

Embodied Energy & CO2 in construction (background, datasets & case study)

University of Cambridge

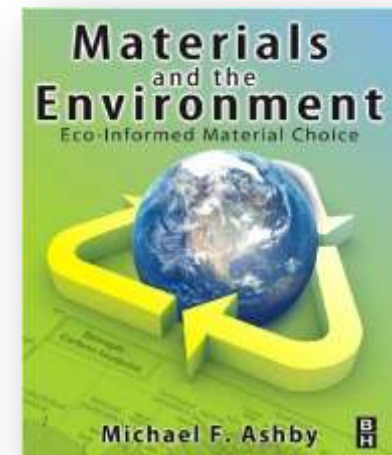
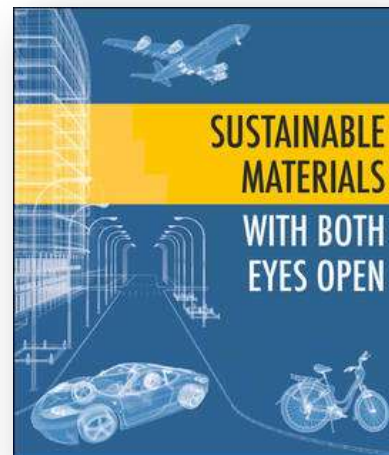
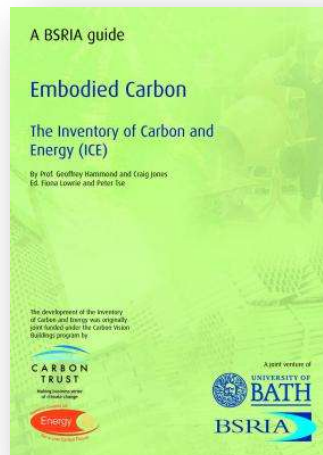
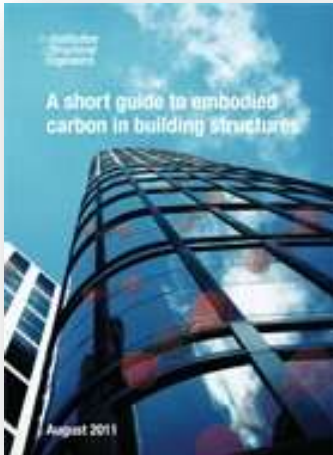
Year 2 Architecture

by Simon Smith

References

www.environment-agency.gov.uk/business/sectors/37543.aspx

Environment Agency Carbon Calculator



Definition of embodied energy

- Energy required to:

- Extract, process, fabricate
- Transport to site
- Erect on site
- Maintain
- Dismantle
- Re-use, re-cycle or dispose

← Cradle to gate

← Cradle to grave

- Different measures:

- Energy (kwh)
- Carbon (C)
- Carbon Dioxide (CO₂)

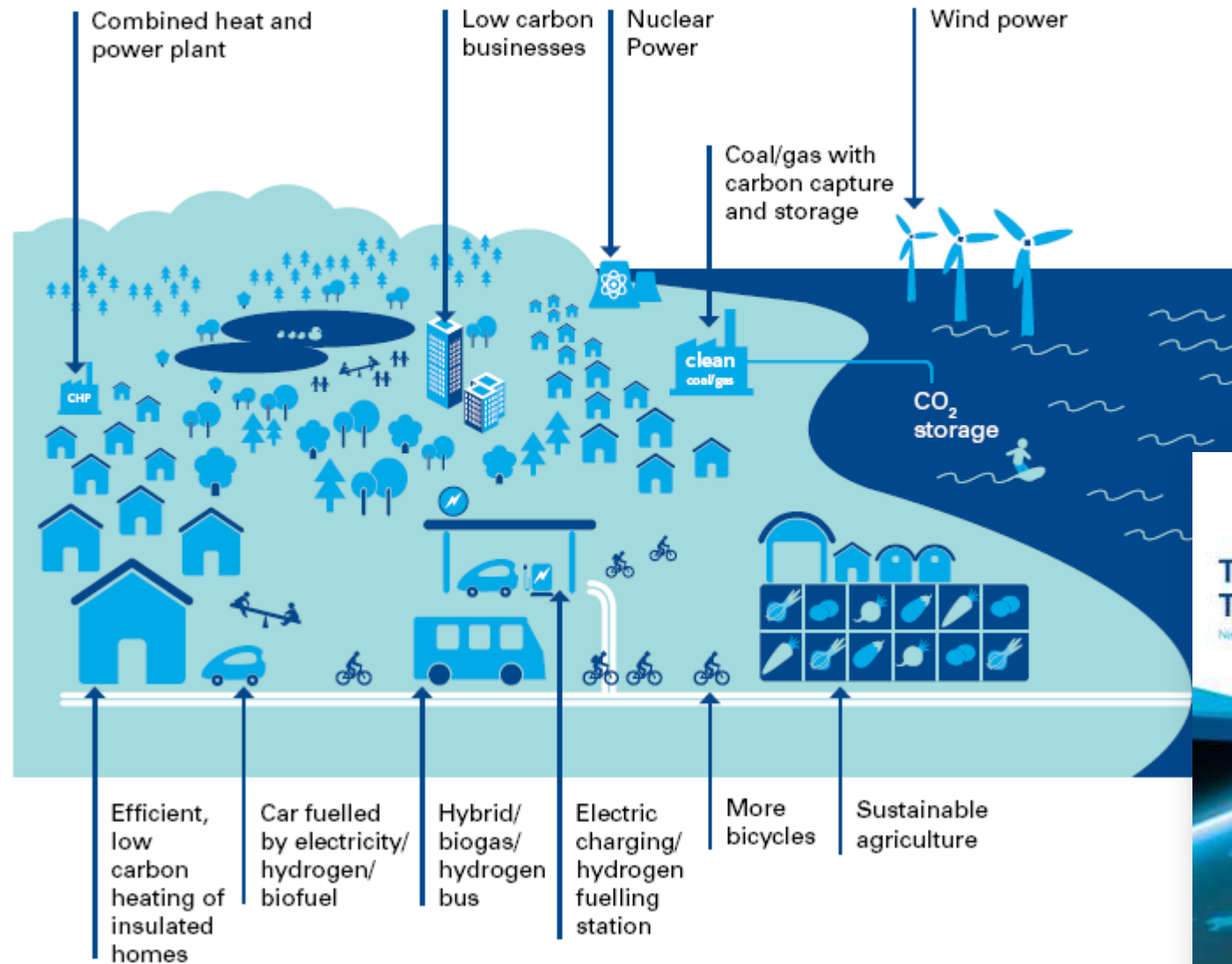
- CO₂ is emerging as the common metric

- 2007 GHG emissions 650mt (UK) CO₂
- GHG are CO₂, methane, nitrous oxide
- CO₂ accounts for 85% of GHG emissions

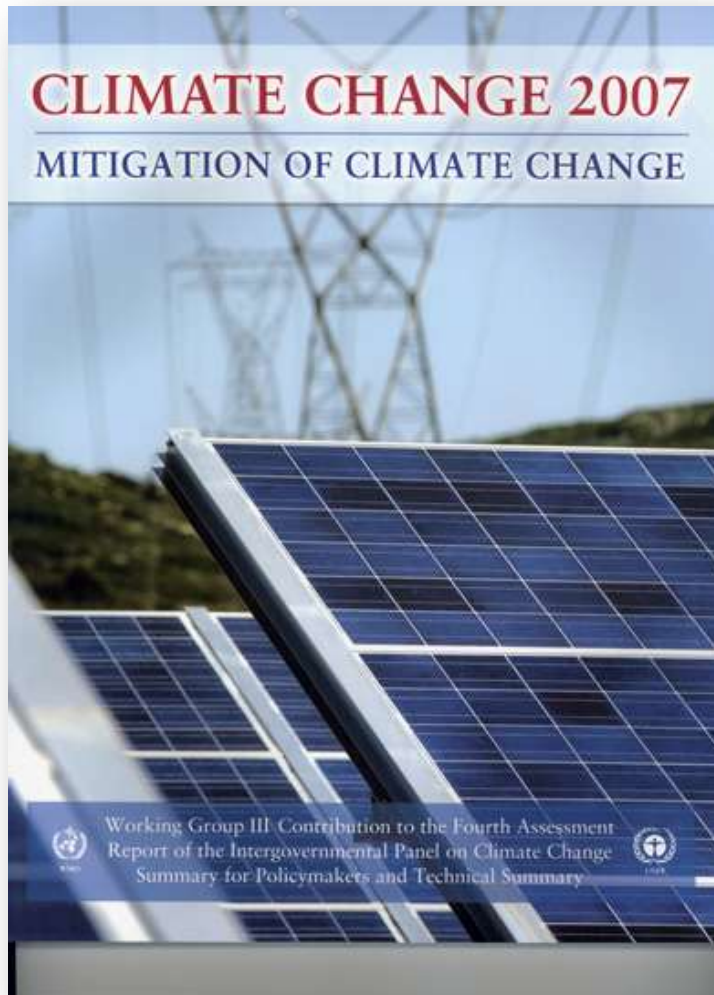


Figure 3

Our energy system in 2050 could look substantially different



Material change?

