Embodied Energy & CO_2 in construction
(background, datasets & case study)

University of Cambridge

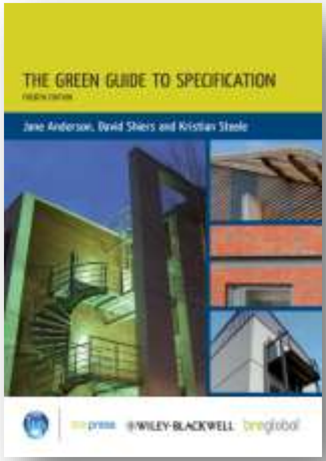
Year 2 Architecture

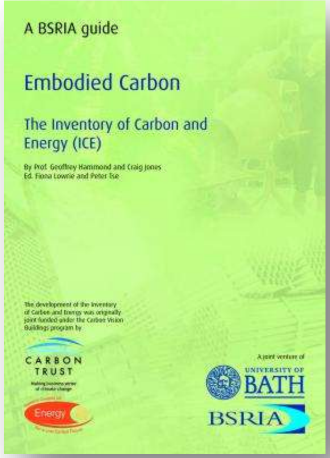
by Simon Smith

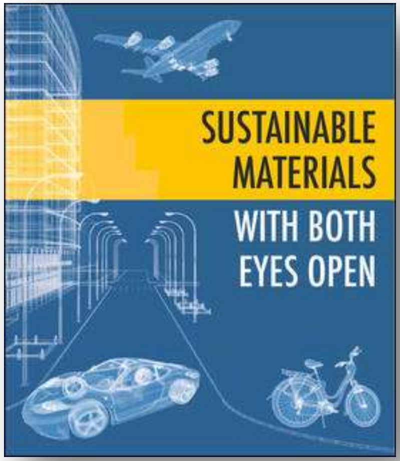
References

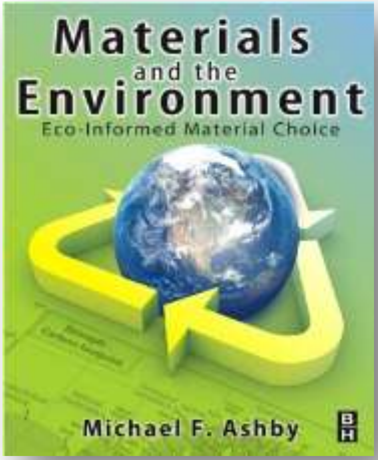
www.environment-agency.gov.uk/business/sectors/37543.aspx

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

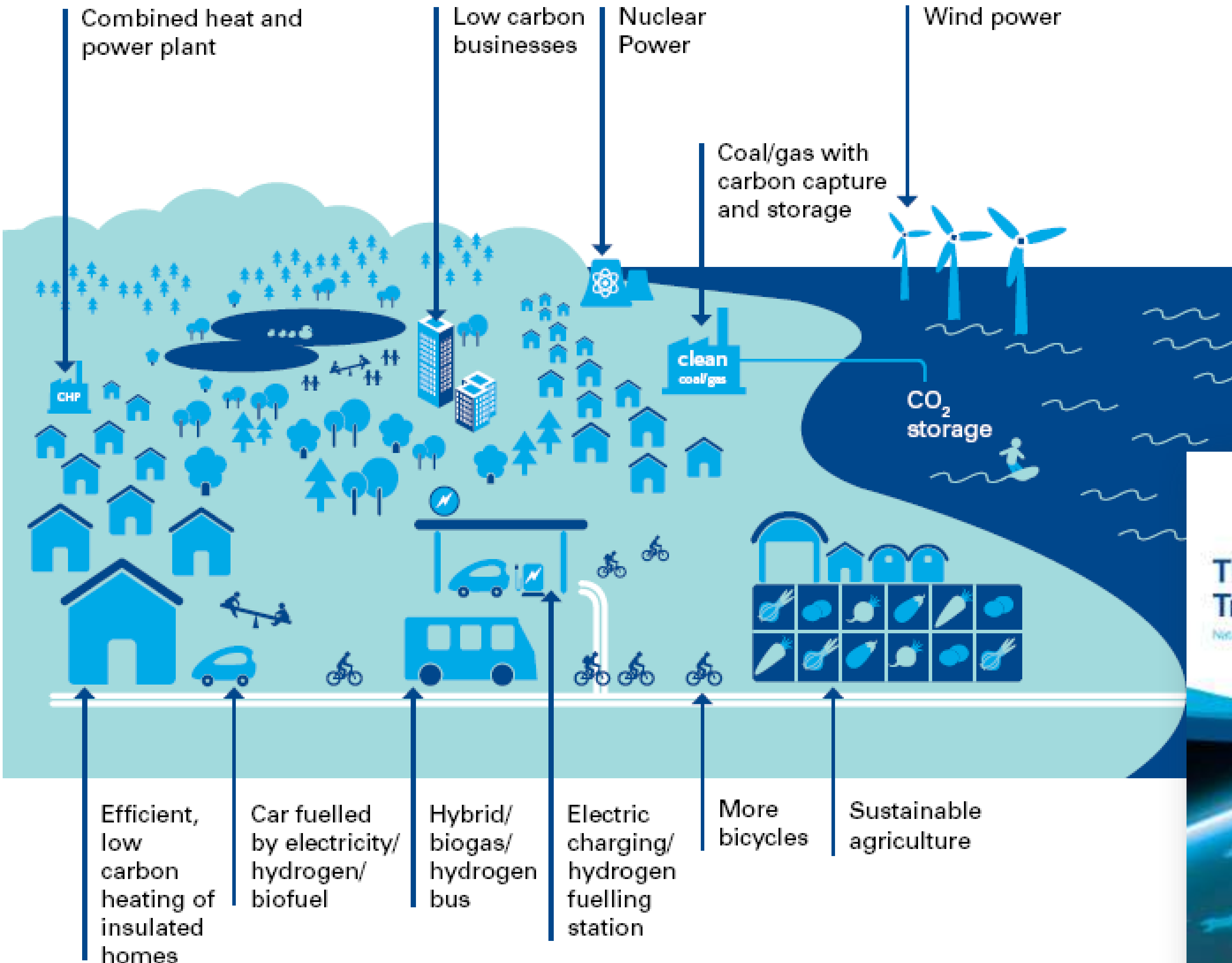
Cradle to gate → Extract, process, fabricate

Cradle to grave → all of the above

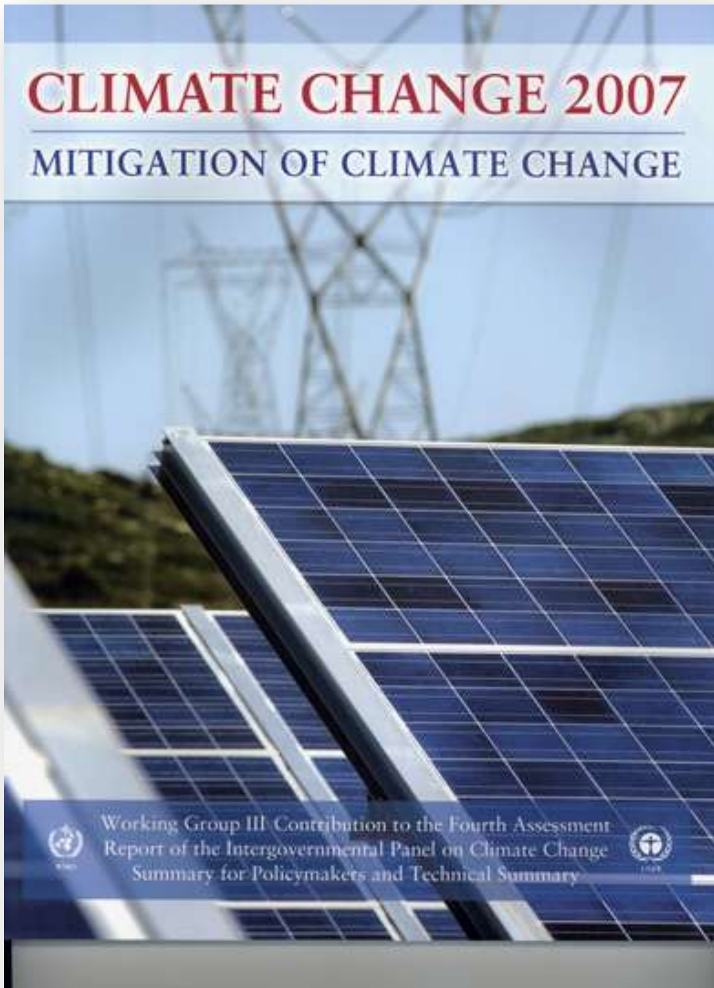
- Different measures:
  - Energy (kwh)
  - Carbon (C)
  - Carbon Dioxide (CO2)
- CO2 is emerging as the common metric
  - 2007 GHG emissions 650mt (UK) CO2
  - GHG are CO2, methane, nitrous oxide
  - CO2 accounts for 85% of GHG emissions

Figure 3

Our energy system in 2050 could look substantially different



Material change?

