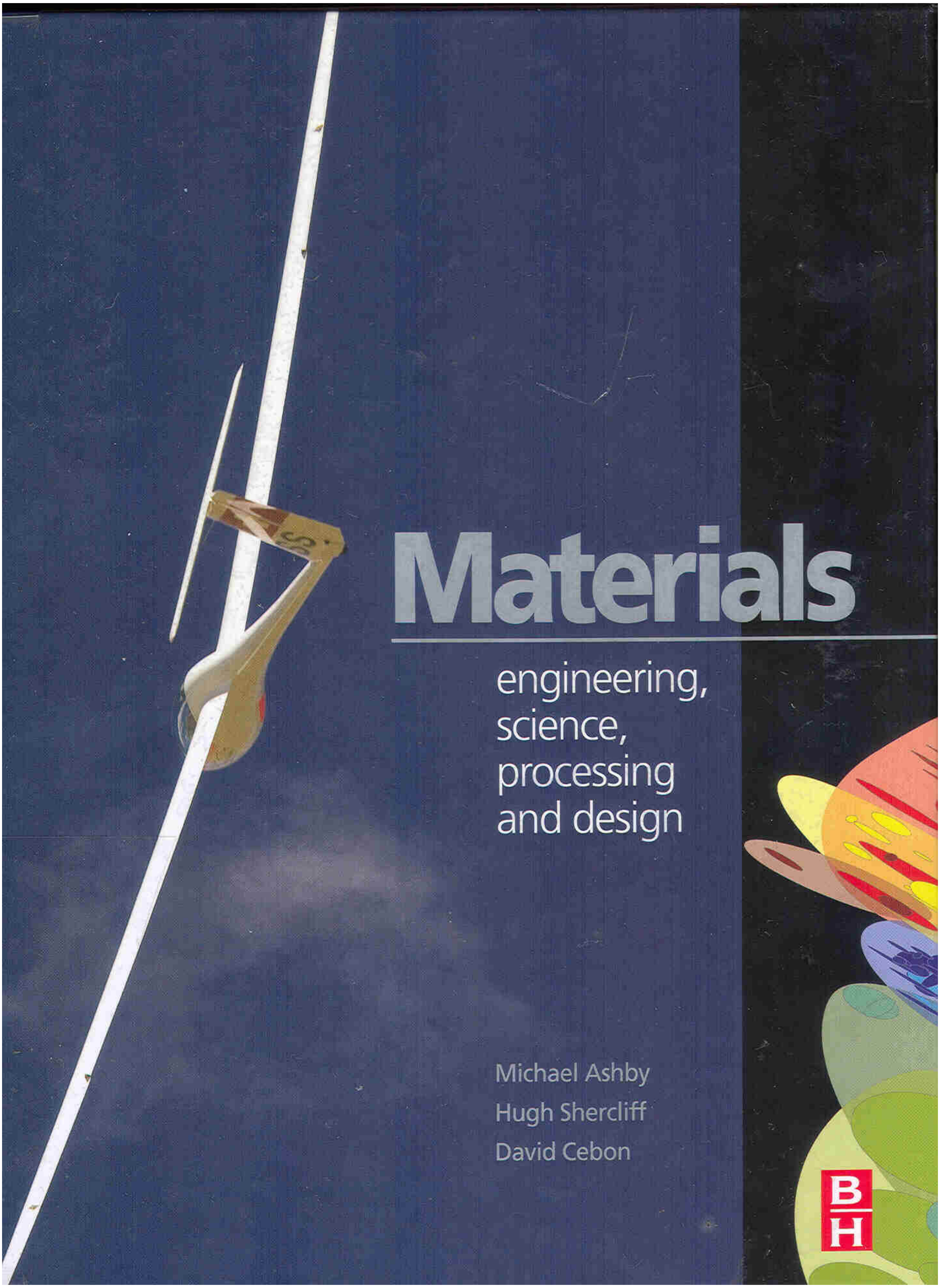
Materials
engineering, science, processing and design
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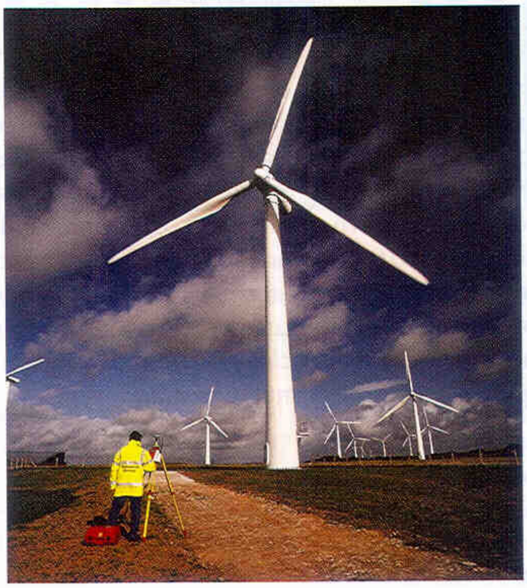
Chapter 20
Materials, processes and the environment



Power from the wind. (Image courtesy of Leica Geosystems, Switzerland.)

Chapter contents

20.1 Introduction and synopsis

The practice of engineering consumes vast quantities of materials and is dependent on a continuous supply of them. We start by surveying this consumption, emphasizing the materials used in the greatest quantities. Increasing population and living standards cause this consumption rate to grow—something it cannot do forever. Finding ways to use materials more efficiently is a prerequisite for a sustainable future.

There is a more immediate problem: present-day material usage already imposes stress on the environment in which we live. The environment has some capacity to cope with this, so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities exceed this threshold with increasing frequency, diminishing the quality of the world in which we now live and threatening the well-being of future generations. *Design for the environment* is generally interpreted as the effort to adjust our present product design efforts to correct known, measurable, environmental degradation; the time-scale of this thinking is 10 years or so, an average product's expected life. *Design for sustainability* is the longer-term view: that of adaptation to a lifestyle that meets present needs without compromising the needs of future generations. The time-scale here is less clear—it is measured in decades or centuries—and the adaptation required is much greater.

20.2 Material consumption and its growth

Material consumption

Speaking globally, we consume roughly 10 billion (10^{10}) tonnes of engineering materials per year. Figure 20.1 gives a perspective: it is a bar chart of the consumption of the materials used in the greatest quantities. It has some interesting messages. On the extreme left, for calibration, are hydrocarbon fuels—oil and coal—of which we currently consume a colossal 9 billion tonnes per year. Next, moving to the right, are metals. The scale is logarithmic, making it appear that the consumption of steel (the first metal) is only a little greater than that of aluminum (the next); in reality, the consumption of steel exceeds, by a factor of 10, that of all other metals combined. Steel may lack the high-tech image that attaches to materials like titanium, carbon-fiber reinforced composites and (most recently) nanomaterials, but make no mistake, its versatility, strength, toughness, low cost and wide availability are unmatched.

Polymers come next: 50 years ago their consumption was tiny; today the combined consumption of commodity polymers polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP) and polyethylene-terephthalate (PET) begins to approach that of steel.

