TECHNISCHE BEDRIJFSKUNDE

7769 Materials, environment and sustainability

HAN_UNIVERSITY
OF APPLIED SCIENCES

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Chapter 20
Materials, environment, and sustainability

20.1 Introduction and synopsis

The practice of engineering consumes vast quantities of materials and relies on a continuous supply of them. We start by surveying this consumption, emphasizing the materials used in the greatest quantities. Increasing population and improved 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.

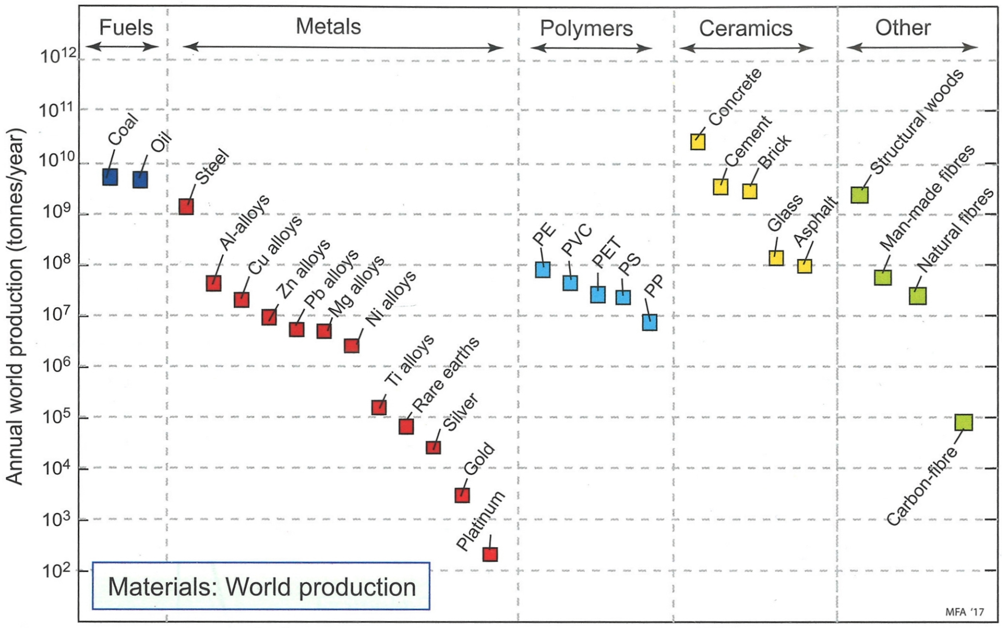
There is a more immediate problem: present-day material usage already imposes stress on the environment in which we live. The environment has some capacity to cope with this so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities exceed 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 timescale of this thinking is 10 years or so, an average product's expected life. *Sustainable design* is more than this: it involves the more complex balance of environmental concerns with those of economics, legality, and social acceptability. This chapter explores these and the ways in which materials are involved.

20.2 Material production, material consumption, and growth

Material consumption Speaking globally, we produce roughly 10 billion (10^{10}) tonnes of engineering materials each year. This production is responsible for about 16% of global energy consumption and carbon release to the atmosphere (cement production alone is responsible for almost 5%). Figure 20.1 gives a perspective; it is a bar-chart of the production of a range of materials including those 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 use 10 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 aluminium (the next); in reality, steel consumption 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-fibre reinforced composites, and (most recently) nano-materials, but make no mistake, its blend of versatility, strength, toughness, low cost, recyclability, and wide availability is unmatched by any other material.

Polymers come next. Fifty years ago their consumption was tiny; today the combined consumption by weight of the commodity polymers, polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), and polyethylene-terephthalate (PET), approaches that of steel, and by volume it is greater.

These may be big, but the really big ones are the materials of the construction industry. Steel is one of these, but the consumption of wood for construction purposes 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 eclipses steel. Concrete, comprising naturally occurring stones and gravel plus about 10% cement, is bigger still; it's the material of bridges, dams, airports, and mega-cities. The modern world without concrete would look very different.



Man-made fibres: predominantly polyester, with lesser quantities of nylon, acrylic and PP
Natural fibres: cotton and wool

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

The last column captures the materials that don't fit easily in the other columns. There are some big players here. Wood we have discussed already; the others are interesting too—all are fibres. Fibres are important: think of clothing, carpets, blankets, sheets, tents, sails, and parachutes. Until the late 19th century, all were natural in origin—hemp, linen, cotton, wool, silk, etc. But over the course of the 20th century, synthetic chemistry overtook nature as a provider of fibres and remains so today. Last in this column is carbon, the fibre used to reinforce high-performance composites. Just 30 years ago this material would not have crept onto the bottom of this chart. Today its production is approaching that of some light alloys and is growing fast.

The data on this figure describe the big players; collectively they account for some 98% of *all* material production by weight. Actual material consumption is even greater than this, because recycling feeds materials back into use, adding to that produced from virgin raw materials—a point we return to in a moment.

The growth of consumption Demand for materials 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 23 years than we have since the start of the industrial revolution 250 years ago. You can prove this for yourself with the Exercises in this chapter, using the following analysis. If the current rate of consumption in tonnes per year is C, then exponential growth means that

$$\frac{dC}{dt} = \frac{r}{100} C \tag{20.1}$$

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

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

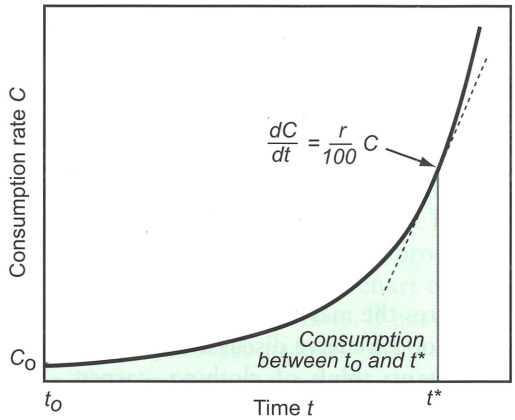


Figure 20.2 Exponential growth in consumption.

After a period of stagnation during the financial crisis of 2008, steel consumption is growing again, averaging 2.8% per year over the last decade, doubling in 25 years. The consumption of plastics today is growing at 4% per year; it doubles about every 18 years. Demand for carbon fibre is currently growing at 8% per year; it doubles in just 9 years.

The picture, then, is one of a global economy ever more dependent on a continuous supply of materials and the energy it takes to make them. This raises two concerns:

- concern for the health of the environment, the life-support system for all living things
- concern for security of access to natural resources, the support system for economic well-being and growth

We start with the environment.

20.3 Natural Capital and the materials life cycle

All life as we know it evolved on earth. The continued existence of life on earth depends on the resources that nature provides: clean air, fresh water, productive land and oceans, bio-diversity, and of course, the mineral and energy resources from which materials are made. We refer to these collectively as *Natural Capital*. The word 'Capital' is deliberately chosen: a Capital is an asset. You can draw it down to use it; you can build it up by conservation or saving; and you can exchange it for other goods and services.

