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Material efficiency: A white paper

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ABSTRACT

For most materials used to provide buildings, infrastructure, equipment and products, global stocks are still sufficient to meet anticipated demand, but the environmental impacts of materials production and processing, particularly those related to energy, are rapidly becoming critical. These impacts can be ameliorated to some extent by the ongoing pursuit of efficiencies within existing processes, but demand is anticipated to double in the next 40 years, and this will lead to an unacceptable increase in overall impacts unless the total requirement for material production and processing is reduced. This is the goal of material efficiency, and this paper aims to stimulate interest in the area. Four major strategies for reducing material demand through material efficiency are discussed: longer-lasting products; modularisation and remanufacturing; component re-use; designing products with less material. In industrialised nations, these strategies have had little attention, because of economic, regulatory and social barriers, which are each examined. However, evidence from waste management and the pursuit of energy efficiency suggests that these barriers might be overcome, and an outline of potential mechanisms for change is given. In bringing together insights into material efficiency from a wide range of disciplines, the paper presents a set of 20 open questions for future work.

1. Introduction

Engineered materials are abundant and life as we currently live it would be impossible without them. Since the industrial revolution, we have processed these materials in an industry operating mainly as an open system, transforming resources to products that are eventually discarded. However as a result of growing demand, mankind now dominates the global flows of many elements of the periodic table (Klee and Graedel, 2004), selected materials have become scarce, and access to materials affects the security of many nations. An expanding population living on finite resources is always in danger of consuming all its resources and according to Diamond (2006), resource expiry may account for the collapse of several past civilisations. In addition, materials production and processing have dramatic impacts on the environment, including land use patterns, the use of water, undesirable emissions to air, water and land and the consumption of other important environmental resources. The risk of catastrophic climate change due to emission of greenhouse gases (GHGs) is currently seen as an urgent threat, and the basis of industrial development in its current form is challenged by the need to reduce GHG emissions by 55–85% by 2050 (Fisher and Nakicenovic, 2007, Table 3.10, p. 229).

This paper concerns a set of opportunities, which we term 'material efficiency', that might provide a significant reduction in the total environmental impact of the global economy, but which are underdeveloped. Material efficiency means providing material services with less material production and processing, and Fig. 1.1 contrasts the approach of material efficiency with the ongoing pursuit of energy efficiency in the energy intensive industries. Our focus is on engineering materials – those used to create buildings, infrastructure and goods, and excludes the use of hydrocarbons for fuel. We distinguish our interests both from those of resource efficiency (where all resources are measured with a single weight measure) and from product based approaches (often driven by Life Cycle Assessment studies, where it is unclear whether improvement to a particular product has any global significance). By focusing on global use of key materials we aim to identify changes that could make a global impact.

Material efficiency was normal practice prior to the industrial revolution, as the relatively high value of materials compared to labour ensured that buildings and products were maintained, repaired and upgraded. However, since concerns over the environmental impacts of post-industrial revolution production have risen to prominence, material efficiency has received limited attention in contemporary analysis and policy. The ambition of this paper is therefore practical: to survey the wide range of interests that intersect the area; to clarify and organise the evidence we already have; to identify the key open questions whose solution will

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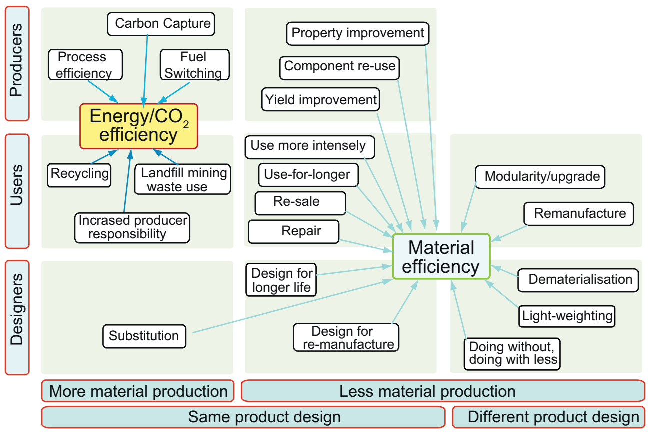

Fig. 1.1. Material efficiency contrasted with energy efficiency.

lead to widespread implementation; to stimulate activity in this area.

2. Is there a need for material efficiency?

Global demand for engineering materials has quadrupled in the past 50 years as shown in Fig. 2.1 and is currently growing at its fastest rate. The International Energy Agency (IEA, 2008a), based on assumed population growth to over 9 billion, and economic growth giving per capita wealth three times greater than the present, forecasts that demand for materials will by 2050 be at least double current levels. This section examines whether this level of demand can be met and if so, whether it can be met without unacceptable environmental stress. If not, material efficiency which aims to provide material services with less material production must be a key response.

2.1. Will we run out of material?

Engineering materials originate from oil (polymers), ores (metals and ceramics) and biomass (timber and paper). The earth's supply of oil and ores, which are non-renewable will eventually be exhausted to the point that their cost exceeds their utility, so the question of whether we will run out of materials can be rephrased as:

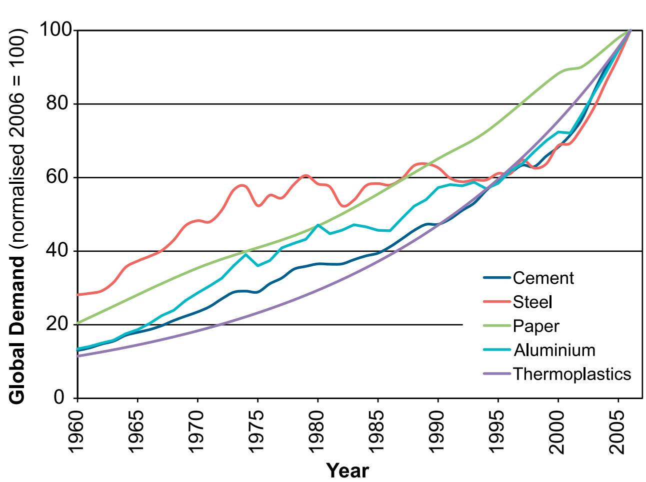

Fig. 2.1. Normalised demand for five key materials 1960–2005. From Allwood et al. (2010).

- When will the difficulty of extracting (non-renewable) oil and ores drive prices to a level that significantly constrains our use of them?
- What rate of use of (renewable) biomass as an engineering material (as opposed to food or fuel) is biologically sustainable?

The criticality of *oil*, particularly the prediction of 'peak oil' – the date beyond which annual oil production declines, has been subject to extensive research. de Almeida and Silva (2009, Table 1) compare 30 predictions of peak oil made since 2000, showing wide variation with several authors predicting a peak before 2020, but some denying that a peak will occur at all. These latter predictions assume that production will expand to match demand, and are derived from forecasts of future GDP. The more credible predictions are based on estimates of physical reserves of un-extracted oil, but these still vary widely. Bentley et al. (2007) explain this discrepancy based on the difference between oil companies' reports of 'proven reserves', which are influential in share price valuation but are dependent on extraction costs, and physically based 'proven and probable' reserves which estimate the remaining contents of each field. Aleklett et al. (2010) in a detailed critique of the '2008 World Energy Outlook' (IEA, 2008b) estimate that 'peak oil' has now occurred, that production from conventional fields will decline, and even with increasing output from new and unconventional sources, total production will decline from ~80 Giga-barrels (Gb)/day now to ~75 Gb/day by 2030. The impact of this on future polymer production is difficult to estimate: demand for oil for transport would grow if not supply-constrained, so declining production will drive up prices. However, the supply of oil for conversion to polymers is secure for the foreseeable future, albeit at increased cost.