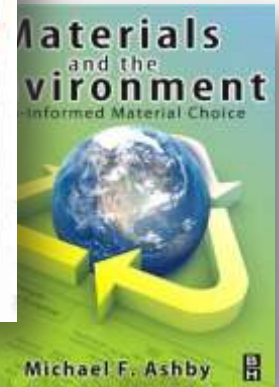
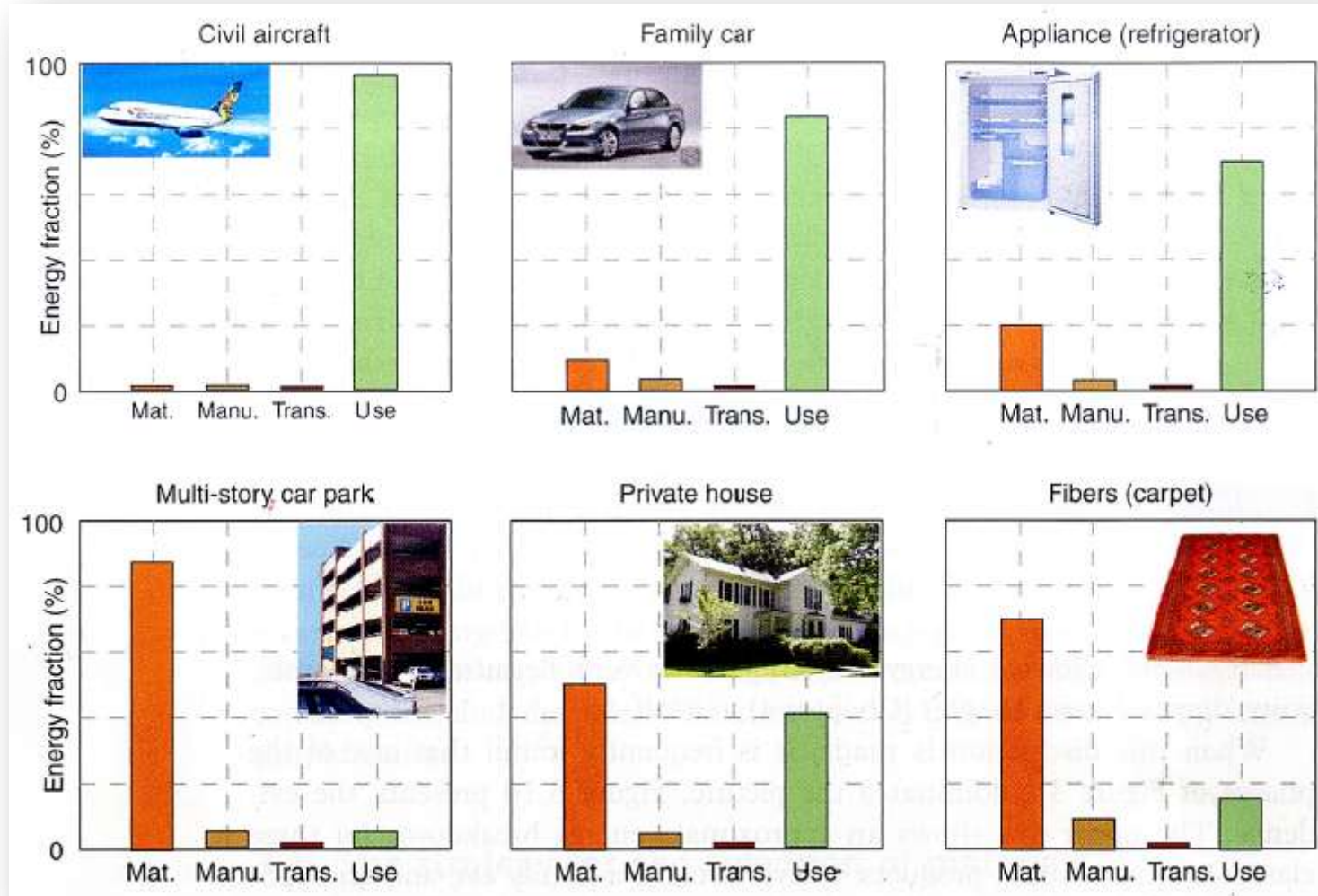


Building codes and other government policies that, where appropriate, can promote substitution of use of sustainably harvested forest products wood for more energy-intensive construction materials may have substantial potential to reduce net emissions (Murphy, 2004). Private companies and

Wood products can displace more fossil-fuel intensive construction materials such as concrete, steel, aluminium, and plastics, which can result in significant emission reductions (Petersen and Solberg, 2002). Research from Sweden and Finland suggests that constructing apartment buildings with

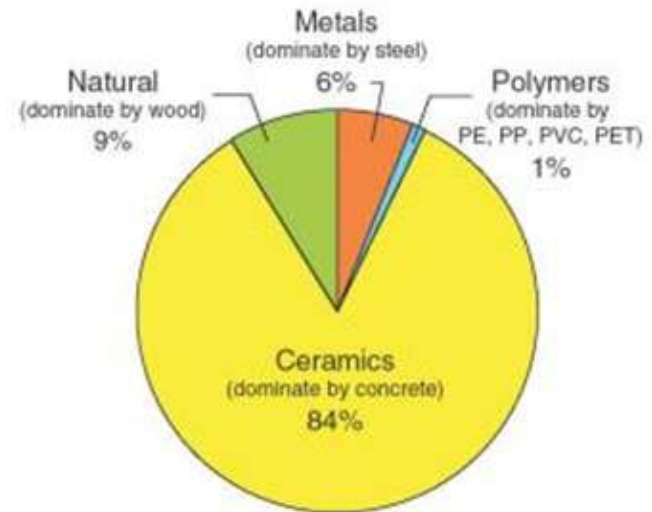
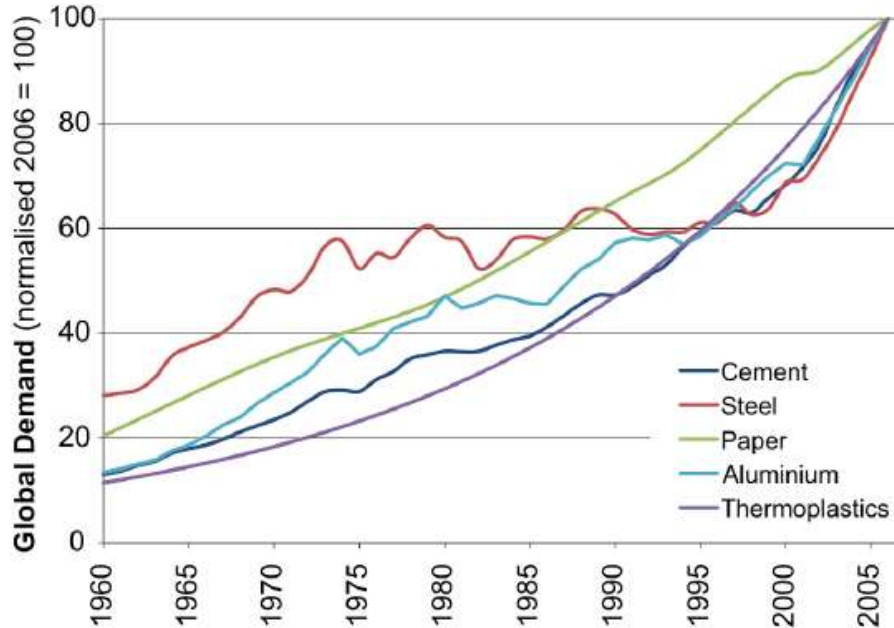
The embodied energy in building materials needs to be considered along with operating energy in order to reduce total lifecycle energy use by buildings. The replacement of materials that require significant amounts of energy to produce (such as concrete and steel) with materials requiring small amounts of energy to produce (such as wood products) will reduce the amount of energy embodied in buildings. Whether

Life cycle analysis



Engineering materials

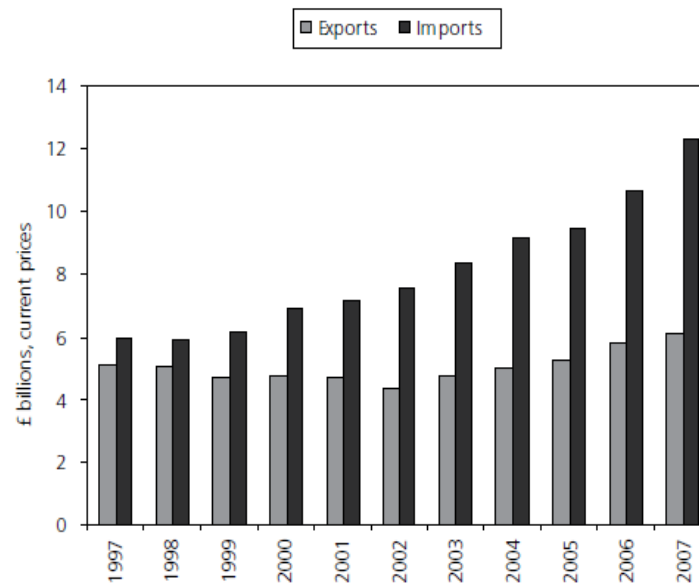
- 10 billion tonnes pa of engineering materials used globally
- 1.5t person pa, main components are concrete, wood, steel, asphalt, glass, brick
- Concrete is by far the dominant engineering material (factor 10) and responsible for some 5% of global CO2 emissions
- 10 billion tonnes pa of oil and coal used globally