We draw down Natural Capital in order to create materials and products. Some—clean air, fresh water, vegetable and animal stocks—are renewable provided they are properly managed. Others—minerals and hydrocarbon deposits for example—are not renewable (once used or burned they are gone) and are finite in extent, although for many, the natural deposits are so large that serious depletion has not, until recently, been seen as a problem. As we have seen, the rate at which this draw-down is taking place is accelerating, with consequences that are now cause for concern. To understand this, we must examine the life cycle of materials and products.

The material life cycle (Figure 20.4) Ores and feedstocks, drawn from Natural Capital, are processed to give materials; these are manufactured into products that are used; and at the end of their lives, a fraction is reused or recycled, while the rest is incinerated or committed to 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—low-grade heat and gaseous, liquid, and solid waste. Resource consumption, emissions and their consequences are assessed by *life-cycle analysis* (LCA). A rigorous LCA examines the life cycle of a product and assesses in detail the associated resource consumption and environmental impact of each phase of life, summing them to give a life assessment. To do this you need information about the life history of the product at a level of precision that is available only after it has been manufactured and used: this type of LCA is a product assessment rather than design tool. This has led to the development of more approximate 'streamlined' life-assessment methods[1] that seek to combine acceptable cost with sufficient accuracy to guide decision-making during the design process—the choice of materials being one of these decisions. We shall follow this route, focusing on the energy and carbon 'footprint' associated with the life of a product. First we need to define what these words mean.

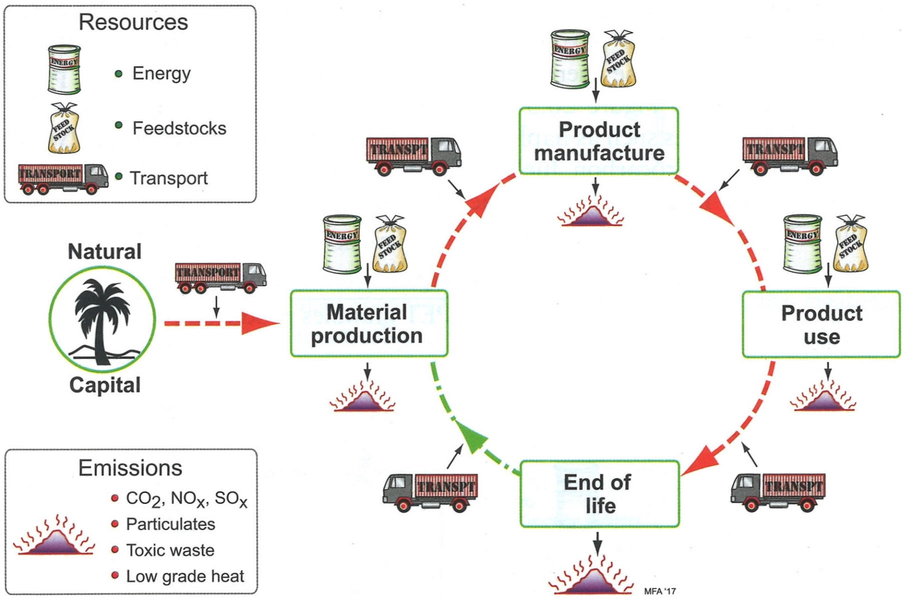


Figure 20.4 The material life cycle. Ores and feedstocks are mined and processed to yield a material. This is manufactured into a product that is used and, at the end of its life, discarded or recycled. Energy and materials are consumed in each phase, generating waste heat as well as solid, liquid, and gaseous emissions.

[1] See Graedel, T. E. (1998) and Ashby M. F. (2012), listed in Further Reading.

20.4 Embodied energy and carbon footprint of materials

Materials are made from naturally occurring ores and feedstocks. Making them requires energy and releases emissions, both on a very large scale. Nations wishing to minimize their impacts now seek ways to minimize the environmental impacts of materials production, so this has to be quantified.

The embodied energy, H_m, of a material is the energy that must be committed to create 1 kg of usable stock—1 kg of steel stock, PET pellets, or cement powder, for example—measured in MJ/kg. The *carbon footprint, $CO_{2,e}$*, is the associated release of CO_2, adjusted to include the carbon-equivalent of other associated emissions, in kg/kg. It is tempting to try to estimate embodied energy via the thermodynamics of the processes involved—extracting aluminium from its oxide, for instance, requires the provision of the free energy of oxidation to liberate it. While it is true that this much energy must be provided, it is only the beginning. The thermodynamic efficiencies of industrial processes are low, seldom reaching 50%. The feedstocks used in the extraction or production themselves carry embodied energy, and transport is involved. The production plant has to be lit, heated, and serviced; and because it was built (at least in part) for the purpose of making the material or product, there is an 'energy mortgage'—a share of the energy consumed to build the plant in the first place.

The upper part of Figure 20.5 shows, much simplified, the inputs to a PET production facility: oil derivatives such as naphtha and other feedstocks, direct power (which, if electric, is generated from hydrocarbon fuels with an efficiency of about 34%), and the energy of transporting the feedstocks 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

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

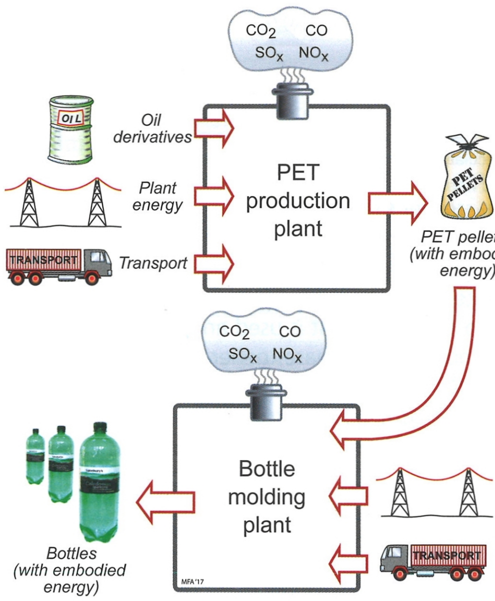


Figure 20.5 The flows of materials and energy in PET production and bottle production.

Figures 20.6 and 20.7 show the embodied energy per kg and m^3 for materials. When compared per unit mass, metals, particularly steels, appear as attractive choices, demanding much less energy than that of polymers. But when compared on a volume basis, the ranking changes and polymers lie lower than metals. Light alloys based on aluminium, magnesium, and titanium are particularly demanding, with energies that are high by either measure.