The really big ones, though, are the materials of the construction industry. Steel is one of these, but the consumption of wood for construction purposes

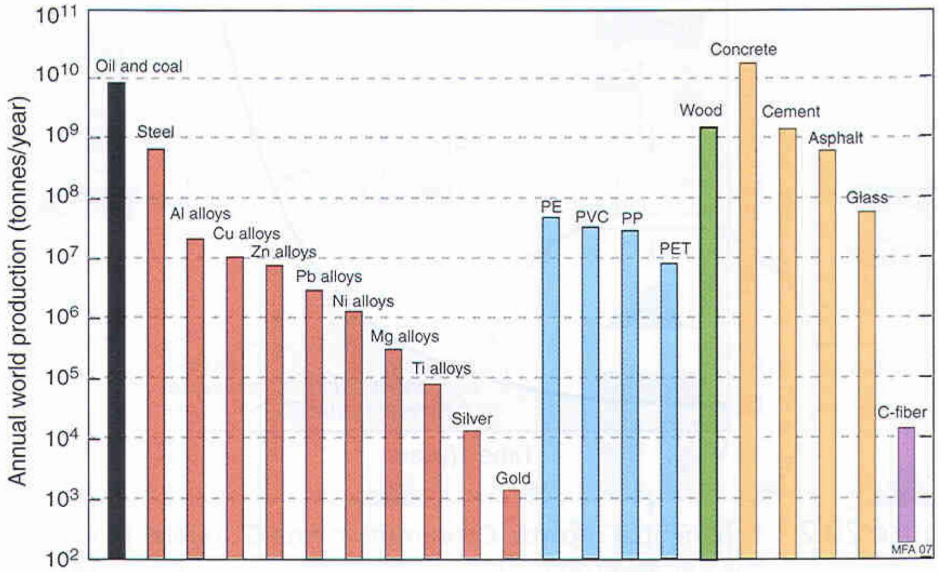


Figure 20.1 The consumption of hydrocarbons (left-hand column) and of engineering materials (the other columns).

exceeds that of steel even when measured in tonnes per year (as in the diagram), and since it is a factor of 10 lighter, if measured in m^3/year, wood totally eclipses steel. Bigger still is the consumption of concrete, which exceeds that of all other materials combined. The other big ones are asphalt (roads) and glass.

The last column of all illustrates things to come: it shows today's consumption of carbon fiber. Just 20 years ago this material would not have crept onto the bottom of this chart. Today its consumption is approaching that of titanium and is growing fast.

The columns in this figure describe broad classes of materials, so—out of the 160 000 materials now available—they probably include 99.9% of all consumption when measured in tonnes. This is important when we come to consider the impact of materials on the environment, since impact scales with consumption.

The growth of consumption

Most materials are being consumed at a rate that is growing exponentially with time (Figure 20.2), simply because both population and living standards grow exponentially. One consequence of this is dramatized by the following statement: 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 (see Exercises). If the current rate of consumption in tonnes per year is C then exponential growth means that

$$\frac{dC}{dt} = \frac{r}{100} C \qquad (20.1)$$

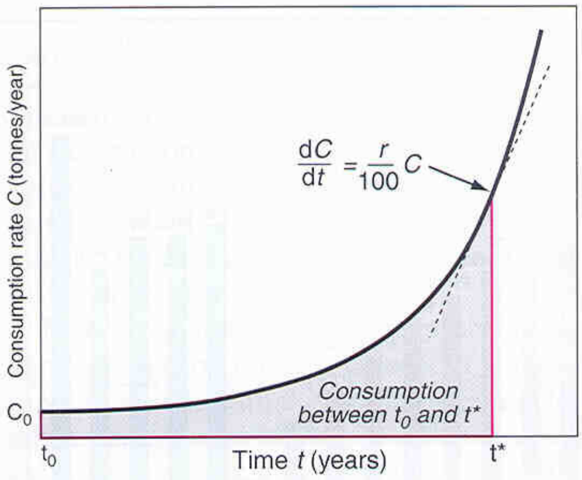


Figure 20.2 Exponential growth. Consumption rate C doubles in a time $t_d \approx 70/r$, where r is the annual growth rate.

where, for the generally small growth rates we deal with here (1–5% per year), r can be thought of as the percentage fractional rate of growth per year. Integrating over time gives

$$C = C_0 \exp\left\{\frac{r(t - t_0)}{100}\right\} \tag{20.2}$$

where C_0 is the consumption rate at time $t = t_0$. The *doubling time* t_D of consumption rate is given by setting $C/C_0 = 2$ to give

$$t_D = \frac{100}{r}\log_e(2) \approx \frac{70}{r} \tag{20.3}$$

After a period of stagnation, steel consumption is growing again, driven by growth in China; at 4% per year it doubles about every 18 years. Polymer consumption is rising at about 5% per year—it doubles every 14 years. During times of boom—the 1960s and 1970s, for instance—polymer production increased much faster than this, peaking at 18% per year (it doubled every 4 years).

The picture, then, is one of a global economy ever more dependent on a supply of materials, almost all drawn from non-renewable resources. To manage these in a sustainable way requires an understanding of the material life cycle. We turn to this next.

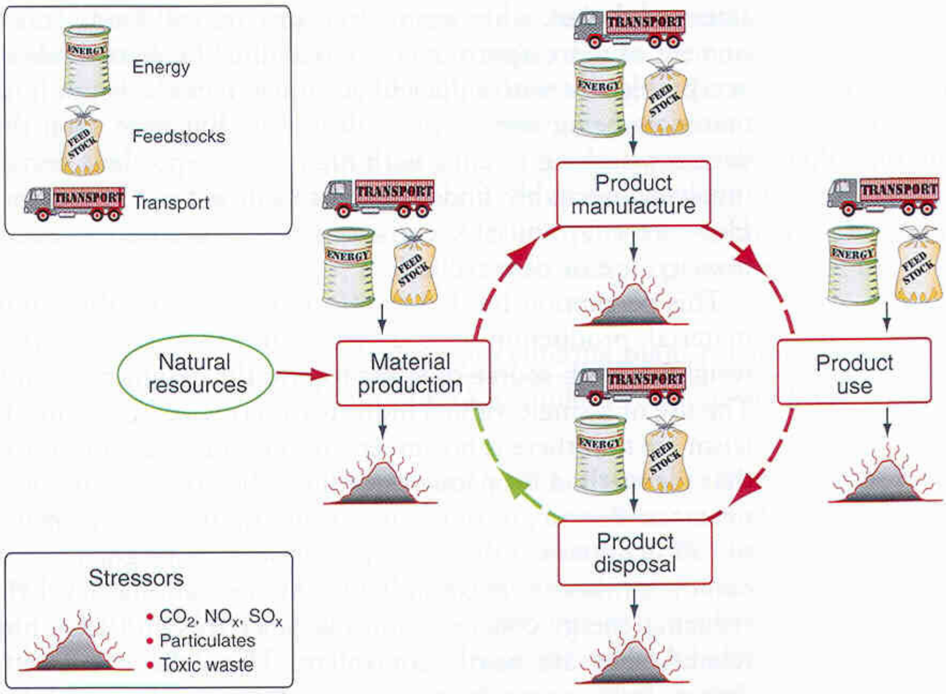


Figure 20.3 The material life cycle. Ore and feedstock are mined and processed to yield a material. This is manufactured into a product that is used and, at the end of its life, discarded or recycled. Energy and materials are consumed in each phase, generating waste heat and solid, liquid and gaseous emissions.

