Properties of Materials

Theme: Materials and the Environment

Lecture 1: Introduction to Sustainable Thinking

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Intended Learning Objectives

- Describe the main factors affecting materials consumption
- Demonstrate how to calculate rates of growth and consumption
- Identify strategic materials and their geographical sources
- Identify end of life options for materials and products
- Explain what is involved in undertaking an eco-audit
- Demonstrate that you understand how embodied energy can inform structural design
- Name the three capitals and their role in sustainable development
- Describe the process of assessing sustainable technology

Overview

Lecture 1: Introduction to sustainability, Factors affecting materials consumption, Strategic materials.

Lecture 2: Material life cycle, Embodied energy, LCA, Eco-audits, Energy fingerprints, Recycling and end of life options.

Lecture 3: Eco-design, case study: crash barriers and drink containers.

Lecture 4: Materials and sustainability (wind turbine).

Today's Lecture Contents

- Introduction to sustainability.
- Factors affecting materials consumption.
- Calculating growth rates.
- What are strategic (critical) materials?

Source: Chapter 20, Leica Geosystems, Switzerland.

Why Study Sustainable Development?

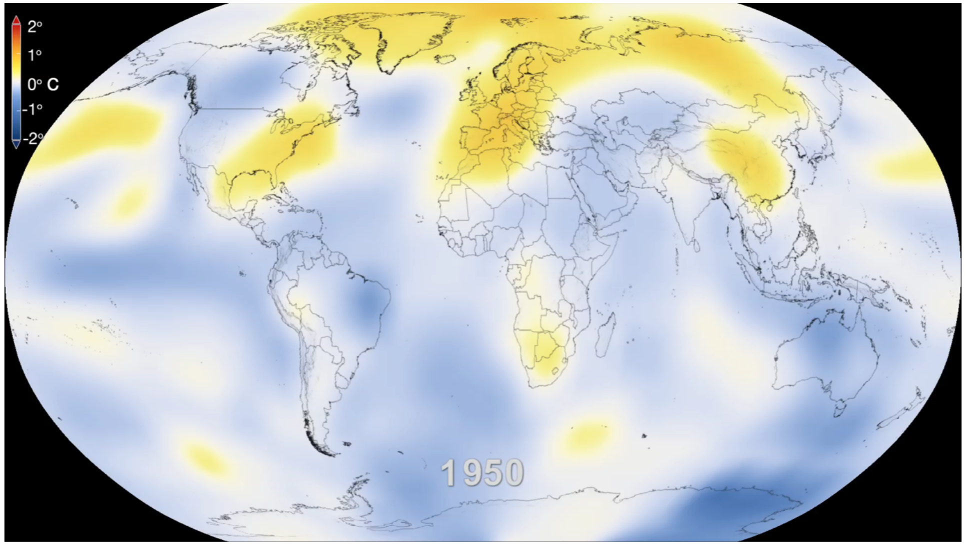
‘Continuation of civilisation is in your hands’

Keynote Address: Sir David Attenborough

UN Climate Conference, Katowice, Poland, 03 Dec- 14 Dec 2018

Climate Change

Climate change is real and the impacts are potentially devastating.

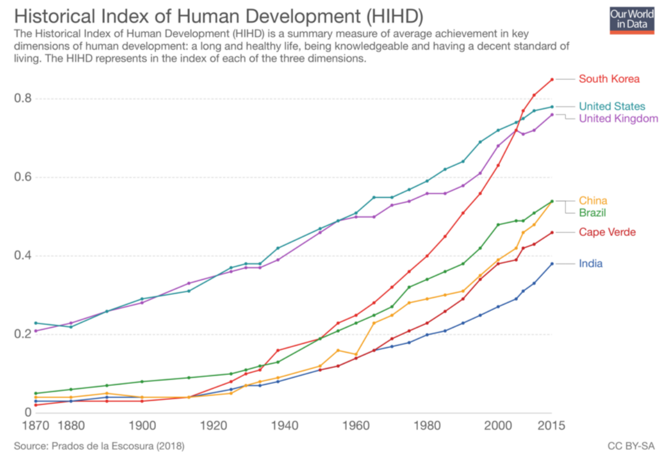


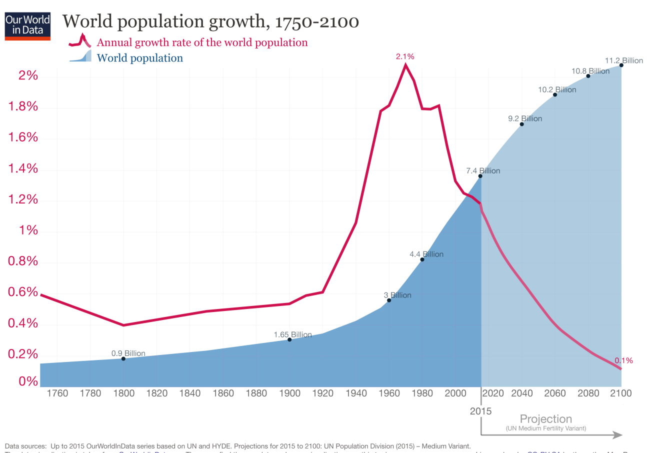
CARBON DIOXIDE	GLOBAL TEMPERATURE	ARCTIC ICE MINIMUM	ICE SHEETS	SEA LEVEL
↑ 409 parts per million	↑ 1.8 °F since 1880	↓ 12.8 percent per decade	↓ 413 Gigatonnes per year	↑ 3.2 millimeters per year

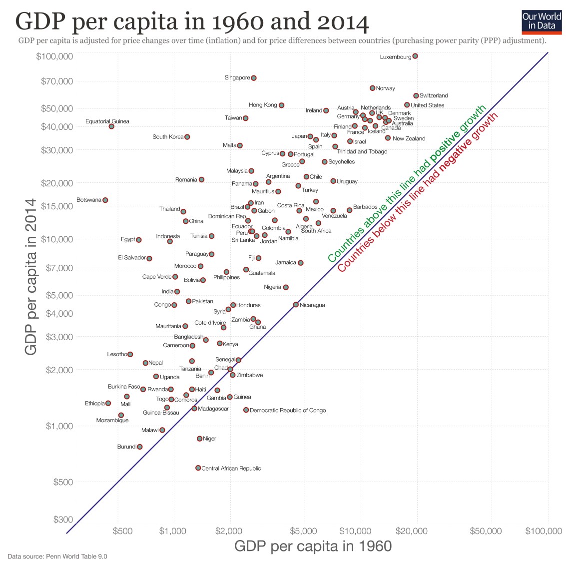
Source: https://climate.nasa.gov/climate_resources/101/video-global-temperature-variation/

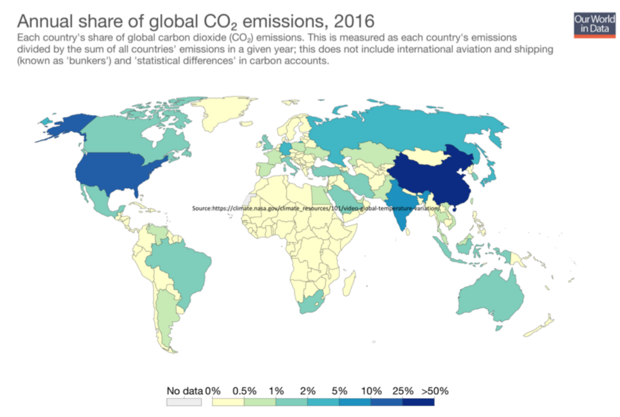
Population and Living Standards

- A growing population for the foreseeable future.
- Increasing human longevity, wealth, health, living standards.
- Growing global CO_2 emissions.





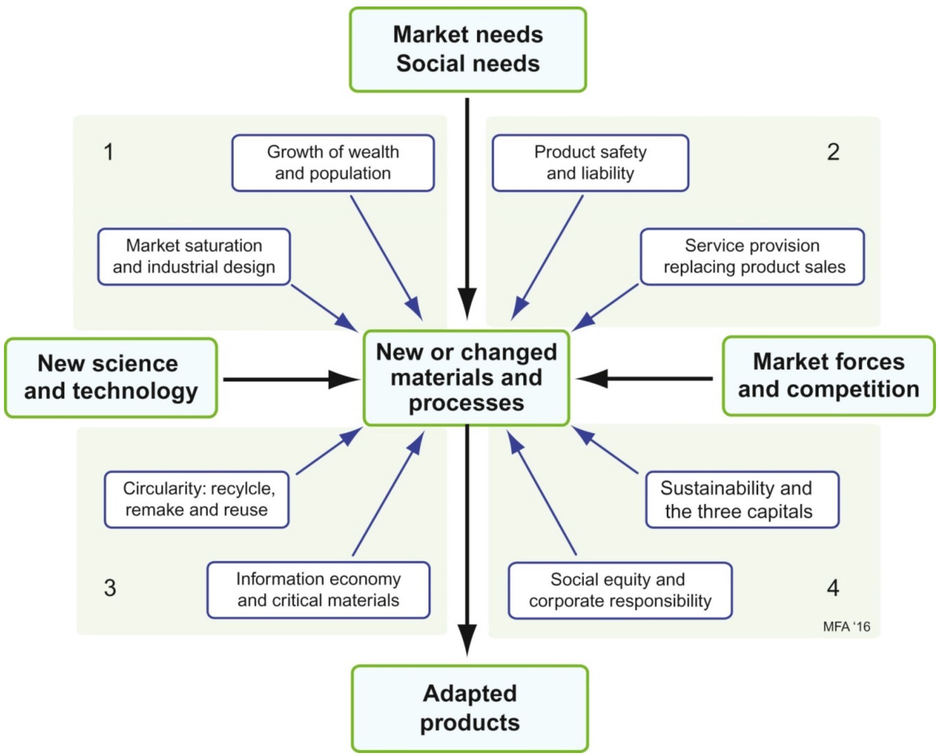




Source: Our World in Data https://ourworldindata.org

Forces for Change

- We live in a dynamic world.
- Many factors exert pressure to change material choice or process.
- Market pull, science push, mega-projects.
- Lead to adapted products.



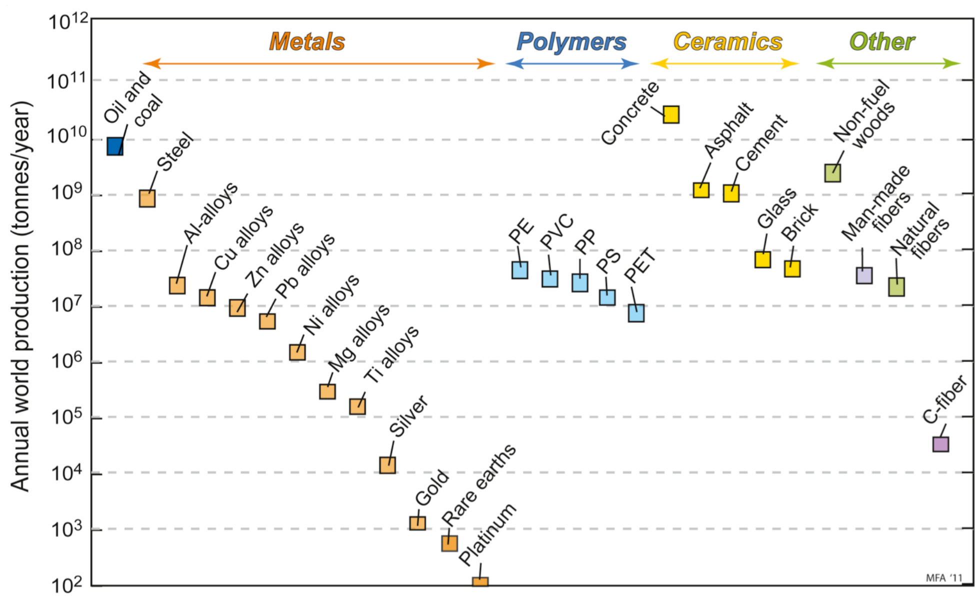
Some forces for change (Materials Section in Mechanical Design, Fig. 16.1)

Materials Consumption

Globally, we consume 10^{10} tonnes of engineering ‘stuff’ *every year.*

Hydrocarbon fuels (oil and coal) dominate - 9 x 10^{10} tonnes *p.a.*

- Construction industry consumes vast quantities of materials (wood, steel, concrete, asphalt (tarmac), glass).
- Big growth in carbon fibre (driven by expansion in aerospace)



The consumption of hydrocarbons and engineering materials (see Fig. 20.1)

The Growth of Materials Consumption

Most materials consumption growing exponentially with time.

- Both population and living standards grow exponentially.

At a global growth rate of just 3% per year we will mine, process, and dispose of more 'stuff' in the next 25 years than in the entire history of human engineering.

Environment has some capacity to cope without lasting damage, but current human activities exceed threshold with increasing frequency, diminishing quality of world and threatening well-being of future generations.

The Growth of Materials Consumption

Design for *Environment*.

- Generally interpreted as effort to adjust present product design efforts to correct known, measurable environmental degradation
- Timescale around 10 years (average product's life).

https://www.weforum.org/agenda/2017/06/when-willwe-see-the-airplane-equivalent-of-a-tesla-the-2017-sae-roadmap-to-more-electric-flight/-

Design for *Sustainability.*

- Longer term view, much greater intervention
- Adaptation to lifestyle to meet present needs of future generations
- Timescale measured in decades or centuries

http://theprereq.com/new_sustainability-building-design/incredible_sustainability-building-design-singapore-energy-efficient-green-heart

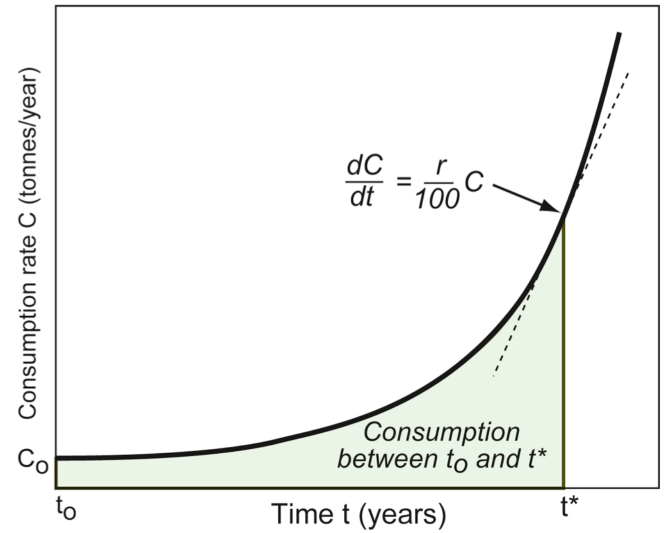
The Growth of Materials Consumption

Most materials consumption growing exponentially with time.