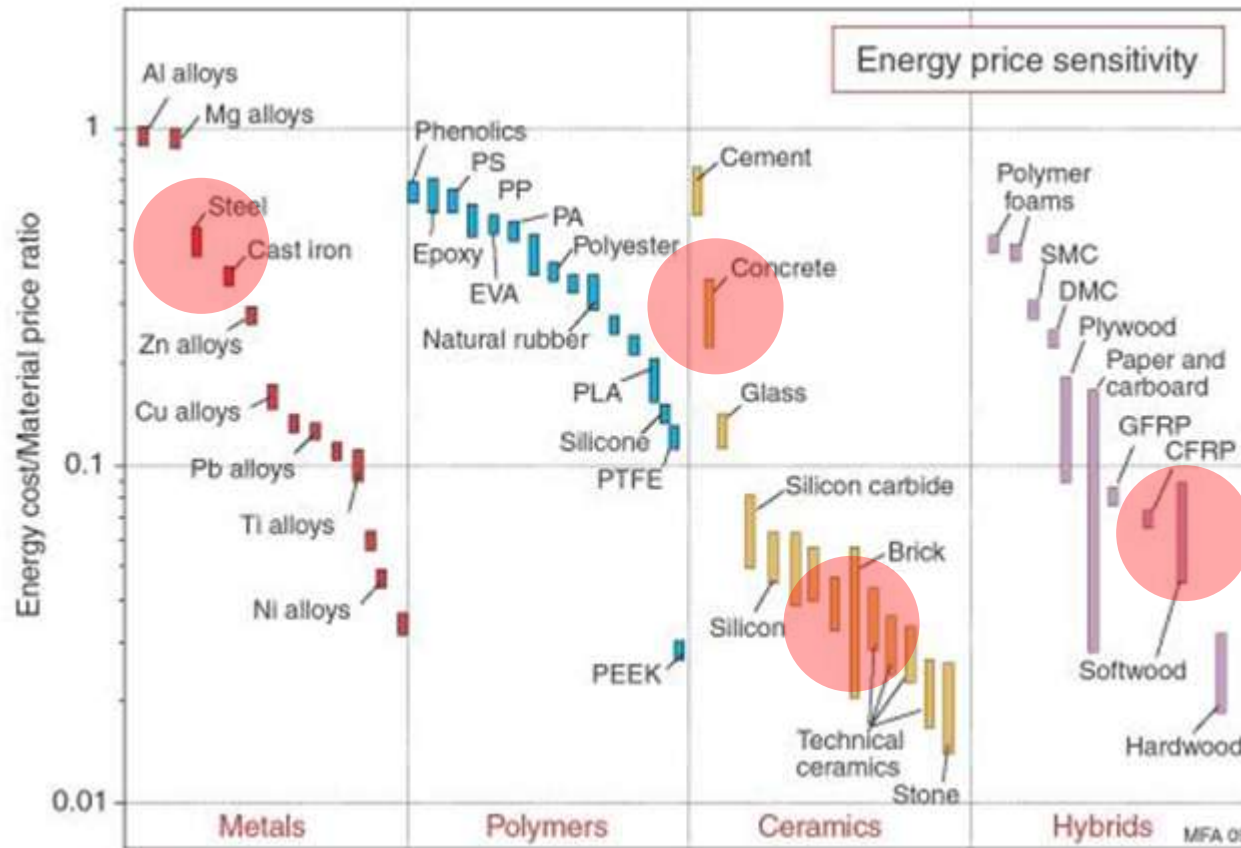
Ref: 'Materials and the Environment' Mike Ashby

UK construction materials

- 400mt construction materials annually
 - 1.4mt steel
 - 100mt concrete
 - 7.5mt timber
- UK is one of world's largest importers of timber



Energy input to construction materials



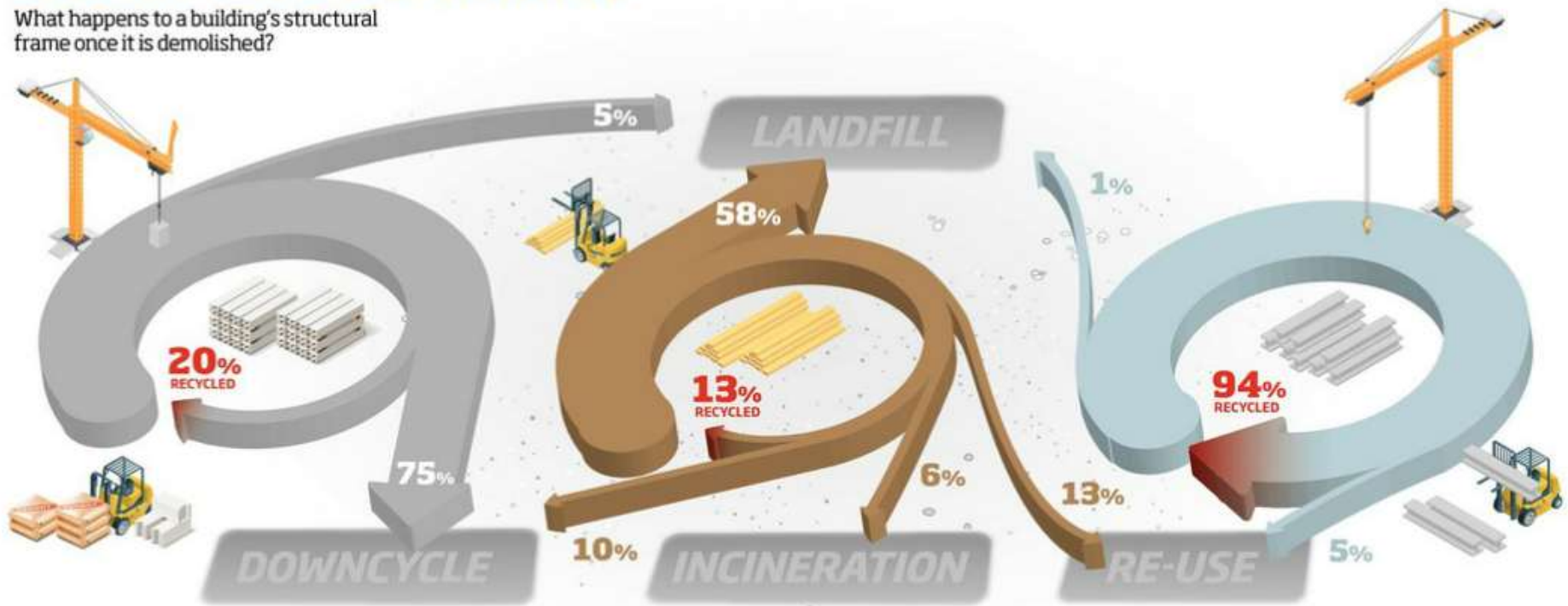
← Energy cost represents 100% of material cost

← Energy cost represents 10% of material cost

← Energy cost represents 1% of material cost

END-OF-LIFE SCENARIOS

What happens to a building's structural frame once it is demolished?



CONCRETE

The great majority of concrete from demolition sites is crushed and used as sub-base or fill. This is downcycling rather than recycling, as a secondary use which is not of the same value as the first. Aggregates from demolition may be re-used in concrete production but its use is restricted both by rules governing maximum percentages allowed and

also by supply, since the amount of aggregate that can be recovered for this purpose is limited. Where aggregates are re-used in concrete, new cement, the source of most of the CO₂ emitted in concrete production, is still needed. The Concrete Centre is the source of the downcycling figure, with the other figures estimated using various sources.

TIMBER

Definitive information on what happens to timber waste following building demolition is difficult to find. Recent publications from TRADA indicate that up to 80% of timber waste in the UK goes to landfill. The information presented here is from the BRE Green Guide.

The downcycling figure is an estimate based on published information on how much timber is diverted from the waste stream for the manufacture of chipboard. Problems with contamination in the waste stream in particular restrict opportunities to divert waste for re-use and recycling.

STEEL

Steel benefits from having a high intrinsic value supported by a well developed and efficient scrap collection infrastructure. It can be recycled at end of life to form products that are of the same, or higher, standard and quality as the original material and most steel components are large and easily captured.

Capture rates vary depending on the ease of extraction from the demolition site but are always above 90% and average 94% for all steel components. For sections, it is 99%. These rates can be found in Material flow analysis of the UK steel construction sector, J. Ley, 2005.

- 'The Whole Story – From Cradle to Grave' – Nov 2011 (Tata Steel & BCSA)
- Bath Uni ICE database says 59% of construction steel re-cycled
- TRADA says 50%+ of wood is re-cycled

Information sources

- Industry claims
 - Steel (SCI) 762 kgCO₂/t
 - RC (Concrete Centre) 115 kgCO₂/t
 - Timber (Wood for Good) -900 kgCO₂/t

New 'wood and the low carbon economy' film

wood for good have launched a new film to support the Wood CO₂s Less campaign. The film promotes the low carbon revolution and the part wood has to play for construction and energy generation. It shows how using more wood is a simple way of helping to build the low carbon economy that is vital to the fight against climate change.