The simplest predictor of *ore* criticality is the static index shown in Fig. 2.2. However:

- The definition of 'reserves' in Fig. 2.2 is pessimistic, as it includes only known deposits that could be extracted profitably with current technology. As these reserves are used, prices will rise, so other technology will become profitable and the motivation to identify and exploit other sources will increase. Where estimates are provided, the figure also shows the index based on 'resources' – the total known supply – which is much greater.
- The static index in Fig. 2.2 assumes that demand in all future years will be the same as this year. This is unlikely, and an alternative view taken by Meadows et al. (1972) is that demand will grow exponentially, so the static index is over-optimistic.

The prediction of future ore shortages thus depends on trading off assumptions about future resource discovery and extraction, against those of future demand. Ericsson (2009) examined these trade-offs for the global non-ferrous metals industry, and showed that over a sustained period, exploration spending has been proportional to metal prices. From 2000 to 2008, metal prices rose rapidly, but despite the associated increase in exploration spending, the rate of discoveries of significant new deposits declined. He attributes this to the fact that most easily detected ore bodies have already been located, so exploration of more remote regions or for less easily detected sources is costly. Graedel (2009) goes further claiming that 'most of the likely locations on Earth have now been explored [so] it is unrealistic to anticipate that major new ore deposits lie hidden.' However, the evidence on 'resources' rather than 'reserves' in Fig. 2.2, and the many references in USGS (2010) to minerals in ocean water, suggests that the problem is not an absolute lack of supply, but in the increasing energy and monetary cost of extracting useful minerals from less concentrated sources. This increase in cost could lead to critical shortages of particular minerals and a first attempt to examine this criticality has been made for 11 materials in the US economy by Eggert et al. (2008)

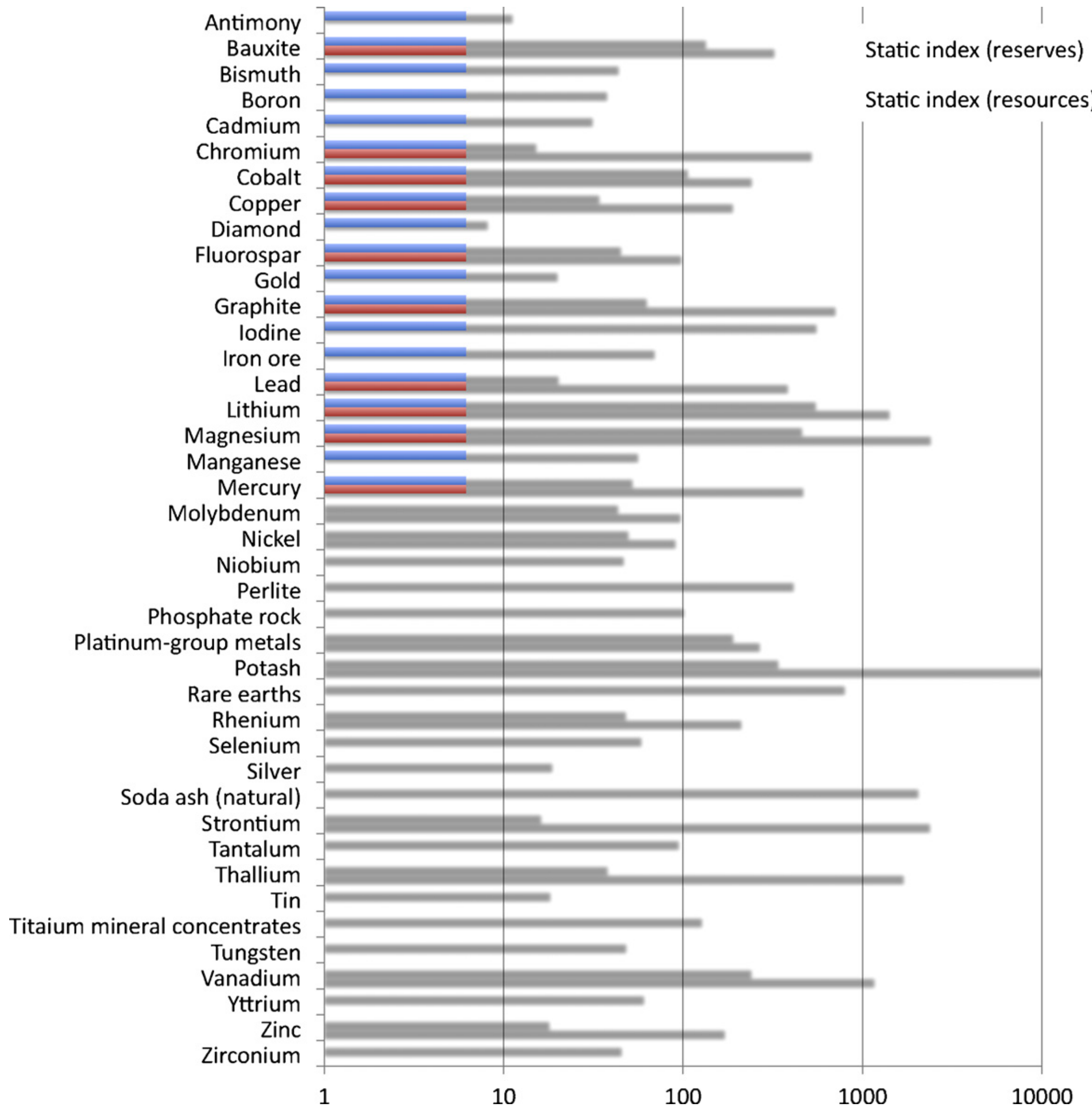

Fig. 2.2. The static index of resource criticality based on 2009 global demand, known reserves and (where given) total resource estimates are given in USGS (2010). The blue (upper) lines indicate the static index based on 'reserves' which are commercially determined, based on the current cost of extraction. The red lines show the static index calculated for estimated global 'resources' – the total known supply regardless of difficulty of extraction. (This estimate is uncertain, due to the need to project total global resources from a small number of very specific bore-hole samples.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

as summarised in Fig. 2.3. In contrast to the static index of 800 years for rare earth elements in Fig. 2.2, Fig. 2.3 rates them as critical – with both a high importance to the US economy and a high supply risk: ~98% of global production occurs in China, which has greatly increasing domestic demand. In summary, it seems unlikely that there will be a shortage of ores to supply the main engineering materials in the near future. However, the supply of some key minerals may be constrained for political reasons, when they are concentrated in few countries.