20.3 The material life cycle and criteria for assessment

Life-cycle assessment and energy

The materials life cycle is sketched in Figure 20.3. Ore and feedstock, drawn from the earth's resources, are processed to give materials; these are manufactured into products that are used and, at the end of their lives, discarded, a fraction perhaps entering a recycling loop, the rest committed to incineration or landfill. Energy and materials are consumed at each point in this cycle (we shall call them 'phases'), with an associated penalty of CO_2, SO_x, NO_x and other emissions—heat, and gaseous, liquid and solid waste, collectively called environmental '*stressors*'. These are assessed by the technique of *life-cycle analysis* (LCA). A rigorous LCA examines the life cycle of a product and assesses in detail the eco-impact created by one or more of its phases of life, cataloging and quantifying the stressors. This requires information for the life history of the product at a level of precision that is only available after the product has been manufactured and used. It is a tool for the evaluation and comparison of existing products, rather than one that guides the design of those that are new. A full LCA is time-consuming and expensive, and it cannot cope with the problem that 80% of the environmental burden of a product is determined in the early stages of design, when many decisions are still fluid. This has led to the development of more approximate 'streamline' LCA methods that seek to combine acceptable cost with sufficient accuracy to guide decision-making, the choice of materials being one of these decisions. But even then there is a problem: a designer, seeking to cope with many interdependent decisions that any design involves, inevitably finds it hard to know how best to use data of this type. How are CO_2 and SO_x emissions to be balanced against resource depletion, toxicity or ease of recycling?

This perception has led to efforts to condense the eco-information about a material production into a single measure or *indicator*, normalizing and weighting each source of stress to give the designer a simple, numeric ranking. The use of a single-valued indicator is criticized by some. The grounds for criticism are that there is no agreement on normalization or weighting factors, and that the method is opaque since the indicator value has no simple physical significance. But on one point there is international agreement: the Kyoto Protocol of 1997 committed the developed nations that signed it to progressively reduce carbon emissions, meaning CO_2. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related, they are nearly equivalent. Thus, there is a certain logic in basing design decisions on energy consumption or CO_2 generation; they carry more conviction than the use of a more obscure indicator. We shall follow this route, using energy as our measure. Before doing this, some definitions.

20.4 Definitions and measurement: embodied energy, process energy and end of life potential

Embodied energy H_m and CO_2 footprint

The *embodied energy* of a material is the energy that must be committed to create 1 kg of usable material—1 kg of steel stock, or of PET pellets, or of cement powder, for example—measured in MJ/kg. The CO_2 *footprint* is the associated release of CO_2, in kg/kg. It is tempting to try to estimate embodied energy via the thermodynamics of the processes involved—extracting aluminum from its oxide, for instance, requires the provision of the free energy of oxidation to liberate it. This much energy must be provided, it is true, but it is only the beginning. The thermodynamic efficiencies of processes are low, seldom reaching 50%. Only part of the output is usable—the scrap fraction ranges from a few percent to more than 10%. The feedstocks used in the extraction or production themselves carry embodied energy. Transport is involved. The production plant itself has to be lit, heated and serviced. And if it is a dedicated plant, one that is built for the sole purpose of making the material or product, there is an 'energy mortgage'—the energy consumed in building the plant in the first place.

Embodied energies are more properly assessed by *input–output analysis*. For example, for a material such as ingot iron, cement powder or PET granules, the embodied energy/kg is found by monitoring over a fixed period of time the total energy input to the production plant (including that smuggled in, so to speak, as embodied energy of feedstock) and dividing this by the quantity of usable material shipped out of the plant. The upper part of Figure 20.4 shows, much simplified, the inputs to a PET production facility: oil derivatives such as naphtha and other feedstock, direct power (which, if electric, is generated with a production efficiency of about 34%), and the energy of transporting the feedstock to the facility. The plant has an hourly output of usable PET granules. The embodied energy of the PET, $(H_m)_{PET}$, with usual units of MJ/kg, is then given by

$$(H_m)_{PET} = \frac{\sum \text{Energies entering plant per hour}}{\text{Mass of PET granules produced per hour}}$$

The *processing energy* H_p associated with a material is the energy, in MJ, used to shape, join and finish 1 kg of the material to create a component or product. Thus polymers, typically, are molded or extruded; metals are cast, forged or machined; ceramics are shaped by powder methods. A characteristic energy per kg is associated with each of these. Continuing with the PET example, the granules now become the input (after transportation) to a facility for blow-molding PET bottles for water, as shown in the lower part of Figure 20.4. There is no

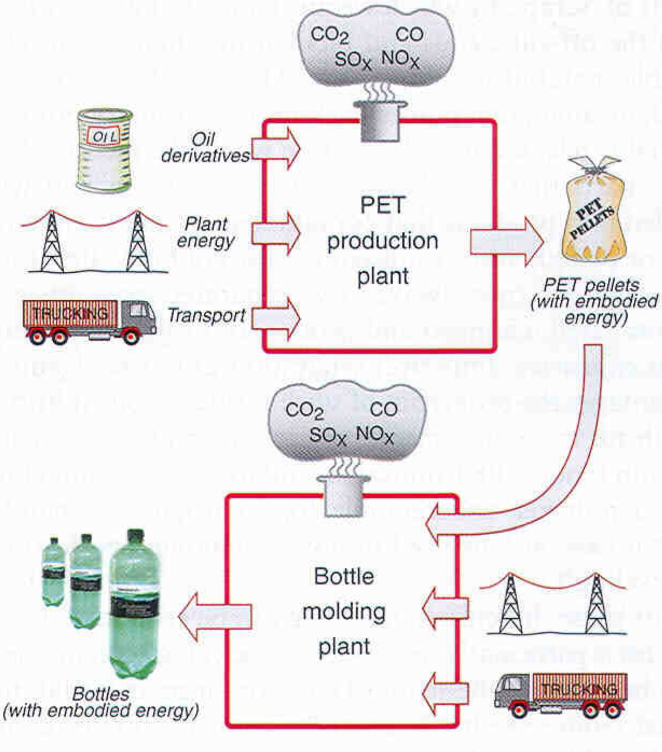


Figure 20.4 An input–output diagram for PET production (giving the embodied energy/kg of PET) and for bottle production (giving the embodied energy/bottle).

need to list the inputs again—they are broadly the same, the PET itself bringing with it its embodied energy $(H_m)_{PET}$. The output of the analysis is the energy committed per bottle produced.

There are many more steps before the bottle reaches a consumer and is drunk: collection, filtration and monitoring of the water, transportation of water and bottles to bottling plant, labeling, delivery to central warehouse, distribution to retailers and refrigeration prior to sale. All have energy inputs, which, when totalled, give the energy cost of as simple a thing as a plastic bottle of cold water.

The *end-of-life potential* summarizes the possible utility of the material at life's end: the ability to be recycled back into the product from which it came, the lesser ability to be down-cycled into a lower-grade application, the ability to be biodegraded into usable compost, the ability to yield energy by controlled combustion and, failing all of these, the ability to be buried as landfill without contaminating the surrounding land then or in the future.

Recycling: ideals and realities

We buy, use and discard paper, packaging, cans, bottles, television sets, computers, furniture, tires, cars, even buildings. Why not retrieve the materials they contain and use them again? What could be simpler?