- Both population and living standards grow exponentially.

$$\frac{dC}{dt} = \frac{r}{100}C$$

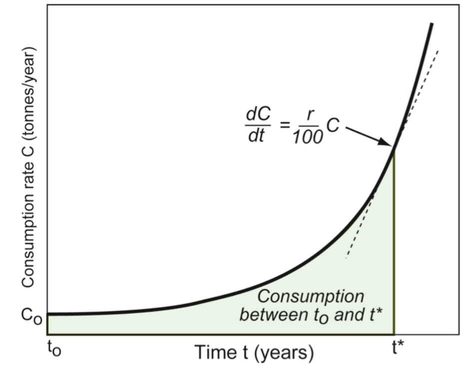
C = current rate of consumption in tonnes/year.



Exponential growth (see Fig. 20.2)

Rates of Materials Consumption

Small growth rates (1-5% per year), consider *r* as percentage fractional rate of growth per year.



Integrating over time:

$$C = C_0 exp\left\{\frac{r(t-t_0)}{100}\right\}$$

where C_0 is consumption rate at $t = t_0$, The doubling-time t_D of consumption rate obtained by setting C/C_0 to give

$$t_D = \frac{100}{r} log_e(2) \approx \frac{70}{r}$$

Calculating Growth Rates

Example 1: Annual growth rate.

World production of silver in 1950 was 4000 tonnes/year. By 2010 it had grown to 21,000 tonnes/year. Assuming exponential growth, what is the annual growth rate of silver production?

Answer:

$$P = P_0 exp\left\{\frac{r(t - t_0)}{100}\right\}$$

where P_0 is production rate at $t = t_0$. Setting P = 21,000 tonnes/year, (P_0 = 4000 tonnes/year) and $(t - t_0)$ = 60 years, then solving for growth rate, r:

$$r = \frac{100}{(t-t_0)} \ln\left(\frac{P}{P_0}\right) = 2.8\% \text{ per year}$$

Calculating Cumulative Growth

Example 2: Cumulative growth.

A total of 5 million cars were sold in China in 2007; in 2008 the sales totalled 6.6 million. What is the annual growth rate of car sales, expressed as %/year?

Answer:

$$C = C_0 exp\left\{\frac{r(t - t_0)}{100}\right\}$$

where C = 6.6 x 10^6, C_0 = 5 x 10^6, $(t - t_0)$ = 1 year, then solve for r: 27.8%/year.

Calculating Cumulative Growth

Example 2: Cumulative growth (continued).

If there were 15 million cars already on Chinese roads, by the end of 2007 and this growth rates continues, how many cars will there be in 2020, assuming that the number that are removed from the roads in this time interval can be neglected?

Answer:

$$Q_{t*} = \int_{t_0}^{t^*} C\,dt = \frac{100C_0}{r}\left(exp\left\{\frac{r(t^* - t_0)}{100}\right\} - 1\right)$$

C_0 = 5 x 10^6 (number in 2007), r = 27.8%/year, time interval ($t*$-t_0) = 13 years (to 2020)

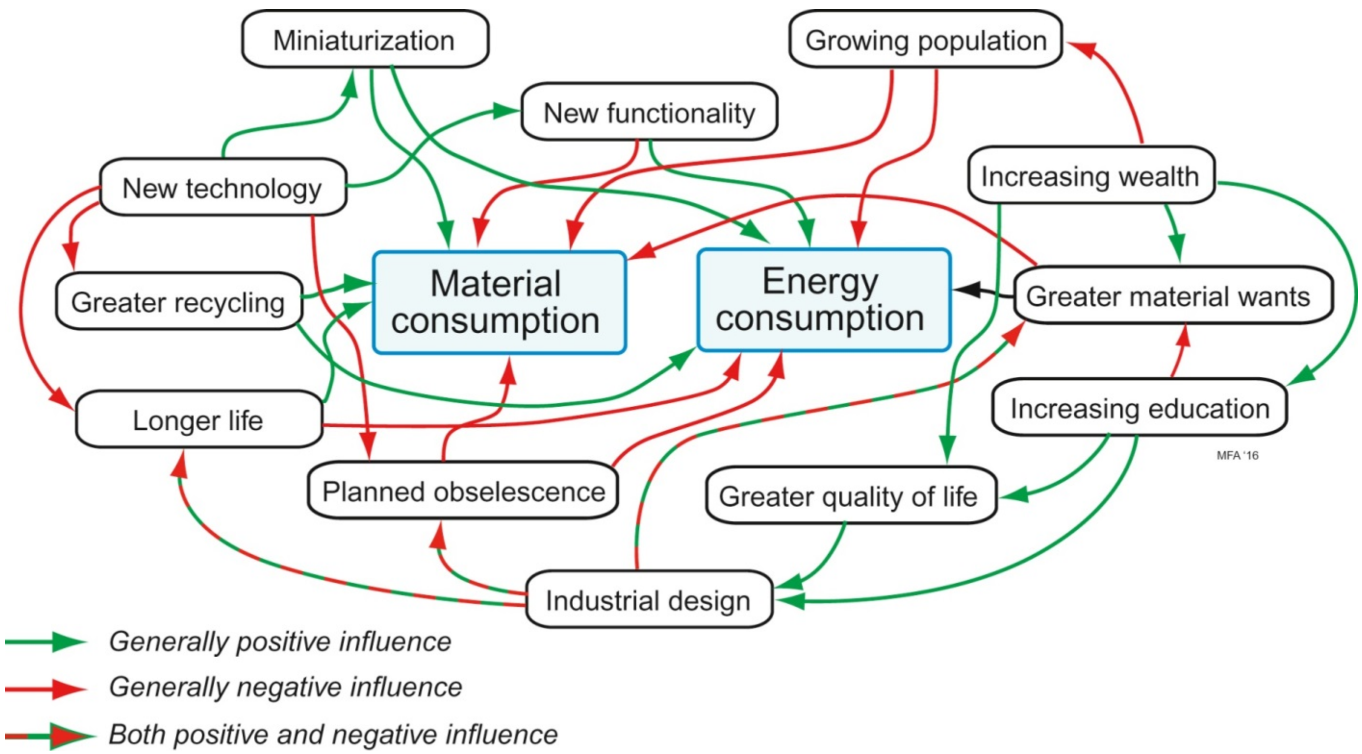
Additional number of cars by 2020 Q_{t*} = 650 x 10^6.

Total number of cars on Chinese roads in 2007 = 5 x 10^6 + 650 x 10^6 = 655 x 10^6.

What Drives Consumption?

Eco-systems are complex (materials and energy interconnected).

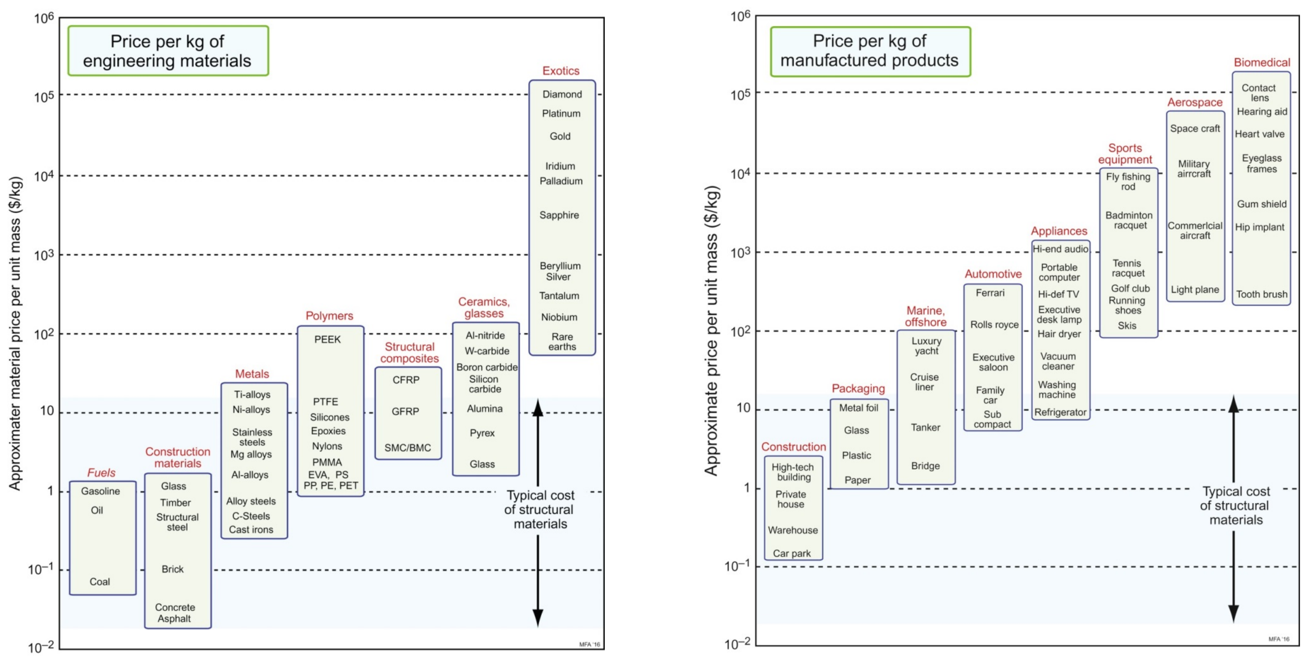
- Primary catalysts of consumption: increasing wealth, population growth, new technology, planned obsolescence.



The influences on consumption of materials and energy (Materials Section in Mechanical Design, Fig. 16.4)

Market Forces and Competition

- End users of materials are manufacturing industries.
- They decided which material they will purchase and adapt for their products.
- Market price is common measure for comparison (crude but has merit – unambiguous, easily determined, some relationship to value added).
- Shaded areas – includes most widely used materials for structural products.



The price per unit weight for selected materials and products (Materials Section in Mechanical Design, Fig. 16.2)

Strategic (Critical) Materials

Mineral resource bases – generally large and widely distributed.

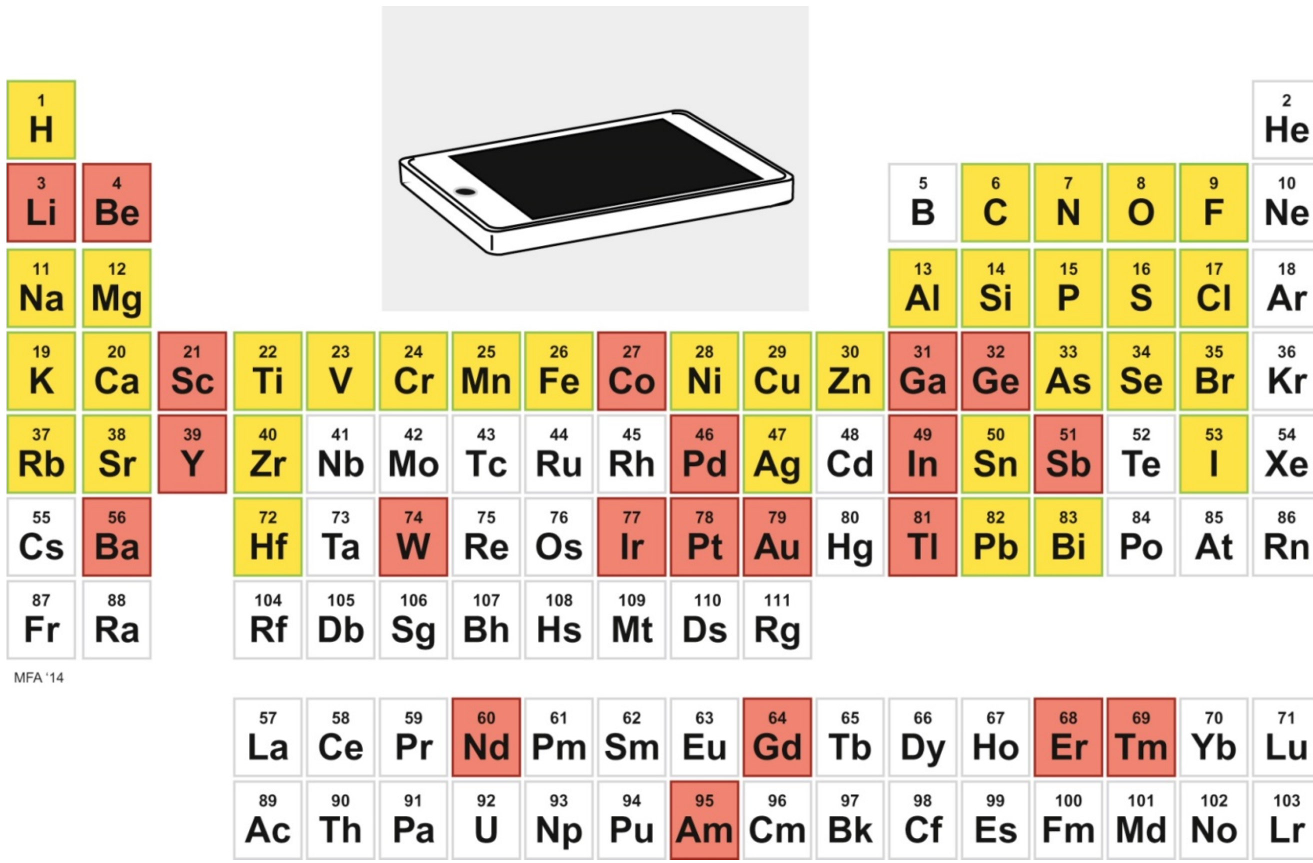
- *e.g.* resource bases supplying steel and aluminium chain
- Vital to economy, but energy resource more likely to limit production

Why are materials 'strategic'?