Bio-plastics, although their production is increasing, are made in only very small volumes compared to plastics made from hydrocarbons (Chadha, 2010), so the key use of *biomass* as an engineering material is for timber and paper. Can we significantly increase the annual supply of timber and paper? Table 2.1 demonstrates that average global annual production is 1 kg of dry biomass per square metre of land. 40% of this is currently appropriated by humans, and it is difficult to increase total output: there is limited land for future expansion, yields can only be increased by small percentages, and at least some of the yield must be composted to provide nutrients for future growth. In a detailed study of biomass production from existing forests in New York State, Castellano et al. (2009) show available production of just 0.15 kg/m^2 per year. Furthermore, the use of biomass for liquid fuels constrains its use for fuel, food and as a material. Eide (2008) reports that in 2007, 23% of US coarse grain production was used to produce ethanol and 47% of EU vegetable oil used for biodiesel, yet in total liquid biofuels provide only 0.36% of global energy supply. The use of biomaterials for material services is thus in competition with other uses, and total biomass appropriation cannot rise significantly in future.

The evidence of this section suggests that we are approaching a limit to the supply of biomass for products and that polymer prices will rise, but it is unlikely that absolute mineral shortages will be a driver of change towards material efficiency. However, the high energy requirements for resource extraction from less concentrated sources may limit future growth. Goeller and Weinberg (1976) illustrate this issue with a simple account taken from narratives by Charles Darwin and H.G. Wells: Malthusian disequilibrium requires a scramble for finite resources; this requires an inex-

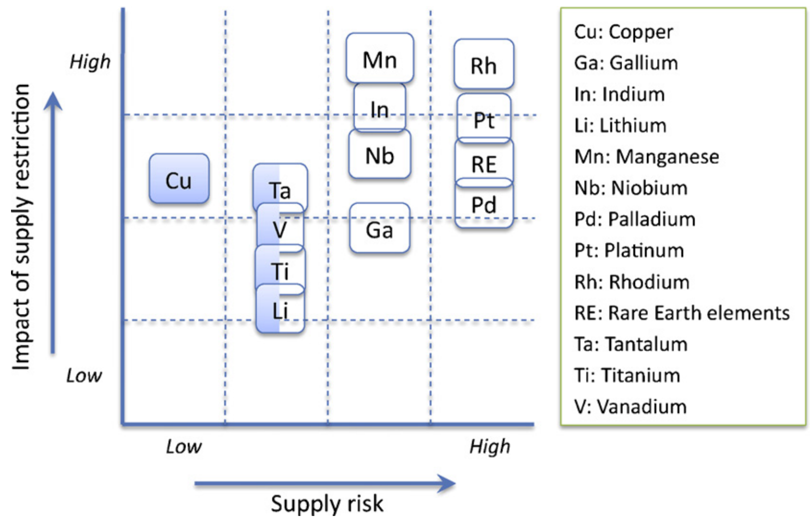

Fig. 2.3. Criticality grid for 11 materials.

Adapted from Eggert et al. (2008).

haustible source of energy, and as high-grade resources dwindle, man expends more energy.

2.2. What is the impact of materials production and processing on climate change?

Preparing useful engineering materials from ores or biomass is energy intensive, and increasingly so for less pure supply sources. An increase in material demand thus implies a greater increase in energy demand, and while most industrial energy is derived from fossil fuels, this in turn implies an increased emission of greenhouse gases. How significant is the contribution of materials production and processing to these emissions?

IEA (2008a) provides the breakdown of global CO_2 emissions (from energy and processes) in Fig. 2.4 demonstrating that 56% of industrial CO_2 emissions, or 20% of all energy and process related emissions, arise from production and processing of just five materials: steel, cement, plastic, paper and aluminium. In assessing the threat of unwanted climate change being driven by these emissions, the Intergovernmental Panel on Climate Change (IPCC) recommends a global reduction in GHG emissions by 55–85% by 2050 (Fisher and Nakicenovic, 2007). Can this level of reduction be achieved for the five key materials in Fig. 2.4, in the light of anticipated demand growth?

Four options exist to reduce CO_2 emissions per unit output within existing production processes:

- *Energy efficiency*: IEA (2008a) presents a review of known energy efficiency options for the five materials prioritised in Fig. 2.4, showing that for steel, 34% of CO_2 emissions per unit output could be saved by a combination of raising all plant to current best practice (18%) and through global adoption of technologies 'beyond best practice' (16%). Equivalent figures for cement (40%), plastic (22%), paper (38%, using further options from Worrell et al., 2000) and aluminium (24%, using further options from Choate and Green, 2003) suggest a limit to improvement in existing process chains of 23–40% reduction in CO_2 emissions per unit output. Operational improvements and supply chain re-design may give further gains if, for instance, the number of thermal cycles in a supply chain can be reduced by co-location, or thermal inertia can be reduced to improve the speed of process start-up. However, Table 2.2 shows that for the materials used in highest volume – iron and aluminium – existing energy requirements are closer to their thermodynamic limits than for less commonly used materials, such as titanium, which implies that there may be less opportunity for future energy efficiency gains from process improvement for these metals.
- *Yield improvement*: More primary material is made than ends up in final goods, and this loss of material between its liquid form and use in a final product is termed the 'yield loss'. For most materials, primary production is the most energy intensive stage, so any yield loss implies an increase in the total energy used per unit of final goods. Yield losses can arise from start-up losses, trimming and scalping during processing, subtractive processing, quality problems, high purity requirements, mismatches between batch and order volumes, and over-ordering. In producing sheet metal components, up to 50% of cast metal is discarded through ingot scalping, rolling trim and blanking skeletons (Mulero and Layton, 2007); in aerospace manufacturing where final product weight

Table 2.1
Global primary production of biomass and its appropriation by humans. Vitousek et al. (1986) popularised by Pimm (2001) present the audit of global primary production of biomass summarised in this table. Their production figures taken from a survey of estimates by other ecologists average 1 kg of dry biomass per square metre per year (with a range between 0.1 kg/m^2/y for deserts up to 1.6 kg/m^2/y for forests). They calculate a low, intermediate and high estimate of human appropriation, and the table reports only the high values. This includes direct use by humans and managed livestock (based on a global human population of 5 billion), material co-opted by humans (excluding other ecosystems) for instance for land clearing, and reduced productivity due to human activity such as pollution.