If you think that, think again. First, some facts. There are (simplifying again) two sorts of 'scrap', by which we mean material with recycle potential. In-house scrap is the off-cuts, ends and bits left in a material production facility when the usable material is shipped out. Here ideals are realized: almost 100% is recycled, meaning that it goes back into the primary production loop. But once a material is released into the outside world the picture changes. It is processed to make parts that may be small, very numerous and widely dispersed; it is assembled into products that contain many other materials; it may be painted, printed or plated; and its subsequent use contaminates it further. To reuse it, it must be collected (not always easy), separated from other materials, identified, decontaminated, chopped and processed. Collection is time-intensive and this makes it expensive. Imperfect separation causes problems: even a little copper or tin damages the properties of steel; residual iron embrittles aluminum; heavy metals (lead, cadmium, mercury) are unacceptable in many alloys; PVC contamination renders PET unusable, and dyes, water and almost any alien plastic renders a polymer unacceptable for its original demanding purpose, meaning that it can only be used in less demanding applications (a fate known as 'down-cycling').

Despite these difficulties, recycling can be economic, both in cash and energy terms. This is particularly so for metals: the energy commitment per kg for recycled aluminum is about one-tenth of that for virgin material; that for steel is about one-third. Some inevitable contamination is countered by addition of virgin material to dilute it. Metal recycling is both economic and makes important contributions to the saving of energy.

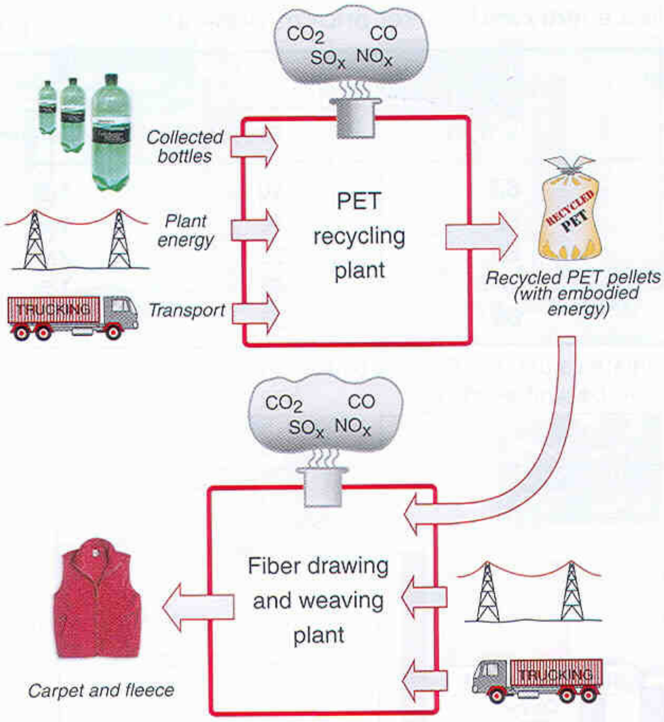


Figure 20.5 A simplified input–output diagram for the recycling of plastics to recover PET, and its use to make lower-grade products such as fleece.

Table 20.1 The energy-absorbing steps in recycling PET

1. Collection	7. Melting
2. Inspection	8. Filtration
3. Chopping	9. Pelletizing
4. Washing	10. Packaging
5. Flotation–separation	11. Plant heating, lighting
6. Drying	12. Transport

The picture for plastics is less rosy. The upper part of Figure 20.5 illustrates this for PET. Bottles are collected and delivered to the recycling plant as mixed plastic—predominantly PET, but with PE and PP bottles too. Table 20.1 lists the steps required to recycle the PET, each one consuming energy, with the results listed in Table 20.2. Some energy is saved, but not a lot—typically 50%.

Recycling of PET, then, can offer an energy saving. But is it economic? Time, in manufacture, is money. Collection, inspection, separation and drying are slow processes, and every minute adds dollars to the cost. Add to this the fact

Table 20.2 Embodied energy and market price of virgin and recycled plastics

Polymer	Embodied energy* (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

*Approximate values; see CES Edu 06 for details.
†Spot prices, December 2005.

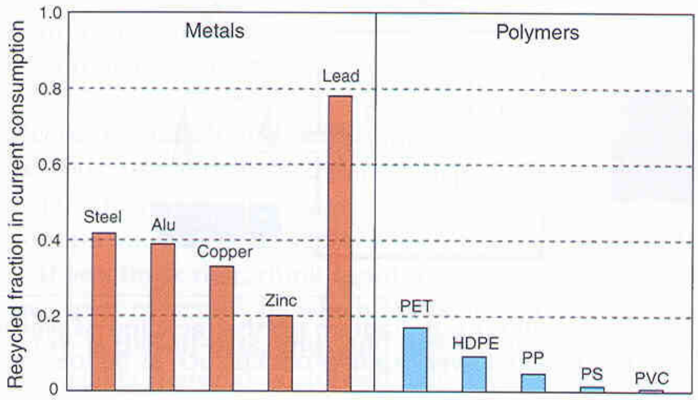


Figure 20.6 The fractional contribution of recycled material to current consumption. For metals, the contribution is large; for polymers, small (2005 data).

that the quality of recycled material is less good than the original, limiting its use to less demanding products, as suggested by the lower part of Figure 20.5—recycled PET cannot be used for bottles. Table 20.2 lists the current market price of granules of five commodity polymers in the virgin and the recycled states. If the recycled stuff were as good as new it would command the same price; in reality it commands little more than half. Thus, using today's technology, the cost of recycling plastics is high and the price they command is low, not a happy combination.

The consequences of this are brought out by Figure 20.6. It shows the current recycle fraction of commodity metals and plastics. The recycle fraction is the fraction of current supply that derives from recycling. For metals it is high: most of the lead, and almost half the steel and one-third of the aluminum we use today has been used at least once before. For plastics the only small success is PET, with a recycle fraction of about 18%, but for the rest the contribution is tiny, for many zero. Oil price inflation and restrictive legislation could change all this, but for the moment, that is how it is.

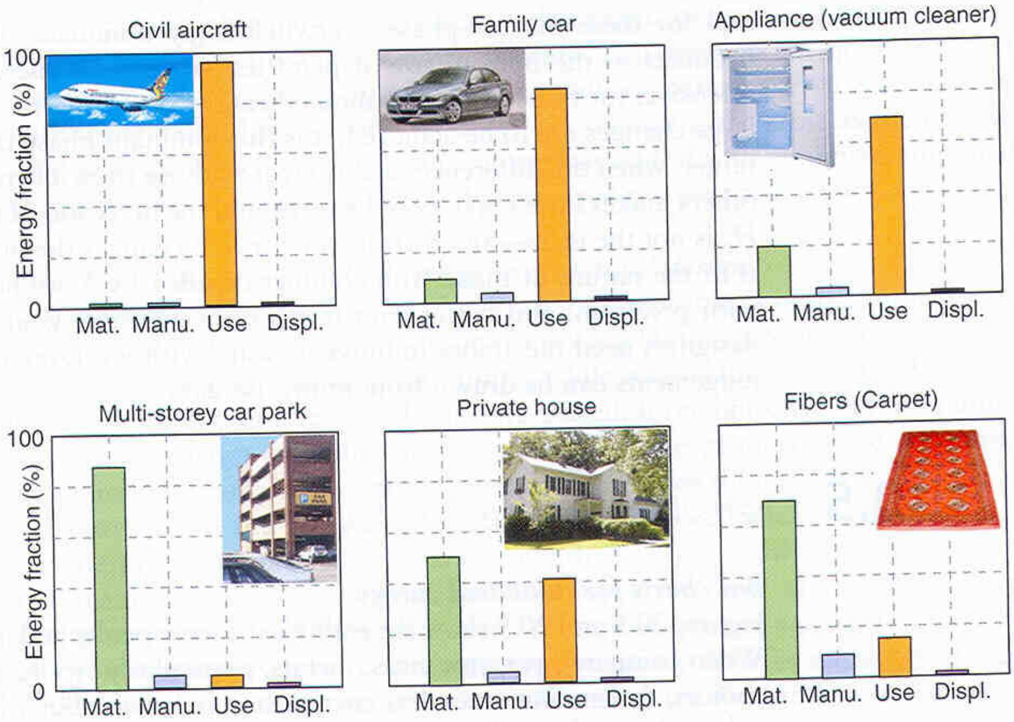


Figure 20.7 Approximate values for the energy consumed at each phase of Figure 20.3 for a range of products. The columns show the approximate embodied energy ('Mat.'), energy to manufacture ('Manu.'), use energy over design life ('Use') and energy for disposal ('Displ.').