	Element	Critical applications	Principal global sources
General Engineering	Copper	Electrical conduction (wiring) in all electro-mechanical items	Canada, Chile, Mexico
	Manganese	Essential alloying element in steels	South Africa, Russia, Australia
	Niobium	Micro-alloyed steels, superalloys, superconductors	Brazil, Canada, Russia
	Tantalum	Ultra-compact capacitors (smart phones), alloying in steels	Australia, China, Thailand
	Vanadium	High speed tool steels, micro-alloyed steels	South Africa, China
	Cobalt	Superalloys, alloying in steels	Zambia, Canada, Norway
	Titanium	Light, high strength, corrosion-resistant alloys	China, Russia, Japan
	Rhenium	High-Performance turbines	Chile
Electronics	Lithium	Lithium ion batteries, Al-Li alloys for aircraft	Russia, Kazakhstan, Canada
	Gallium	Gallium-arsenide Photo-Voltaic devices, semi-conductors	Canada, Russia, China
	Indium	Transparent conductors, InSb semi-conductors, LEDs	Canada, Russia, China
	Germanium	Solar Cells	China
Catalysts	Platinum	Catalyst in chemical engineering and engine exhausts	South Africa, Russia
	Palladium	Catalyst in chemical engineering and engine exhausts	South Africa, Russia
	Rhodium	Catalyst in chemical engineering and engine exhausts	South Africa

‘The Periodic Table of Smart Phones’

- Smart phones are dependent on many elements.



Materials Section in Mechanical Design (see Fig. 16.4)

Strategic (Critical) Materials (continued)

Highly localised.

- Both population and living standards grow exponentially.

Rare Earth Elements

Element	Critical applications	Principal global sources
Lanthanum	High RI glass, H storage, battery electrodes (hybrid cars), camera lenses	China, Japan, France
Cerium	Catalysis, alloying element in aluminium alloys	China, Japan, France
Praesodymium	Rare earth magnets, materials for lasers	China, Japan, France
Neodymium	Rare earth permanent magnets, materials for lasers	China, Japan, France
Promethium	Nuclear batteries (*beta*-emissions to electric power)	China, Japan, France
Samarium	Rare earth magnets, lasers, neutron capture	China, Japan, France
Europium	Red and blue phosphors, lasers, mercury-vapour lamps	China, Japan, France
Gadolinium	Rare-earth magnets, high RI glass, garnets, lasers, X-ray tubes, computer memory	China, Japan, France
Terbium	Green phosphors, lasers, fluorescent lamps	China, Japan, France
Dysprosium	Rare earth magnets, materials for lasers	China, Japan, France
Holmium	Materials for lasers	China, Japan, France
Erbium	Materials for lasers, vanadium steel	China, Japan, France
Ytterbium	Infrared lasers, high temperature superconductors	China, Japan, France
Lutetium	Catalyst in petroleum industry	China, Japan, France

Summary

- Increasing pressures (climate change, population growth, materials consumption) all threaten finite resources.
- The consumption of materials and energy are complex and interconnected.
- Global economy increasingly dependent on supply of materials from non-renewable resources whose future availability is uncertain.
- We need to understand material life cycles to manage resources sustainably.

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Lecture 2: The Material Life Cycle

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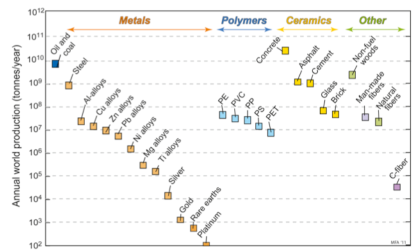
Previously – Materials Consumption

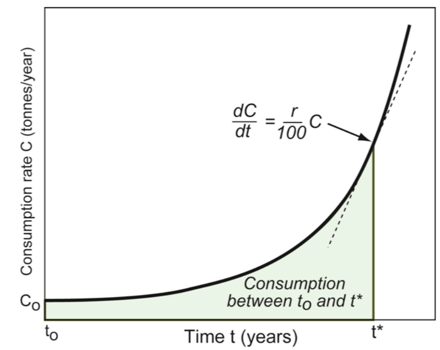
Materials Consumption

- Colossal amounts used
- Mainly oil/coal
- Unsustainable



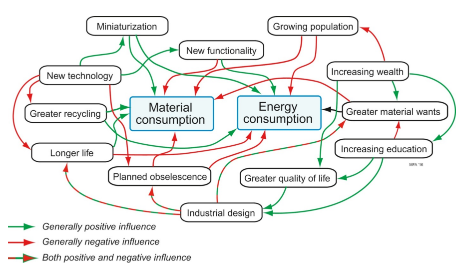
Rates

- Exponential
- Population
- Living standards



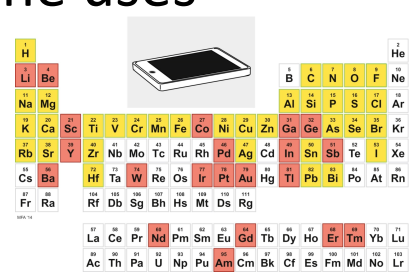
Materials Eco-system

- Catalysts to consumption
- Interconnected
- Unintended consequences



Strategic (critical) materials

- Global distribution
- Security of supply
- Niche uses



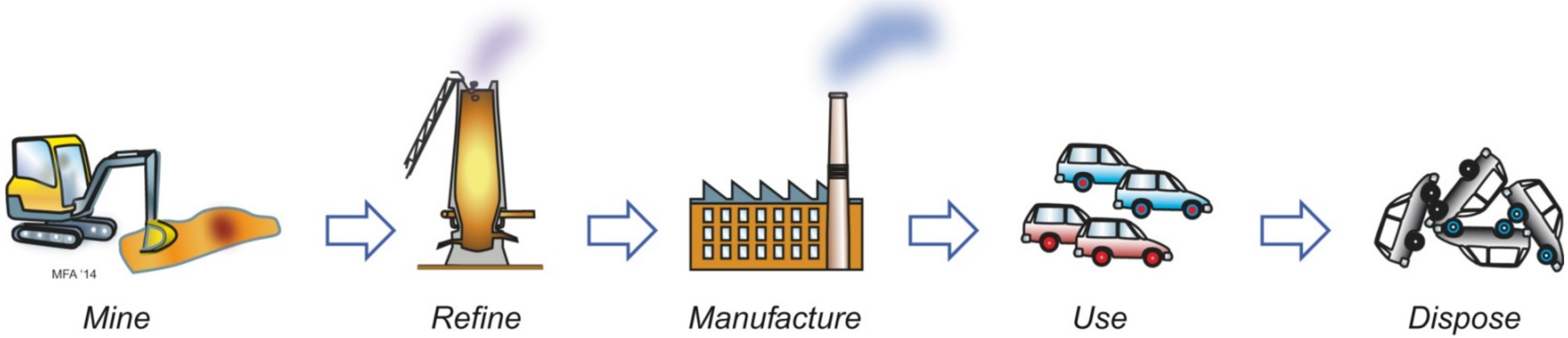
Today's Lecture Contents

- Material life cycle.
- Definitions (forms of energy) and measurement.
- Life Cycle Assessment.
- Recycling and end of life options.
- Eco-audits.

The Linear Materials Economy

Remember: At a global growth rate of just 3% per year we will mine, process, and dispose of more 'stuff' in the next 25 years than in the entire history of human engineering.

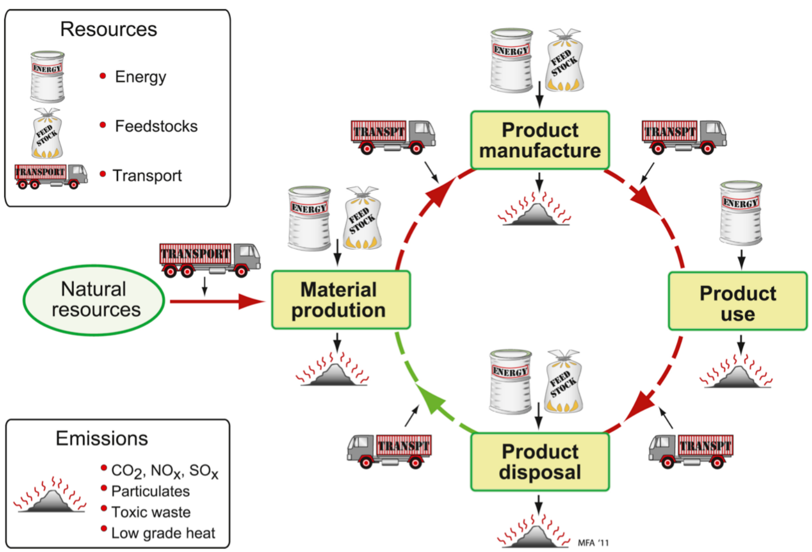
Traditional (historical) approach to materials production and use was often wasteful and unsustainable.



The linear materials economy: take – make – use – dispose (Materials Section in Mechanical Design, Fig. 16.5)

The Material Life Cycle

- Life cycle broken down into phases
  - production, manufacture, use, disposal.
- Energy and materials consumed in each phase
  - associated penalties CO_2, SO_x, NO_x other emissions (heat, gas, liquid, solid waste)
- Environmental 'stressors' catalogued, quantified by life-cycle analysis (LCA)
  - Examines life cycle of product, gives detailed assessment of eco-impact



The material life cycle (see Fig. 20.3)

Embodied Energy

- Energy committed to creating 1kg of usable material
  - Steel stock, PET pellets, cement powder, *etc.* measured in MJ/kg
  - CO_2 footprint = associated release of CO_2 measured in kg/kg

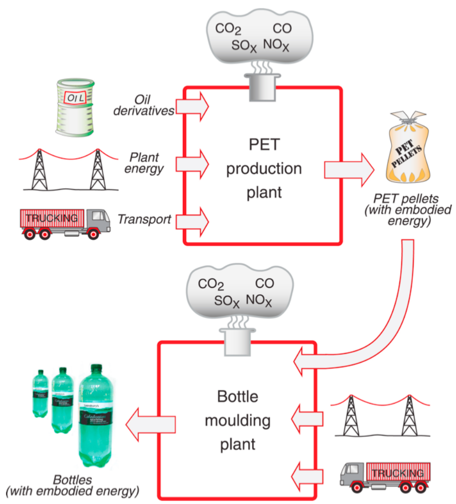
- Embodied energies assessed by input-output analysis.
  - Found by monitoring over fixed period total energy input to production plant (including embodied energy of feedstock)

- Embodied energy (H_m) of PET (MJ/kg)

- Inputs:
  - oil derivatives (naphtha) other feedstocks, direct power (electricity is 34% efficient), energy of transporting feedstock.

- Output:
  - Hourly output of usable PET granules

- $(H_m)_{PET} = \dfrac{\sum energies\ entering\ plant\ per\ hour}{Mass\ of\ PET\ granules\ produced\ per\ hour}$



An input-output diagram for PET Production and recycling (see Fig. 20.4)

Processing Energy

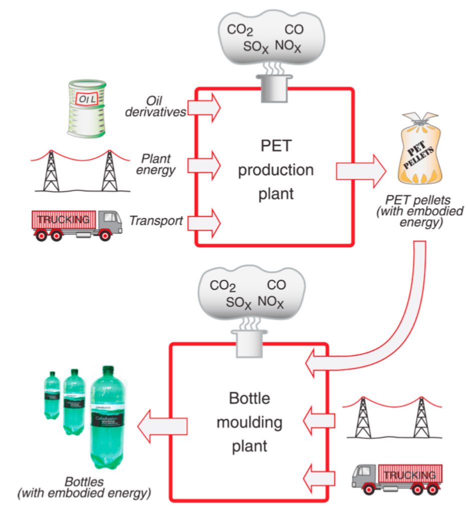
- Energy (MJ) used to shape, join, finish 1kg of usuable material to create component or product.
  - Polymers (moulded or extruded), metals (cast, forged), ceramics (powder method)
  - Energy associated with process measured in MJ/kg

- Processing energy (H_p) of PET (bottles)

- Inputs:
  - PET granules (after transportation to blow moulding facility) (H_m)
  - oil derivatives (fuel) other feedstocks, direct power

- Output
  - Energy committed per bottle produced

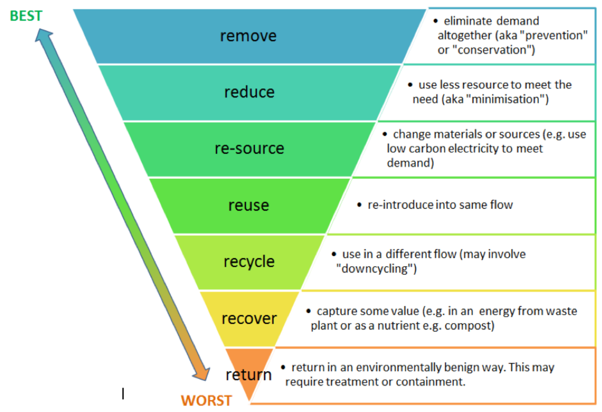
- Many steps before bottle reaches consumer (and used)
  - Collection, filtration, water/ingredients monitoring, transportation of drink and bottles to bottling plant, labelling, delivery to central warehouse, distribution to retailers, possible refrigeration.



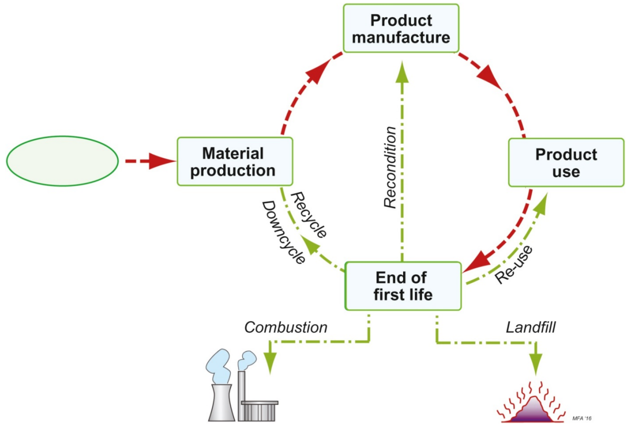
An input-output diagram for PET Production and bottle manufacture (see Fig. 20.4)

‘End of Life’ Options for Materials

- Landfill
  - most rejected products
  - big pressures on land availability
  - landfill tax currently €50/tonne and rising.
- Combustion with heat recovery
  - allows some energy stored in material to be retrieved by <u>controlled</u> combustion.
  - Requires primary sorting to remove non combustibles.
  - Expensive equipment to control temperature/atmosphere and limit residue/trap fumes.
  - Imperfect as incomplete reaction and latent heat of trapped moisture.
- Recycling
  - Upgrades product or recoverable components.
- Reconditioning (re–engineering)
  - Upgrades product or recoverable components.
- Re-use
  - Redistribution of product to a component sector willing to accept it in used state.