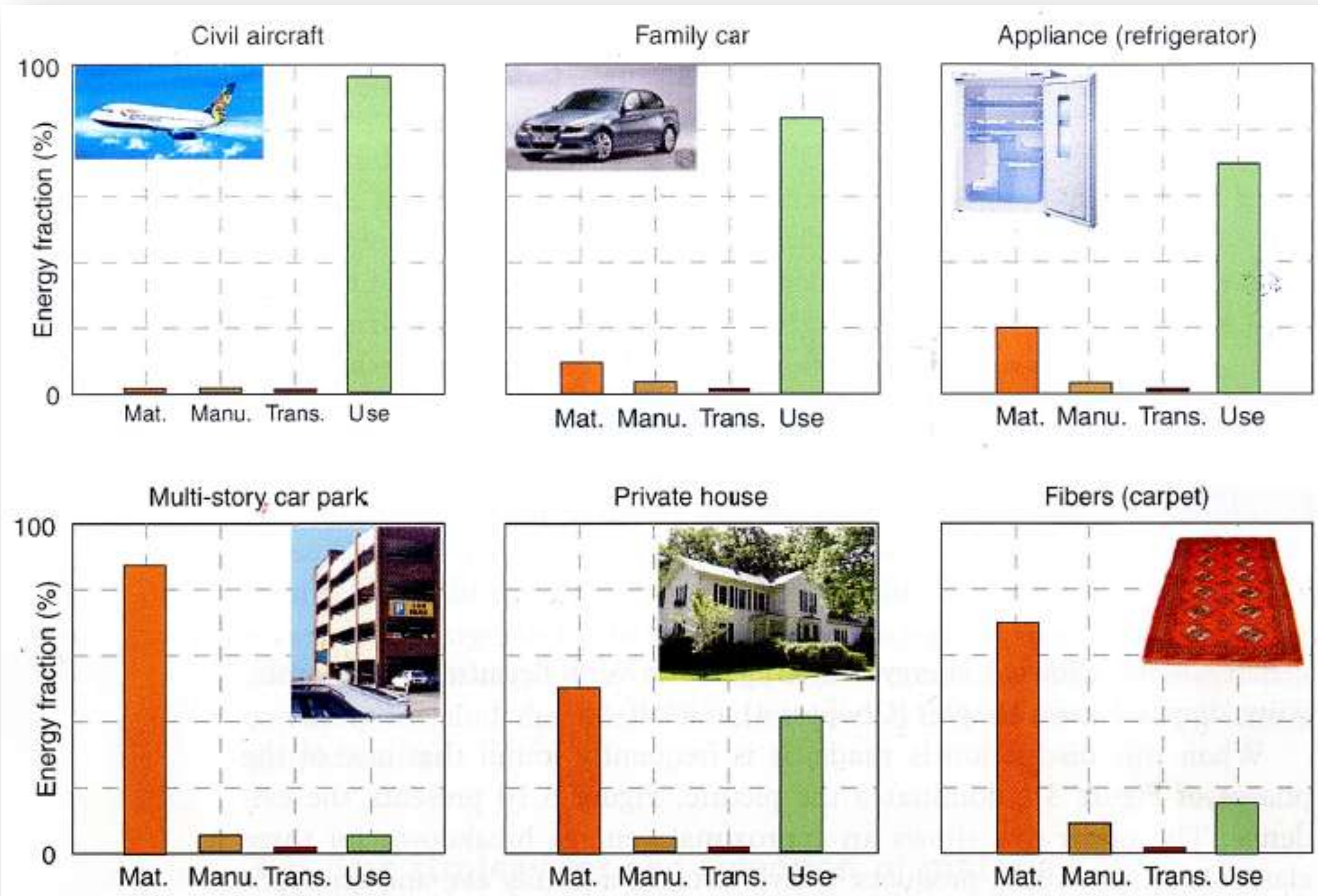


Building codes and other government policies that, where appropriate, can promote substitution of use of sustainably harvested forest products wood for more energy-intensive construction materials may have substantial potential to reduce net emissions (Murphy, 2004). Private companies and

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

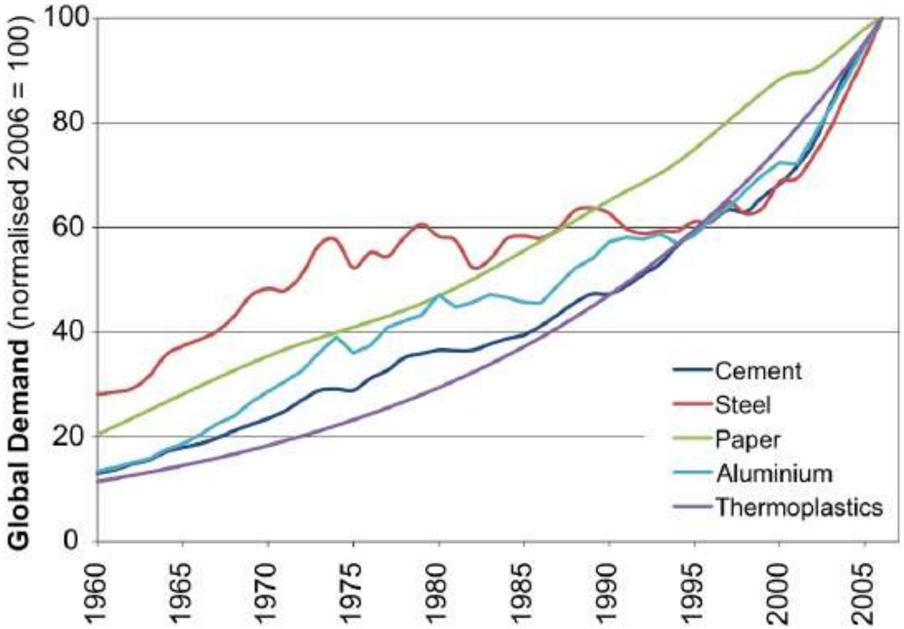
The embodied energy in building materials needs to be considered along with operating energy in order to reduce total lifecycle energy use by buildings. The replacement of materials that require significant amounts of energy to produce (such as concrete and steel) with materials requiring small amounts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