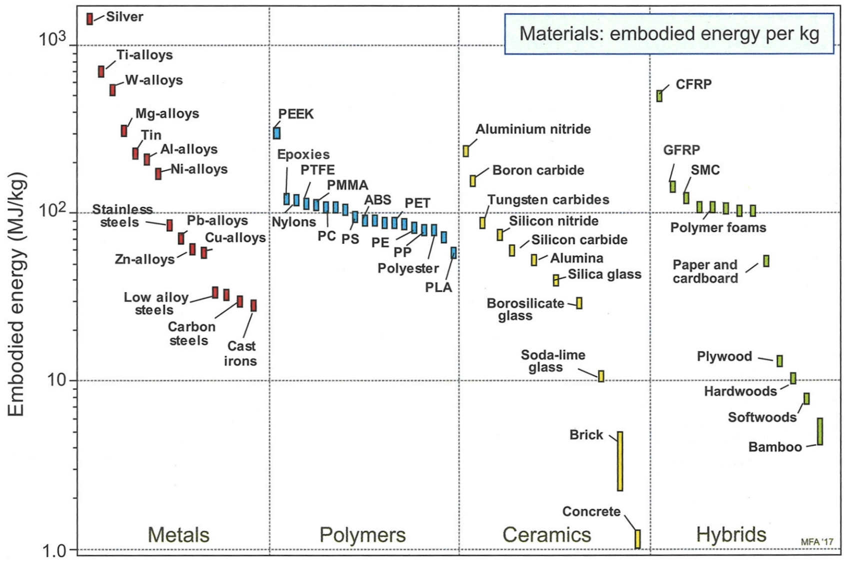


Figure 20.6 Bar chart of embodied energy of basic materials by weight. By this measure, polymers are more energy intensive than many metals.

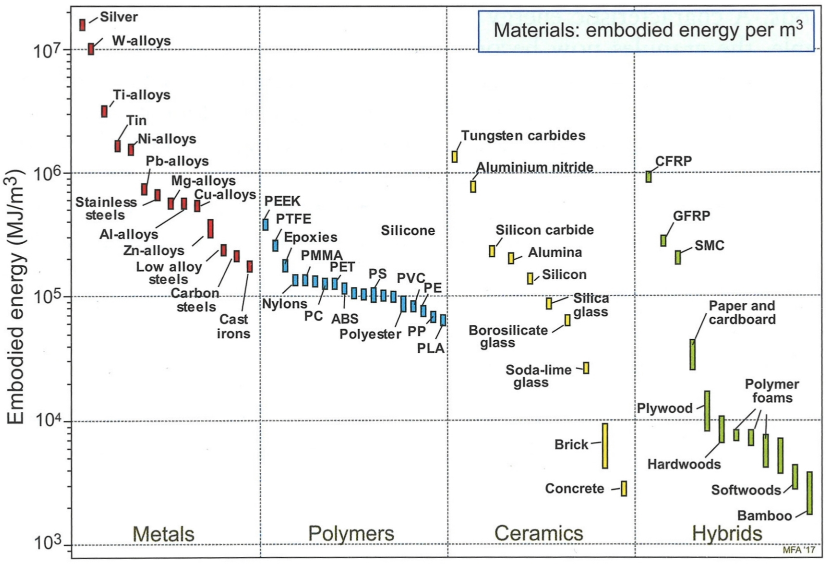


Figure 20.7 Bar chart of embodied energy of basic materials by volume. By this measure, polymers are less energy intensive than many metals.

Example 20.3 Material substitution

The casing of a power tool is made of 0.75-mm thick aluminium alloy sheet. It is proposed to replace it with a polypropylene (PP) molding of the same overall size, but 3 mm thick. Does this reduce or increase the embodied energy and carbon footprint of the product? (Data for density, embodied energy, and carbon footprint may be found in Appendix A.)

Answer. The relevant data, drawn from Appendix A, are shown in the table below using the mid-range values of the ranges. The last two columns list embodied energy and carbon footprint per unit volume.

Material	Density ρ (kg/m^3)	Embodied energy H_m (MJ/kg)	Carbon footprint CO_2 (kg/kg)	$H_m \rho$ (GJ/m^3)	$CO_2\ \rho$ (Mg/m^3)
Aluminium alloy	2700	210	12.5	567	34
Polypropylene, PP	900	80	3.15	72	2.8

The PP casing is four times thicker than the aluminium one and thus requires four times the volume of material. The ratio of embodied energy per unit volume of aluminium is eight times that of PP; its carbon footprint is twelve times larger. So even though the PP casing is four times thicker, it still has a lower embodied energy and carbon footprint than those of the aluminium casing.

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; and ceramics are shaped by powder methods. A characteristic energy per kg is associated with each. 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 20.5. There is no need to list the inputs again—they are broadly the same, the PET bringing with it its embodied energy $(H_m)_{PET}$. The output of the analysis is the energy committed per bottle produced, and the carbon footprint is assessed in a similar way.

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 that, when totaled, give an energy commitment and carbon footprint even for a product as simple as a plastic bottle of cold water.

At the end of its first life as a bottle, the material is still there. What happens to it then?

Recycling: ideals and realities We buy, use, and discard paper, packaging, cans, bottles, furniture, smart phones, computers, cars, even buildings. Why not retrieve the materials they contain and use them again? It's not that simple.

First, some facts. There are (simplifying again) two sorts of 'scrap', by which we mean material with recycling 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 can be realized; almost 100% is recycled, meaning that it goes back into the primary production loop, even though additional energy is used in doing so. But once a material is released into the outside world, the picture changes. It is processed to make parts that may be small, numerous, and widely dispersed; it is assembled into products that contain other materials; it may be painted, printed, or plated; and its subsequent use contaminates it further. To reuse the material, it must be collected (not always easy), separated from other materials, identified, decontaminated, chopped, and processed. Collection is time- and transport-intensive, and this adds expense. Imperfect separation causes problems: even a little copper or tin damages the properties of steel; residual iron embrittles aluminium; 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 in both materials and energy terms. This is particularly so for metals: the energy commitment per kg for recycled aluminium is about one-tenth that for virgin material; for steel it is about one-third. Some inevitable contamination is countered by the addition of virgin material to dilute it. Metal recycling is both economic and makes important contributions to the saving of energy and the efficient use of materials.

The recycling picture for plastics is less rosy. Figure 20.8 illustrates this for PET. In the upper part of the figure, bottles are collected and delivered to the recycling plant as mixed plastic—predominately PET, but with PE and PP bottles too. Table 20.1 lists the steps required to recycle the PET, each one consuming energy. Table 20.2 compares the overall embodied energies for virgin and recycled plastics. Some energy is saved, but not a lot—typically 50%.