The energy demands of products

With this background, we can proceed to look at the way products consume energy in each of the four life phases of Figure 20.3. The procedure is to tabulate the main components of the product together with their material and weight. The embodied energy and energy of processing associated with the product are estimated by multiplying the weights by the energies H_m and H_p, and summing. The use-energy of energy-using products may be estimated from information for the power, the duty cycle and the source from which the power is drawn. To this should be added the energy associated with maintenance and service over the useful life of the product. The energy of disposal is more difficult: some energy may be recovered by incineration, some saved by recycling, but, as already mentioned, there is also an energy cost associated with collection and disassembly. Transport costs can be estimated from the distance of transport and the energy/km.kg of the transport mode used.

Despite the uncertainty in some of the data, the outcome of this analysis is revealing. Figure 20.7 presents the evidence for a range of product groups. It has two significant features, with important implications. The product groups in the top row all consume energy as an unavoidable consequence of their use and for these the use-phase overwhelmingly dominates the life energy. The products in the bottom row depend less heavily on energy but are material intensive; for these it is the embodied energy of the material that dominates. If large changes are to be achieved, it is the dominant phase that must be the first target; when the differences are as great as those shown here, a reduction in the others makes little impact on the total, and the precision of the data for H_m and H_p is not the issue—an error of a factor of 2 changes the outcome very little. It is in the nature of those who conduct detailed LCA studies to wish to do so with precision, and better data is always a desirable goal. But engineers and designers need the ability to move forward without it, recognizing that precise judgements can be drawn from imprecise data.

20.5 Charts for embodied energy

Bar charts for embodied energy

Figures 20.8 and 20.9 show the embodied energy per kg and per m^3 for materials. When compared per unit mass, metals, particularly steels, appear as attractive choices, demanding much less energy than polymers. But when compared on a volume basis, the ranking changes and polymers lie lower than metals. The light

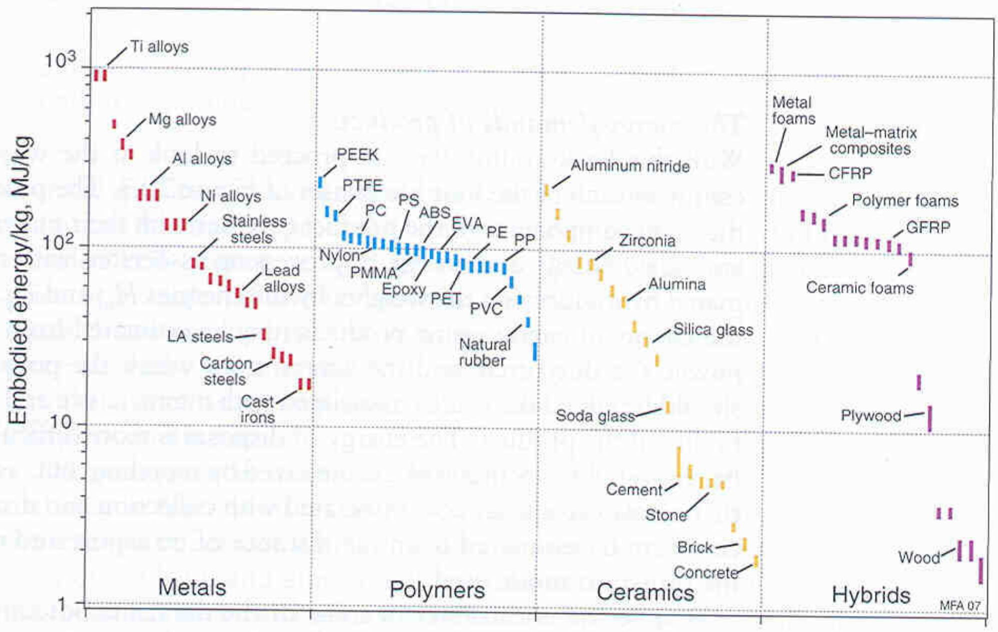


Figure 20.8 Bar chart of embodied energy of basic materials by weight. By this measure polymers are more energy intensive than many metals

alloys based on aluminum, magnesium and titanium are particularly demanding, with energies that are high by either measure. This prompts the question: what measure should we choose to make meaningful comparisons if we wish to minimize the embodied energy of a product? The answer is the same as the one we used with the objectives of minimizing mass or cost: it is to minimize embodied energy *per unit of function*. To do that we need the next two charts.

Property charts for embodied energy in structural design

Earlier chapters discussed the property trade-offs in problems of structural design. The function of the design might be, for example, to support a load without too much deflection, or without failure, while minimizing the mass. For this, modulus–density or strength–density were used. If the objective becomes minimizing the energy embodied in the material of the product while providing structural functionality, we need equivalent charts for these.

Figures 20.10 and 20.11 are a pair of materials selection charts for minimizing energy H_m per unit stiffness and strength. The first shows modulus E plotted against $H_m\rho$; the guidelines give the slopes for three of the commonest performance indices. The second shows strength σ_y plotted against $H_m\rho$; again, guidelines give the slopes. The two charts give survey data for minimum energy design. They are used in exactly the same way as the E–ρ and σ_y–ρ charts for minimum mass design.

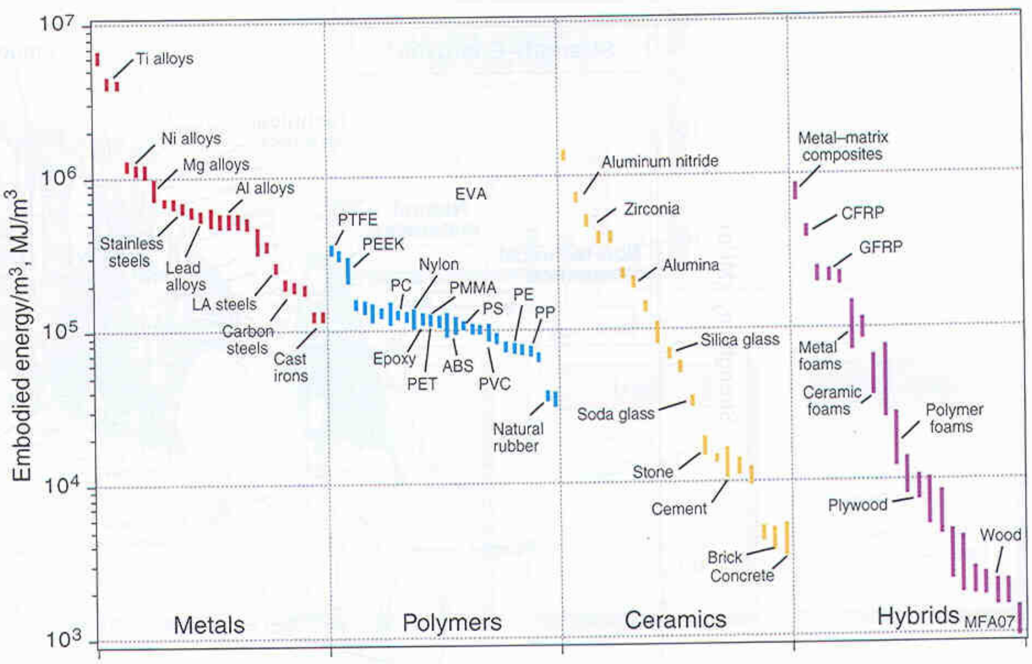


Figure 20.9 Bar chart of embodied energy of basic materials by volume. By this measure polymers are less energy intensive than any metal.