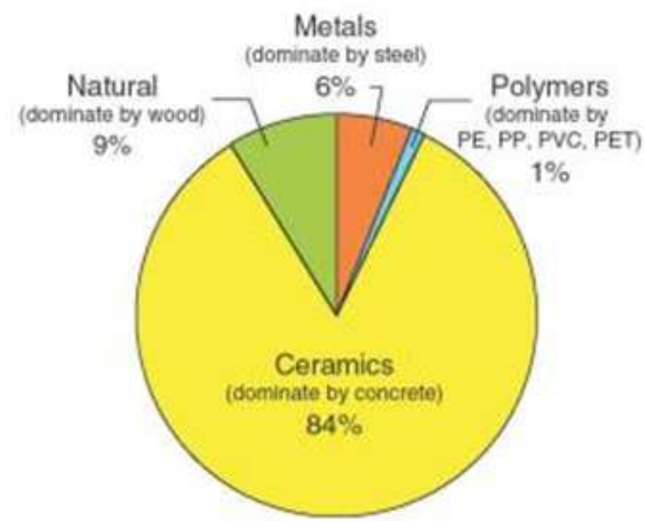
Life cycle analysis



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

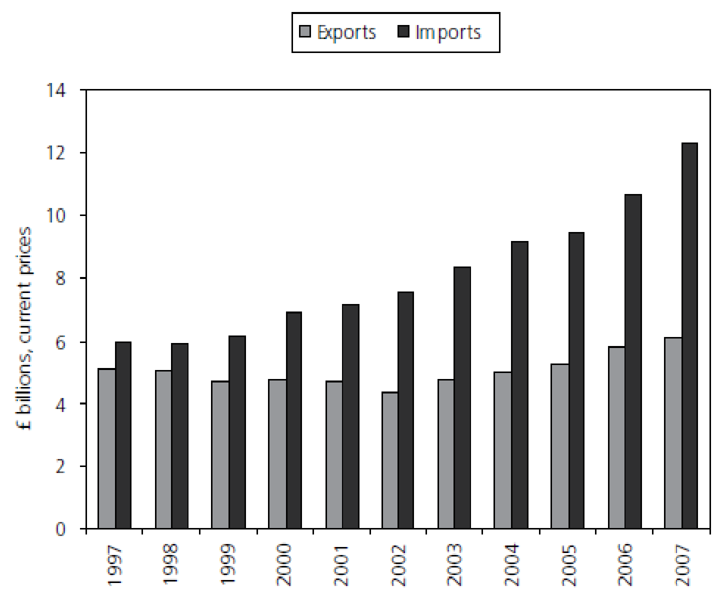




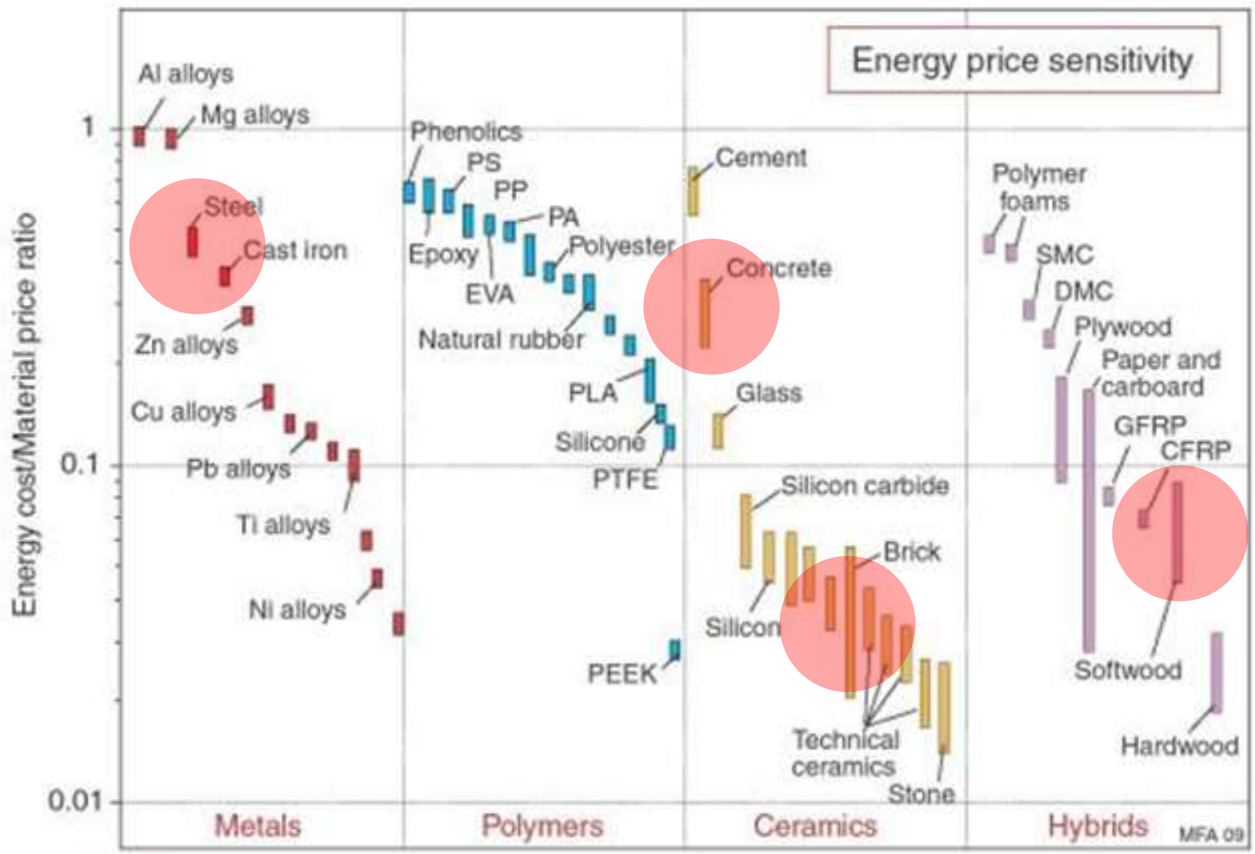
Ref: 'Materials and the Environment' Mike Ashby