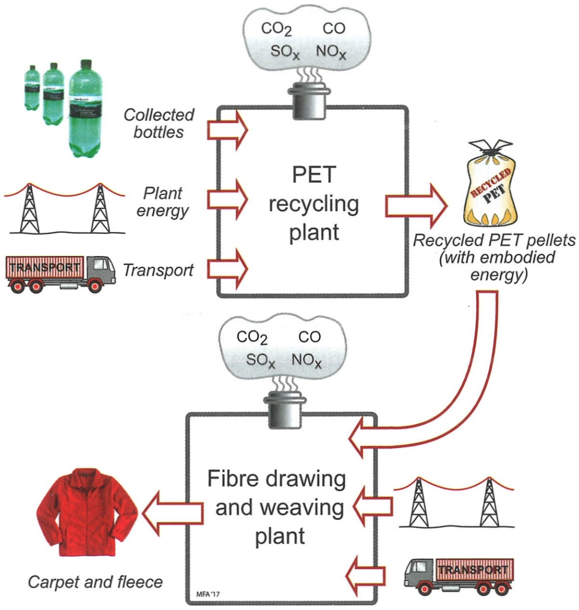


Figure 20.8 The flows of material and energy during the recycling of plastic bottles to recover PET.

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

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

	Energy[a] (MJ/kg)		Energy ratio (%)	Price[b] ($/kg)		Price ratio (%)
Polymer	Virgin	Recycled	Recycle/Virgin	Virgin	Recycled	Recycle/Virgin
HDPE	82	50	61	1.8	1.1	61
PP	82	50	61	1.4	0.9	64
PET	85	39	46	1.9	1.2	63
PS	97	48	51	2.4	1.3	54
PVC	58	36	62	1.7	0.8	47
PC	108	43	40	3.7	2.0	54
ABS	95	46	48	3.1	0.88	28

a. Approximate values; see CES EduPack for details.
b. Spot price, January 2017 (http://www.plasticsnews.com/resin).

Recycling of PET, then, can offer some energy saving. But is it economic? Time in manufacture is money. Collection, inspection, separation, and drying are slow processes, all adding cost. And the quality of recycled material may be less than that of the original—plastics are rarely recycled in a closed loop but go into secondary products (as shown in the lower part of Figure 20.8). Table 20.2 compares the current market price of granules of the major polymers in their virgin and 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, and these figures also tend to be volatile because the cost of energy itself fluctuates. 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 20.9. It shows the recycle fraction of the main materials classes; that is, the fraction of current supply that derives from recycling. For metals it is high: most of the lead, almost half the steel, and one-third of the aluminium we use today has been used at least once before. For plastics the only significant success is PET with a recycle fraction of about 32%, up from 18% a decade ago, but for the rest the contribution is small, or (for many) zero. Oil price inflation and restrictive legislation could change all this, but for the moment, that is how it is.

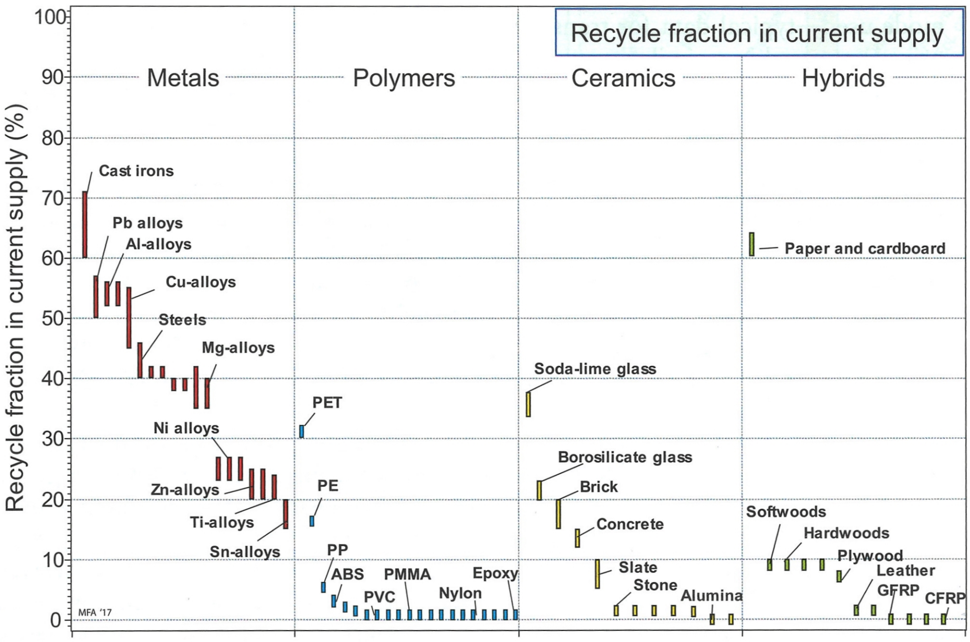


Figure 20.9 The fractional contribution of recycled materials to current consumption. For metals, the contribution is large; for polymers, small (2015 data).

Before we go further, a word of warning. Some material properties—density, modulus, and specific heat for example—can be measured with precision, so the values listed in handbooks can be accepted as accurate and reproducible. Eco-properties are not like that. Assessing embodied energies, carbon footprints, and recycle fractions is an imprecise science. The values depend on local conditions—copper mined and refined in Peru has an embodied energy that differs from that produced in the United States because the ores and technologies of the two countries differ, and even within the United States there are differences between different producers. The numbers in Appendix A, Table A8, must be viewed as approximate, with a precision of ±10% at best.

Eco-audits of products: streamlined life-cycle assessment With this background, we can explore the way products consume energy in each of the four life-phases of Figure 20.4. The procedure is to tabulate the main components of the product together with their materials and mass (the 'Bill of Materials' or BoM). The embodied and processing energies associated with the product are estimated by multiplying each mass by the appropriate energies H_m and H_p and adding them up. The use energy is calculated from the power consumption and the duty cycle (i.e. the proportion of the time in use), and the source from which the power is drawn, allowing for suitable efficiencies in converting energy from one form to another (from electricity to heat, for example). To this should be added the energy associated with maintenance and service over product life. The energy of disposal is more difficult: some energy may be recovered by incineration, others saved by recycling, reconditioning, or reuse, 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/tonne·km of the transport mode used—typical data for transport energies are given later in this chapter. Carbon footprint is assessed in a similar way.

Despite the imprecision of the data mentioned earlier, the outcome of this analysis is revealing. Figure 20.10 presents the evidence for a range of product groups[2]. It has two significant features, with important implications. Products 1 and 2 are materials-intensive; for these, it is the embodied energy of the material that dominates. Buildings (product 3) are also materials-intensive, but they also last a long time—and if they are inhabited, they are lit and may be heated or cooled, which can consume more energy than the materials that went into the building (shown here is a car park, unheated but lit). In contrast, products 4–6 are energy-intensive—for these, the use phase completely dominates. If you want to make large reductions in life-cycle energy, the dominant phase of life must be the first target; when the differences are as great as those in the figure, a reduction in the others has little impact on the total.

Eco-audits like these involve many approximations—they are order-of-magnitude estimates, not precise analyses. Their role is to identify the big contributors to energy, focusing on re-design objectives. Product re-design is proving increasingly effective in reducing use-energy consumption: for example, LED lighting, light-weighting, and energy-efficiency improvements in cars, energy-efficient housing, and energy-recovery systems capturing waste heat and kinetic energy. This has an interesting consequence: the embodied energies of the materials of products (which are often increased by these changes) are emerging as an increasing focus of attention.