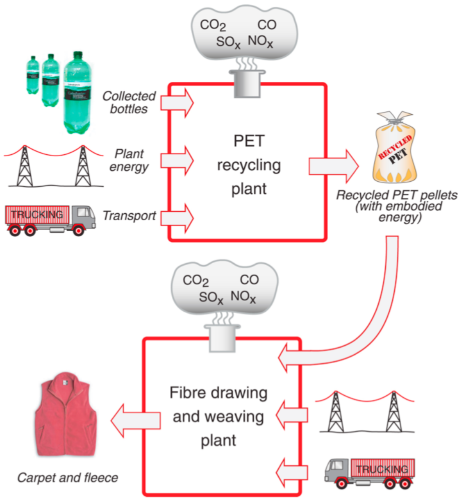
Source: https://www.sustainsuccess.co.uk/wp-content/uploads/2013/08/heirarchy-full.png



End of life options (Materials Section in Mechanical Design, Fig. 14.3)

Recycling: Ideals and Realities

- Why not recycle more often?
- Two types of ‘scrap’
  - in-house (off cuts, ends, below spec. material left in production facility)
  - Post consumer waste (mixed, contaminated, finished)
- Contamination of polymers can make some unusable (PVC in PET)
  - Fit only for ‘down cycling’
  - Recycled PET cannot be used for bottles
- Recycling can be economic (in terms of cash and energy)
  - Particularly for metals, less so for some plastics
- PET (and PP) bottles collected/delivered to recycling plant (mixed)
  - Mixed waste stream must be separated
- Energy absorbing steps in recycling PET
  - Collection, inspection, chopping, washing, flotation-separation, drying, melting, filtration, pelletising, packaging, plant heating/lighting, transport



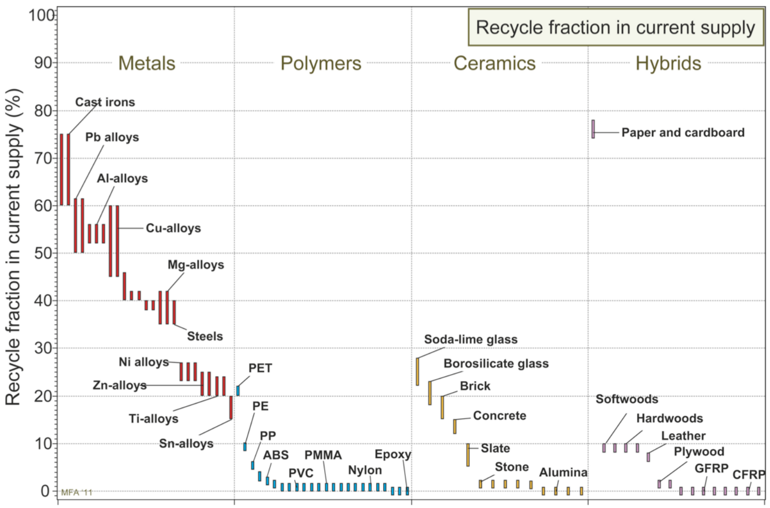
An input-output diagram for PET recycling (see Fig. 20.5)

The Economics of Recycling

- Some energy is saved during PET recycling
  - not a lot, perhaps 50%.
- Recycling of PET can save energy but is it economic?
- Cost of recycling plastics high; value of recyclate low
- Recycle fraction = fraction of recyclate in current supply
- Metals (high)
  - most lead, almost 1/2 steel, 1/3 aluminium used at least once
- Polymers (low)
  - PET most successful (recycle fraction 20%)
  - Other polymers contribution < 15%
  - Thermosets almost zero.
- Oil price inflation/restrictive legislation could change this.

Embodied energy and market price of virgin and recycled polymers (see Tab. 20.3)

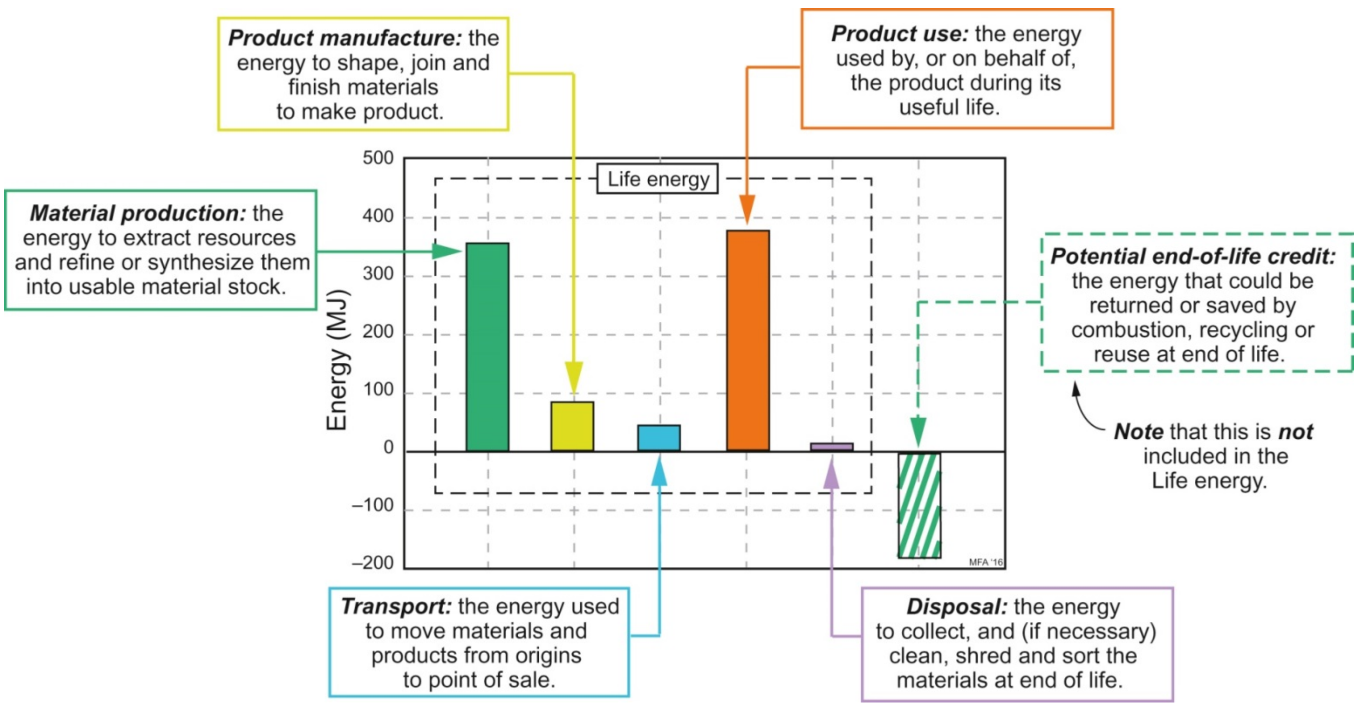
Polymer	H_m (MJ/kg)		Price ($/kg)	
	Virgin	Recycled	Virgin	Recycled
HDPE	82	40	1.9	0.9
PP	82	40	1.8	1.0
PET	85	55	2.0	1.1
PS	101	45	1.5	0.8
PVC	66	37	1.4	0.9



Fractional contribution of recycled material to current consumption (see Fig. 20.6)

Eco-Audits

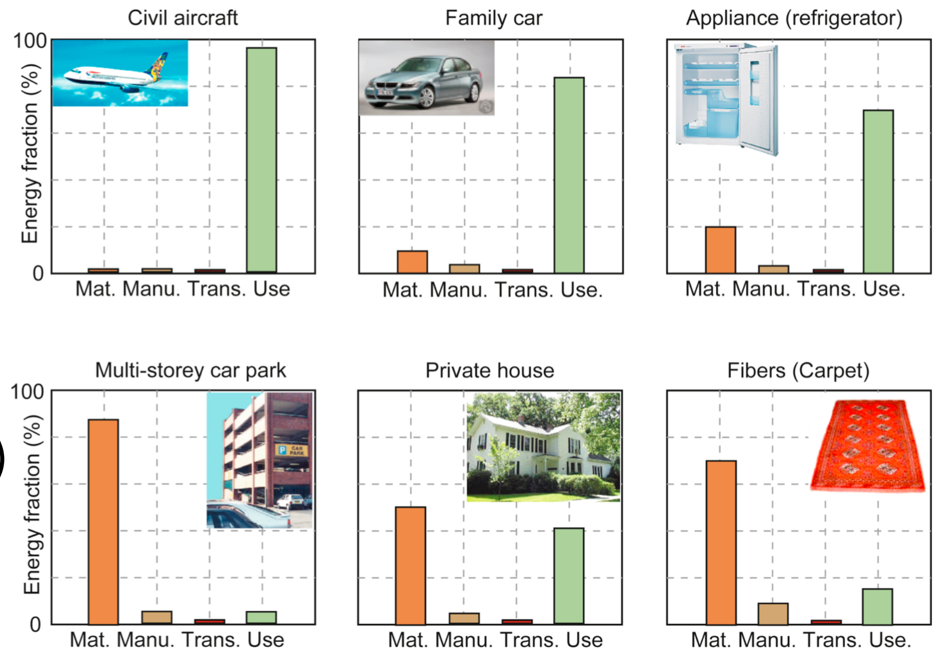
- Consider how products consume energy in each of four phases of life cycle
- Some phases are harder to estimate (*e.g.* product disposal phase)



Output of an eco-audit: energy fingerprint of product
(Ashby: Materials Section in Mechanical Design, Fig. 14.4)

Energy Demands of Products

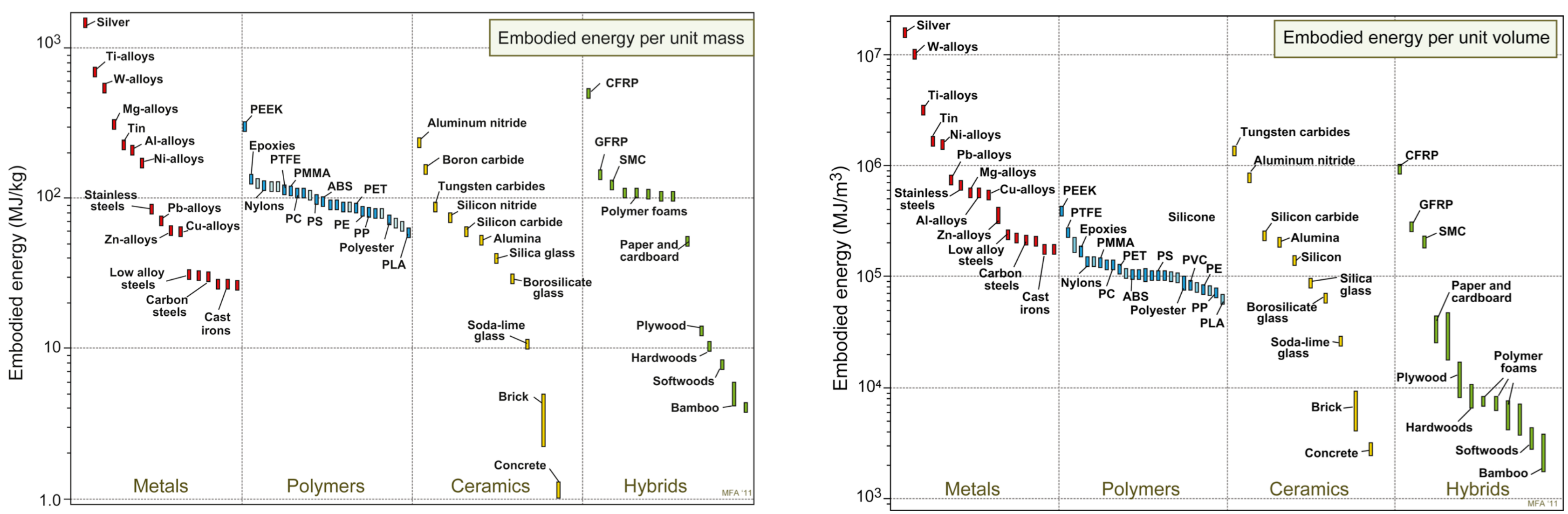
- Tabulate main components of product (with material and weight)
  - Estimate embodied energy (multiply masses by H_m and H_p and sum them)
  - Use energy estimated from power, duty cycle, power source
  - Energy of disposal (difficult to estimate)
  - Transport costs (distance and energy used)
- Products in top row all consume energy during use (dominates life energy)
- Products in bottom row depend less heavily on energy, but material intensive (embodied energy of material dominates)
- To achieve large changes dominant phase must be first target



Energy fingerprints of products (see Fig. 14.5)

Charts for Embodied Energy

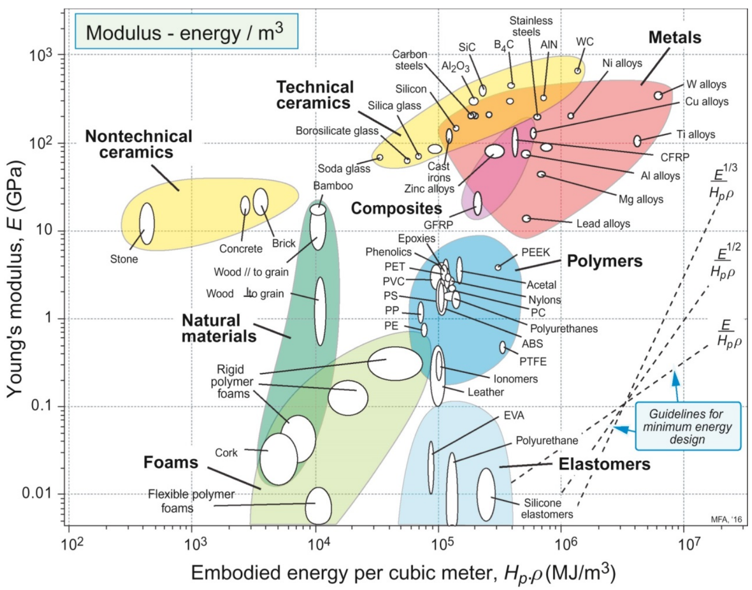
- Compared per unit mass, metals (especially steels) appear attractive (lower energy)
- Compared on a volume basis, ranking changes (polymers lower than metals)
- Light alloys (aluminium, magnesium, titanium) have high energies by either measure
- How to make meaningful comparisons and minimise embodied energy?