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

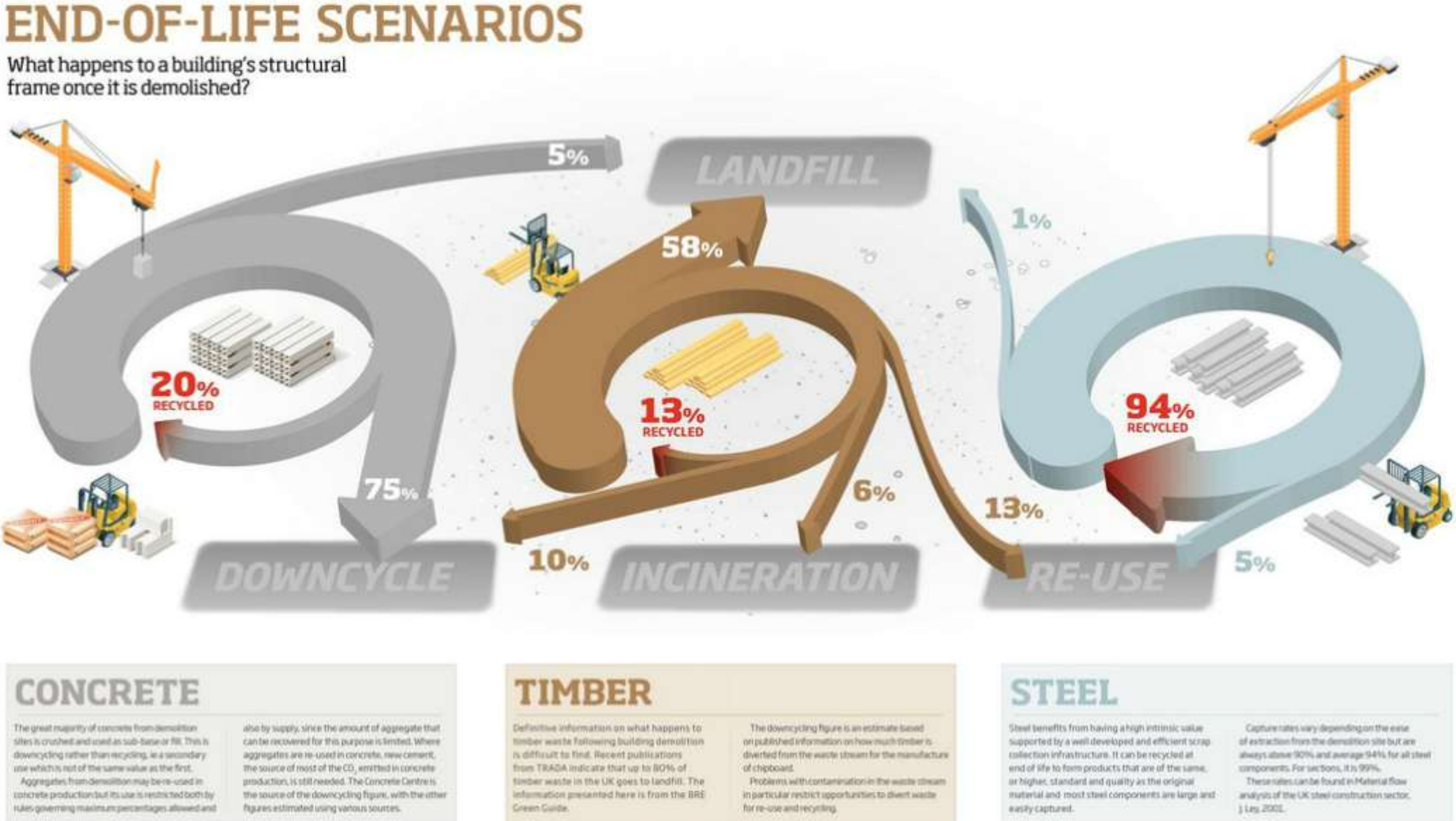


Energy cost represents 100% of material cost

Energy cost represents 10% of material cost

Energy cost represents 1% of material cost

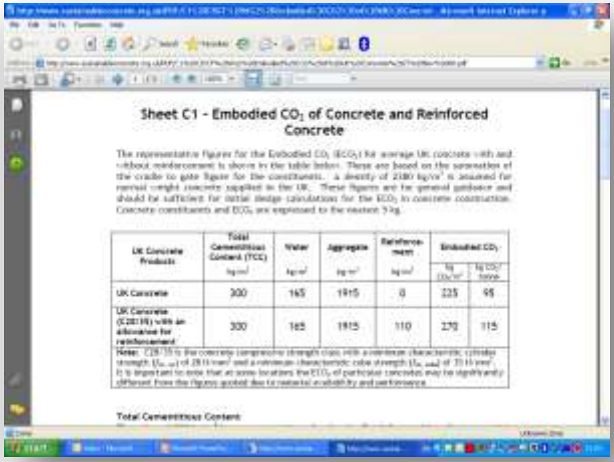
Ref: 'Materials and the Environment' Mike Ashby



- ‘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



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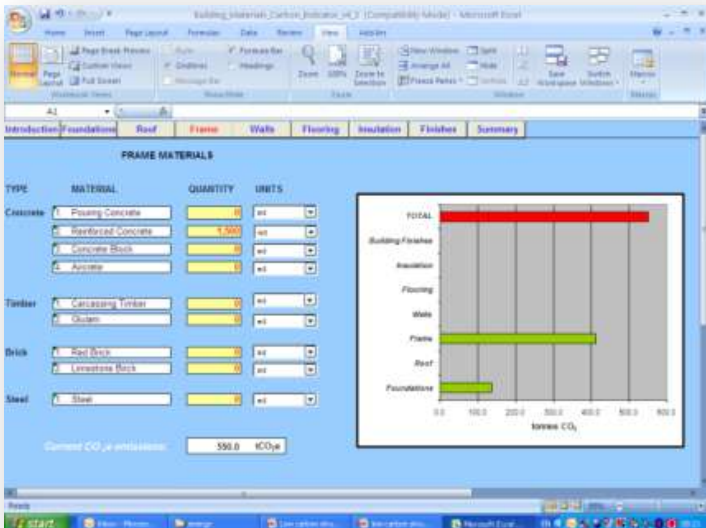
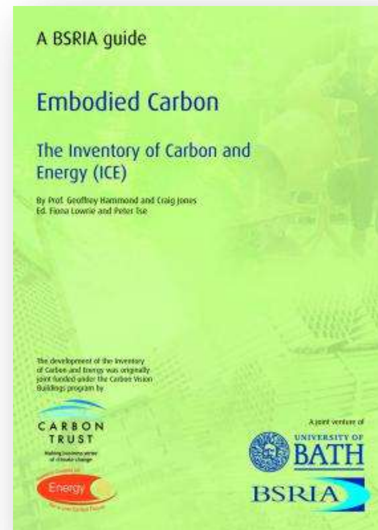
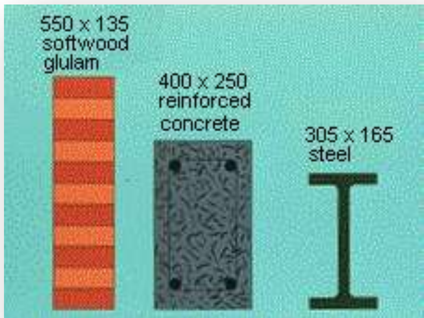




- Edinburgh centre for carbon management
  - Steel 2300 kgCO2/t
  - RC 250 kgCO2/t
  - Timber -1000 kgCO2/t
- Bath University
  - Steel 1440 kgCO2/t
  - RC 210 kgCO2/t
  - Timber 420 kgCO2/t
  - Brickwork 210 kgCO2/t