Production	Gt/y	Consumption	Gt/y
Forest	49	Food for humans from cultivated land	1
Woodland, grassland and Savanna	52	Livestock grazing and fodder	2
Deserts	3	Construction and fibre	1
Arctic-alpine	2	Firewood	1
Cultivated land	15	Non food from cropland	13
Other (chaparral, box, swamps, marshes)	11	Conversion of forest to pasture	11
		Fires on grazing land	1
		Forest lost to fire, unused trimmings, clearances	12
		Difference in agricultural and natural productivity	9
		Desertification	4
		Loss to human occupation	3
Total production	132	Total consumption	58

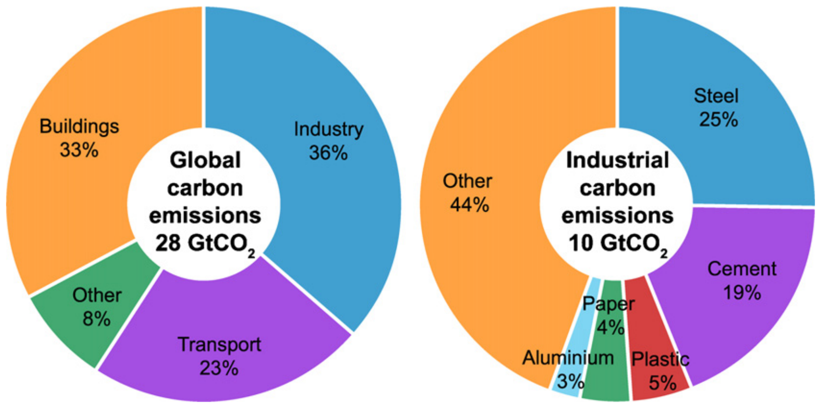

Fig. 2.4. Breakdown of global CO_2 emissions in 2006 demonstrating the importance of five key materials.

dominates all other concerns, the 'buy-to-fly' ratio for material in the product compared to material purchased can be as poor as 10:1 (Boyer, 2010); in construction, over-ordering to minimise the risk of shortages on-site can lead to waste of up to 25% of actual requirements (Navon and Berkovich, 2005). These losses have driven developments such as the design of optimal cutting algorithms for sheet goods, and improved construction management. In developed economies, labour costs often dominate material costs, so the incentive to reduce yield losses may be low. However, if the costs of energy and emissions rise in future, further reductions in yield losses are possible and pursuit of these reductions must be an important component of future material efficiency strategies.

- *Increased recycling rates*: Except for cement, where there is currently no route to create new cement from old, recycling (in which used material is reduced to liquid form) is significantly less energy intensive than primary production so already has strong commercial motivation. Current rates of recycling (the fraction of annual discarded material that becomes part of future production) for steel (65%, from Wang et al., 2007), paper (43%, from IEA, 2007) and aluminium (39%, from IAI, 2007) show how important this route is, even at current relatively low energy prices. However, increasing recycling rates raise technical, economic and operational challenges. The *technical challenge* is summarised in Fig. 2.5. Streams of material available for recycling become increasingly impure as they move further along the materials processing chain, and therefore refining the stream for future high quality use becomes more difficult. In particular, recycling materials from mixed-material products discarded in mixed waste streams, is most difficult – but with the increased complexity of many high-value products, this stream is potentially the largest and most valuable. This difficulty drives the principal *economic challenge* of recycling which is the high cost of collection and separation. In an analysis of 20 distinctly different products, Dahmus and Gutowski (2007) show that products with higher material values are currently recycled provided their mixture is not too complicated. However, they also show by looking at the history of cars, refrigerators and computers that over time, products tend to become more mixed – and hence less economically attractive to recycle. In addition the *operational challenge* of recycling is great: uncertainty over the availability of recycled material streams, dictates that large stocks of recycled materials are required to match supply to demand; the logistics and infrastructure of material collection and sorting are complex; the time delay between production and disposal creates problems in material characterisation; if demand for goods is growing and is the sum of replacement and new demand, the supply of recycled material can never match demand until new demand ceases.
- *Decarbonisation of the global energy system*: The CO_2 emissions from materials production and processing could be reduced if the processes were powered by less carbon intensive energy. However, renewable energy supplies require large land commitment (Mackay, 2009), Carbon Capture and Storage (CCS) and nuclear power installations are expensive (Rubin et al., 2007), and the transition from one energy system to another has historically taken many decades (Smil, 2010). Accordingly, most energy agencies are predicting only modest substitution of the energy mix by non carbon-emitting sources by 2050 – for example, the scenarios of IEA (2008a) predict industrial emissions reduction by 17–37% by 2050 due to CCS. In the US, only 20% of industrial energy use is currently supplied as electricity, so the potential for decarbonisation through new electricity supply is further limited, unless novel electrically powered processing routes are widely adopted.

Table 2.2
Comparison of theoretical and current energy requirements for some metallic elements. Szargut (1989, 2007) provides a table of the standard chemical exergy for nine elemental metals, which is contrasted here with current embodied energy estimates from Smil (2008) and Ashby (2009).

Element	Standard chemical exergy[a]		Estimated embodied energy (MJ/kg)	Apparent efficiency (%)
	kJ/mol	MJ/kg		
Al	795.7	29.5	190–230	14
Cu	134.2	2.1	60–150	2
Fe	374.3	6.7	20–25	30
Mg	626.1	25.8	356–394	7
Ni	232.7	4.0	135–150	3
Pb	232.8	1.1	30–50	3
Sn	558.7	4.71	40	12
Ti	907.2	18.9	600–1000	2
Zn	339.2	5.2	70–75	7

[a] Standard chemical exergy is the minimum reversible work required to produce a pure material from its reference composition at standard temperature and pressure. As an illustration, iron (Fe) is produced from Fe_2O_3 at its crustal composition.

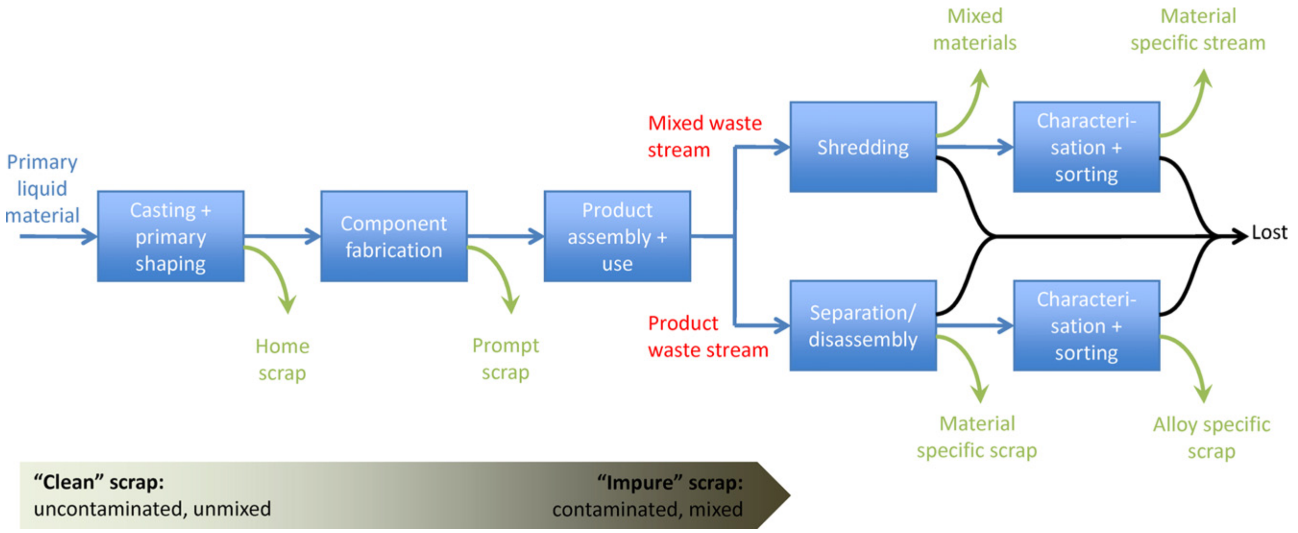

Fig. 2.5. Recycling streams of decreasing purity adapted from the analysis of metal recycling by Graedel et al. (2010).