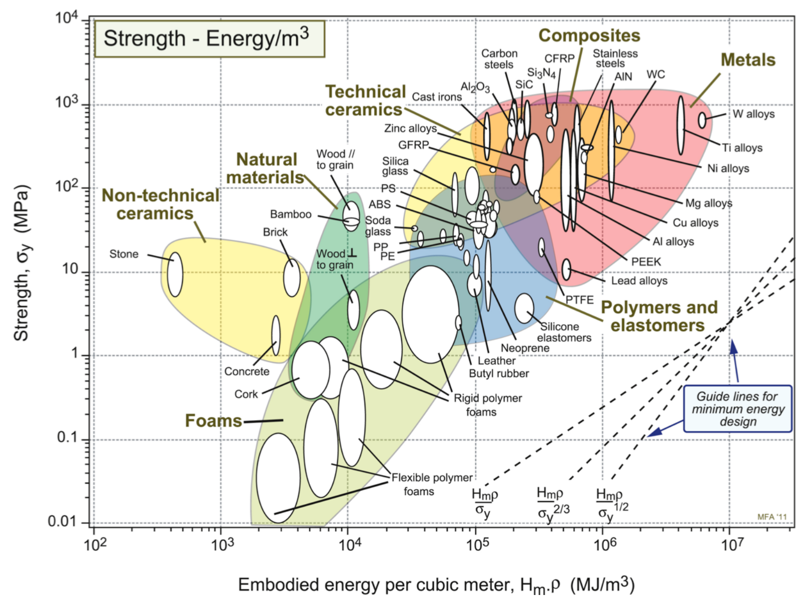


Bar charts of embodied energy of basic materials (see Fig. 20.8, 20.9)

Embodied Energy in Structural Design

- Selection depends on function of design (*e.g.* support load while minimising mass)
- If objective to minimise energy embodied in product and provide structural functionality then need equivalent charts
- Plots of modulus and strength *versus* $H_m.\rho$ (slopes are common performance indices) $(H_m.\rho)/E$, $(H_m.\rho)/E^{1/2}$, $(H_m.\rho)/E^{1/3}$.





Plots of modulus-embodied energy and strength-embodied energy (see Fig. 20.10, 20.11)

Summary

- A materials life cycle comprises production, manufacture, use, and disposal.
- The embodied energy and process energy reflect energy committed to producing and finishing 1 kg of usable material/product.
- The hierarchy of materials disposal options reflects their level of sustainability.
- Cost of recycling, value of recyclate, and cost of crude oil all influence economics of recycling.
- An eco audit determines how products consume energy in each of the four phases of their life cycles.
- Charts of mechanical properties in terms of embodied energy (as a function of mass or volume) allow meaningful comparisons to be made to minimise embodied energy?

Properties of Materials

Theme: Materials and the Environment

Lecture 3: Design – Selecting Materials for Eco-design

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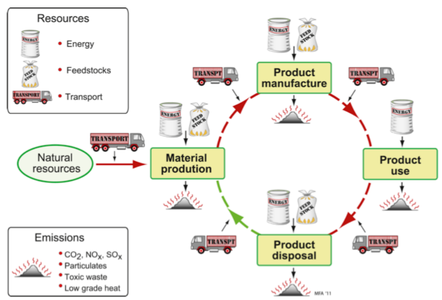
Previously – The Material Life Cycle

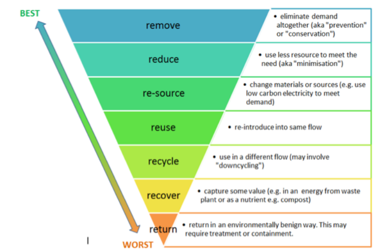
<u>Materials Life cycle</u>

- Different phases
- Energy/mass balances
- LCA



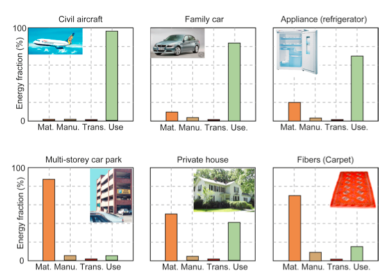
<u>Waste Heirarchy</u>

- 'ecology of materials'
- Preferred options
- Living standards



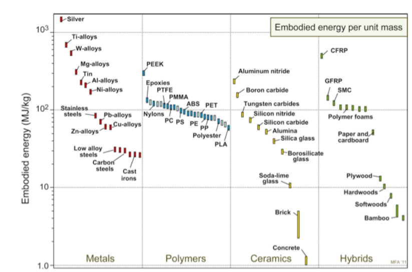
<u>Energy Fingerprints</u>

- Consider all material phases
- Audit energy/material use
- Use results to try and reduce impact



<u>Embodied Energy</u>

- Choose material to minimise embodied energy
- Consider trade offs mechanical properties



Today’s Lecture Contents

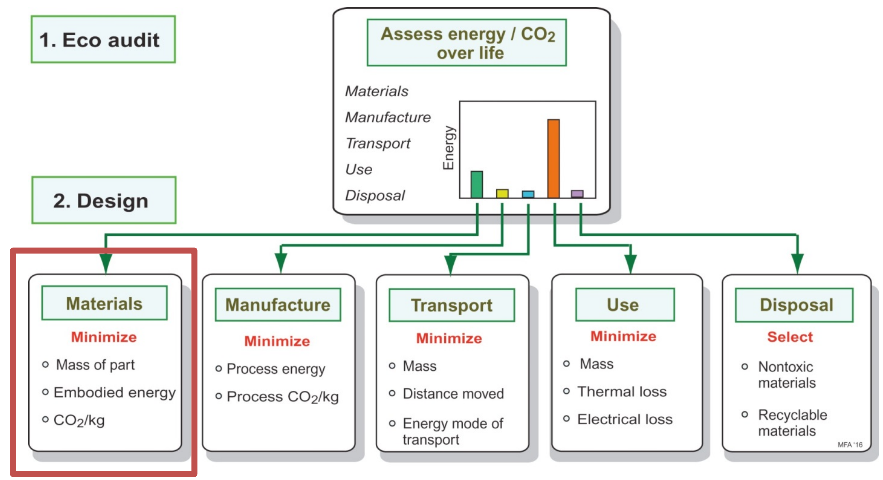
- Eco-audit of different phases of life cycle.
- Case study 1. crash barriers.
- Case study 2. beverage bottles.

Material Production Phase

- If material production consumes more energy than other phases then it becomes first target (e.g. drinks containers – see later).

- Large civil structures (buildings, bridges, roads) are material intensive (embodied energy of materials is largest commitment).

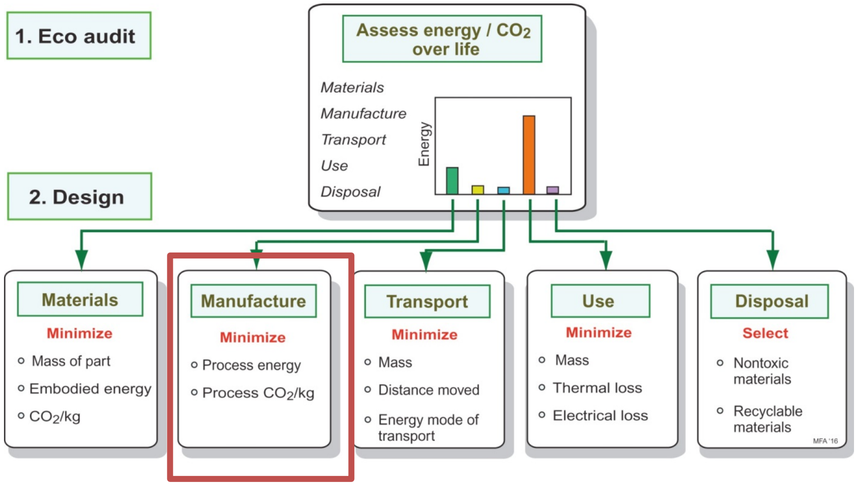
- Architects and civil engineers focus on embodied energy as well as thermal efficiency of structures.



Design for environment (see Fig. 20.12)

Product Manufacture Phase

- Energy required to shape a material usually much less than that to create it originally.
- Important to save energy in production.
- Higher priority often to minimise local impact of emissions or toxic waste.
- Clean manufacture is key.

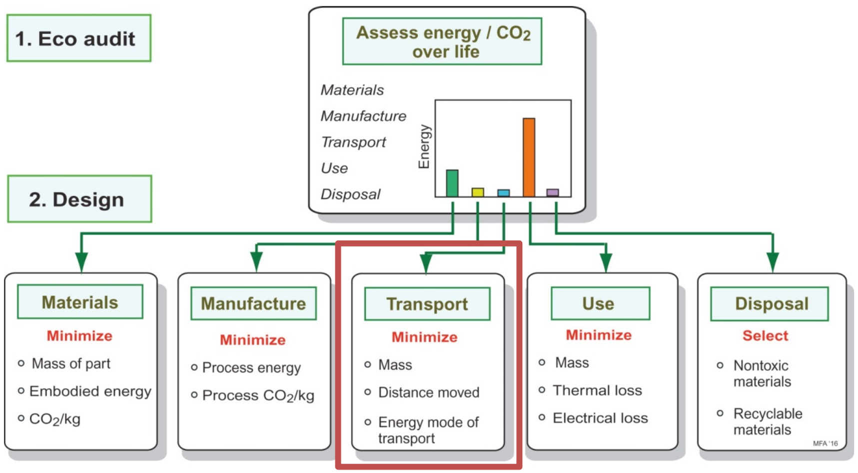


Design for environment (see Fig. 20.12)

Transport

- Energy involved with transportation occurs throughout a manufacturing process.
- Raw materials are transported to factory from source.
- Haulage of additives, chemical feedstocks, packaging.
- Movement of product for assembly, finishing.
- Transportation to distribution centre or retailer.
- Collection for disposal.

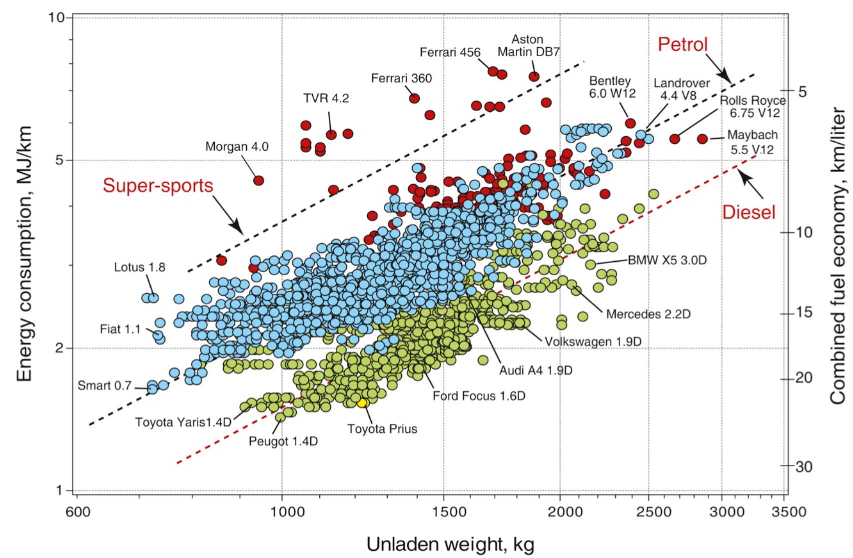
Transport	Energy requirement MJ/tonne-km
Sea freight	0.16
Barge	0.36
Rail freight	0.25
2-axle truck (14t)	1.5
3-axle truck (24t)	1.1
4-axle truck (32t)	0.94
Air freight	6.9-15 (size/type aircraft)



Design for environment (see Fig. 20.12)

Energy Consumption and Fuel Economy

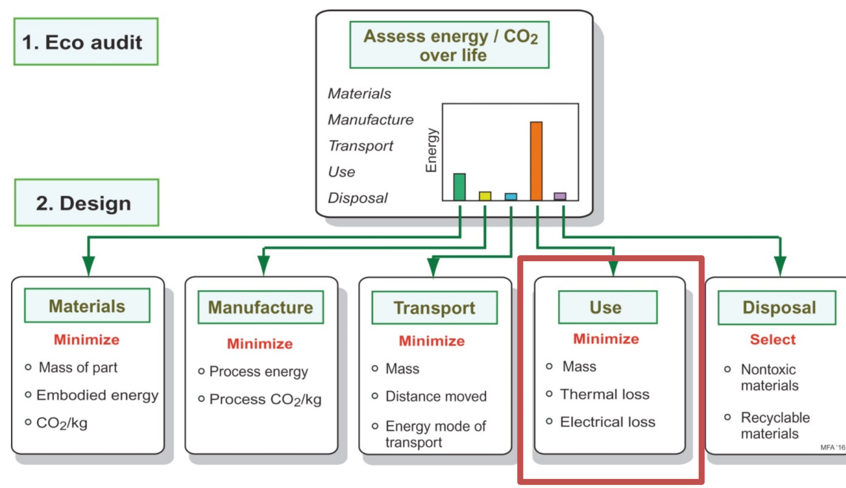
- Fuel efficiency (MJ/km) correlates closely with mass of vehicle.
- Objective becomes minimising mass
- Fuel economy of 4000 European car models (2005 data) compared (unladen mass, engine type).
- Linear correlations (green and blue) are clear.
- Solution is minimum mass design.
- Super-sport, luxury (red symbols) fuel economy not design priority.
- One hybrid included (yellow)



Energy consumption and fuel economy (see Fig. 20.13)

Product Use Phase

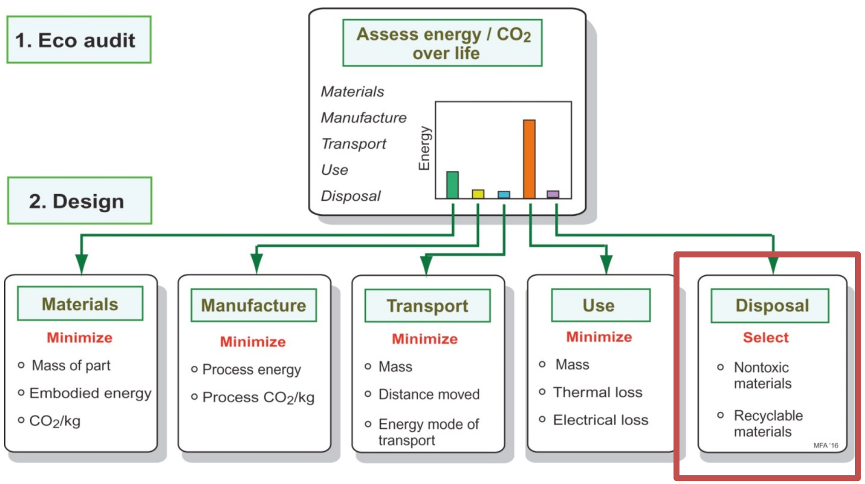
- Eco-impact of use phase of energy-using products unrelated to embodied energy of materials.
- Minimising this may have opposite effect on use energy (depends on mechanical, thermal, electrical efficiencies – which should be maximised).
- Large civil structures (buildings, bridges, roads) are material intensive (embodied energy of materials largest commitment).
- Architects and civil engineers focus on embodied energy as well as thermal efficiency of structures.