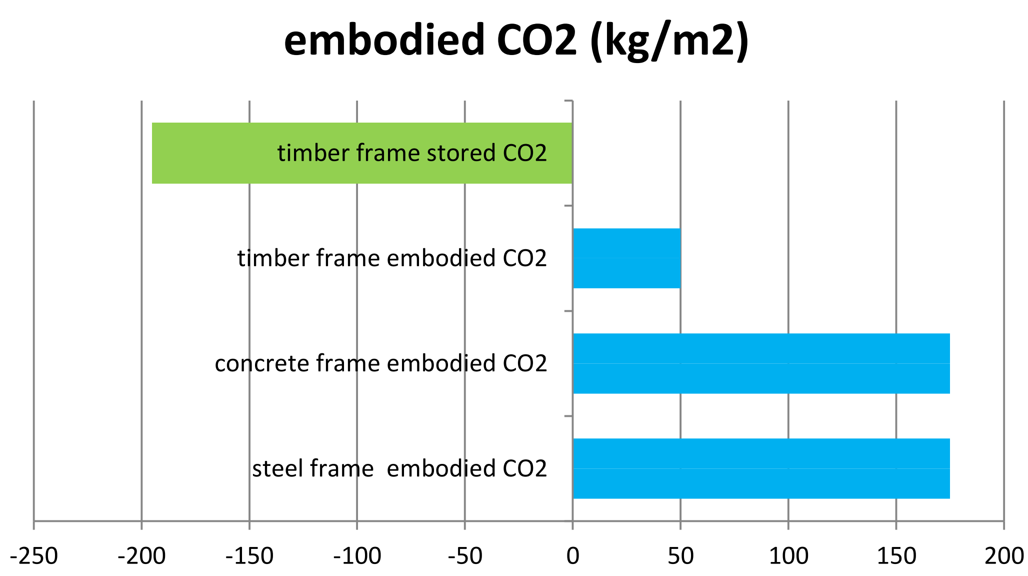
Structural performance



- Timber beam 15kgCO2
- Concrete beam 50kgCO2
- Steel beam 60kgCO2

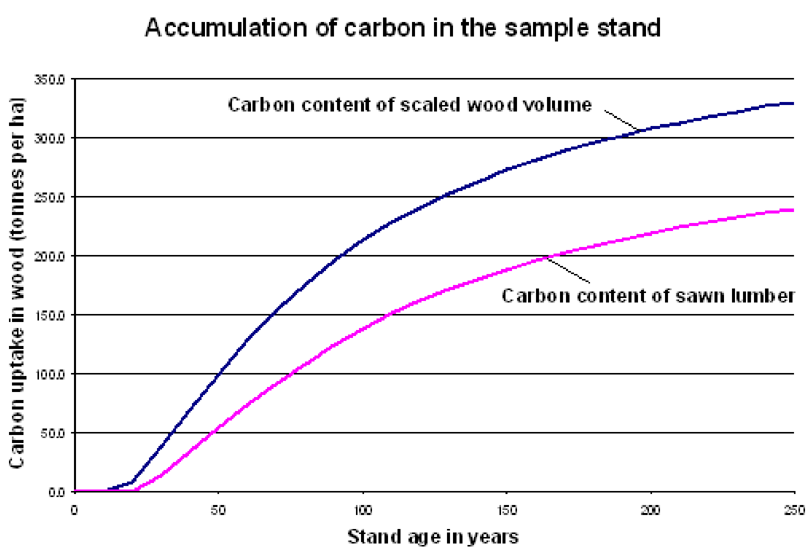
- …….but 60kgCO2 stored in timber beam

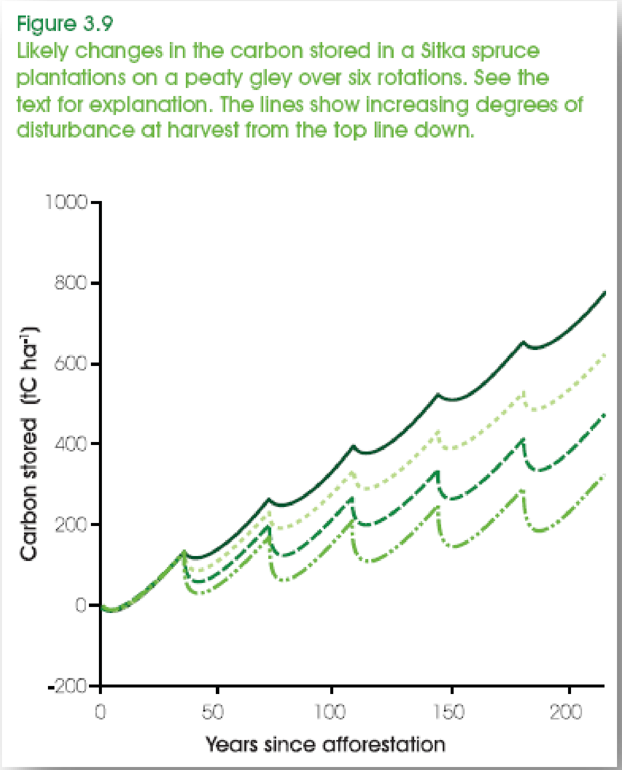
- Timber CLT frame
- Concrete flat slab frame
- Steel frame and holorib slab



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





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

Tress and carbon

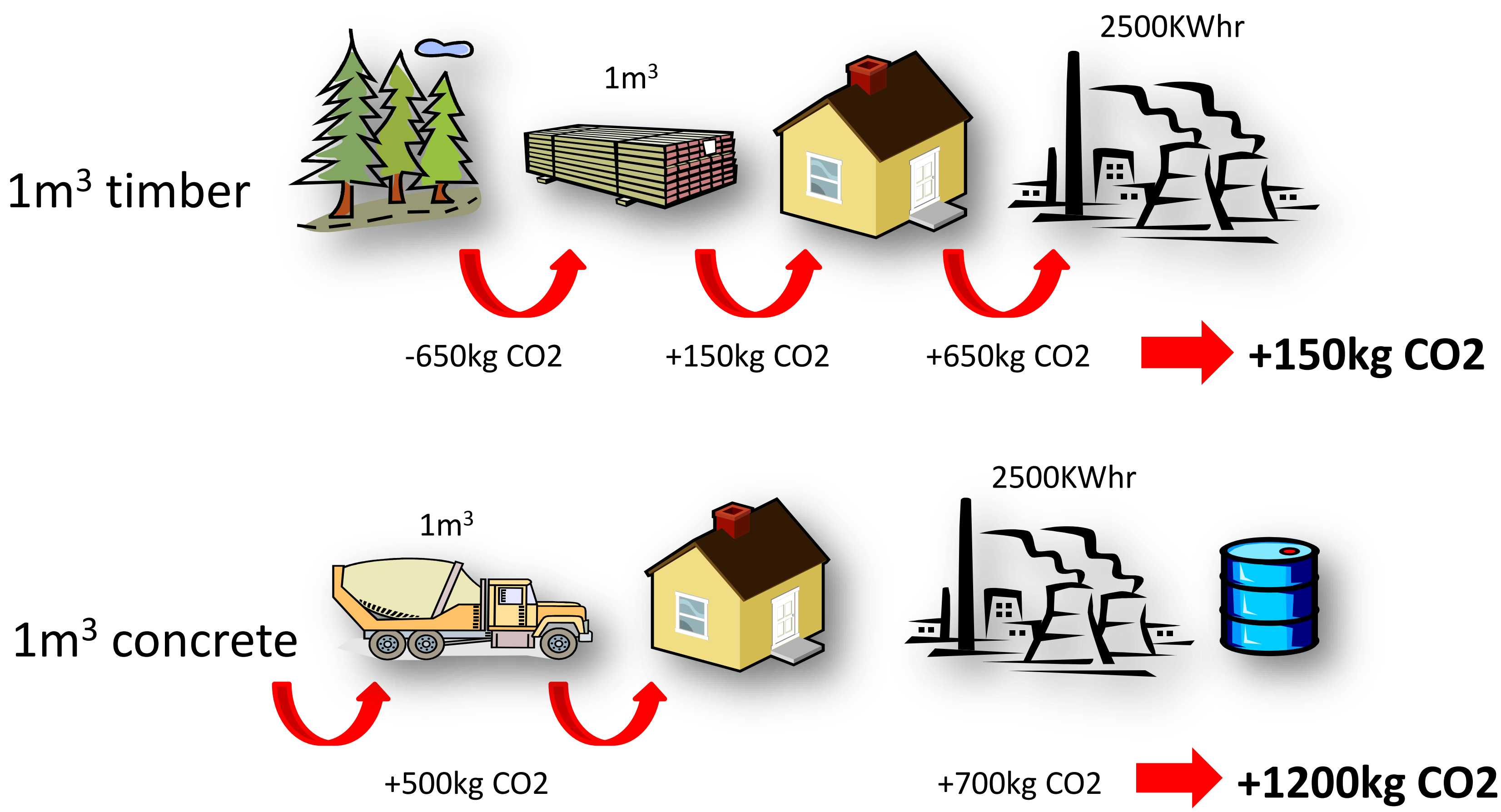
Table 6.6

Timber carbon content ($tCO_2e\ m^{-3}$), typical ranges of maximum mean annual volume increment (MMAI: $m^3\ ha^{-1}\ year^{-1}$) 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	*Picea sitchensis* (Bong.) Carr.	0.62	8–24	64–46	Oak	*Quercus robur* L., *Q. petraea.* (Matt.) Liebl.	1.12	4–8	90–68
Norway spruce	*Picea abies* L. Karst.	0.64	8–20	84–65	Birch	*Betula pendula* (Roth.), *B. pubescens* (Ehrh.)	1.10	4–12	49–40
Scots pine	*Pinus sylvestris* L.	0.84	6–12	82–69	Sweet chestnut	*Castanea sativa* 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 CO_2 figures given
  - Floors -18 to 150 kgCO_2/m2
  - Roofs -4 to 290 kgCO_2/m2
  - External walls -3 to 370 kgCO_2/m2