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[2] These eco-audits are discussed in greater depth in the companion text, Ashby, M. F. (2012). *Materials and the environment* (2nd ed.). Elsevier. ISBN 978-0-12-385971-6.

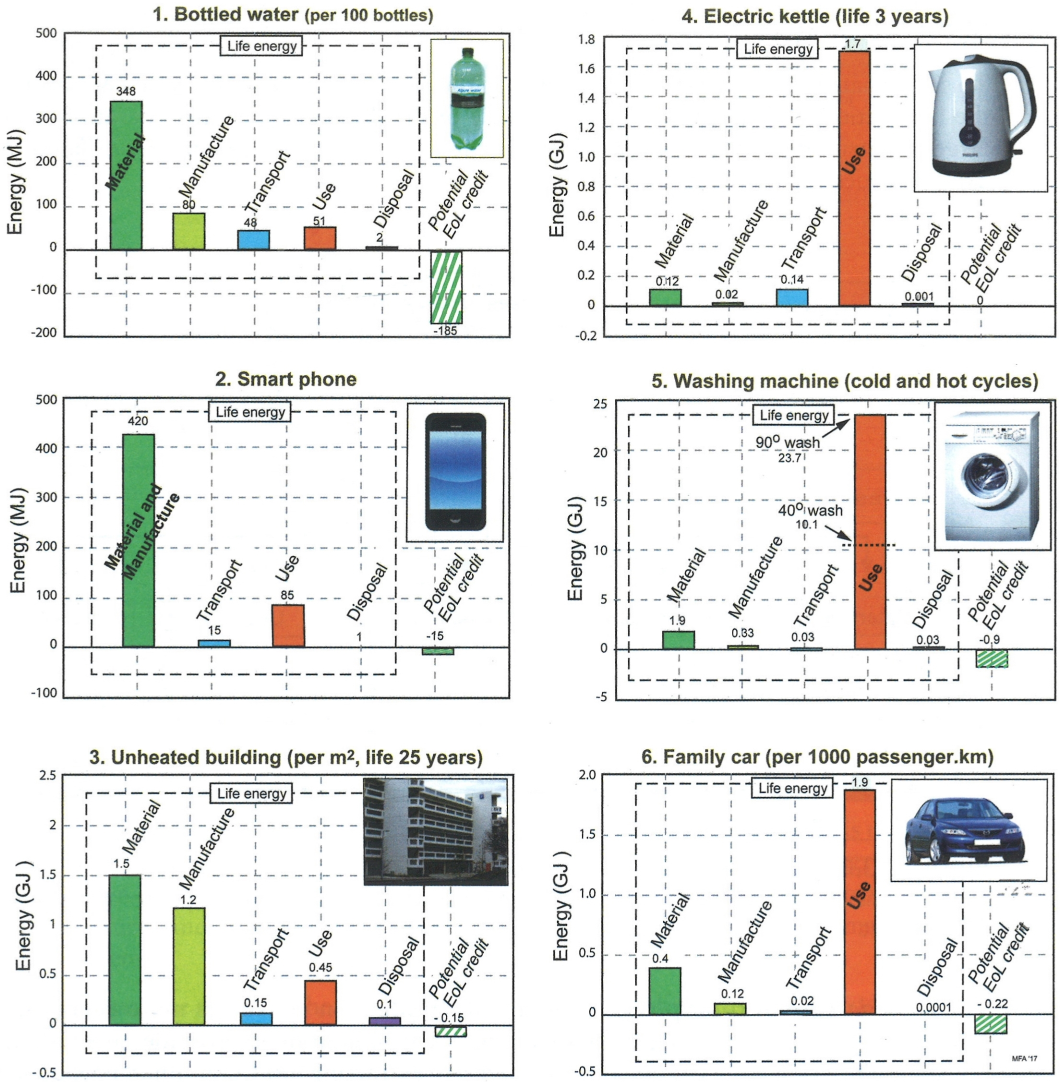

Figure 20.10 The energy consumed at each phase of the life cycle of Figure 20.4 for a range of products. The columns show the embodied energy of the materials for manufacture, transport, use, and disposal over the stated life. Carbon emissions follow an almost identical pattern.

20.5 Materials and eco-design

To select materials to minimize the impact on the environment we must first ask—as we did in the last section—which phase of the life cycle of the product under consideration makes the largest contribution? The answer guides the choice of strategy to ameliorate it (Figure 20.11). The strategies are described below.

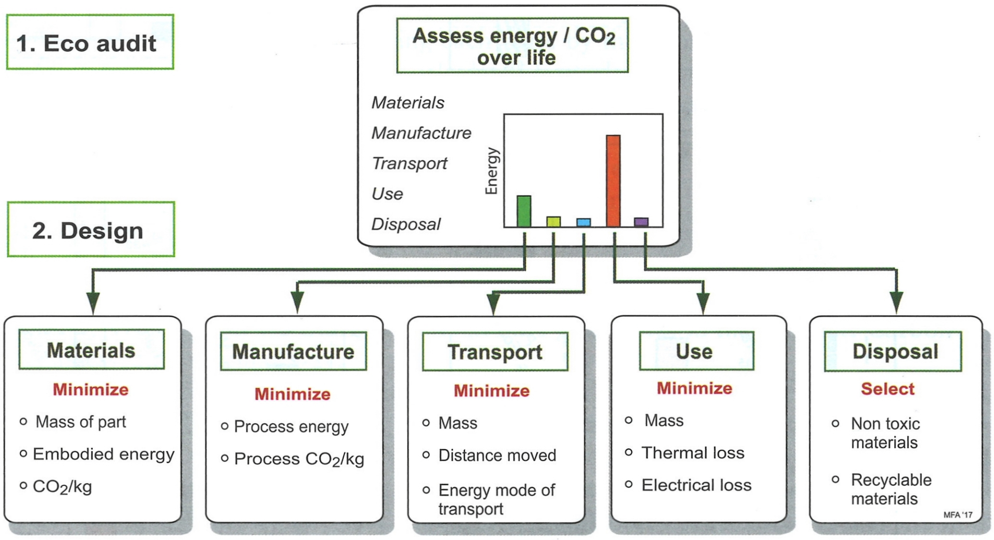

Figure 20.11 Rational use of life-cycle assessment starts with an analysis of the life phase(s) to be targeted. The decision then guides the method of selection to minimize the impact of that phase on the environment.

The materials production phase If materials 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. Large civil structures—buildings, bridges, and 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 manufacture. But 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. Energy efficiency in heating systems is achieved by minimizing the heat flux from the system where we don't want it, whereas for refrigeration we aim to minimize the heat flux into the system; either way, the objective is to minimize thermal conductivity or thermal inertia. Energy efficiency in electrical generation, transmission, and conversion is maximized by minimizing the various losses in the system, such as ohmic heating in the conductors; here the objective is to minimize electrical resistance while meeting necessary constraints on strength, cost, etc. Selection to meet these objectives is exactly what earlier chapters of this book were about.

