, a ten per cent increase in the

	producing 41kg of particulate matter in the UK in 2020 and four tonnes of sodium.[179]	proportion of cullet reduces air pollution from already low levels by 20 per cent and water pollution by 50 per cent.[180]
End of life	Only a third of flat glass is currently recycled, compared to 71 per cent for container glass used in packaging.[181] Industry experts confirmed that direct reuse of flat glass is extremely difficult, due to the presence of invisible fractures in glass that affect performance, as well as tight quality control regulations.	If all the flat glass currently going to landfill was diverted to being recycled, the CO_2 savings would be around 150,000 tonnes (300kg CO_2e/t).[182] However, the availability of high-quality cullet is currently a limiting factor to circularity in the glass sector, especially as quality requirements for flat glass are more stringent than container glass and there are technical barriers in removing intact windows.[183,184] Some studies are looking into delamination processes that would increase the possibility of reuse, but these are often complicated and not considered favourable.[185]

Endnotes

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[14] Experts we consulted were clear that overspecification, ie putting more material in than is required, is commonplace in construction and for infrastructure particularly. Research has demonstrated overspecification can range from 25-50 per cent (https://www.meicon.net/what-we-do). The highest levels of overspecification occur for in-ground aspects of projects, such as concrete foundations, rather than leaner, more technical aspects. To account for this, we have applied a 25 per cent reduction in overspecification across all infrastructure.

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[21] In the baseline year (based on M Drewniok et al, preprint, op cit) 42,000 homes are delivered as converted flats. These are flats converted from commercial buildings to residential. Ninety four per cent of the floor area of demolitions in 2018 were commercial buildings. To model the impact of extending the lifetime of buildings and reducing demolition rates, we assumed additional housing could be delivered as converted flats. The commercial floor space demolished in 2018 would have supported five times as many converted flats, if no demolition took place. However, not all commercial buildings will be suitable for residential conversion, and some may contain hazardous materials. We therefore tripled the number of homes delivered as converted flats. This reduced the floor area of commercial buildings demolished by 57 per cent. To maintain housing delivery, we reduced all other domestic house building by 24 per cent.
[22] Assumptions on the potential for reused steel to meet demand were taken from C F Dunant et al 2017, *Real and perceived barriers to steel reuse across the UK construction value chain* who analyse steel scrap generation and quality to estimate that 40-80 per cent of steel demand could be met through reuse. For timber and bricks assumptions on reuse reducing demand for raw material are taken from modelling assumptions from the CIEMAP academic project, which were used as the basis for Green Alliance, 2018, op cit. Reuse of structural timber reduces demand for timber by 18 per cent, and reuse of bricks reduces demand by 30 per cent.
[23] Reuse of foundations results in no new concrete required for five per cent of projects. J Norman et al 2021, op cit
[24] Reuse of other construction materials reduces demand for raw materials by five per cent, based on modelling assumptions from the CIEMAP academic project, which were used as the basis for Green Alliance, 2018, op cit.
[25] Modelling assumptions from the Centre for Industrial Energy, Materials and Products (CIEMAP) academic project, which were used as the basis for Green Alliance, 2018, *Less in, more out.* Assuming change in English house building to typical Scottish mix (i.e. more timber frame and structural insulated panels and less masonry); widespread use of hybrid timber-steel in retail and warehousing. Use of cross-laminated timber and glulam in multi-storey construction for frame and flooring. Maximum technical potential would lead to ~500 per cent increase in wood for ~15 per cent decrease in steel and concrete, ~70 per cent decrease in brick.
[26] Projections from Savills (https://www.savills.co.uk/research_articles/229130/301059-0) and McKinsey (https://www.constructioncarbon.com/articles/modular-homes-a-way-for-the-future) suggest 20 per cent of housing could be delivered by MMC by 2030. Experts we consulted for the project suggested this could be up to 50 per cent by 2035 if problems with the planning system and financing models were tackled by government. For this analysis, we have taken 30 per cent of building stock as an ambitious scale up of MMC by 2035, but there is potential for further uptake with the right policy support. One of the benefits of MMC for the environment is that it reduces the amount of material wasted, and therefore the amount of raw material needed to be extracted. Case studies have demonstrated a range of wastage rate reductions, up to 90 per cent in the highest case. To account for overlap with other design interventions which reduce material use, such as increased use of precast concrete over ready mixed, for this analysis we have taken a mid-point estimate that MMC can halve the wastage rates compared to current practice. This is supported by multiple statements from the evidence submitted to the House of Lords Science and Technology Committee enquiry, *Off-site manufacture for construction: building for change*.
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