REPLACE WITH... A cubic metre of wood saves 0.7 - 1.1 tonne CO₂

1m³ WOOD = 1t CO₂

Edinburgh Centre for Carbon Management

You can download the film by clicking [here](#). (15MB download)

corus Corus in construction

The embodied carbon content of steel

To calculate the environmental impacts of steel manufacture, the World Steel Association analysed the 'cradle-to-gate' carbon footprint of the UK's 14,000 tonnes of steel production (2010/11).

These figures represent an average for the combined carbon content of steel, from pig iron and scrap, and are not intended to represent the carbon content of individual steel products. For more information, please visit [www.worldsteel.org](#).

Steel Type	CO ₂ (kg/t)	CO ₂ (kg/t)	CO ₂ (kg/t)
Hot Rolled	2,440	2,440	2,440
Hot Rolled	2,440	2,440	2,440
Hot Rolled	2,440	2,440	2,440

Source: World Steel Association, 2010/11

Sheet C1 - Embodied CO₂ of Concrete and Reinforced Concrete

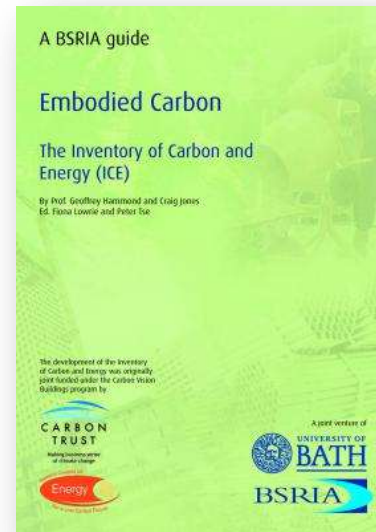
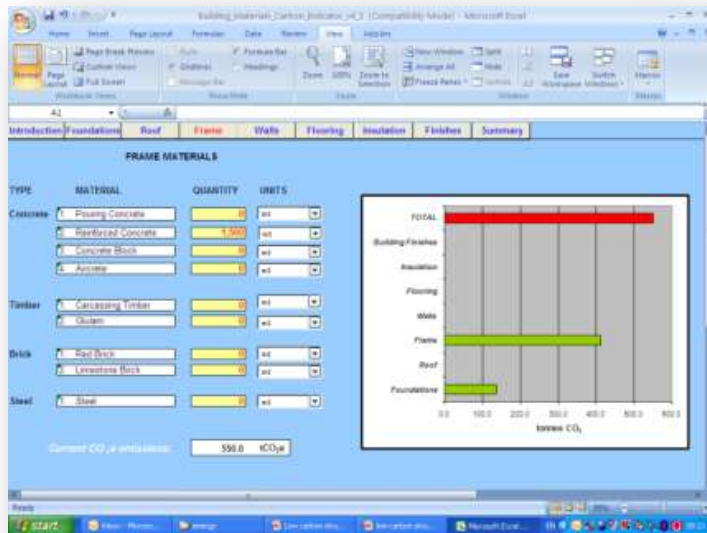
The representative figures for the Embodied CO₂ (ECOC) for average UK concrete with and without reinforcement is shown in the table below. These are based on the assumption of the cradle to gate figure for the constituents. A density of 2380 kg/m³ is assumed for normal weight concrete supplied in the UK. These figures are for general guidance and should be adjusted for certain design considerations for the ECOC of concrete construction. Concrete constituents and ECOC are expressed in the metric 5 kg.

UK Concrete Products	Total Cementitious Content (TCC) (kg/m ³)	Water (kg/m ³)	Aggregate (kg/m ³)	Reinforcement (kg/m ³)	Embodied CO ₂ (kg CO ₂ /m ³)
UK Concrete	300	165	1915	0	225
UK Concrete (C20/25) with an alternative for reinforcement	300	165	1915	110	270

Note: C20/25 is the concrete compressive strength class with a minimum characteristic cylinder strength (f_{ck}) of 20 N/mm² and a minimum characteristic cube strength (f_{cu}) of 25 N/mm². It is important to note that at some locations the ECOC of particular concretes may be slightly and/or different from the figures quoted due to material availability and performance.

Total Cementitious Content

Information sources



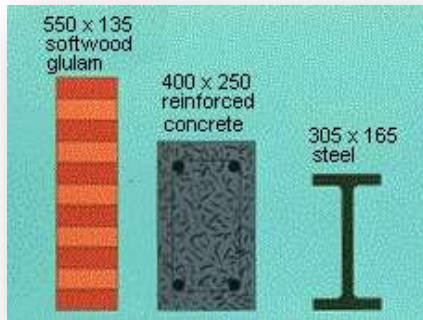
- Edinburgh centre for carbon management

- Steel 2300 kgCO₂/t
- RC 250 kgCO₂/t
- Timber -1000 kgCO₂/t

- Bath University

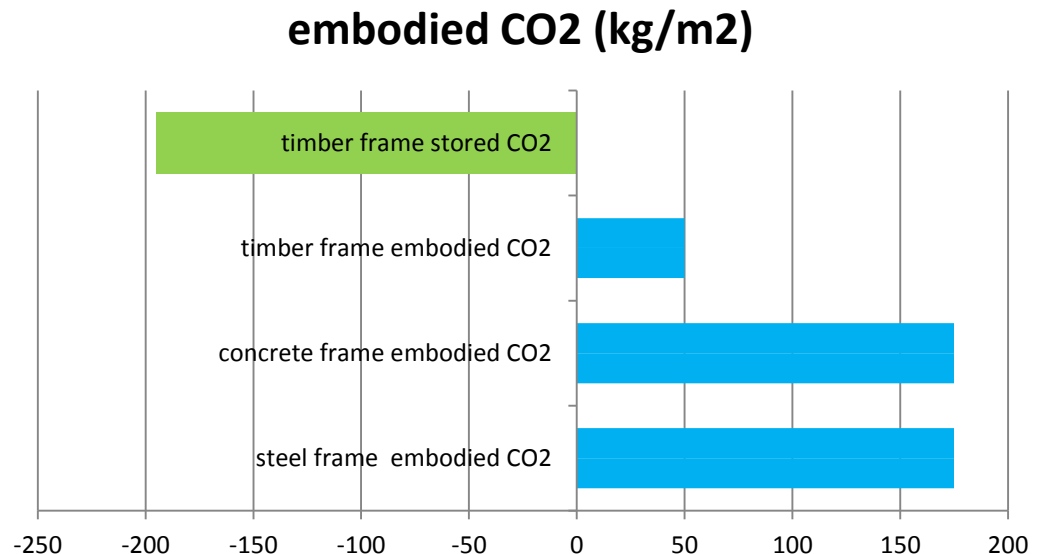
- Steel 1440 kgCO₂/t
- RC 210 kgCO₂/t
- Timber 420 kgCO₂/t
- Brickwork 210 kgCO₂/t

Structural performance



- Timber beam 15kgCO₂
- Concrete beam 50kgCO₂
- Steel beam 60kgCO₂
-but 60kgCO₂ stored in timber beam

- Timber CLT frame
- Concrete flat slab frame
- Steel frame and holorib slab



Trees and carbon

- Wood is about 50% carbon (by dry mass)
- x 3.67 to convert C to CO₂
- Broadleaf forests 100-250 tC per ha
- Conifer plantations 70-90 tC per ha
- Carbon uptake 4 tC per ha per year in fast growing stands

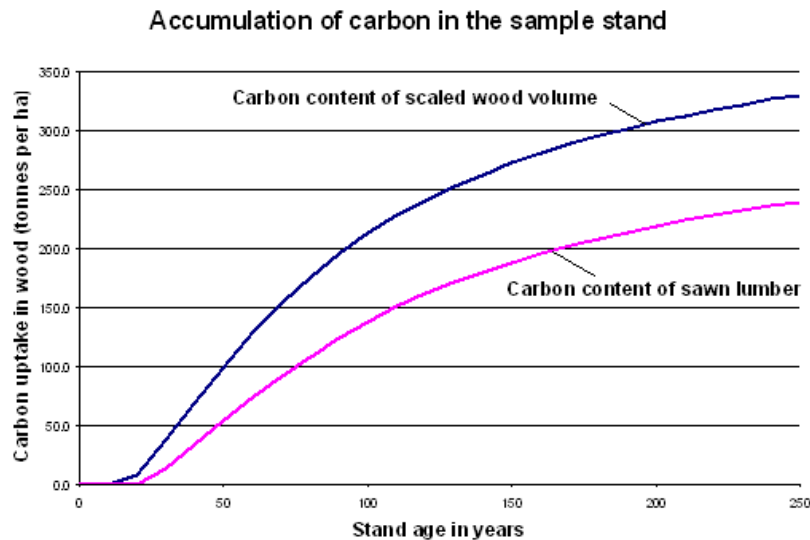
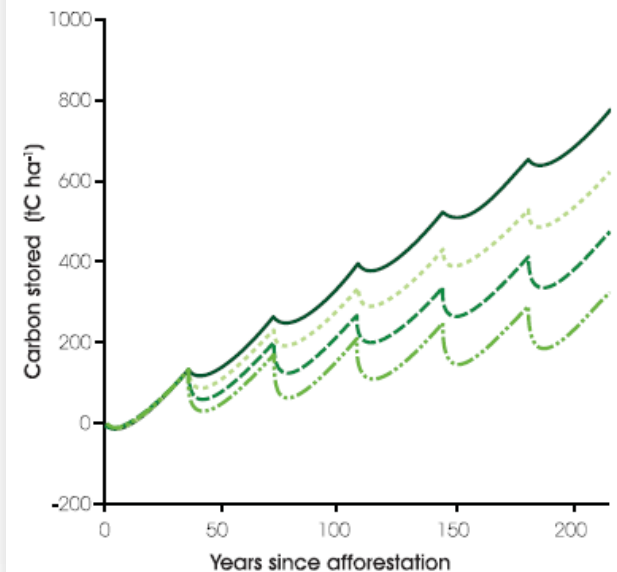


Figure 3.9

Likely changes in the carbon stored in a Sitka spruce plantations on a peaty gley over six rotations. See the text for explanation. The lines show increasing degrees of disturbance at harvest from the top line down.