Example 20.6 Carbon footprint and cost of use phase

A small car weighs 1300 kg; it covers 175,000 miles over its life at an average fuel economy of 35 miles per US gallon. The car carries a spare wheel and tire weighing 13 kg, which the owner has never had occasion to use. If fuel consumption scales linearly with vehicle weight, what has been the carbon and cost penalty of carrying the spare wheel over the vehicle life (gasoline costs around \$3 per gallon in the United States; burning one US gallon of gasoline releases 11 kg of carbon dioxide)?

Answer. The car burns 175,000/35 = 5000 gallons of gasoline costing around \$15,000 over its life and releases 56,540 kg of carbon dioxide. Increasing its weight by 1% (the contribution of the spare wheel) thus carries a penalty of 565 kg of carbon dioxide and costs about \$150 over its life. In Europe the carbon penalty is the same, but the cost is about twice as much.

The product disposal phase The environmental consequences of the disposal phase at the end of the product life have many aspects. Increasingly, legislation dictates disposal procedures, take-back and recycle requirements, and—through land-fill taxes and subsidized recycling—deploys market forces to influence the end-of-life choice.

Transport Globalization means that materials and products are transported over large distances before reaching the consumer. This is often seen as misguided—better, it is argued, to use indigenous materials and to manufacture locally. Economists argue otherwise—the lower labor costs in emerging economies more than offset the cost of transporting materials and products between them and the developed countries where they are sold and used. Table 20.3 gives an idea of the energy and carbon footprint for various transport modes.

Table 20.3 Approximate energy and carbon footprint for transport

Transport type and fuel	Energy (MJ/tonne.km)	Carbon footprint (kg CO_2/tonne.km)
Shipping—diesel	0.18	0.014
Rail—diesel	0.35	0.027
Large truck—diesel	0.71	0.055
Small truck—diesel	1.5	0.12
Family car—diesel	1.4–2.0	0.11–0.15
Family car—gasoline	2.2–3.0	0.15–0.2
Family car—hybrid	1.4	0.10
Aircraft, long-haul—kerosene	6.5	0.54
Aircraft, short-haul—kerosene	11	0.9

Example 20.7 Estimating energies and carbon footprints for transport

Television sets are manufactured in Shanghai, China, and transported to Le Havre, France. What is the carbon footprint per set (shipping mass 21 kg per unit) if sent by sea freight? By air freight? (Search online for estimates of relevant distances.)

Answer. The distance from Shanghai to Le Havre by sea (via the Suez Canal) is 19,200 km. The carbon footprint of this transport leg is $0.021 \times 0.014 \times 19{,}200 = 5.6$ kg CO_2.

The distance from Shanghai to Le Havre by air over Russia is 9330 km. The carbon footprint of this transport leg is $0.021 \times 0.54 \times 9330 = 106$ kg CO_2, about 19 times more than by sea.

20.6 Materials dependence

Critical (strategic) materials New technologies create new materials demands. Wind and solar power, advanced batteries, energy-efficient lighting, electric vehicles, aerospace, and IT are large in scale and rely more heavily on the less-abundant elements in the lower part of the periodic table. Demand has grown rapidly in the last 2 decades for lithium (Li), indium (In), tellurium (Te), gallium (Ga), antimony (Sb), beryllium (Be), high-purity quartz, and rare earth elements (REE) in particular, and supply has not always kept pace. For some elements this is because they are very rare; for others, geopolitical issues can result in export quotas, or conflicts in supplying countries or their neighbors can disrupt supply.

Elements that are essential to a nation for economic or security reasons, and for which supply is uncertain, are classified as 'critical' (Table 20.4). The nation responds by creating stockpiles, seeking strategic alliances with supplier countries to get privileged access, and promoting recycling schemes to recover stock that has already been used. But this supply risk does not always translate into business risk. The requirements of a given manufacturer depend on the concentration of the element in their products and the scale of production; criticality becomes a business risk when the element provides key functionality that cannot be achieved in any other way. Businesses minimize risk by identifying alternative suppliers and exploring substitutes for the element, should supply levels decrease, or prices rise, to an unacceptable level.

Table 20.4 Examples of critical elements and their applications[a]

Critical element	Applications
Lithium (Li)	Batteries, Al–Li alloys
Indium (In)	Transparent conductors, InSb semiconductors
Tellurium (Te)	Photovoltaics
Gallium (Ga)	Gallium arsenide PV devices, semiconductors
Antimony (Sb)	Batteries, flame retardants in plastics, semiconductors
Beryllium (Be)	Cu–Be alloys; X-ray windows, automotive, aerospace
Rare earths (notably Nd, Eu, Ds, Y, La, Ce, Te)	Magnets, lasers, catalysis, phosphors, batteries
Platinum group metals (Pt, Pd, Ir, Os, Rh, Ru)	Catalyst in chemical engineering and auto exhausts

a. Sources: USGS (2002); USGS (2016); US Department of Energy (2010a, 2010b); Jaffee and Price (2010).

Restricted (hazardous) substances Business risk arises in another way. There is increasing awareness that some elements and an increasing number of compounds can cause damage to human health and the bio-sphere. Many of these are substances used in extracting and processing materials (hexavalent chromium in chrome plating, for instance) or are added to materials to give added functionality (fire-retardants and plasticizers in plastics are examples). Nations restrict the use of these substances—the severity of restriction depends on the quantity used and the level of damage they might cause. In the United States, such substances are documented in a series of additions to the Toxic Substance Control Act (TSCA) of the Environmental Protection Agency. In Europe, they are published as REACH[3] directives; early warning of new additions is provided in the wonderfully named SIN ('Substitute It Now') list.

Dealing with risk Dependence on critical elements or restricted substances exposes a manufacturer to business risk and loss of market. The risk is not static: changing relationships between nations can rupture supply-chains, and the list of restricted substances increases every year. Increasingly, manufacturers protect themselves by screening during product development, exploring substitutes before they are needed, and if they can afford it, engaging in R&D to create lower-risk alternatives. Beyond that, they adopt measures to use materials more efficiently (reducing demand) and to retain ownership of the products they make and the materials they use (allowing reuse). This circular approach to materials conservation has increasing appeal.

Circular materials economy[4] Nature operates a circular materials economy. It transforms resources through biological growth. The kingdom of plants captures energy from the sun, carbon dioxide from the atmosphere, and minerals and water from the earth to create carbohydrates; the animal kingdom derives its energy and essential minerals from those of plants or each other. When the organism dies, the waste of nature is recycled with 100% efficiency, drawing on renewable energy (sunlight) and natural decay processes to return it to the ecosystem. This eco-sphere provides the raw materials and other primary resources for further growth, acts as a reservoir for waste, and sustains the essential environment for life, meaning fresh water, a breathable atmosphere, tolerable temperatures, and protection from UV radiation. The natural system manages, for long periods, to live in balance with the eco-sphere.