Design for environment (see Fig. 20.12)

Product Disposal Phase

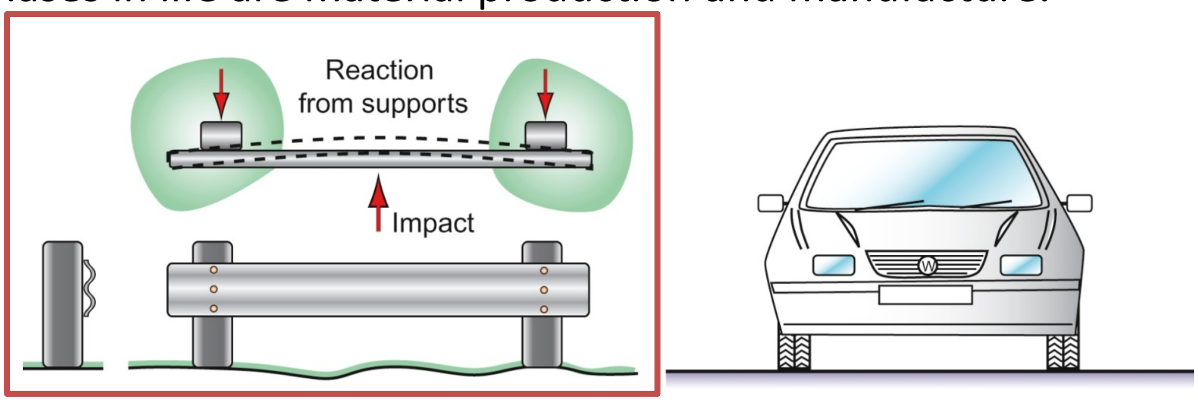
- Environmental consequences of final phase vary, but general considerations:
- Avoid toxic materials (heavy metals, organometallics) – can contaminate soil/groundwater in landfill.
- Consider replacing materials that cannot be recycled.
- Maximise recycling (**hierarchy**) where possible.
- Where recycling impractical, try to recover energy (controlled combustion)
- Consider using bio-/photo-degradable materials (but degrade slowly in landfill).



Design for environment (see Fig. 20.12)

Case Studies – Static Crash Barrier

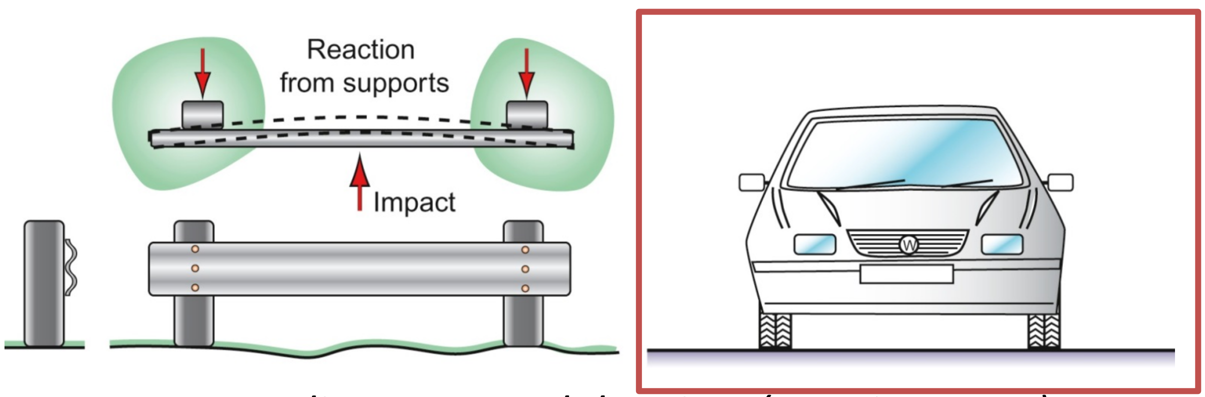
- Barriers protect driver and passengers of road vehicles.
- Two types: static (central barrier separating two lanes) and moveable (vehicle bumper).
- Static type – lines tens of thousands of miles of road.
- Once in place, consume no energy, create no CO_2, long lasting.
- Dominant phases in life are material production and manufacture.



Case studies: two crash barriers (see Fig. 14.10)

Case Studies – Dynamic Crash Barrier

- Mobile barrier (bumper) – part of vehicle,
- Adds to weight, and fuel consumption
- Dominant phase in life is use phase.



Case studies: two crash barriers (see Fig. 14.10)

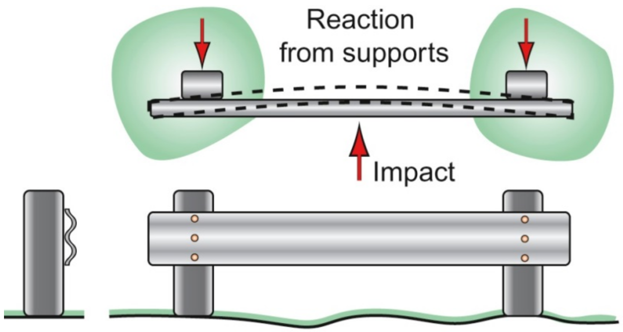
Case Studies – Dynamic Crash Barrier

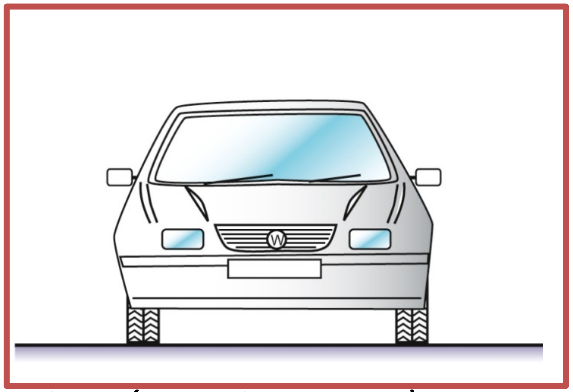
- If eco-design is the objective, criteria for selecting materials for two barriers differ.

- Function of barrier transfers load from point of impact to support structure.

- Either
  - 1. structure collapses, absorbing energy or
  - 2. barrier and supports react against vehicle, energy absorbed in crush elements (designed into vehicle).

- Barrier must have adequate strength (σ_y), ability to be shaped/joined cheaply, and recyclable.

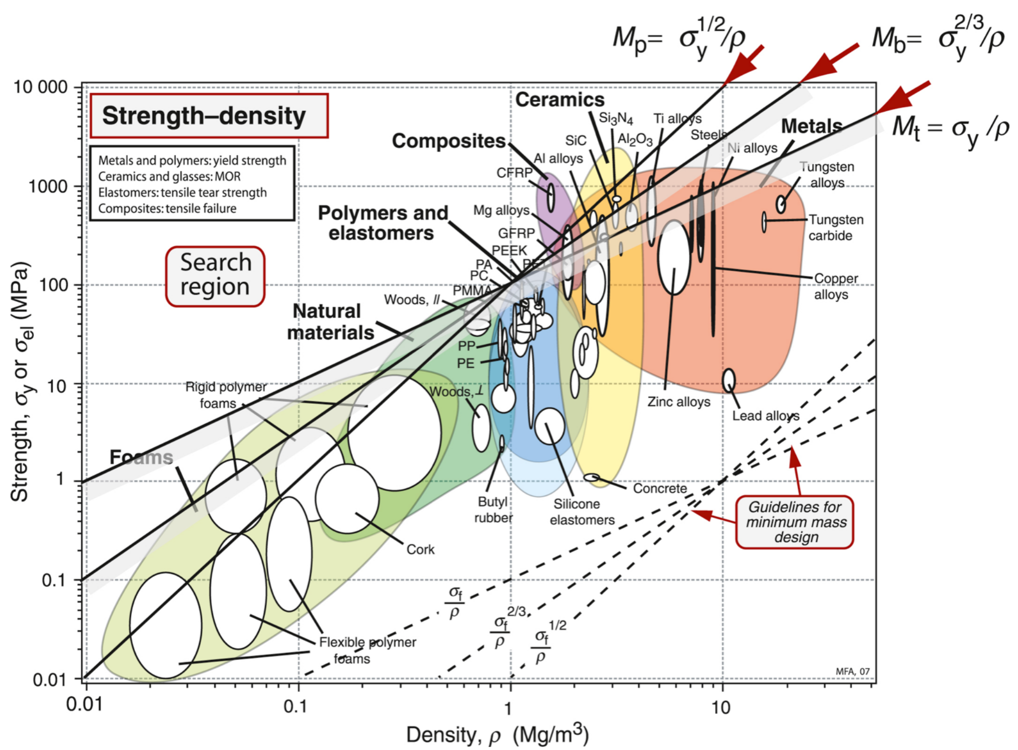




Case studies: two crash barriers (see Fig. 14.10)

Materials Selection for Car Bumper

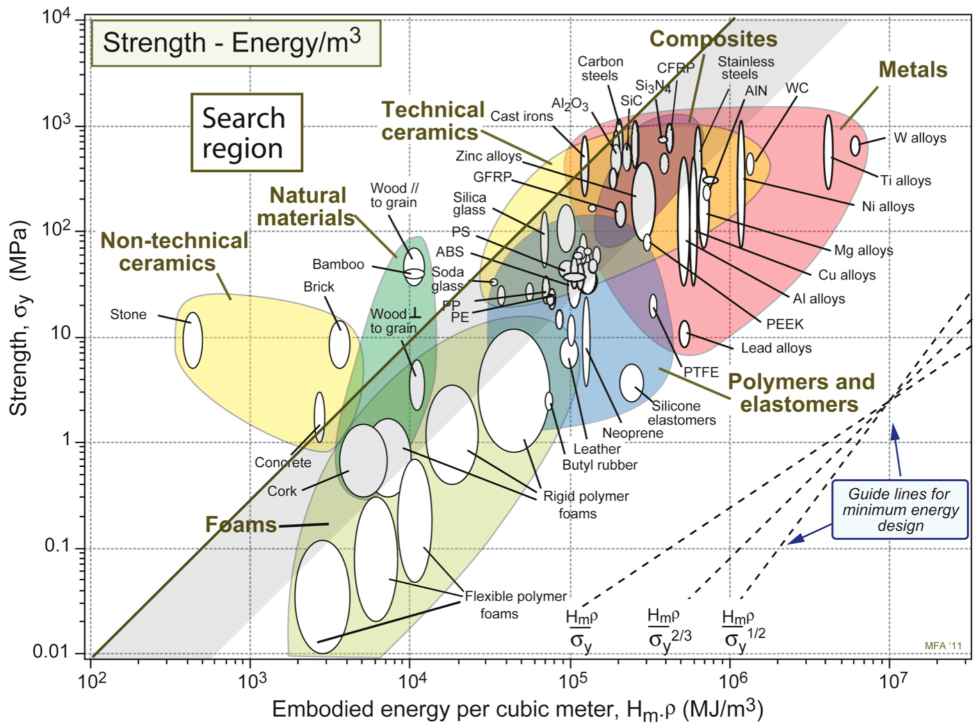
- Material must meet constraints with minimum mass (reduces use energy).
- For strength loaded in bending, materials with high values of index $M_1 = \frac{\sigma_y^{\frac{2}{3}}}{\rho}$
- CFRP leads the way (with suitable choice of matrix).



Strength-density chart with selected indices (see Fig. 7.8)

Materials Selection for Static Barrier

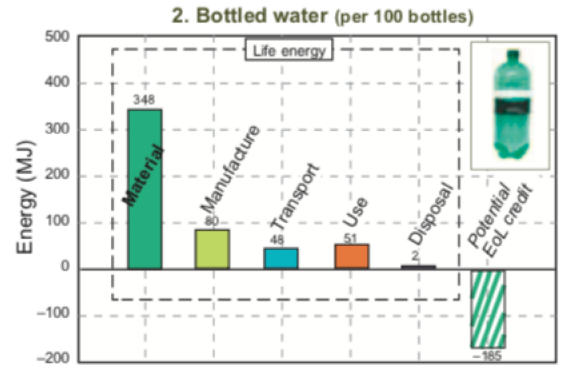
- For static barrier, embodied energy (not weight) is the problem.
- If objective is minimum embodied energy then require materials with $M_2 = \frac{\sigma_y^{\frac{2}{3}}}{H_m \rho}$
- Leaving aside brittle ceramics, H_m minimised using carbon steel, cast iron, wood.

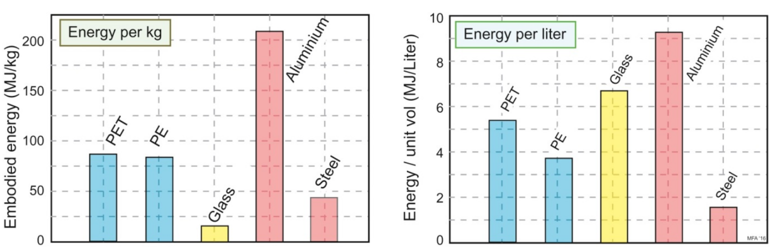


Selection chart for strength with minimum production energy (see Fig. 14.8)

Case Study – Drinks Containers

- Drinks containers consume materials and energy during material extraction, container production (little afterwards)
- Selecting materials with low embodied energy and using less of them would be best way forward.
- Compare glass, PE, PET, aluminium, steel – all can be recycled.
- Which has the lowest energy penalty and carbon footprint?
- Glass has lowest energy per kg, but among highest per litre.





Case studies: liquid containers Materials selection in Mechanical Design (Fig. 14.9)

Case Study – Drinks Containers

- Must take density into account to enable comparisons to be made.
- Steel container has lowest energy penalty per unit volume.
- Aluminium container has highest energy penalty per unit volume.

Container type	Material	Embodied energy (MJ/kg)	Mass (g)	Mass/litre (kg/L)	Energy/Litre (MJ/L)
PET 400 ml bottle	PET	84	25	62	5.4
PET 1 litre milk bottle	HDPE	81	38	38	3.2
Glass 750 ml bottle	Soda glass	15.5	325	433	8.2
Al 440 ml can	5000 series Al alloy	210	20	45	9.0
Steel 440 ml can	Plain carbon steel	32	45	102	**2.4**

Summary

- If material production consumes more energy than other phases then it becomes first target.