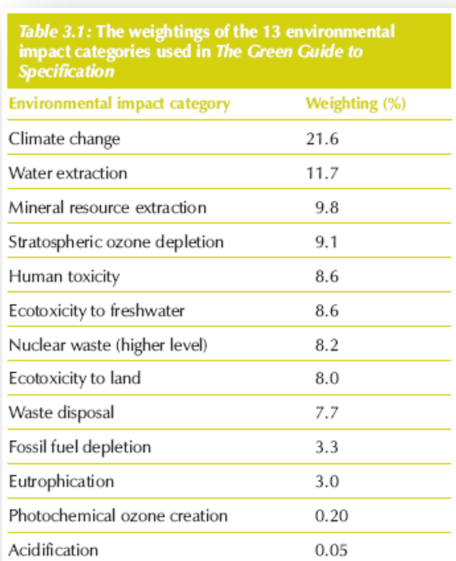
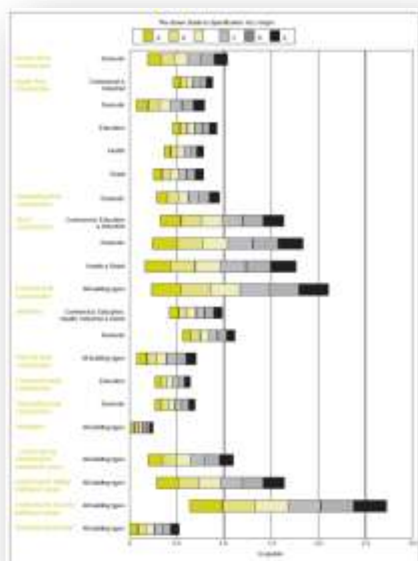
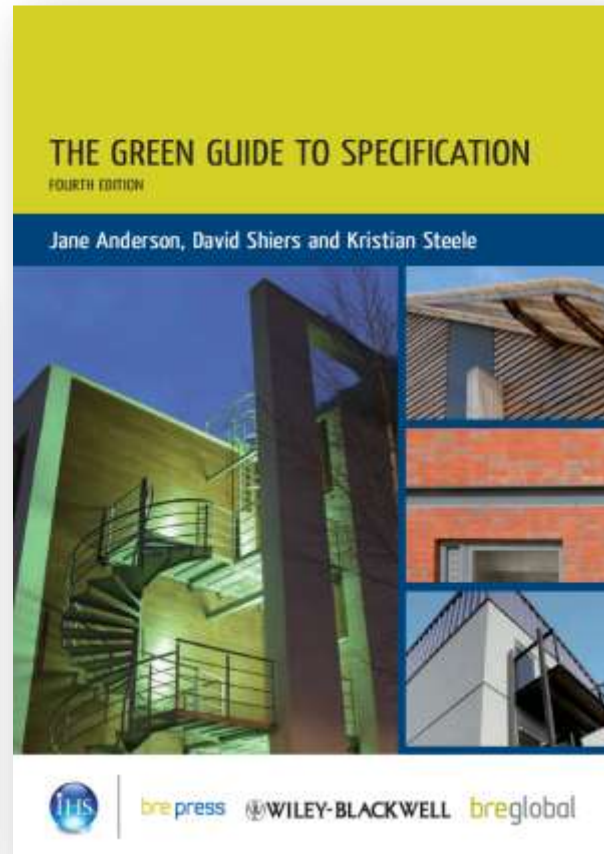


Table 3.1: The weightings of the 13 environmental impact categories used in The Green Guide to Specification

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



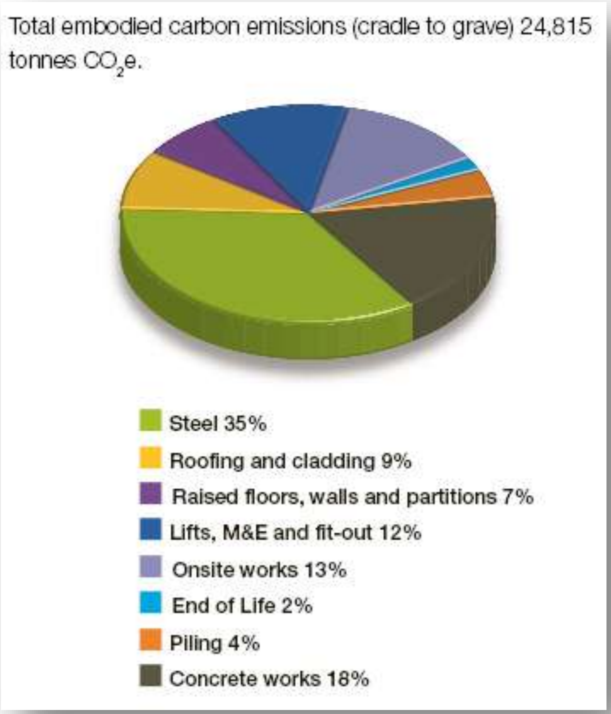


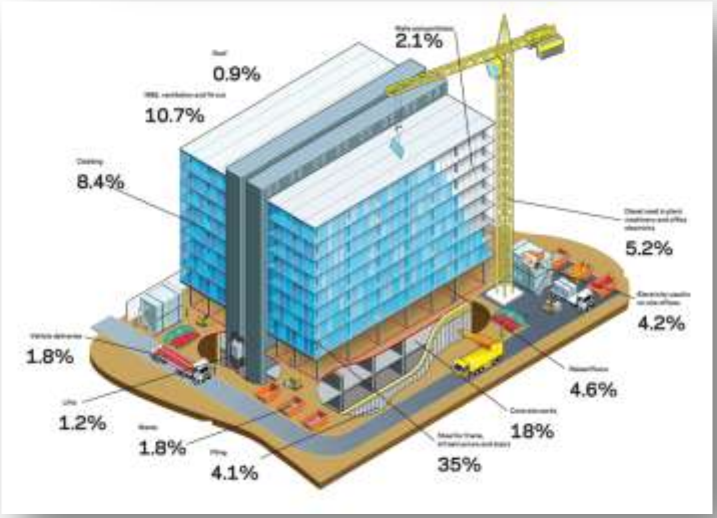
Information sources

- 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



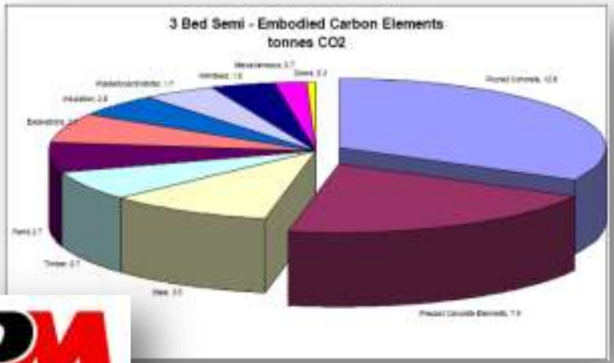


Residential building study

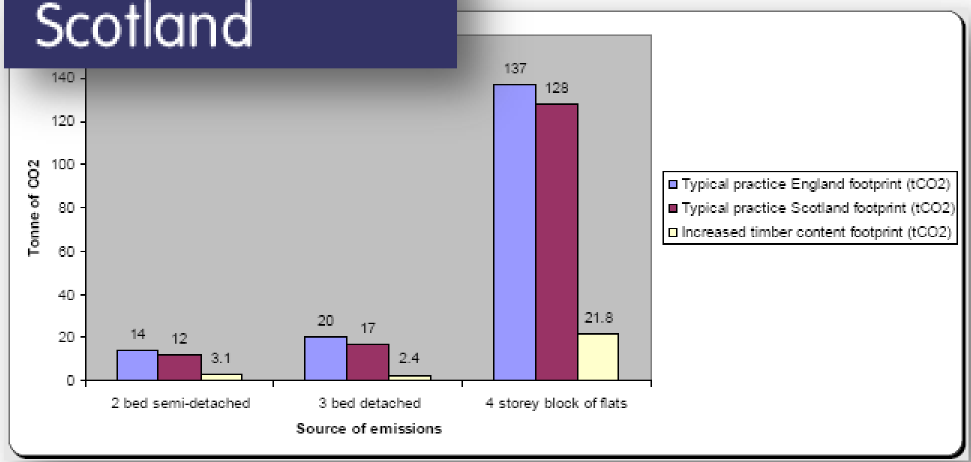
- Statistics
  - 3 bed house 20-40 tCO2
  - Embodied 300-675 kgCO2/m2
  - Operation 30-50 kgCO2/m2 ?