Ref: 'Combating Climate Change: A role for UK forests' – UK Forestry Commission

Tress and carbon

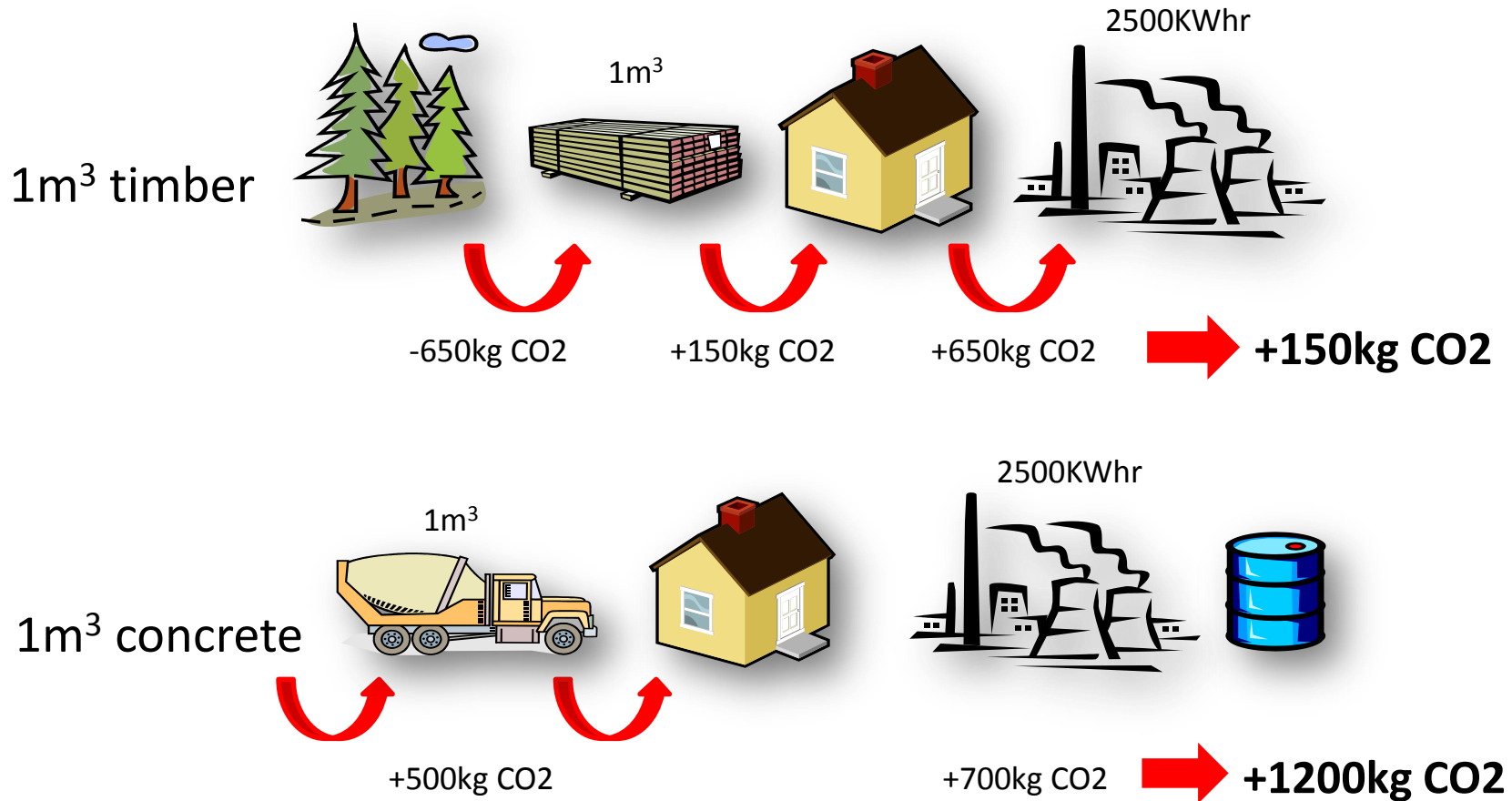
Table 6.6

Timber carbon content ($\text{tCO}_2\text{e m}^{-3}$), typical ranges of maximum mean annual volume increment (MMAI: $\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$) and ages of MMAI for a range of conifers and broadleaves grown in Britain or which might be considered for planting under anticipated climate change (after Edwards and Christie, 1981; Lavers, 1983).

Conifers					Broadleaves				
Species	Scientific name	Carbon content	MMAI	Age	Species	Scientific name	Carbon content	MMAI	Age
Sitka spruce	<i>Picea sitchensis</i> (Bong.) Carr.	0.62	8–24	64–46	Oak	<i>Quercus robur</i> L., <i>Q. petraea</i> . (Matt.) Liebl.	1.12	4–8	90–68
Norway spruce	<i>Picea abies</i> L. Karst.	0.64	8–20	84–65	Birch	<i>Betula pendula</i> (Roth.), <i>B. pubescens</i> (Ehrh.)	1.10	4–12	49–40
Scots pine	<i>Pinus sylvestris</i> L.	0.84	6–12	82–69	Sweet chestnut	<i>Castanea sativa</i> Mill.	0.84	4–10	50–41

Ref: 'Combating Climate Change: A role for UK forests' – UK Forestry Commission

CO2 cycles for timber and concrete

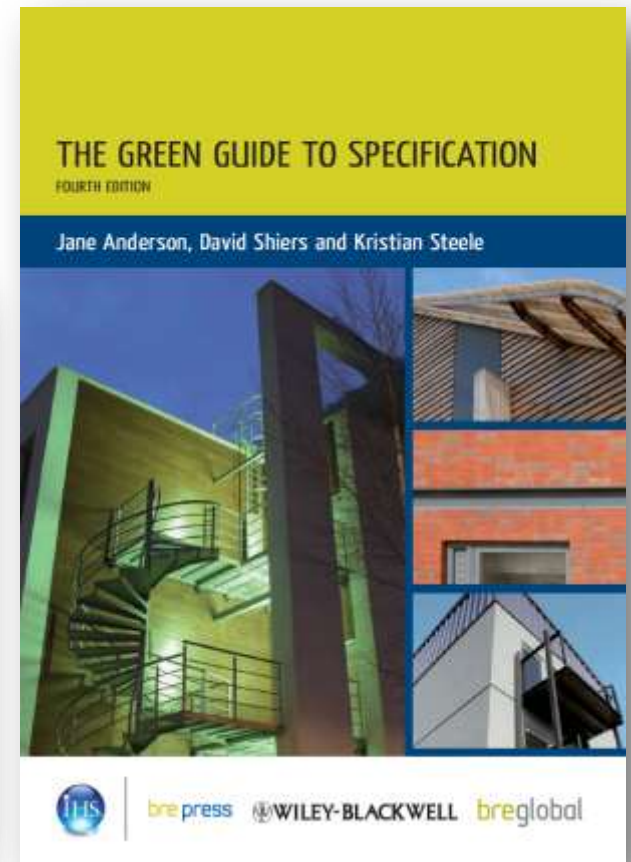
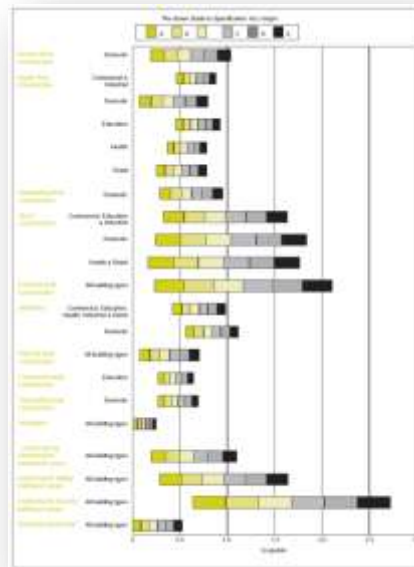


Information sources

- Embodied CO2 figures given
 - Floors -18 to 150 kgCO2/m2
 - Roofs -4 to 290 kgCO2/m2
 - External walls -3 to 370 kgCO2/m2

Table 3.1: The weightings of the 13 environmental impact categories used in *The Green Guide to Specification*