Fig. 2.6 anticipates the combined effect of implementing these four options and shows that due to demand growth, 2050 emissions will not be below 50% of current levels for any of the materials under any demand scenario, even with exceptional world-wide improvements to existing processes. Thus the carbon emissions reduction targets recommended by the IPCC cannot be achieved for the five key materials of Fig. 2.4, if future demand is met by the existing supply chain, regardless of how efficient it becomes.

2.3. Other environmental concerns

In addition to concern about energy and climate change, production and processing of materials have many other impacts on the eco-system, summarised in Table 2.3. Hujbregts et al. (2006) observe that, apart from toxicity, many impacts are correlated with cumulative fossil fuel use – so constraint of energy/carbon has related benefits. One important exception to this is concern in densely populated nations over the availability of land for landfilling waste, which has led to recent changes in waste legislation in the European Union (Mazzanti and Zoboli, 2008). Another exception is concern over the availability of fresh-water, which is already becoming critical in several regions. Fig. 2.7 suggests that extraction and processing of minerals are not major driver of water use, although locally, water stress may constrain some processing. The major impact of current materials processing on water is through toxic releases.

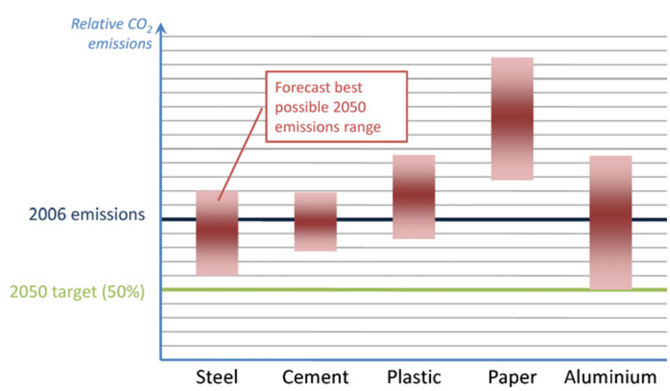

Fig. 2.6. Anticipated emissions in 2050 relative to 2006 levels with an optimistic projection of future efficiency in the existing supply chain: global implementation of all known energy efficiency measures; 20% reduction of yield losses; recycling rates increased to a maximum (i.e. all products recycled except where material is dispersed e.g. aluminium oxide in toothpaste) or cannot be reused (e.g. paper products used for hygiene); 20% de-carbonisation of all energy supplies. The emissions forecasts are dependent both on anticipated demand, and on the rate at which demand is growing in 2050 – less growth implies that a greater fraction of demand can be met by recycling used material. The figure thus shows anticipated CO_2 emissions in 2050 with demand varying by ±20% from IEA predictions (IEA, 2008a) and the fraction of annual purchases being added to stock varying between 0 and 40%. Figure summarised from the analysis of Allwood et al. (2010).

2.4. The limits to the efficiency of existing production processes drive the need for material efficiency

This section has demonstrated that demand for materials is likely to increase substantially. A consequence of "peak oil" is that oil and hence polymer prices will rise but in general we will not run out of minerals. We cannot expand our use of timber and paper significantly due to competition with other uses of biomass. The energy, climate and other environmental impacts of materials production are serious, mainly arising in the early stages of the supply chain, in the primary and secondary production of materials in

Table 2.3
Indicators of environmental impacts associated with products in Europe, from a survey of 11 analyses of the environmental impact of consumption spending in Europe reported by Tukker and Jansen (2006). This list mixes resources (land), specific substances (CO_2), types of substance (waste), the ways the substances change a species or system (acidification) and the long term effect of that change (years of life lost).

Emissions to air	Global warming potential (CO_2, SO_2, NOx)
	Ozone depletion potential
	Photochemical ozone creation potential
	Chemical oxygen demand
Emissions to water	Toxicological impact (in various categories)
	Human toxicological impacts
	Ecotoxicological impacts
Emissions to land	Waste
	Heavy metals
Impact on species	Years of life lost
	Acidification
	Abiotic depletion potential
	Eutrophication potential
Resource indicators	Primary energy consumption
	Depletion of non-renewable resources
	Ecological Footprint
	Total materials requirement
	Land use
	Water consumption
	Fish (!)

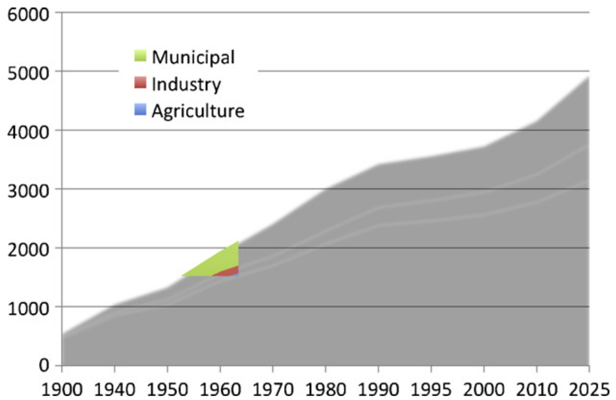

Fig. 2.7. Global freshwater use from Shiklomanov (2010) showing global freshwater use rising steadily since 1900, but dominated by agriculture, with industrial use at around 10% of the total, half of which is required for power generation.

liquid or powder form (molten steel, aluminium and polymers, cement, pulp.) We do not have enough options to reduce these impacts to levels targeted by current policy by seeking greater efficiencies within current production systems. Therefore, if we really want to reduce the impacts, we need to examine options to provide the material services we want with less production of liquid material, whether from primary or secondary sources. This is the concern of material efficiency.

The argument of this section is based on clear evidence, but is not yet well known. The need to clarify and reinforce this logic leads to the open questions in Table 2.4.

3. Material efficiency options

What options do we have to provide more material services with less production and processing? What experience do we have already in implementing this options?

The UK government has extensively promoted a waste hierarchy of “reduce, re-use, recycle” (DoETR, 1995) now taken up in China as the ‘Circular Economy’ (Yuan et al., 2006), of which the first two options describe material efficiency, but in reality much policy has been oriented towards promoting the third (Bulkeley and Gregson, 2009). In the Netherlands, an extended version of this structure is provided by ‘Lansink’s ladder’ (Parto et al., 2007) which prioritises in order: waste prevention, design for waste prevention, product re-use, material recycling, material recovery for use as a fuel, incineration, landfill. However these are intended as phrases for easy recall, and do not aim to be comprehensive. Is there an organising principle by which we can identify all possible material efficiency options?

Table 2.4
Open questions about the need for material efficiency.