- Energy required to shape a material during product manufacture phase usually much less than that to create it originally.

- Energy involved with transportation occurs throughout the life cycle.

- Eco-impact of use phase of energy-using products unrelated to embodied energy of materials.

Properties of Materials

Theme: Materials and the Environment

Lecture 4: Materials and Sustainability (Wind Turbine)

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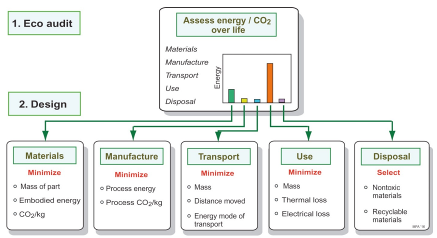
Previously – Materials for Eco-Design

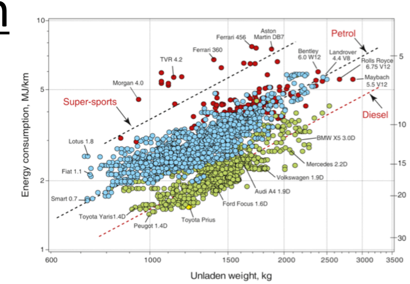
Eco-audit

- Different phases
- Energy/mass balances



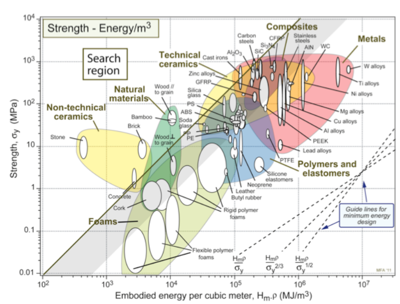
Energy consumption

- Fuel economy & mass related
- Minimum mass design



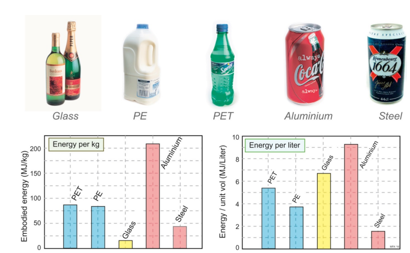
Materials Selection

- Crash barrier and car bumper
- Different selection criteria
- Consider mass for bumper



Exercise

- Choose material to minimise embodied energy
- Consider density to make comparison



Today’s Lecture Contents

- Materials and sustainability.
- The three capitals.
- Sustainable development.
- Sustainability analysis of technology

Offshore Wind Turbines. Source: https://www.carbonbrief.org/five-innovations-that-could-cut-the-cost-of-offshore-wind

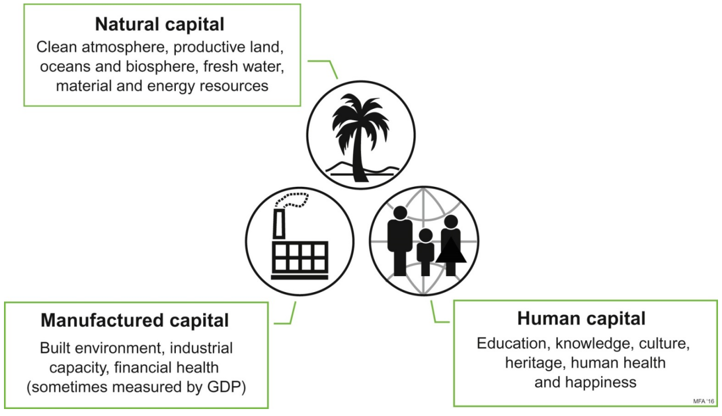
Materials and Sustainability

- 'Sustainable development is development that meets the needs of the present without compromising the ability' Brundtland Report of the World Council on Economic Development, 1987.
- Using accountancy terms - Triple Bottom Line (3BL)
- Corporation's ultimate success and health should be measured not just by financial bottom line, but also social-ethical and environmental performance.
- Balance sheet must include income/outgoings ('prosperity'), environmental ('planet'), social ('people').
- Sustainable business practice requires all three balance columns show positive balances (sweet spot).

Triple Bottom Line or PPP Thinking (see Fig. 20.16)

The Three Capitals

- **Manufactured capital** – industrial capacity, institutions, roads, built environment, financial wealth (GDP).
- **Human capital** – health, education, skills, technical expertise, accumulated knowledge, happiness.
- **Natural capital** – clean atmosphere, fresh water, fertile land, productive oceans, accessible minerals and fossil energy.

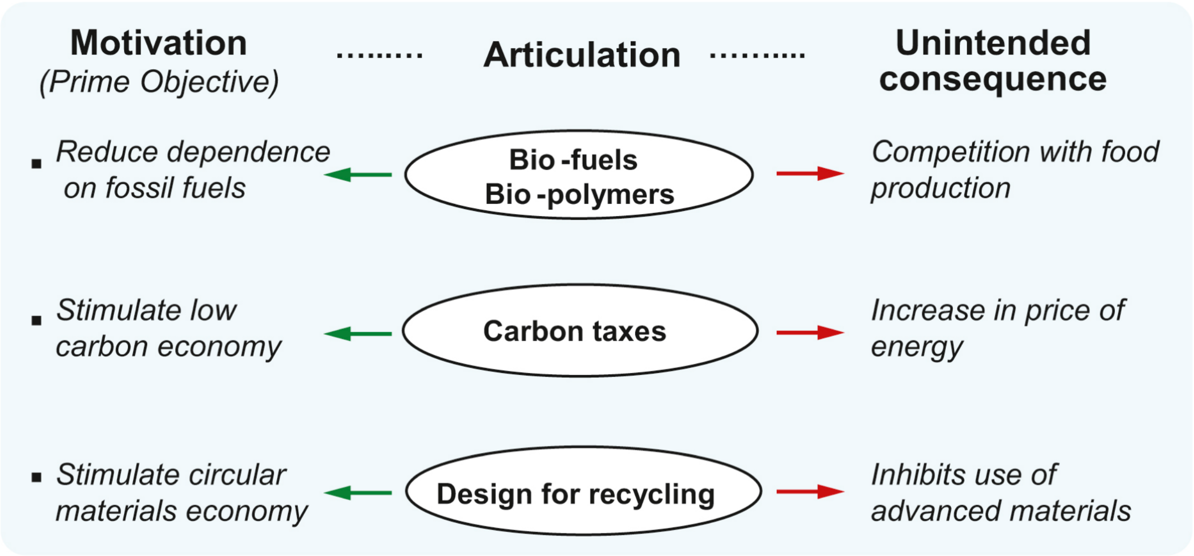


The three capitals (see Fig. 16.7)

- All can be quantified in a common measure (some with difficulty) *e.g.* dollars.
- Sum of all three (net comprehensive capital) measures national or global wealth.
- Assigning precise values difficult, but sign and order of magnitude to change possible.
- Strong sustainability (positive growth in all three capitals), weak sustainability (positive comprehensive capital, even if one diminished).
- Main force driving three capitals is pressure for economic growth.

Competing Articulations

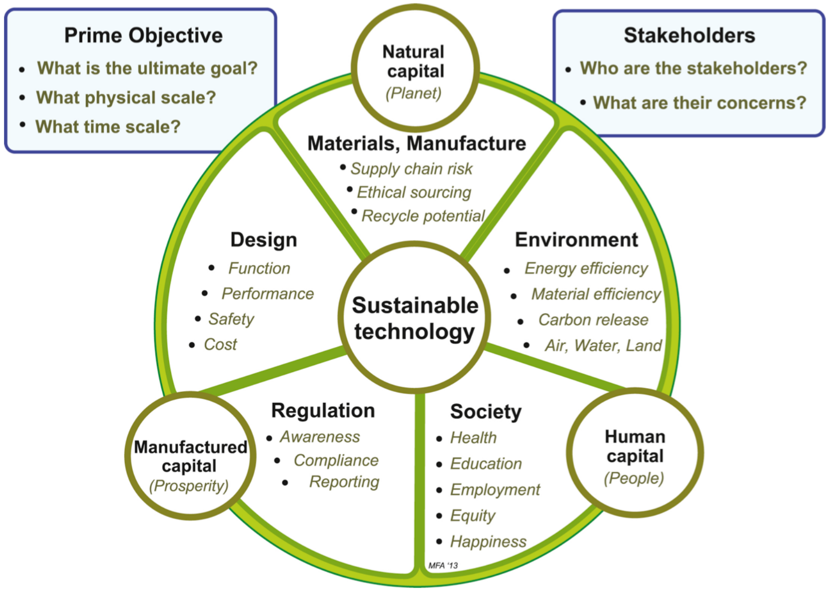
- Sustainable development takes many forms (‘articulations’).
- Each has a particular motivation.
- Unfortunately, almost all are in conflict
  (addressing one facet of a particular problem may aggravate another).



Competing articulations of sustainable technology conflict (see Fig. 20.18)

Sustainable Technology

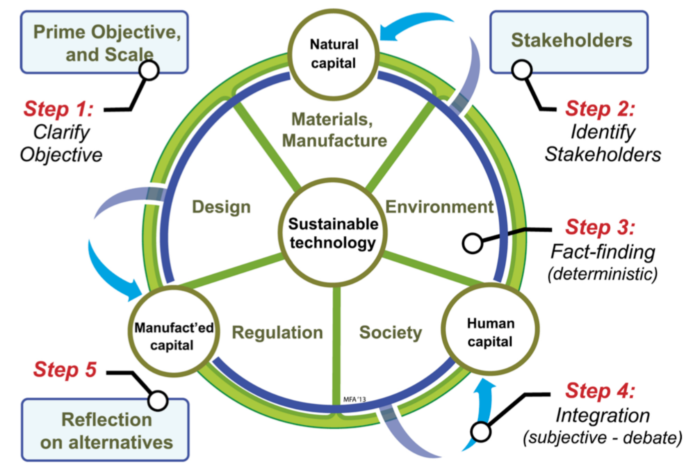
- Checklist for a sustainable technology
- **Materials and Manufacture** – ethical sourcing, supply chain risk, recycle potential.
- **Design** – product function, performance, material selection, safety and cost.
- **Environment** – material efficiency, energy efficiency, bio-efficiency, preserving clean air, water, and land.
- **Regulation** – awareness of, and compliance with, national and international agreements, restrictions, and agreements.
- **Society** – health, education, shelter, employment, equity, happiness.



Necessary components of sustainable technology (see Fig. 20.19)

Assessing Sustainability

- Any articulation of sustainability has underlying motive (Prime Objective) with physical scale and time scale.
- 1. Clarify **objective** – physical scale and time scale.
- 2. Identify **stakeholders** and their concerns.
- 3. **Fact Finding** – factual, objective, conclusions.
- 4. **Integration** – informed debate, form balanced judgement about impacts on three capitals.



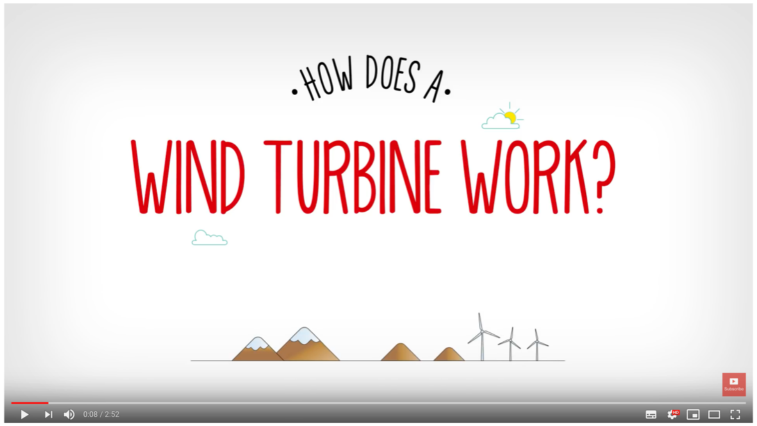
Five-step sustainability analysis of technology (see Fig. 20.21)

- 5. **Reflection** on alternatives – is the prime objective achieved? Does it do so on a scale to make it significant? Do negative impacts on three capitals outweigh the benefits? Have stakeholders' concerns been met? Can analysis suggest, less damaging route?

Case Study: Wind Farms

- Many nations seek to reduce carbon emissions arising from electric power generation (and diversify their electrical power sources).

Wind Turbines



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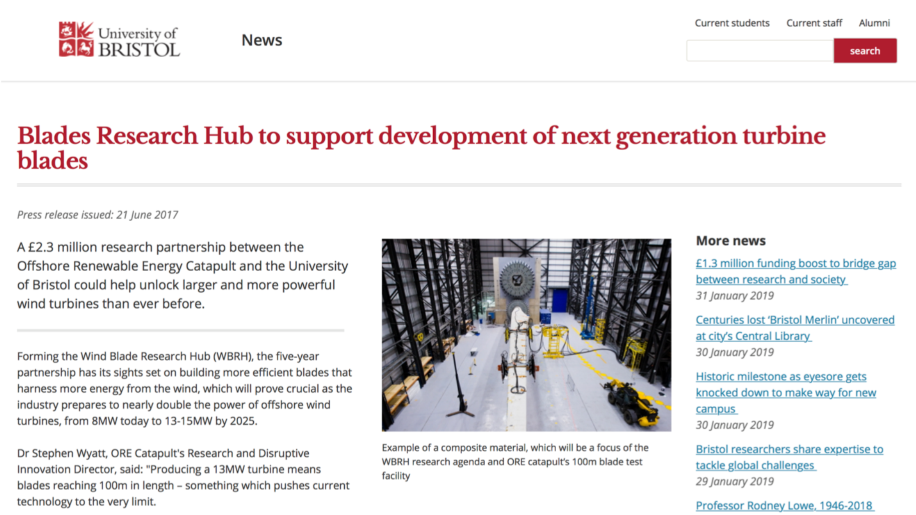
https://www.youtube.com/watch?v=y1g_DTaMDng



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Blades Research Hub to support development of next generation turbine blades

Press release issued: 21 June 2017

A £2.3 million research partnership between the Offshore Renewable Energy Catapult and the University of Bristol could help unlock larger and more powerful wind turbines than ever before.

Forming the Wind Blade Research Hub (WBRH), the five-year partnership has its sights set on building more efficient blades that harness more energy from the wind, which will prove crucial as the industry prepares to nearly double the power of offshore wind turbines, from 8MW today to 13-15MW by 2025.