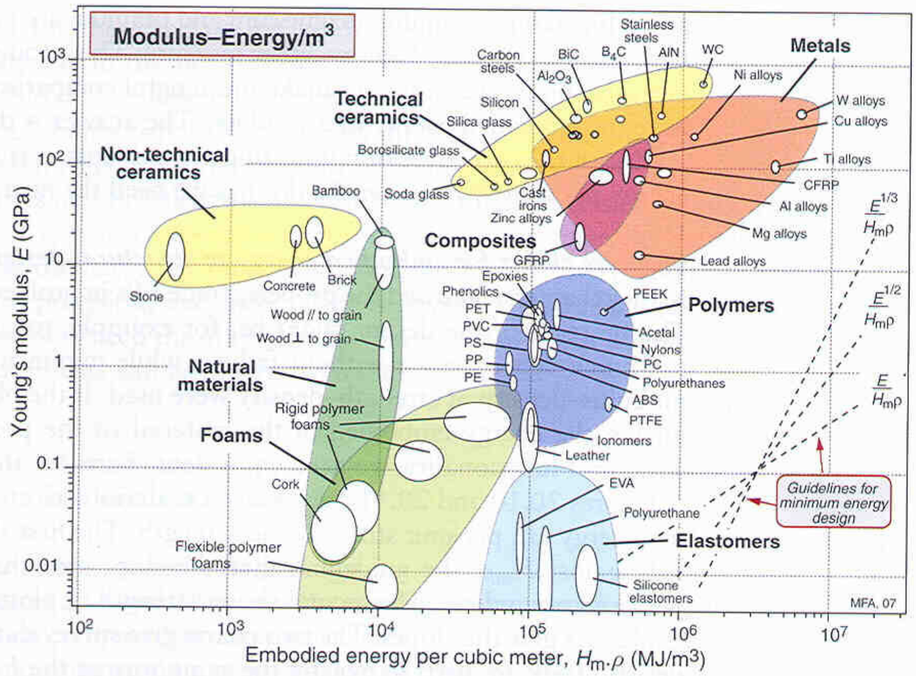


Figure 20.10 The modulus–embodied energy chart made with the CES software. It is the equivalent of the $E-\rho$ chart of Figure 4.6 and is used in the same way.

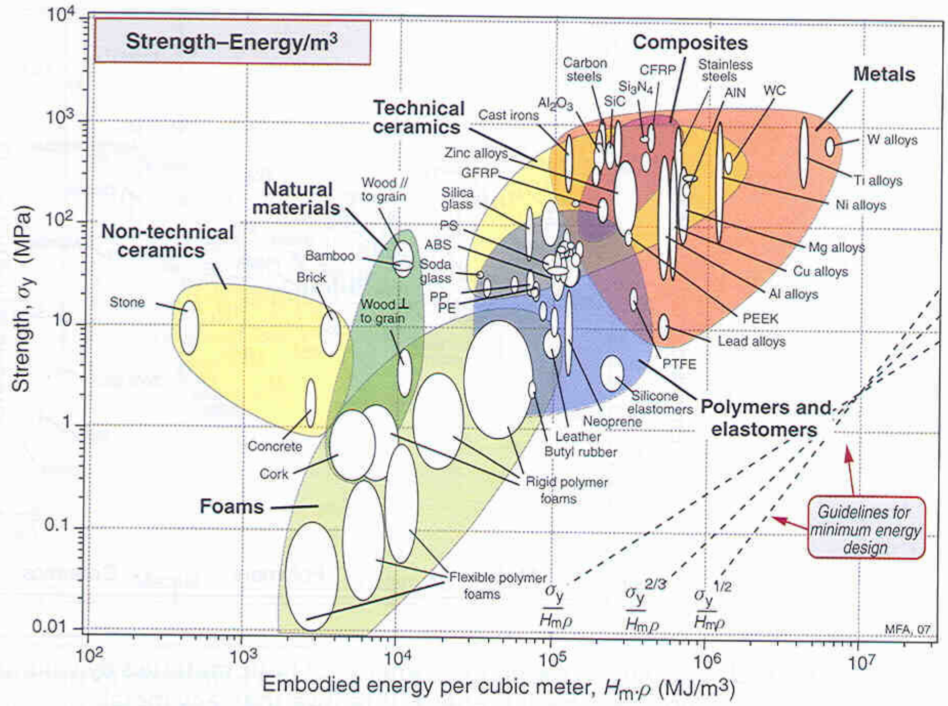


Figure 20.11 The strength–embodied energy chart made with the CES software. It is the equivalent of the $\sigma_y-\rho$ chart of Figure 6.6 and is used in the same way.

20.6 Design: selecting materials for eco-design

For selection of materials in environmentally responsible design we must first ask: which phase of the life cycle of the product under consideration makes the largest impact on the environment? The answer guides the effective use of the data in the way shown in Figure 20.12.

The material production phase
If material production consumes more energy than the other phases of life, it becomes the first target. Drink containers provide an example: they consume materials and energy during material extraction and container production, but, apart from transport and possible refrigeration, not thereafter. Here, selecting materials with low embodied energy and using less of them are the ways forward. Figure 20.7 made the point that large civil structures—buildings, bridges, roads—are material intensive. For these the embodied energy of the materials is the largest commitment. For this reason architects and civil engineers concern themselves with embodied energy as well as the thermal efficiency of their structures.