OQ1	Which minerals will become critical in which countries and when, and what will be the impact?
OQ2	In future competition for land-use and biomass, which renewable materials will be constrained and what impact will this have?
OQ3	In practice, how far can energy and yield efficiency approach the theoretical limits? Can we expect radical process innovations? To what extent are further process efficiency steps inhibited by incumbent industrial players/structure?
OQ4	To what extent will it ever be possible to create a closed-loop materials system? Which technical barriers cannot be overcome? Does the pursuit of maximum performance from materials/products act against the needs of a materially efficient system – would we be better off with fewer material options?
OQ5	Which chemicals associated with materials processing are most damaging, where are they used and how can their use be avoided or minimised?

By analogy with the Kaya identity (Kaya, 1990) we can express the total emissions associated with the production and processing of some material by,

$$C = D \times \frac{M_p}{D} \times \frac{M_s}{M_p} \times \frac{C}{M_s} \quad (1)$$

where the total energy and process emissions associated with the material (C) is the product of demand for goods containing the material (D), the average mass of material per product (M_p/D), the yield ratio of material supplied to material eventually occurring in the product (M_s/M_p) and the average emissions per unit of primary material (C/M_s). We can expand (1) to show how demand D is the sum of new demand N and replacement demand (S/L) where S is the stock of existing goods, and L is their average lifespan, and to account for the different emissions factors when the material is sourced from primary ore (C_o/M_o) recycling (C_r/M_r) and re-use (C_u/M_u) with $M_s = M_o + M_r + M_u$, and $f_o = M_o/M_s$ etc. This leads to,

$$C = \left(N + \frac{S}{L}\right) \times \frac{M_p}{D} \times \frac{M_s}{M_p} \times \left(f_o\frac{C_o}{M_o} + f_r\frac{C_r}{M_r} + f_u\frac{C_u}{M_u}\right) \quad (2)$$

Eq. (2) allows a structuring of options to reduce emissions associated with materials processing. The options already discussed in Section 2.2 were:

- Reducing C_o or C_r – improving the energy efficiency or decarbonising existing processes for creating liquid material.
- Reducing M_s/M_d – improving the yield ratio.
- Increasing f_r – increasing the recycling rate.

The other options revealed by (2) are:

- Reducing N – which is uncomfortable if taken to mean impeding growth in developing countries, but could imply supporting a less materially intensive path to prosperity.
- Increasing L – either by using products more intensely and for longer, or by providing means to repair, upgrade or remanufacture products when discarded by their first owner.
- Reducing M_p/D – designing ‘lightweight’ products with less material input.
- Increasing f_u – the fraction of material supplied by re-use when, as is often the case, C_u is small.

These then are the options for implementing material efficiency, resembling those put forward by Geiser (2001) in his examination of historical and present-day actions and attitudes relating to material conservation. Fig. 3.1 illustrates all the above options on a schematic of a typical material supply chain. The remainder of this section presents current evidence about implementation of these material efficiency options.

3.1. Longer life, more intense use, repair and re-sale

Between 2000 and 2005, UK consumers on average increased the number of garments they purchase annually by 33%, and it is cheaper to buy a new pair of trousers than repair a hole in their pockets (Allwood et al., 2006). Product lifespans are shrinking, for instance between 1985 and 2000 the lifespan of computers purchased in US universities dropped from 10.7 to 5.5 years (Babbitt et al., 2009). 28 million cars are licensed for use in the UK each year, for 60 million people who spend an average of 225 h per year in a car, so on average 98.4% of all licensed car seats in the UK are not in use at any time (DfT, 2009). Even if used furniture is given away for free in the UK, the economic case for re-selling it is at best marginal (Alexander and Smaje, 2008). These examples suggest that consumers in developed countries are continuing to expand their material consumption well beyond their basic needs,

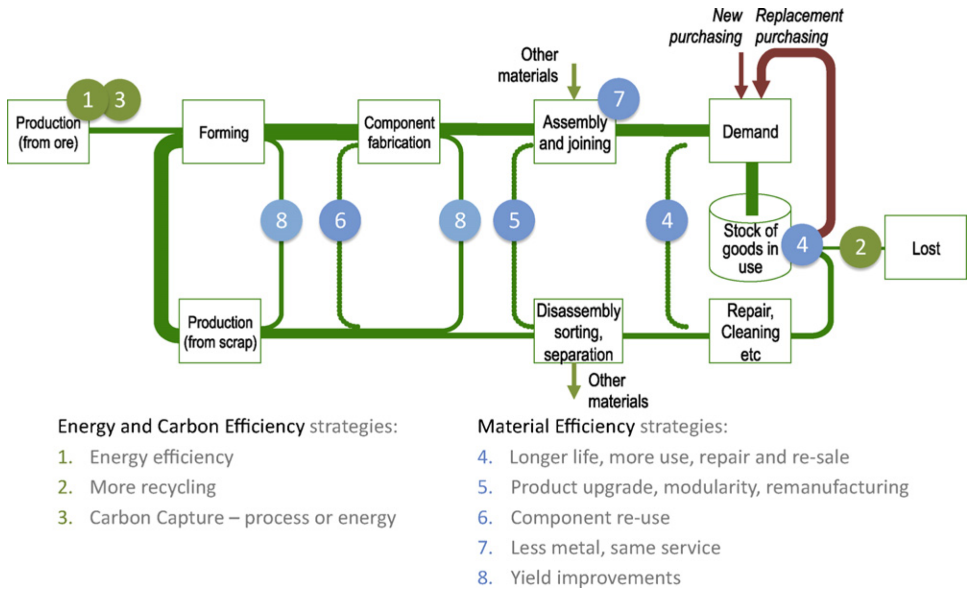

Fig. 3.1. Conventional and material efficiency options. The numbered circles indicate (1–4) the energy and carbon efficiency options discussed in Section 2.2, and (5–8) options for achieving material efficiency. Recycling, in which the material is reduced to liquid form, is included in the first list because it implies no change in the volumes of the liquid material produced. In contrast, options 5–7 show demand reduced by material re-use, while option 8 considers changed product designs. The figure emphasises the difference between annual demand, and accumulated stocks, and shows a separation between new and replacement demands.

that they discard goods before they are expired, that the drive for individual ownership has led to excess capacity and that the pursuit of fashion, even in investment products such as furniture and white goods, leads to rapid economic depreciation regardless of function. Evidently, such consumers could maintain their quality of life with a lower rate of new product purchasing. Three strategies that might support this are life-extension, shared ownership and product repair.

For products with little impact in use, but high impact in production, *life-extension* is beneficial. However, if the impacts in use are significant, and if technology improvements lead to reductions in those impacts, it may be better to replace products earlier as illustrated in Fig. 3.2. Some evidence on this trade-off is provided by a study of eight domestic appliances by Truttman and Rechberger (2006). They found that, with strong assumptions in favour of re-use but real data on technology improvements and use energy, a 50% life extension would on average lead to only a 12% reduction in total energy requirements: apart from the computer, energy in use dominated production energy for all other products. Therefore, for these products, life extension reduced the (lesser) production or embodied energy component but delayed adoption of improvements to the (greater) use phase energy requirement.