Environmental impact category	Weighting (%)
Climate change	21.6
Water extraction	11.7
Mineral resource extraction	9.8
Stratospheric ozone depletion	9.1
Human toxicity	8.6
Ecotoxicity to freshwater	8.6
Nuclear waste (higher level)	8.2
Ecotoxicity to land	8.0
Waste disposal	7.7
Fossil fuel depletion	3.3
Eutrophication	3.0
Photochemical ozone creation	0.20
Acidification	0.05



Information sources

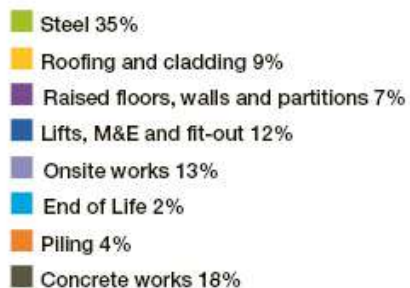
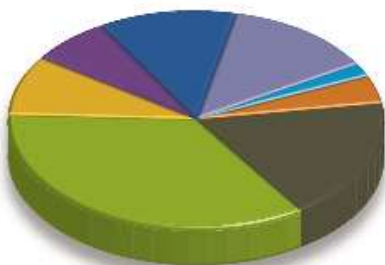
- ICE
 - The Institute of Civil Engineers (ICE) Civil Engineering Standard Method of Measurement 3 (CESMM3) now includes carbon and prices for every material and unit of work.
- RICS
 - The Royal Institution of Chartered Surveyors (RICS) has established a working group to examine embodied carbon and to also link it to the New Rules of Measurement (NRM) framework.
- EU
 - The European CEN TC 350 series of standards relates to the “sustainability of construction works”. The series includes a set methods for calculating the embodied impacts of construction materials and projects and a standard on the communication of results (Environmental Product Declarations, EPD’s).
- Other
 - PAS 2050 (UK Carbon Trust), PAS 2060 (BSI),
 - ISO/CD 14067, BS 8903:2010

Office building study

- Statistics

- 32,500m² NIA or GIA?
- Embodied 765 kgCO₂/m²
- Operation 60-90 kgCO₂/m²

Total embodied carbon emissions (cradle to grave) 24,815 tonnes CO₂e.



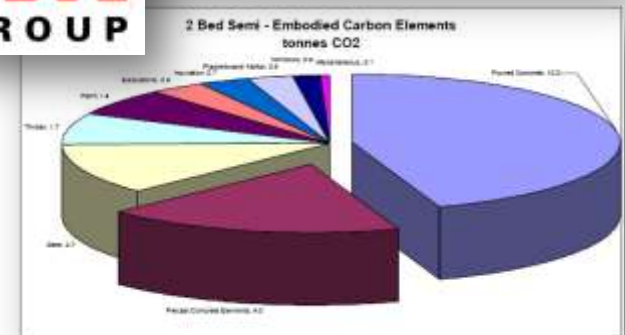
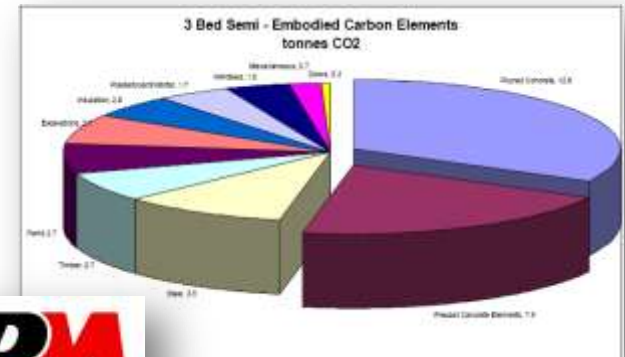
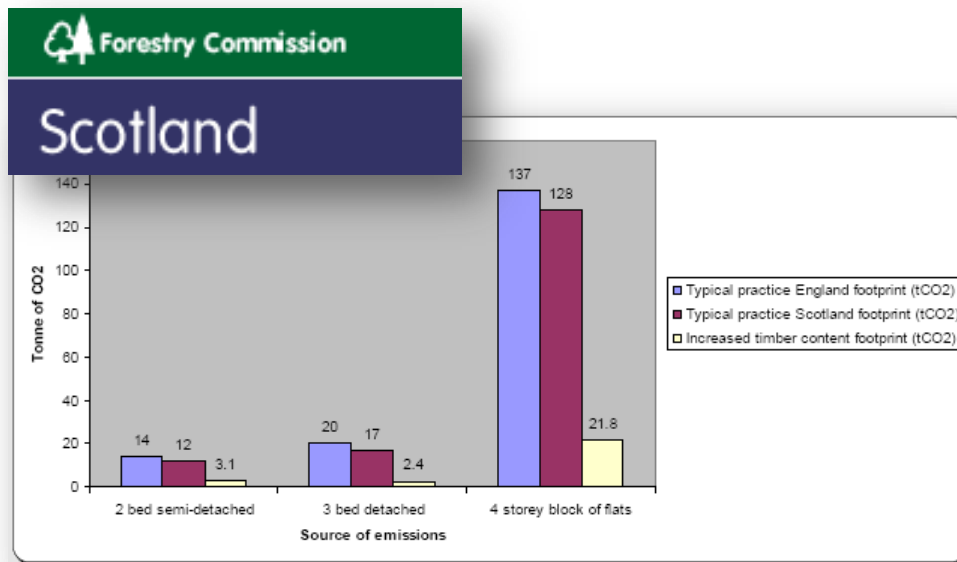
Residential building study

• Statistics

- 3 bed house 20-40 tCO₂
- Embodied 300-675 kgCO₂/m²
- Operation 30-50 kgCO₂/m² ?



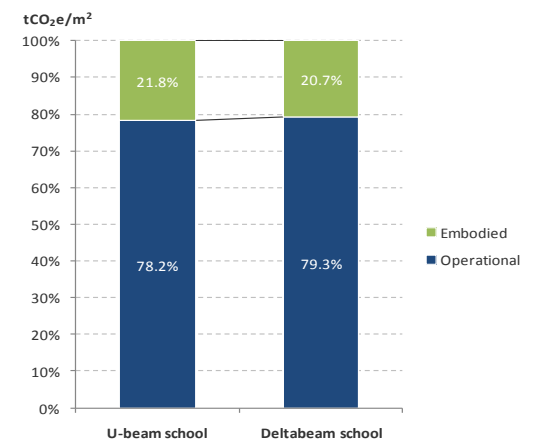
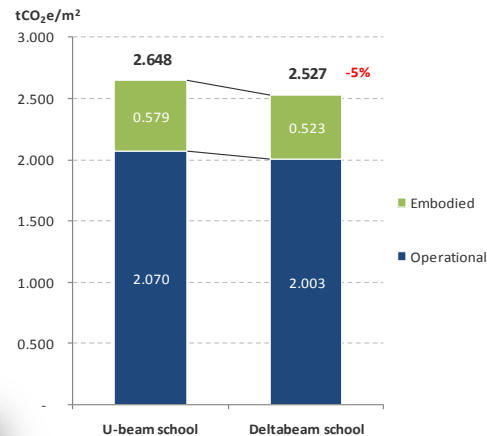
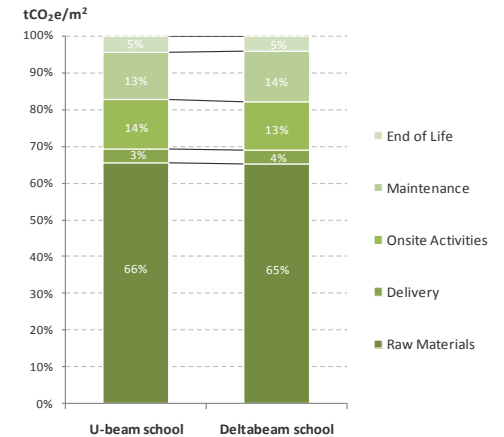
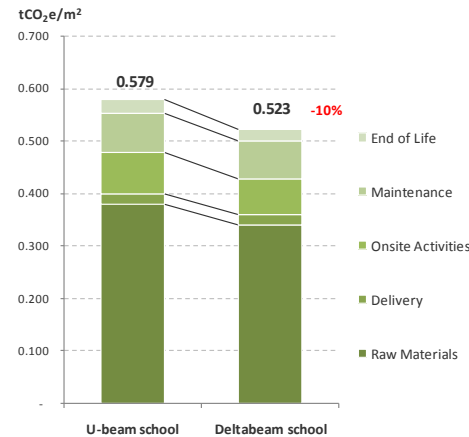
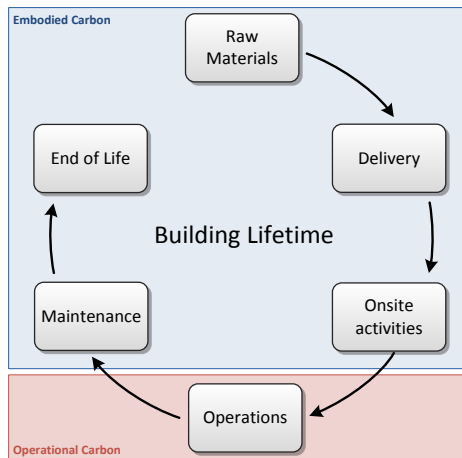
UK housing. The total embodied CO₂ of BedZED is 675kg/m², whilst typical volume house builders build to 600-800kg/m². Despite the increased