Dr Stephen Wyatt, ORE Catapult's Research and Disruptive Innovation Director, said: "Producing a 13MW turbine means blades reaching 100m in length – something which pushes current technology to the very limit.

Example of a composite material, which will be a focus of the WBRH research agenda and ORE catapult's 100m blade test facility

More news

£1.3 million funding boost to bridge gap between research and society
31 January 2019

Centuries lost 'Bristol Merlin' uncovered at city's Central Library
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Bristol researchers share expertise to tackle global challenges
29 January 2019

Professor Rodney Lowe, 1946-2018

https://goo.gl/images/izUY5a

Step 1: Prime Objectives and Scale

- Step 1 Prime objectives – reduce national carbon emissions, provide more diverse portfolio of electric power sources.

- To satisfy this objective and make a real difference to emissions, power from wind farms must:

  (a) have lower carbon footprint that conventional power.

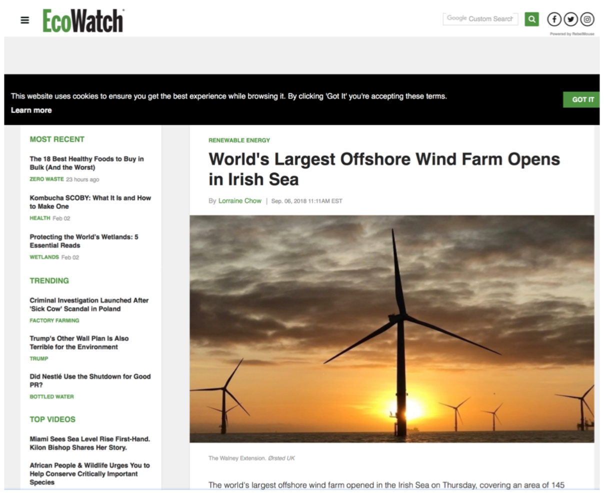
  (b) make a significant (e.g. 20%) contribution to total.

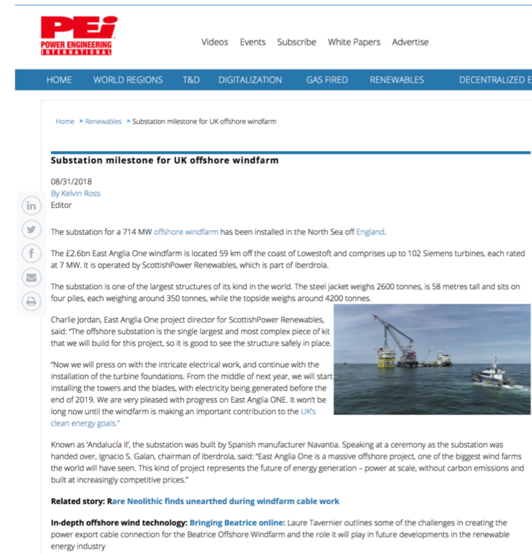
Fuel	Energy content
Coal, lignite	15-19 MJ/kg
Coal, anthracite	31-34 MJ/kg
Oil	11.69 kWh/L = 47.3 MJ/kg
Petrol	35 MJ/L = 45 MJ/kg
Gas	10.42 kWh/m^3
LPG	13.7 kWh/L = 46.5-49.6 MJ/kg

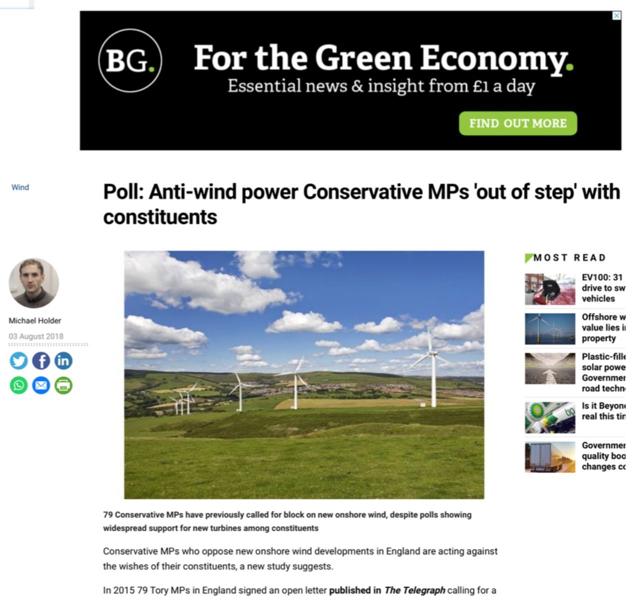
- An appropriate scale of target on desired scale *e.g.* currently 50,000 new units/year.

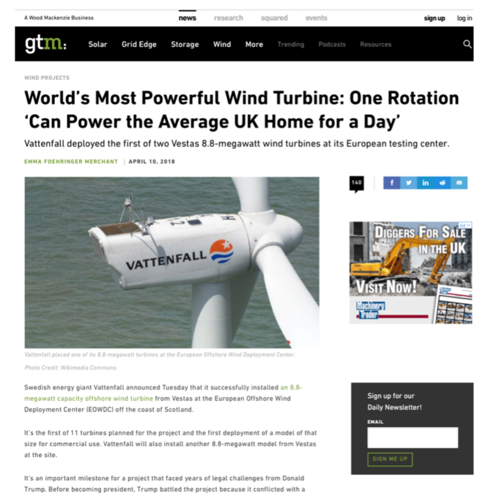
Step 2: Stakeholders and Concerns

- National press reports initiatives to promote windfarms and the reactions these provoke.









Step 2: Stakeholders and Concerns

- Stakeholders need to be heard, reassured, persuaded, or compensated if large-scale windfarms are to be sustainable.

- **National and Local Government** – nations impose taxes on carbon emissions and subsidise renewable energy projects to encourage construction (which creates jobs).

- **Energy providers** – electricity generation from fossil fuels releases carbon to atmosphere. Carbon taxes or carbon-trading schemes and carbon penalties create financial incentives for energy providers to reduce use of fossil fuels.

- **Wind turbine makers** – developing a manufacturing base for wind turbines requires considerable investment.

- Turbine makers want assurances that

  – government policy on renewable energy is consistent and transparent and will not suddenly be withdrawn.
  – Supply chain for essential materials is secure.

Step 2: Stakeholders and Concerns

- **Local communities** – Opposition to land-based turbines in some communities where turbines are audible and visible.
  Even off-shore wind forms objectionable to some.

- Feed-in tariffs for small scale generation and compensation aim to make turbines more acceptable.

- **The public at large** – Opinion divided (some see turbines as necessary and beautiful; other object as power generation is intermittent and expensive, turbines are visually and acoustically intrusive and harmful to wildlife.

Wind Farms: Step 3 (Fact Finding)

- **Materials and manufacture** – Wind turbine generators use neodymium-boron rare-earth permanent magnets.

- 25g Nd in each turbine, annual construction (50,000) new turbines/year requires 1,250 tonnes Nd per year (6% current global production).

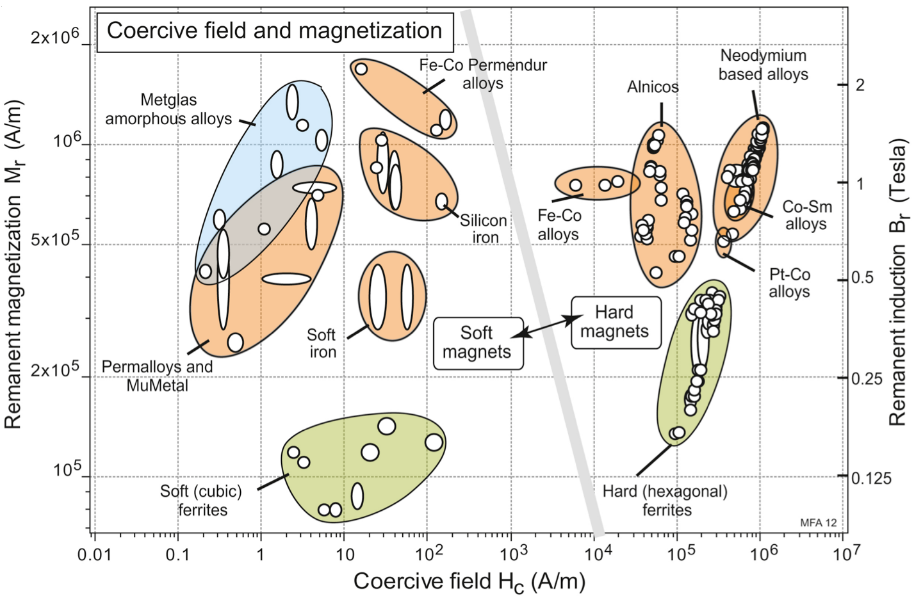
- 95% of annual global production of Nd is derived from one nation: China.

Nd-B magnets	Weight %
*Neodymium (Nd)	30
Iron (Fe)	66
Boron (B)	1
Aluminium (Al)	0.3
*Niobium (Nb)	0.7
*Dysprosium	2

Rare-earth source	Tonnes/year
China	130,000
India	3,000
Brazil	550
Malaysia	30
World	133,580

Wind Farms: Step 3 (Fact Finding)

- **Design -** Permanent magnets for electric turbines require high remnant induction with high coercive force.
- Neodymium-based magnets have largest values for this pair of properties.
- Next best choice AlNiCo magnets.
- No obvious substitute.



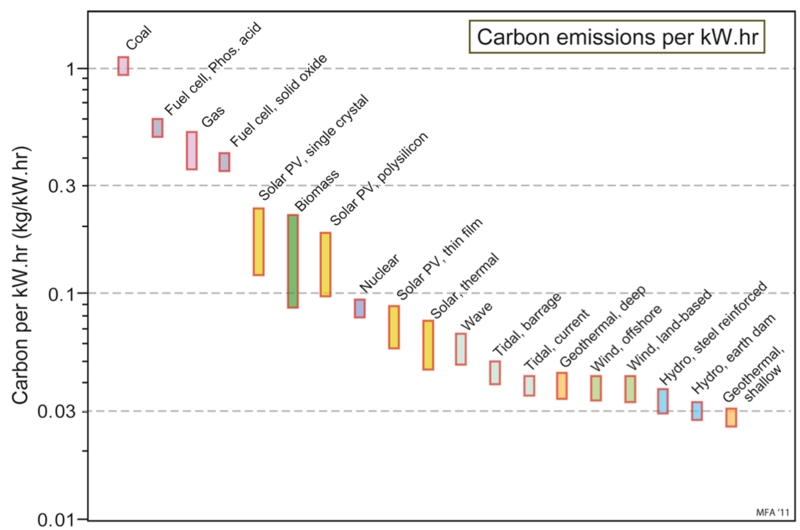
Remnant magnetisation and coercive force (see Fig. 15.8)

Wind Farms: Step 3 (Fact Finding)

- **Environment** - Primary objective is that power from wind farms must have lower carbon footprint that conventional power.

- Meets objective only if carbon emissions associated with construction offset by low carbon emissions during life so net emissions per kW.hr

- Data approximate, but can establish that wind power may achieve objective over life.



Carbon footprint per kW.hr of electrical power sources (see Fig. 20.21)

Wind Farms: Step 3 (Fact Finding)

- **Regulation** – Relevant legislation relating to renewable energy and carbon emissions.

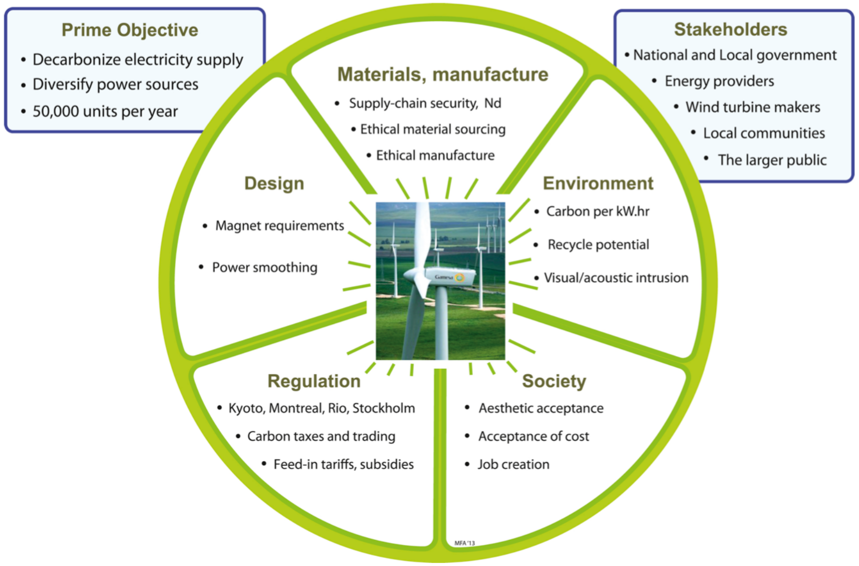
- Making and installing wind farms made financially attractive by ‘green’ subsidies and feed-in tariffs.

- However, changes to initiatives at short notice make market unpredictable.

Relevant Regulation and Legislation
Carbon off-setting
Carbon tax
Carbon trading
Energy-Efficient Buildings Directive
Feed-in Tariffs
U.S. Business Investment Tax Credit
U.S. Recovery Act 1603 Programme

Wind Farms: Step 3 (Fact Finding)

- **Society** – Manufacture of wind turbines creates jobs (positive).
- Without subsidies, electricity from wind farms is more expensive than from gas-fired power stations (cost passed on to industrial and domestic customers and, *via* subsidies, to taxpayers).
- Per unit of generating power, wind farms require land area almost 1000x gas-fired power station.
- If New York state (19.5 million) relied solely on wind power (33 kW.hr per day or 1.4 kW per person), wind farms would cover 131,255 km^2 (21% of area of entire state)



Fact-finding for wind farms (see Fig. 20.22)

Summary

- ‘Sustainable development is development that meets the needs of the present without compromising the ability’ Brundtland Report of the World Council on Economic Development, 1987.

- Three capitals are Manufactured capital, Human capital, and Natural capital. All can be quantified in a common measure (some with difficulty) and sum of all three (net comprehensive capital) measures national or global wealth.

- Sustainable development takes many forms (‘articulations’) and each has a particular motivation. Addressing one facet of a particular problem may aggravate another.

- Assessing sustainable technology is based on five steps:

- 1. Clarify objective, 2. Identify stakeholders and their concerns, 3. Find facts, 4. Have informed debate, 5. Reflect on alternatives.