However, such a calculation of optimal life, ignores consumer choice and in reality there are many other reasons why consumers opt to replace products. Ashby (2009) describes product life as the shortest of: the physical life (when the product breaks beyond economic repair); the functional life (the need for the product ceases); the technical life (the product is obsolete); the economical life; the legal life; the life in which the product remains desirable. Of these, the major causes of engineering failure that determine the physical life are summarised in Table 3.1, showing that technical options for responding to them are available. Consumers thus choose to replace goods which have not physically expired, even though designers have options to make longer lasting goods.

Considering replacement from the viewpoint of consumers, van Nes and Cramer (2006) describe four motivations for replacing a product: wear and tear (Ashby's physical life); improved utility; improved expression; new desires. The last two of these reflect the 'emotional' significance of products where consumers assume that ownership of particular products helps to establish part of their identity, or where new ambitions require new products. It is this emotional content that has driven interest in 'sustainable consumption' which seeks to identify means to reduce demand by understanding its social significance. Cooper (2005) describes the design of a product as a combination of 'shape and surfaces' (physical content and appearance) its 'signs and scripts' (the signals it conveys within human relationships) and the 'sales and services' by which it is bought. Based on the first two of these, Cooper proposes that the desire to replace goods might be contained if consumers had better information on durability or if they can be involved in personalising production, so they will not discard goods so easily. Based on the third, he identifies several alternative means to delay product replacement: adding value during the product life cycle (through extended warranties for instance); avoiding purchasing through leasing (as described in the literature on 'product service systems' for instance Behrendt et al., 2003); use of products through a service provider (such as a laundrette); shared ownership.

Table 3.1
Technical causes of end-of-life and options to overcome them.

Failure mechanism	Options in response	Examples of leading edge practice
Fatigue	Material inspection for cracks prior to manufacturing, and in service; redesign for reduced load cycling.	Aeroplane wings experience significant cyclic loading throughout their life, but failure is now extremely rare
Wear	Surface hardening and polishing, design for reduced contact pressures	Automotive bearings are now sold guaranteed for life
Corrosion	Sacrificial anodes, other electro-chemical response, coatings	Oil rigs operate in salt water without significant repair throughout the life time of a particular oil field
Creep	Reduction of cracks and grain boundaries in vulnerable components	Blades in high performance gas turbine engines are made from single crystals to withstand high centrifugal loads for long periods of service at high temperatures

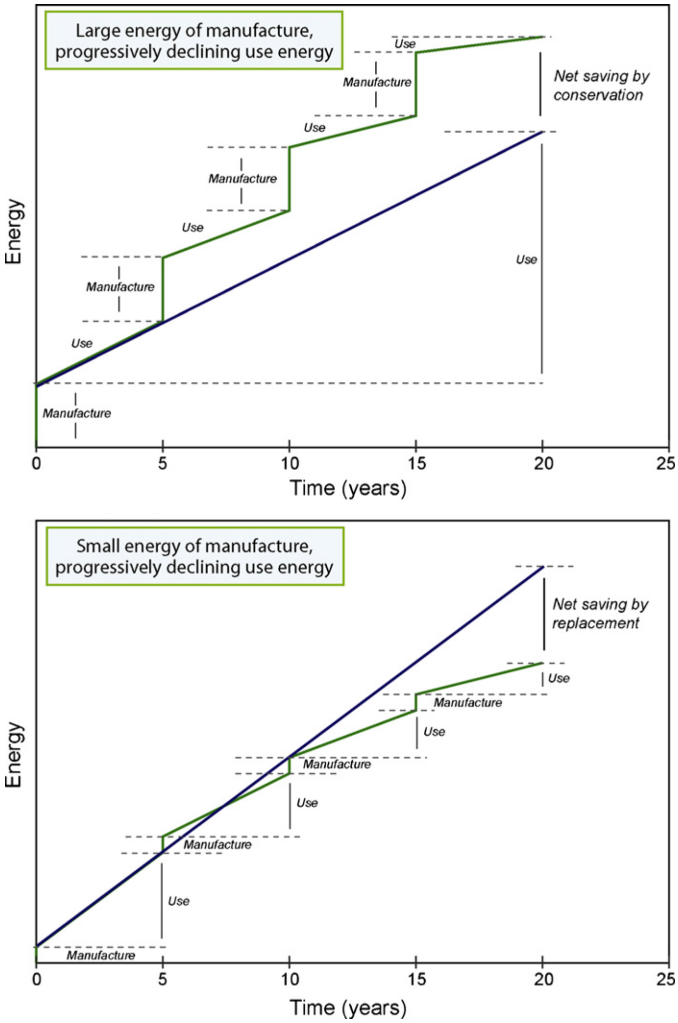

Fig. 3.2. Trade-off between production and use phase impacts with technology improvements (adapted from van Nes and Cramer, 2006). The long-run environmental impact of product ownership depends on the balance between production energy (steps in the lines), use-phase energy (slope of the lines), life span (time between steps) and the rate of technology improvement (reduction in the gradient of the slopes with time).

One of the few reported examples of attempts to *increase intensity of use* through shared ownership has been in the development of 'car-pools'. Prettenthaler and Steininger (1999) based on detailed questionnaires sent to 198 Austrian members of car-sharing organisations report that members reduce their driving mileage and show a cost-saving if driving fewer than 15,000 km per year. This should make membership attractive to around 70% of car-owning Austrian households. However, having recognised the value of having a car available without waiting, and the prestige of car ownership, they revise their estimate of benefit down to only 9%.

The business case for *repair*, to extend product life, is generally weak in developed economies with high labour costs and where most products are sourced from low labour cost countries with high economies of scale. Nevertheless, Whelan et al. (2006) provide detailed analysis of electric motor repair at industrial sites, with evidence that significant cost savings can be achieved by: correct motor specification; maintenance of appropriate spare parts; intelligent preventative maintenance; standardised repairs; detailed documentation. However, the business of second-hand sales does exist within such economies, and in some cases is growing. Matsumoto (2009) examines four second-sales businesses in Japan (books, cars, car-parts, LCD screens) and observes that volume of sales is a key driver of success. Accordingly he defines the key characteristics of re-sale businesses as requiring a secure volume of supply, guaranteeing volumes of demand by providing clear quality assurance, and ensuring price transparency for example by setting re-sale prices as a fixed fraction of the new price. The need for trustworthy quality assurance is to overcome the problem of 'information asymmetry' described by Akerlof (1970) in which sellers of second-hand goods know more about the quality of their offering than buyers.

The evidence on increasing product lifespans suggests that unless the product has a high use phase impact, life extension is beneficial and technically not difficult, but is not currently wanted by consumers or producers. The decision to delay product replacement depends on a shift of consumer attitudes, and the little available evidence in this area suggests that this might happen if consumers find in products some emotional content so their disposal represents a personal loss. There is little evidence on shared ownership in developed economies, but examples of successful re-sale businesses suggest that a high volume of turnover is essential.