The product manufacture phase
The energy required to shape a material is usually much less than that to create it in the first place. Certainly it is important to save energy in production. But

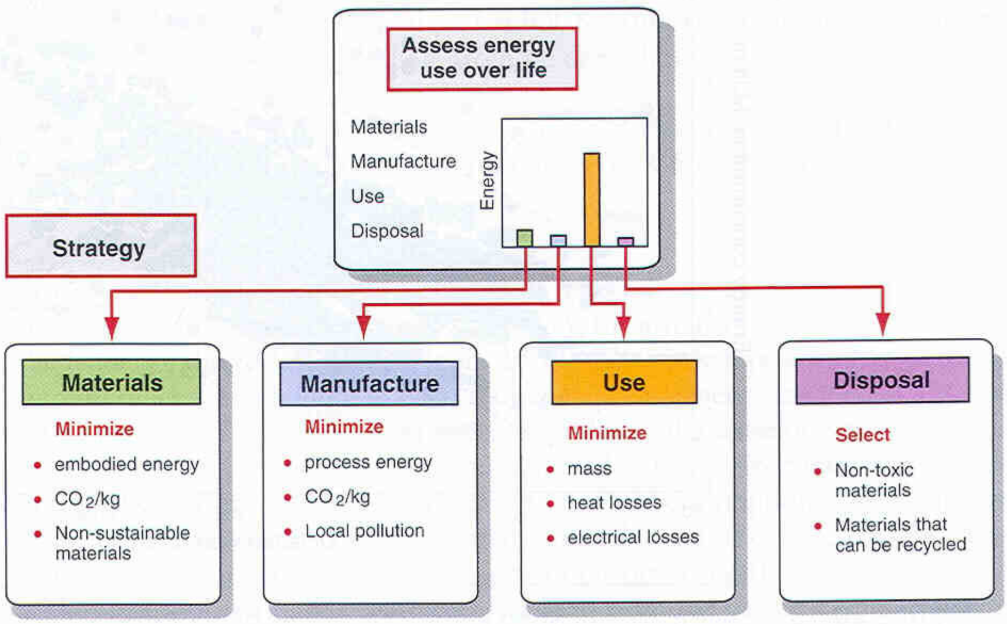


Figure 20.12 Rational use of the database starts with an analysis of the phase of life to be targeted. The decision then guides the method of selection to minimize the impact of the phase on the environment.

higher priority often attaches to the local impact of emissions and toxic waste during manufacture, and this depends crucially on local circumstances. Clean manufacture is the answer here.

The product use phase

The eco-impact of the use phase of energy-using products has nothing to do with the embodied energy of the materials themselves—indeed, minimizing this may frequently have the opposite effect on use energy. Use energy depends on mechanical, thermal and electrical efficiencies; it is minimized by maximizing these.

Fuel efficiency in transport systems (measured, say, by MJ/km) correlates closely with the mass of the vehicle itself; the objective then becomes that of minimizing mass. The evidence for this can be seen in Figure 20.13, showing the fuel consumption of some 4000 European models of car against their unladen mass, segregated by engine type (super-sport and luxury cars, shown as red symbols, are separated out—for these, fuel economy is not a design priority). The lines show linear fits through the data: the lowest, through the green symbols, for diesel-powered cars, the one above, through the blue symbols, for those with petrol engines. One hybrid model is included (yellow symbol). The correlation between fuel consumption and weight is clear. Here the solution is *minimum*

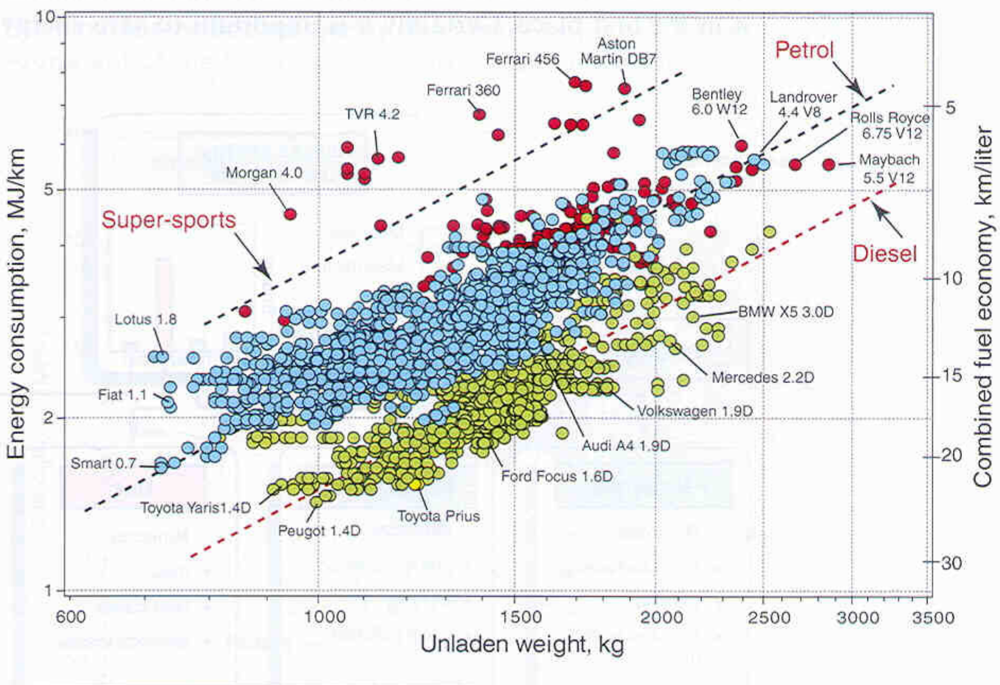


Figure 20.13 Energy consumption and fuel economy of 2005 model European cars, plotted against the unladen weight. The open red symbols are diesels, the open black are petrol driven and the full red symbols are for cars designed with performance, above all else, in mind. The broken lines are best fits to data for each type. Note the near-linear dependence of energy consumption on weight.

mass design, discussed extensively in earlier chapters; it is just as relevant to eco-design as to performance-driven design.

Energy efficiency in refrigeration or heating systems is achieved by minimizing the heat flux into or out of the system; the objective is then that of minimizing thermal conductivity or thermal inertia. Energy efficiency in electrical generation, transmission and conversion is maximized by minimizing the ohmic losses in the conductor; here the objective is to minimize electrical resistance while meeting necessary constraints on strength, cost, etc. Material selection to meet these objectives is well documented in other chapters and the texts listed under 'Further reading'.

The product disposal phase

The environmental consequences of the final phase of product life have many aspects. The ideal is summarized in the following guidelines:

- Avoid toxic materials such as heavy metals and organometallic compounds that, in landfill, cause long-term contamination of soil and groundwater.
- Examine the use of materials that cannot be recycled, since recycling can save both material and energy, but keep in mind the influence they have on the other phases of life.
- Seek to maximize recycling of materials for which this is possible, even though recycling may be difficult to achieve for the reasons already discussed.
- When recycling is impractical seek to recover energy by controlled combustion.
- Consider the use of materials that are biodegradable or photo-degradable, although these are ineffectual in landfill because the anaerobic conditions within them inhibit rather than promote degradation.

Implementing this requires information for toxicity, potential for recycling, controlled combustion and biodegradability. The CES software provides simple checks of each of these.

Case study: crash barriers

Barriers to protect driver and passengers of road vehicles are of two types: those that are static (the central divider of a freeway, for instance) and those that move (the fender of the vehicle itself) (Figure 20.14). The static type lines tens of thousands of miles of road. Once in place they consume no energy, create no CO_2 and last a long time. The dominant phases of their life in the sense of Figure 20.7 are those of material production and manufacture. The fender, by contrast, is part of the vehicle; it adds to its weight and thus to its fuel consumption. The dominant phase here is that of use. This means that, if eco-design is the objective, the criteria for selecting materials for the two sorts of barrier will differ.