School building study

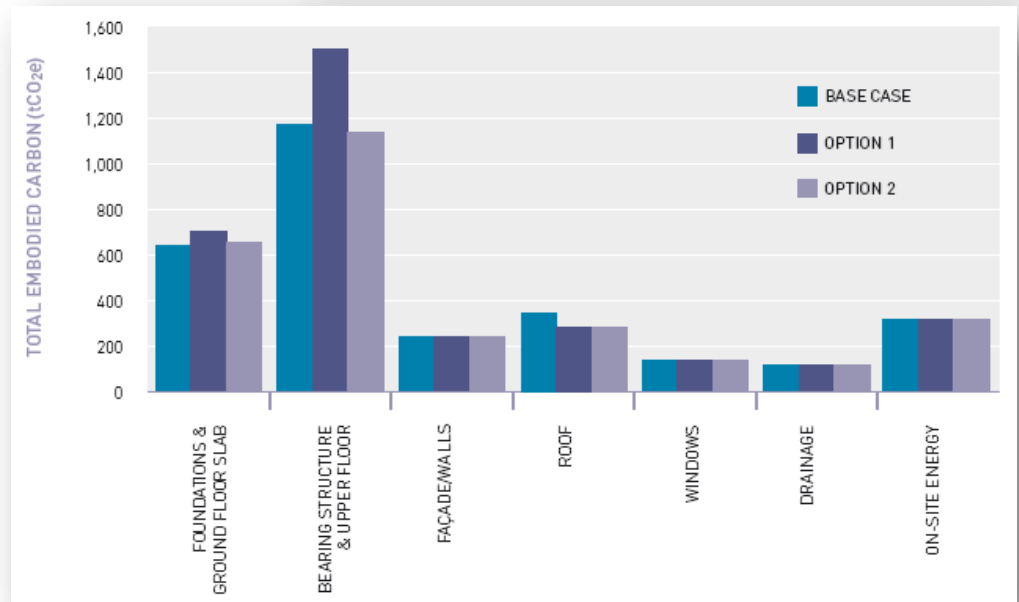
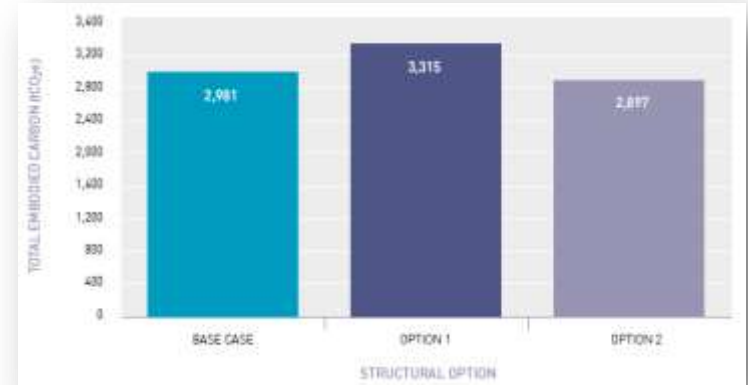
Statistics

- 2 different structure solutions
- Embodied 300-600 kgCO₂/m²
- Operation 25-35 kgCO₂/m²



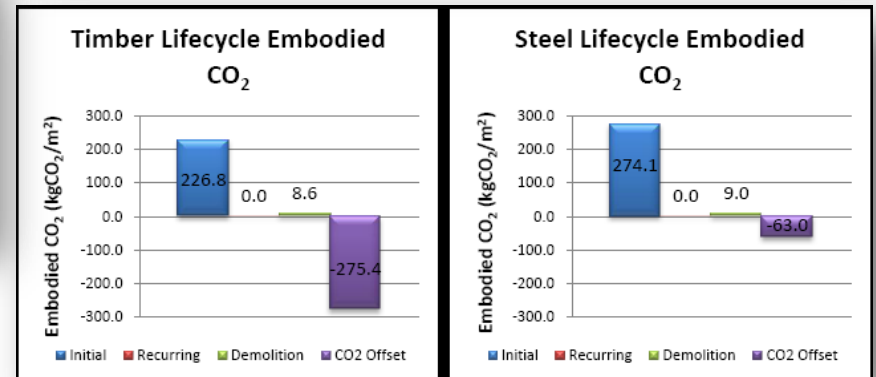
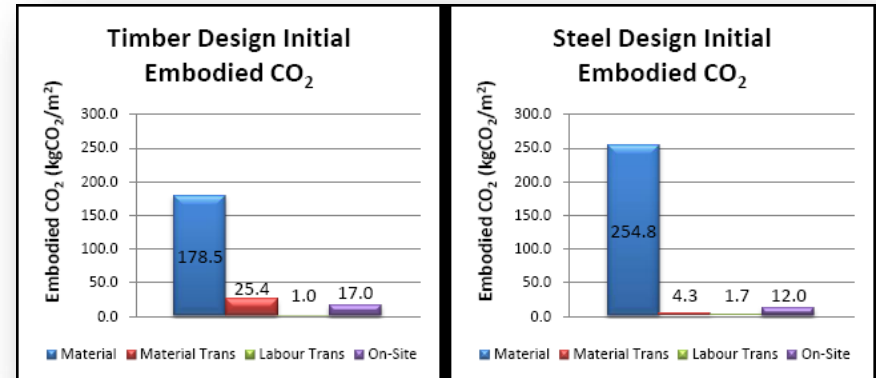
School building study

- Steel industry research
 - £22.5m 10,000m²
 - Embodied 300-350 kgCO₂/m²
 - Operation 27 kgCO₂/m²
 - Structure 10% of cost, 60% of embodied CO₂



School building study

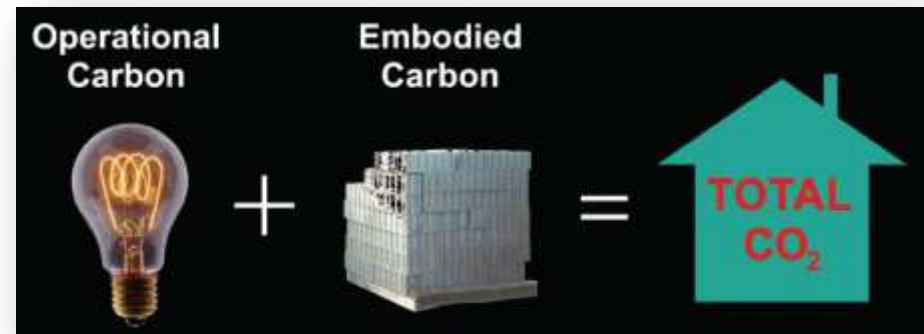
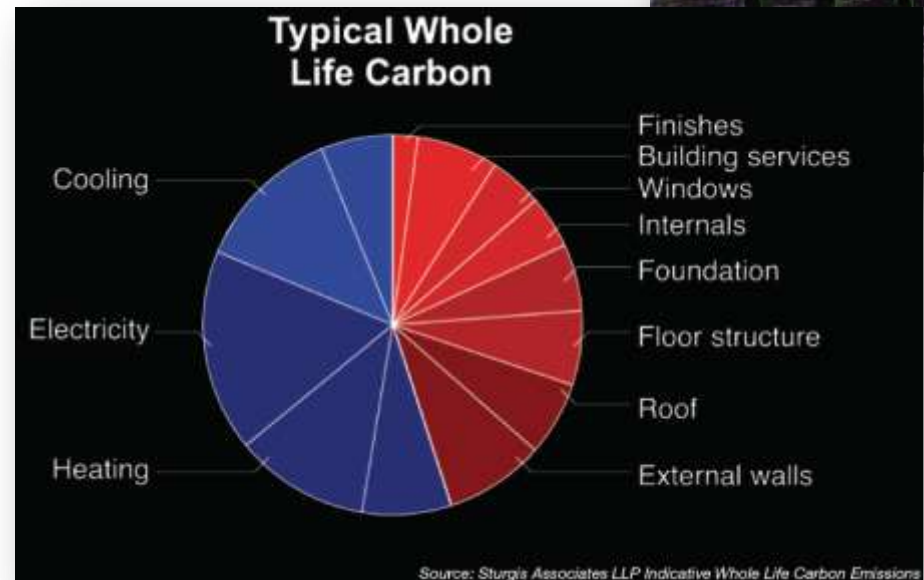
- Timber versus steel
 - 975m² Sports hall and Studio
 - Timber LCA -40tCO₂
 - Steel LCA 220tCO₂
 - Embodied CO₂ of structure only