BioRegional
solutions for sustainability

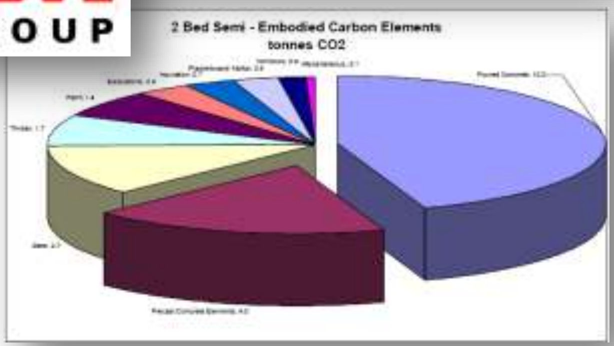
UK housing. The total embodied CO_2 of BedZED is 675kg/m², whilst typical volume house builders build to 600-800kg/m². Despite the increased



Forestry Commission
Scotland

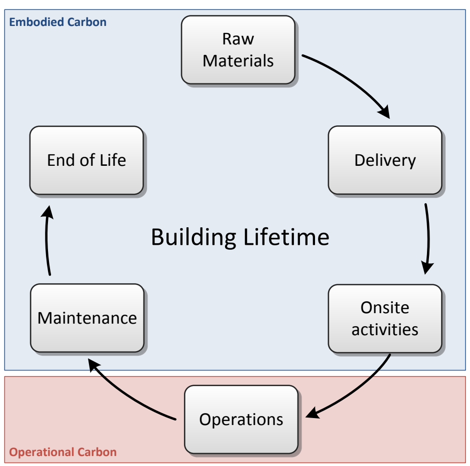


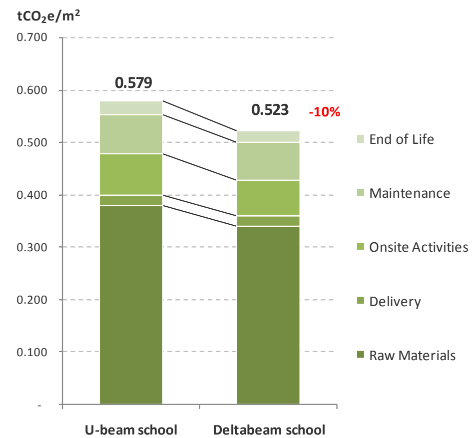
PM GROUP

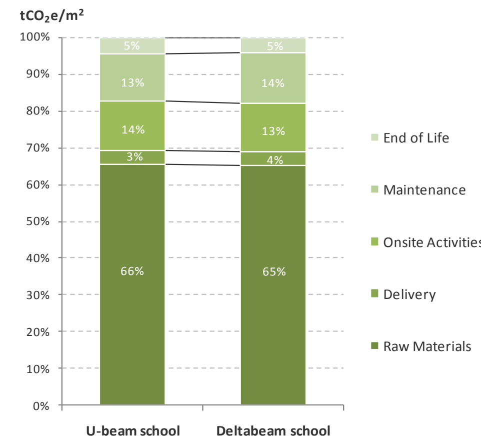


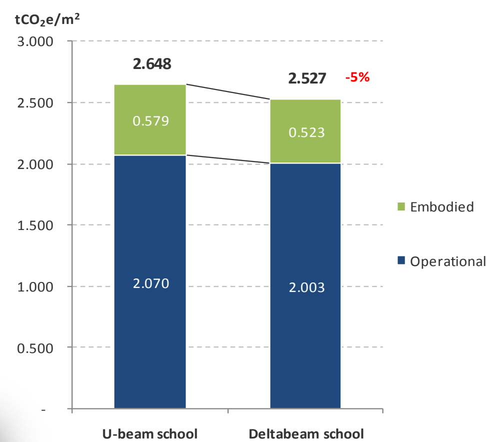
School building study

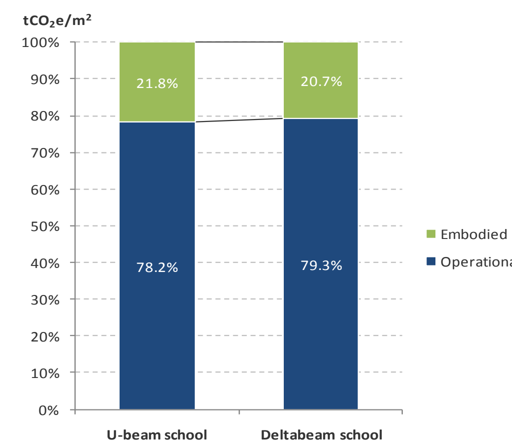
- Statistcs
  - 2 different structure solutions
  - Embodied 300-600 kgCO_2/m2
  - Operation 25-35 kgCO_2/m2







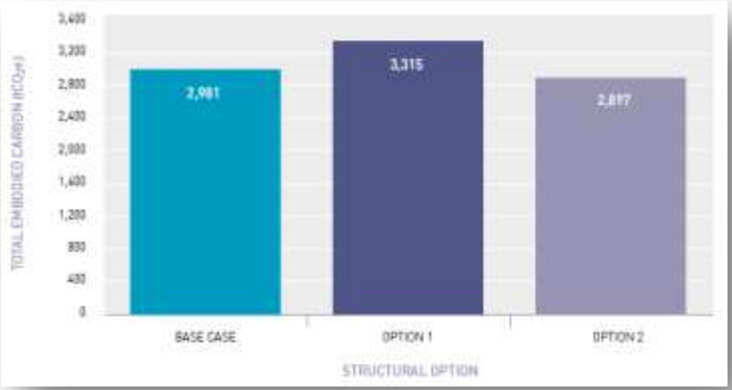


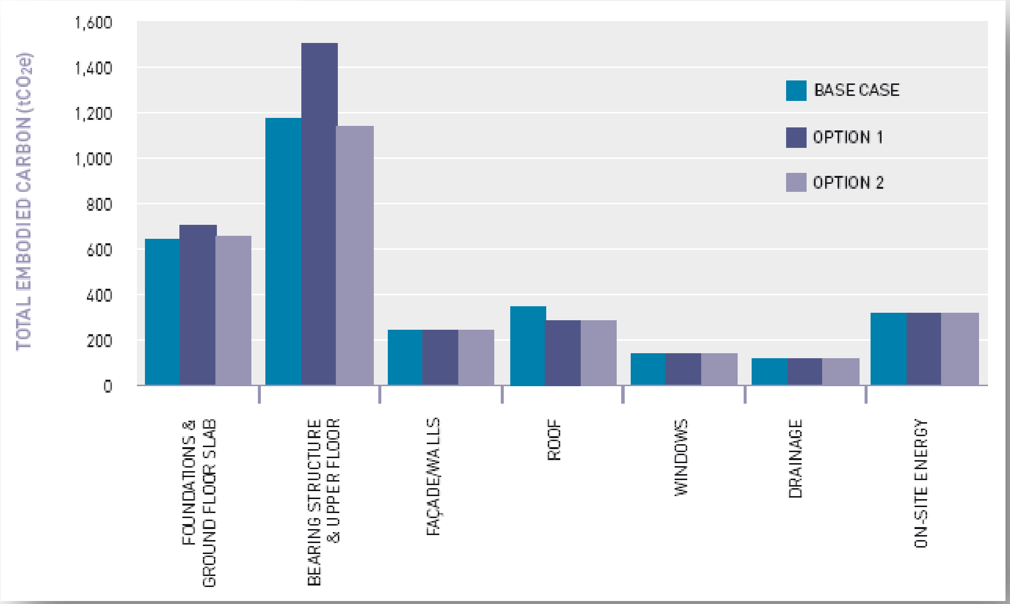


dcarbon8
CARBON & SUSTAINABILITY CONSULTANTS

School building study

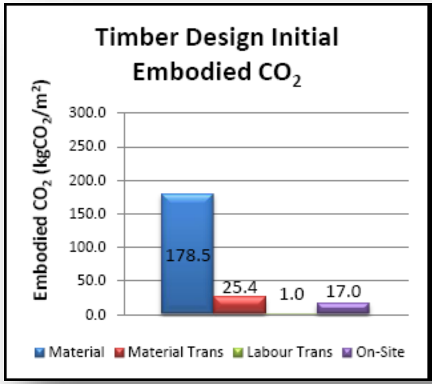
- Steel industry research
  - £22.5m 10,000m2
  - Embodied 300-350 kgCO2/m2
  - Operation 27 kgCO2/m2
  - Structure 10% of cost, 60% of embodied CO2