Since the industrial revolution, large-scale mining and global trade have allowed materials costs to decline[5] in relative terms. At the same time, labor costs have risen, stimulating the development of manufacturing methods that minimize the use of labor (mass production, robotic manufacture, and the like). The low cost of materials has encouraged industry to adopt a linear materials economy best summarized as *take—make—use—dispose* (Figure 20.12).

Some 80% of materials usage still follows such a path, but there is increasing awareness that this cannot go on. The global population is increasing, and all strive for a higher standard of living. The global consumption of materials, at present about 77 billion tonnes per year, is expected to rise to 100 billion by 2030[6]. The stress on the global eco-sphere caused by industrial development is already a cause for concern. And—a more immediate

[3] *REACH = Registration, Evaluation, Authorisation and Restriction of Chemicals.*
[4] https://kumu.io/ellenmacarthurfoundation/educational-resources#circular-economy-educational-.
[5] World Bank. (2013). http://blogs.worldbank.org/prospects/category/tags/historical-commodity-prices.
[6] http://www.foe.co.uk/sites/default/files/downloads/overconsumption.pdf.

driver—the cost of materials is now increasing faster than that of labor. An incentive is emerging to conserve materials rather than reject them. Increased material efficiency, reducing the resources per unit of manufacturing output, can make non-renewable resources last longer, but their loss at the end of product life is a continuing drain. One way forward is to establish a more circular materials economy[7,8].

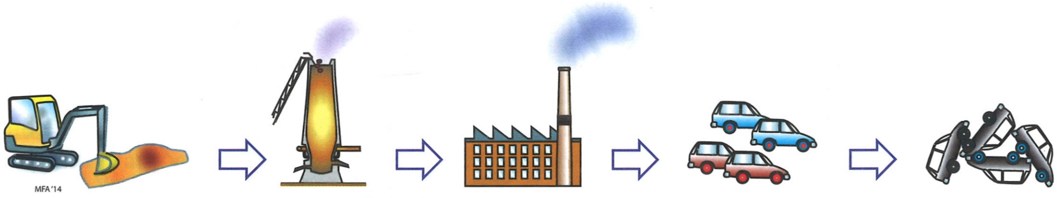

Figure 20.12 The linear materials economy: take—make—use—dispose.

Materials in a circular economy are seen not as a disposable commodity, but as a valued asset to be tracked and conserved for reuse, in rather the same way that financial capital is invested, recovered as revenues, and re-invested. Figure 20.13 introduces the idea. Materials are produced and manufactured into products that enter service, where they remain for their design life. In the circular model, disposal at the end of life as landfill or waste is not an option. Instead, the product is reused in a less demanding way, reconditioned to give it a second lease of life, or dismantled into its component materials for recycling. All three options retain product materials as *active stock* (the upper green box on the figure). It may be impractical to recycle perishable materials; those that are bio-degradable can be composted, returning them to the bio-sphere; those that are combustible can be incinerated with energy recovery; only the remaining residue goes to landfill. The more material that can be retained within the green 'Active stock' box (the upper part of Figure 20.13), the less that needs to be added through primary production. Indeed, if design improvements use materials more efficiently, it may be possible to function, at least for a while, with no primary production at all, thereby creating a circular materials economy.

A *circular economy* means more than just efficient recycling. Taken literally, it means relying on renewable energy, tracking materials through the economy so that their location is known, and using them in designs that allow their reuse with as little reprocessing as possible. The concept goes beyond the mechanics of production and consumption of goods, moving from the idea of *consuming* materials to one of *using* them, somewhat in the way properly managed land is used for agriculture without consuming it. This implies a different approach to design, one focused on material legacy, creating an economy that retains or regenerates materials over many manufacturing cycles, and reduces demand on the use of critical materials. It is an

[7] Ellen MacArthur Foundation. (2014). www.ellenmacarthurfoundation.org.
[8] Webster, K., Bleriot, J., & Johnson, C. (2013). *A new dynamic: effective business in a circular economy*. UK: Ellen MacArthur Foundation. ISBN 978-0-9927784-1-5.

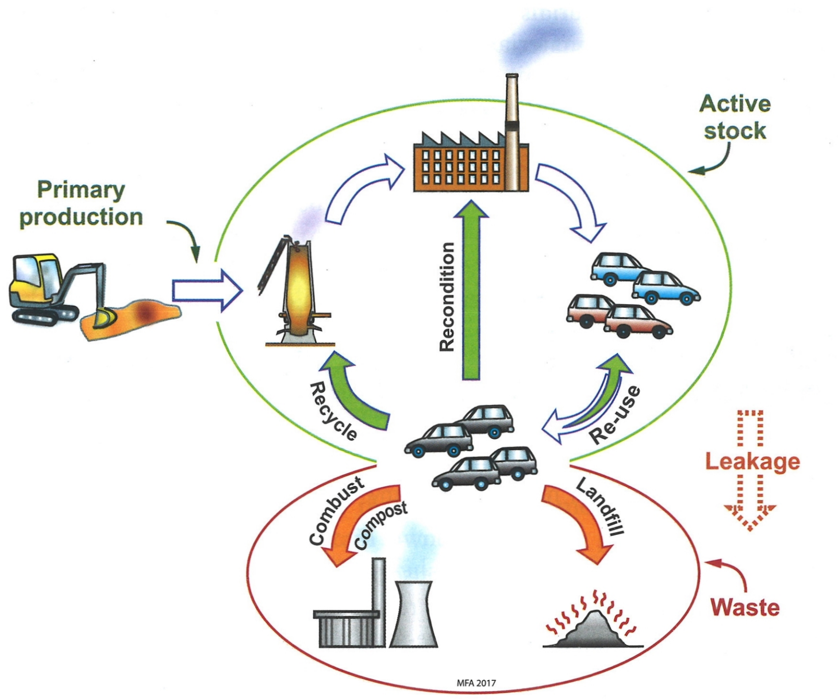

Figure 20.13 The circular materials economy. The aim is to retain materials in the 'Active stock' box by reuse, reconditioning, and recycling, thus minimizing leakage into the 'Waste' box.

important part of a resource-efficient and low-carbon economy, reducing costs and supply risks, and generating value[9,10].

That is the ideal. Ideals do have value; they set a target, something to work toward even if perfect fulfillment is not possible.

20.7 Materials and sustainable development

What is 'sustainable development'? It has become a buzz-phrase, something warm and comfortable but often meaning little more than 'environmentally desirable'; and it has become a favored way of relabeling a current activity to give it the ring of responsibility. We need to do better than that. Here is a short answer: '*A sustainable development is one that provides needed products or services in ways that reduce the drain on natural resources, is legal, economically viable, acceptable to all stakeholders, and equitable both within and between generations*'.