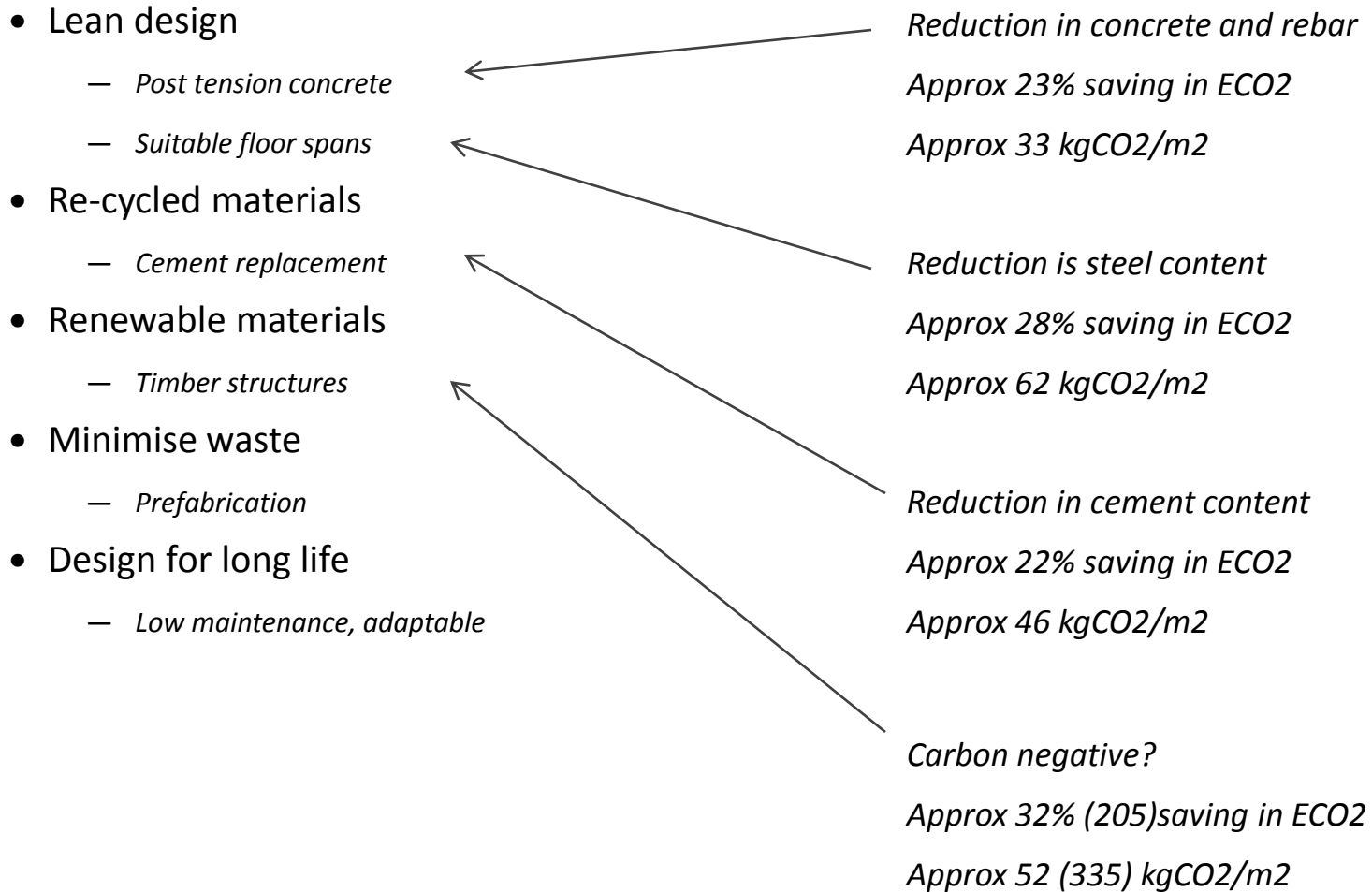
Summary



- Current studies
 - Offices 750-1000 kgCO₂/m²
 - Residential 300-675 kgCO₂/m²
 - Schools 300-600 kgCO₂/m²
- Typically 50% of a new buildings embodied CO₂ is in the structure and foundations
- Recent studies indicate that embodied CO₂ can represent between 20% to 60% of the whole life CO₂ of a building

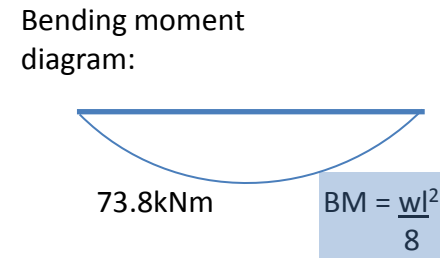
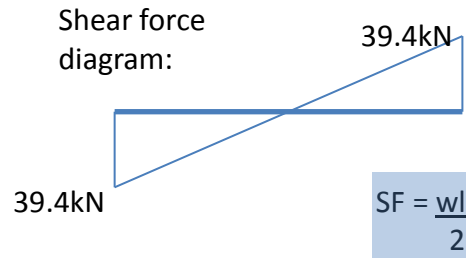


Reducing embodied CO2



Timber beam design example

A glulam timber floor beam spanning $l = 7.5\text{m}$
 Spacing of beams is 3m
 Lightweight floor construction = 1 kN/m^2
 Office floor loading = 2.5 kN/m^2
 ie: beam loading $w = 3\text{m} \times (1 + 2.5) = 10.5\text{ kN/m}$



Design:

Choose initial beam size based on span to depth ratios

For timber beams span to depth ratios of 10-15 are recommended, therefore $7.5\text{m} / 12.5 = 600\text{mm}$

From glulam supplier information try a beam $115\text{mm} \times 630\text{mm}$ & C24 timber grade

Allowable stresses:

As the glulam beam is made from C24 grade timber we use C24 timber allowable stresses:

Allowable bending stress = $7.5\text{N/mm}^2 \times K_7 \times K_{15} = 9.6\text{N/mm}^2^*$

Modulus of elasticity = $10,800\text{N/mm}^2 \times K_{20} = 11,550\text{N/mm}^2^*$

** Allowable stresses in glulam beams are affected by a number of factors (number of laminations, depth of beam etc.)*

Assumed that beam is fully restrained by floor against lateral torsional buckling



Bending check:

Bending stress in beam = $\frac{BM}{z} = \frac{73.8 \times 6}{115 \times 630^2} = 9.7\text{N/mm}^2$

Where z = elastic modulus = $\frac{bd^2}{6}$

Applied stress is marginally higher than allowable

Deflection check:

Deflection = $\frac{5wl^4}{384EI} = \frac{5 \times 10.5 \times 7500^4 \times 12}{384 \times 11,550 \times 115 \times 630^3} = 15.6\text{mm}$

Where I = second moment area = $\frac{bd^3}{12}$

Allowable deflection = $0.003 \times \text{span} = 22.5\text{mm}$

Embodied CO2:

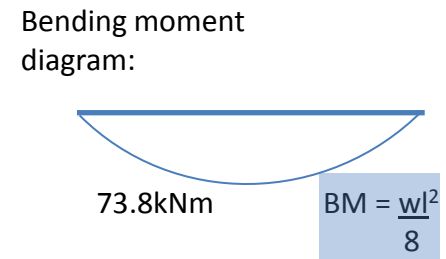
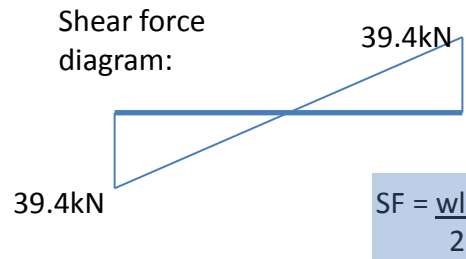
= $0.115 \times 0.63 \times 160$
 = $12\text{kgCO}_2/\text{m}$

Sequestered CO2:

= $0.115 \times 0.63 \times 650$
 = $47\text{kgCO}_2/\text{m}$

Steel beam design example

A steel floor beam spanning $l = 7.5\text{m}$
 Spacing of beams is 3m
 Lightweight floor construction = 1 kN/m^2
 Office floor loading = 2.5 kN/m^2
 ie: beam loading $w = 3\text{m} \times (1 + 2.5) = 10.5\text{ kN/m}$



Design:

Choose initial beam size based on span to depth ratios

For steel beams span to depth ratios of 20-25 are recommended, therefore $7.5\text{m} / 22.5 = 330\text{mm}$

From steel tables try a beam $356\text{mm} \times 127\text{mm} \times 33\text{kg/m}$ grade S275

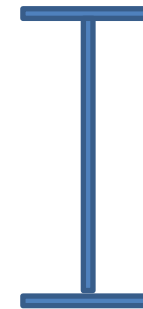
Allowable stresses:

Allowable bending stress = 165N/mm^2 *

Modulus of elasticity = $205,000\text{N/mm}^2$

**Alternative to allowable stress would be to use factored loads and limit state design (ie Eurocode)*

Assumed that beam is fully restrained by floor against lateral torsional buckling



Bending check:

$$\text{Bending stress in beam} = \frac{BM}{z} = \frac{73.8}{473,000} = 156\text{N/mm}^2$$

Where z = elastic modulus = 473cm^3 (see steel tables)

Applied stress is lower than allowable therefore beam okay in bending.

Deflection check:

$$\text{Deflection} = \frac{5wl^4}{384EI} = \frac{5 \times 10.5 \times 7500^4}{384 \times 205,000 \times 82,490,000} = 25.6\text{mm}$$

Where I = second moment area (from steel tables)

Allowable deflection = $\text{span}/200 = 37.5\text{mm}$
 (or $\text{span}/360$ for office or live load only)

Embodied CO2:

$$\begin{aligned} &= 33\text{kg} \times 1.44\text{kgCO}_2/\text{kg} \\ &= 48\text{kgCO}_2/\text{m} \end{aligned}$$