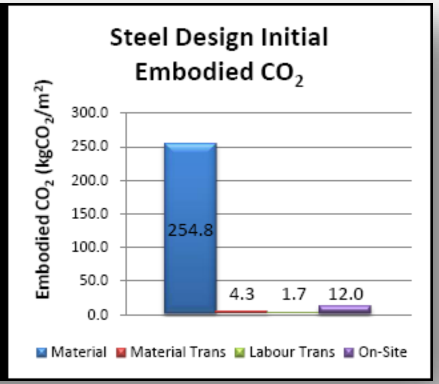


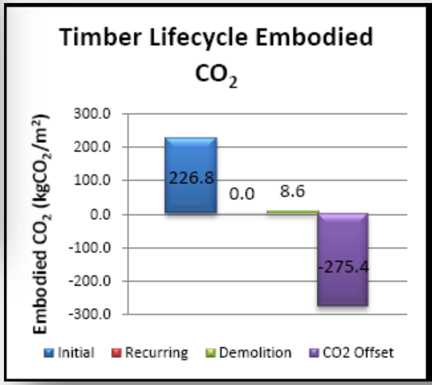


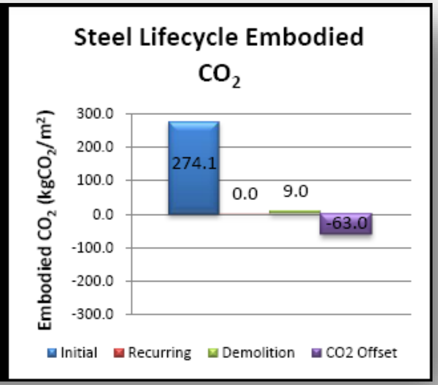
School building study

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









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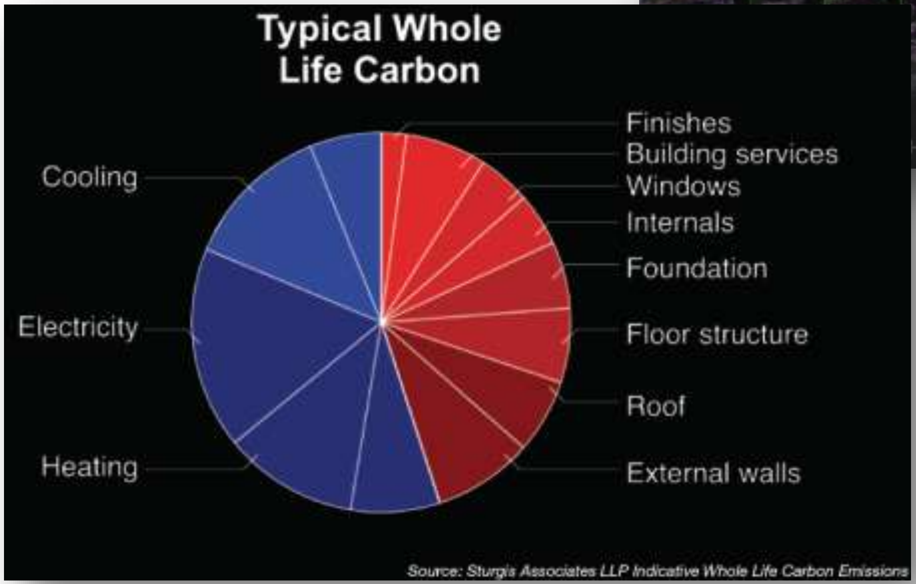
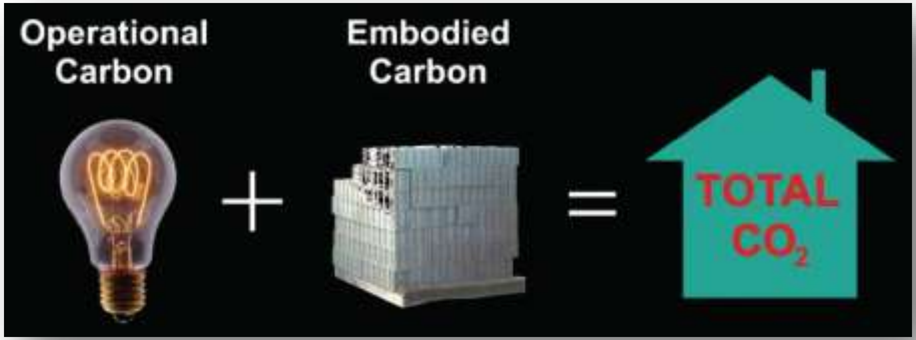
Summary

- 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

- Lean design
  - *Post tension concrete*
  - *Suitable floor spans*
- Re-cycled materials
  - *Cement replacement*
- Renewable materials
  - *Timber structures*
- Minimise waste
  - *Prefabrication*
- Design for long life
  - *Low maintenance, adaptable*

Reduction in concrete and rebar

Approx 23% saving in ECO2

Approx 33 kgCO2/m2

Reduction is steel content

Approx 28% saving in ECO2

Approx 62 kgCO2/m2

Reduction in cement content

Approx 22% saving in ECO2

Approx 46 kgCO2/m2

Carbon negative?

Approx 32% (205)saving in ECO2

Approx 52 (335) kgCO2/m2

Timber beam design example

A glulam timber floor beam spanning l = 7.5m

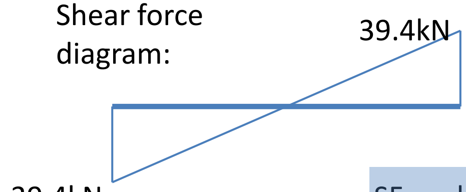
Spacing of beams is 3m

Lightweight floor construction = 1 kN/m2

Office floor loading = 2.5 kN/m2

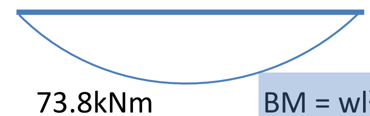
ie: beam loading w = 3m x (1 + 2.5) = 10.5 kN/m

Shear force diagram:



$SF = \frac{wl}{2}$

Bending moment diagram:



$BM = \frac{wl^2}{8}$

Design:

Choose initial beam size based on span to depth ratios

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

From glulam supplier information try a beam 115mm x 630mm & C24 timber grade

Allowable stresses:

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

Allowable bending stress = 7.5N/mm2 x K_7 x K_{15} = 9.6N/mm2*

Modulus of elasticity = 10,800N/mm2 x K_{20} = 11,550N/mm2*

**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 = $\frac{BM}{z} = \frac{73.8 \times 6}{115 \times 630^2}$ = 9.7N/mm2

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

Applied stress is marginally higher than allowable

Deflection check:

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

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

Allowable deflection = 0.003 x span = 22.5mm

Embodied CO2:

=0.115x0.63x160

=12kgCO2/m

Sequestered CO2:

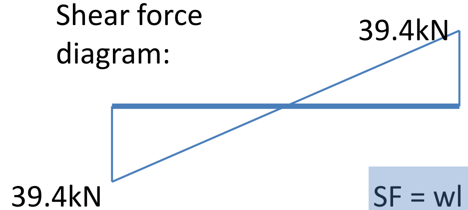
=0.115x0.63x650

=47kgCO2/m

Steel beam design example

A steel floor beam spanning l = 7.5m
Spacing of beams is 3m
Lightweight floor construction = 1 kN/m2
Office floor loading = 2.5 kN/m2
ie: beam loading w = 3m x (1 + 2.5) = 10.5 kN/m

Shear force diagram:



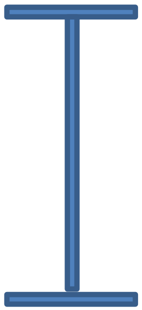
$SF = \frac{wl}{2}$

Bending moment diagram:

$BM = \frac{wl^2}{8}$

Design:

Choose initial beam size based on span to depth ratios
For steel beams span to depth ratios of 20-25 are recommended, therefore 7.5m / 22.5 = 330mm
From steel tables try a beam 356mm x 127mm x 33kg/m grade S275



Allowable stresses:

Allowable bending stress = 165N/mm2*
Modulus of elasticity = 205,000N/mm2
**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:

Bending stress in beam = $\frac{BM}{z} = \frac{73.8}{473,000}$ = 156N/mm2
Where z = elastic modulus = 473cm^3 (see steel tables)
Applied stress is lower than allowable therefore beam okay in bending.

Deflection check:

Deflection = $\frac{5wl^4}{384EI} = \frac{5x10.5x7500^4}{384x205,000x82,490,000}$ = 25.6mm
Where I = second moment area (from steel tables)
Allowable deflection = span/200 = 37.5mm
(or span/360 for office or live load only)

Embodied CO2:

=33kgx1.44kgCO2/kg
=48kgCO2/m