The function of a barrier is to transfer load from the point of impact to the support structure, where reaction from the foundation or from crush elements in the vehicle support or absorb it. To do this the material of the barrier must have adequate strength, σ_y, and the ability to be shaped and joined cheaply, and (thinking of the disposal phase of life) recyclable. That for the car fender must

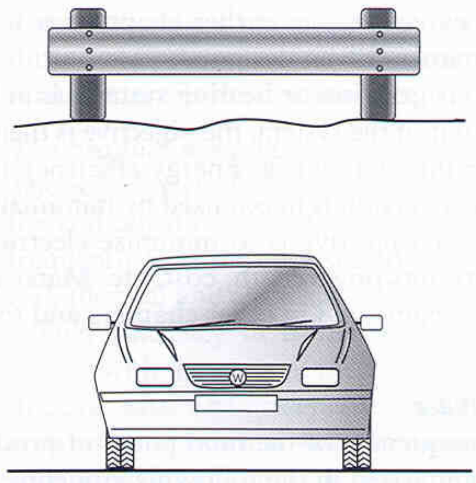


Figure 20.14 Two crash barriers, one static, the other—the fender—attached to something that moves. Different eco-criteria are needed for each.

meet these constraints with minimum mass, since this will reduce the use energy. As we know from Chapter 7, this means materials with high values of the index

$$M_1 = \frac{\sigma_y}{\rho}$$

where σ_y is the tensile strength and ρ is its density. For the static barrier embodied energy, not weight, is the problem. If we change the objective to that of *minimum embodied energy*, we require materials with large values of

$$M_2 = \frac{\sigma_y}{H_m \rho}$$

where H_m is the embodied energy per kg of material.

The chart of Figure 7.8 guides selection for the mobile barrier, where we seek strength at low weight. CFRPs excel by this criterion, but they are not recyclable. Heavier, but recyclable, are alloys of magnesium, titanium and aluminum. Ceramics are excluded both by their brittleness and the difficulty of shaping and joining them.

The chart of Figure 20.11 guides the selection for static barriers, where we seek strength at low embodied energy. The index M_2 is plotted in Figure 20.15. The chart shows that embodied energy per unit strength (leaving ceramics aside because of brittleness) is minimized by making the barrier from carbon steel, cast iron or wood; nothing else comes close.

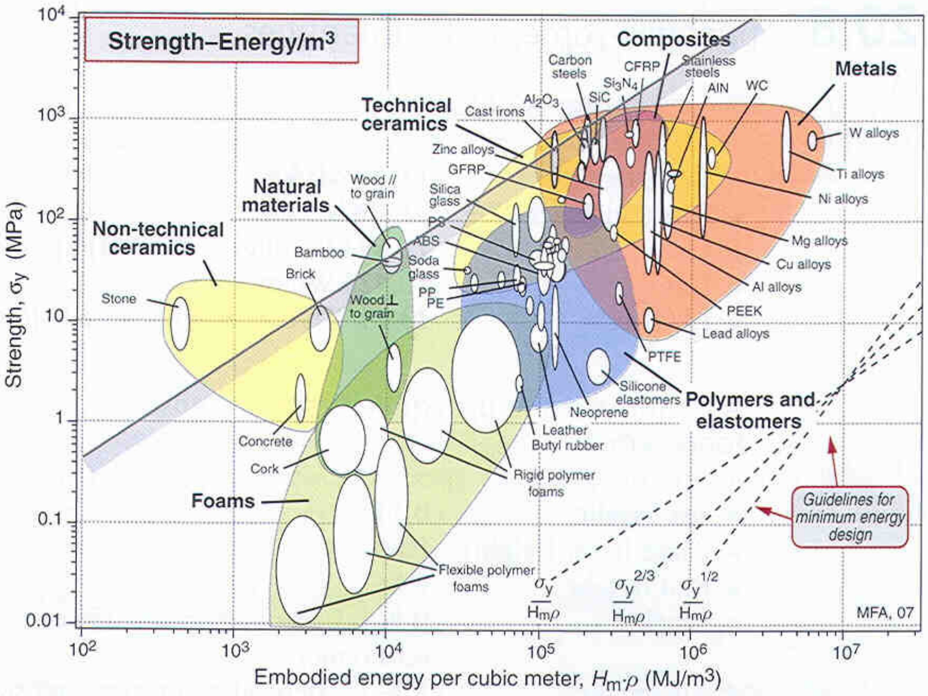


Figure 20.15 The selection of materials for strength at minimum embodied energy. The best choices (rejecting ceramics because they are brittle) are cast iron, steel and wood.

Stiffness-limited design is treated in a similar way. Achieving it at minimum mass was the subject of Chapters 4 and 5. To do so at minimum embodied energy just requires that ρ is replaced by $H_m\rho$.

20.7 Summary and conclusions

Rational selection of materials to meet environmental objectives starts by identifying the phase of product life that causes greatest concern: production, manufacture, use or disposal. Dealing with all of these requires data not only for the obvious eco-attributes (energy, CO_2 and other emissions, toxicity, ability to be recycled, and the like) but also data for mechanical, thermal, electrical and chemical properties. Thus, if material production is the phase of concern, selection is based on minimizing the embodied energy or the associated emissions (CO_2 production, for example). But if it is the use phase that is of concern, selection is based instead on low weight, or excellence as a thermal insulator, or as an electrical conductor while meeting other constraints on stiffness, strength, cost, etc. The charts of this book give guidance in meeting these constraints and objectives. The CES databases provide data and tools that allow more sophisticated selection.

20.8 Appendix: some useful quantities

Energy contents of fuels

• Coal, lignite	15–19 MJ/kg
• Coal, anthracite	31–34 MJ/kg
• Oil	11.69 kWh/liter = 47.3 MJ/kg
• Gas	10.42 kWh/m^3
• LPG	13.7 kWh/liter = 46.5–49.6 MJ/kg

Approximate energy requirements of transport systems in MJ per tonne-km

• Sea freight	0.11
• Barge (river freight)	0.83
• Rail freight	0.86
• Truck	0.9–1.5, depending on size of truck (large are more economic)
• Air freight	8.3–15, depending on type and size of plane

Conversion factors

- 1 BthU = 1.06 kJ
- 1 kWh/kg (sometimes written kW/kg/h) = 3.6 MJ/kg
- A barrel of oil = 42 US gallons = 159 liters = 138 kg = 6210 MJ
- At $50 per barrel, a dollar buys 124 MJ

20.9 Further reading

Ashby, M.F. (2005) *Materials Selection in Mechanical Design*, 3rd edition, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-6168-2. *(A more advanced text developing the ideas presented here.)*

Brundlandt, D. (1987) *Report of the World Commission on the Environment and Development*, Oxford University Press, Oxford, UK. ISBN 0-19-282080-X. *(A much quoted report that introduced the need and potential difficulties of ensuring a sustainable future.)*

Dieter, G.E. (1991) *Engineering Design, A Materials and Processing Approach*, 2nd edition, McGraw-Hill, New York, USA. ISBN 0-07-100829-2. *(A well-balanced and respected text focusing on the place of materials and processing in technical design.)*

Goedkoop, M., Effting, S. and Collignon, M. (2000) *The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment, Manual for Designers* (14 April 2000), http://www.pre.nl. *(An introduction to eco-indicators, a technique for rolling all the damaging aspects of material production into a single number.)*

Graedel, T.E. (1998) *Streamlined Life-cycle Assessment*, Prentice-Hall, New Jersey, USA. ISBN 0-13-607425-1. *(An introduction to LCA methods and ways of streamlining them.)*

Kyoto Protocol (1997) United Nations, Framework Convention on Climate Change. Document FCCC/CP1997/7/ADD.1 (http://cop5.unfccc.de) O) 14040/14041/14042/14043, 'Environmental management—life cycle assessment' and subsections, Geneva, Switzerland. *(The international consensus on combating climate change.)*