[9] http://www.ellenmacarthurfoundation.org/.
[10] https://www.innovateuk.org/competition-display-page/-/asset_publisher/RqEt2AKmEBhi/content/resource-efficiency-new-designs-for-a-circular-economy.

This sounds right, but how is it to be achieved? And where do materials fit in? The definition gives no concrete guidance. So let's try another view of sustainability, one expressed in the language of accountancy—the Triple Bottom Line or 3BL (Figure 20.14). The idea is that a corporation's ultimate success and health should be measured not just by the traditional financial bottom line, but also by its social/ethical and environmental performance. Instead of just reporting the standard bottom line of income and expenses ('Profit'), the balance sheet should also include the bottom lines of two further accounts: one tracking the impact of the environmental balance sheet ('Planet') and one tracking the social balance sheet ('People'). In this view, sustainable business practice requires that the bottom lines of all three columns show positive balances, represented by the 'sustainable' sweet-spot on Figure 20.14. Many businesses now claim to implement 3BL reporting; indeed, the Dow Jones Sustainability Index[11] of leading industries is based on it. But is it really possible for all three bottom lines to be positive at the same time? And do the terms 'Planet' and 'People' really capture what we are trying to say?

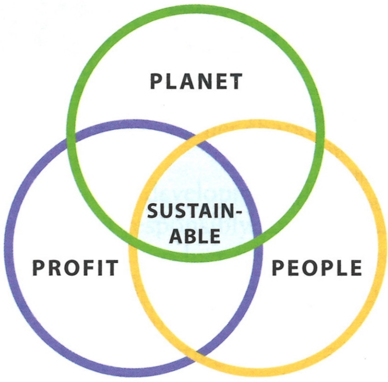

Figure 20.14 The 'Triple Bottom Line': Planet, Profit, People.

The three capitals We make better progress if we separate the circles of Figure 20.14 and unpack their content, so to speak. Here a view of sustainability through the lens of economics can help. Global or national 'wealth' can be seen as the sum of three components: *net natural capital, net manufactured capital,* and *net human capital* (Figure 20.15). They are defined like this:

- *Natural Capital*—clean atmosphere, fresh water, fertile land, productive oceans, accessible minerals and energy.

[11] Dow Jones Sustainability Index. (2012). http://www.sustainability-index.com/.

- *Manufactured Capital*—industrial capacity, institutions, roads, built environment, financial wealth (GDP).
- *Human Capital*—health, education, skills, technical expertise, accumulated knowledge, culture, heritage, and (ultimately) happiness.

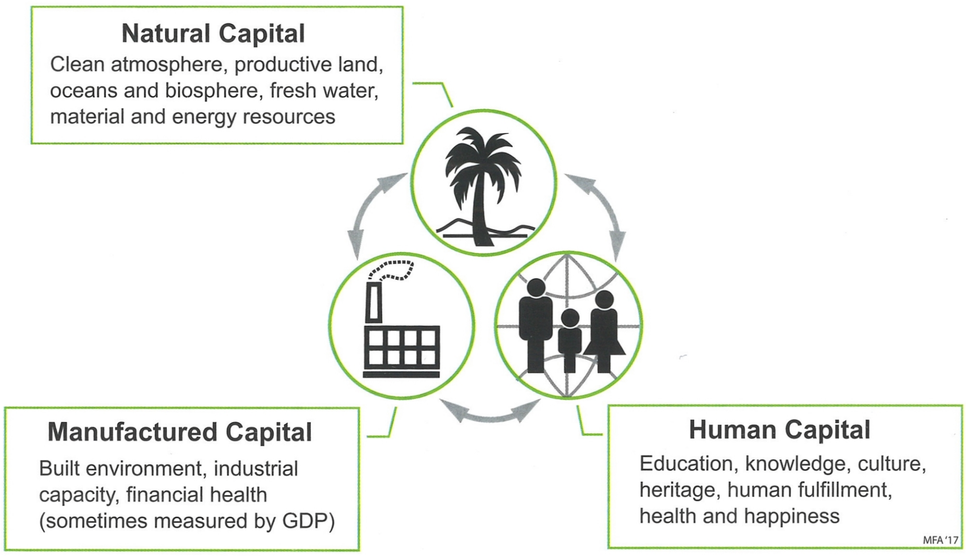

Figure 20.15 The three Capitals. They underpin society as we know it today.

We encountered the first of these earlier when exploring eco-design. Like Natural Capital, Manufactured Capital and Human Capital can be regarded as assets on which we draw and into which contributions can be made. They are mutually supportive provided they remain in balance. Each depends on the health of the others, as suggested by the grey arrows. Natural Capital is drawn down to create Manufactured Capital. The wealth generated in this way underwrites the education and welfare systems that support and expand Human Capital, although it can also diminish it by encouraging unfair labor practices and social inequality. It is the understanding and foresight enabled by education that guide human interventions to support Natural Capital, and it is the resources generated by Manufactured Capital that pay for it.

Thus sustainable development is not one thing; it is many. While the starting point may be an environmental one, sustainability extends far beyond eco-design to embrace economics and legislation as well as social and ethical issues. Some examples will bring out the difficulties.

Advocates of *bio-fuels and bio-polymers* do so because bio-derived products diminish dependence on fossil hydrocarbons—but the land and water required to grow them is no longer available for the cultivation of food. *Carbon taxes* are designed to stimulate a low-carbon economy—but they increase the price of energy, and hence of materials and products. *Design for recycling* is intended to meet the demand for materials with less drain on natural resources—but it constrains the use of light-weight composites because most cannot be recycled. The motivation for *ethical sourcing of raw materials* (sourcing them only from nations with acceptable records of human rights) is that of social responsibility—but a side-effect is to suppress jobs where they may be most needed. Many proposals for sustainable technology aim to support one or another of the three capitals of Figure 20.15, but they often support only one facet of a multi-faceted challenge.

20.8 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, and electrical properties. Thus if material production is the phase of concern, selection is based on minimizing the embodied energy or associated emissions (CO_2 production for example). But if the use-phase is of most concern, selection is based instead on low weight, or excellence as a thermal insulator, or an electrical conductor, while meeting other constraints on stiffness, strength, cost, etc. The charts in earlier chapters of this book give guidance on how to meet these constraints and objectives.

Eco-design is one aspect of sustainable development, but it is not the only one. Sustainable development requires clean energy and responsibly sourced materials that, as far as possible, are recovered and reused at the end of product life. It requires an economy that generates sufficient wealth to provide for daily needs and investment in education, health, and industrial infrastructure. And if it is really to be sustainable, it must be equitable, not merely catering to the wishes of a sector of society, but benefitting society as a whole. Rational assessment of proposed sustainable development requires facts, and the willingness to debate the implications of the facts for the three key Capitals: Natural, Manufactured and Human.

You can find out much more about materials, the environment, and sustainability in two companion texts: *Materials and the Environment* and *Materials and Sustainable Development*, listed in Further Reading at the end of this chapter.

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