3.2. Product upgrades, modularity and remanufacturing

A second opportunity to extend the life-span of the materials in a product arises when a discarded product can be upgraded to overcome the loss of utility, expression or desirability that caused its discard. Academic work in this area under the broad banner of 'remanufacturing' has spawned a vast literature, but much of this is visionary rather than practical, including extensive efforts to optimise hypothetical models of reverse logistics systems. However, several practical case-studies have been reported including the re-use of modules in Xerox photocopiers (Ayres et al., 1997; Kerr and Ryan, 2001), re-use of 'disposable' cameras by Kodak (Bogue, 2007), remanufacturing of engine blocks at Caterpillar and others (Smith and Keoleian, 2004; Sutherland et al., 2008; Seitz, 2007), tyre remanufacture by Michelin and others (Ferrer, 1997a), appliances (Sundin and Bras, 2005), packaging (Tsiliyannis, 2005) and automotive parts (Subramoniam et al., 2009). In addition, some more structured analyses of these products and related studies have been performed by Ferrer (1997b), Ferrer and Ayres (2000) and Zwolinski et al. (2006). Summarising the lessons learnt from these studies:

- *Motivation*: Where remanufacturing is undertaken by independent operators, profit is the only motivation. However, most remanufacturing is pursued by original equipment manufacturers who in general are *not* motivated to do so by profit, environmental impact or environmental legislation. Instead, it is undertaken to prevent competition in after-sales support, to protect intellectual property, or to protect brands (against degraded performance after servicing or re-sale by independents). Remanufacturing also provides a means for supplying parts for products that have been phased-out, and in some cases may be a cheaper or faster source of parts than new replacements – for instance if products are replaced due to the technical obsolescence of some but not all of their components.
- *Conditions for success*: Products for which remanufacturing is likely to be successful are typically at the mature end of their life cycle, in a market with slow technology development. The price of the used product prior to remanufacturing is ~0–20% of the new price, and the remanufactured product retails at 40–60% of the new price. Successful remanufacturing tends to occur in more vertically integrated companies, but it is not clear if this is cause or effect.
- *Design guidance*: Only a few authors have reported design recommendations for products intended to be remanufactured as summarised in Table 3.2. An emerging option for modular products is to embed sufficient electronic monitoring into the product

Table 3.2
Design guidelines for remanufacturing within a framework based on that of Sundin and Bras (2005) with the columns indicating a typical remanufacturing process, and the rows being design attributes. The table also includes insights from the large literature on 'Design for X' (see for instance Huang, 1996) in which 'X' might be 'disassembly', 'environment', 'remanufacturing' or other related words. Most of this work aims to define performance measurements for 'X' and iteratively improves them during the design process, but Watson et al. (1996) and Bogue (2007) provide some specific design guidelines.

Product property	Design guidelines	Remanufacturing step						
		Inspection	Cleaning	Disassembly	Storage	Repair	Reassembly	Testing
Ease of identification	Use identical or grossly dissimilar parts; color coding	X		X	X			X
Ease of verification	Well documented testing procedures; easy access to test points	X						
Ease of access	Avoid sharp edges and thresholds	X	X	X		X		X
Ease of handling	Minimise component count; aim at modular design; use standardised parts where possible, avoid fragile parts			X	X	X	X	
Ease of separation	Minimise number of joints; eliminate hidden joints; use reversible joints or connectors with fracture points; avoid welding, adhesives and coatings; avoid long disassembly paths; simplify electronic connections; ensure screw threads are sufficiently robust			X		X		
Ease of securing	Standardise joints						X	
Ease of alignment	Aim at self-locating interfaces; maximise part symmetry						X	
Ease of stacking	Avoid protrusions outside regular volume				X			
Wear resistance	Aim to concentrate wear damage in small detachable parts (inserts and sleeves.)		X	X		X	X	

to predict the expiry of different modules based on their specific use history.

- *Consequences*: Although environmental impacts are not the motivation for current remanufacturing, the approach is beneficial and various case studies suggest energy and material savings between 30 and 90% compared to manufacturing new parts. Cost savings also occur, but the costs of remanufacturing are dominated by storage, administration and part replacement. Widespread development of remanufacturing in a national economy could increase employment, if it led to a substitution of labour for materials, but its other effects are unclear.

Remanufacturing appears to be commercially more attractive than life-extension as manufacturers can add value to what would otherwise be scrap products. Its success depends on sourcing old goods at a low value, and with only low cost operations, upgrading them to allow resale at lower than new prices, without disrupting the market for new goods. To date, however, it appears that most examples of remanufacturing are pursued to prevent competitive actions, and businesses as configured today have not identified an advantage from upgrading older models.

3.3. *Component re-use*

Life extension and remanufacturing as discussed would extend the life of materials within the product in which they were originally used, but a further option is to separate the product into components, which can then be used in new products. Table 3.3 suggests a classification of this type of component re-use as 'non-destructive recycling'.

Such non-destructive recycling has been examined most widely in construction (for instance Gorgolewski (2008) based on case studies in Canada and Da Rocha and Sattler (2009) in Brazil), but it is also applied through the re-rolling of steel plates following ship-breaking in India (Tilwankar et al., 2008; Asolekar, 2006) and has been explored by Counsell and Allwood (2008) for office paper,

Table 3.3
Material re-use – from re-sale to recycling.

Structural change	Description and examples of recycling process	Type of recycling
No change	The product is transferred from one application to another. *Examples*: Re-use of bottles, second-hand sales of books and clothing, modular construction/deconstruction	Direct re-use
Superficial	Changes are made to the surface of the product only. *Examples*: toner removal from paper, refurbished cardboard boxes (label/print/tape removal), molten-salt processing, thermal cleaning, ultrasonic sound waves, non-abrasive blasting media	
Deformative	Alterations are made to the form of the product without addition or subtraction of material *Examples*: bending metal beams, reforming steel columns, re-folding of cardboard boxes, re-rolling of steel plate (Indian ship salvage)	Non-destructive recycling
Subtractive	Material is removed from the original product *Examples*: dye-cutting of used cardboard, removal of oxide coating, cutting new shapes from used steel plate	
Additive	Products are joined together e.g. by welding or gluing *Examples*: cold bonding of aluminium, welding processes (selective recasting, friction welding, laser cladding, wire-arc spraying), gluing of plastics/paper	
Destructive	Breaking down a material so it can be used as feedstock in conventional production processes. *Examples*: melting of plastics and metals, re-pulping of paper/board	Conventional recycling

by Allwood et al. (2010a) for steel and aluminium across sectors, and by Gronostajski et al., 1997 for scrap aluminium. Typically, a re-use process might comprise collection, separation, sorting, cleaning, upgrade, inspection, certification, stock-holding, market access, delivery, modification and eventual reassembly.

The environmental benefits of component re-use appear to be clear, particularly for large components that can be reused without substantial modification. Evidence from Allwood et al. (2010a) suggests that re-use processes require very little energy, so imply additional emissions only if re-used material is used inefficiently, must be augmented by new material, or requires additional maintenance. Economically, re-use also appears attractive – more so in a low labour-cost country, but even in developed economies the additional cost of deconstruction appears to be offset by the increased revenue from sale of reclaimed components, and the avoidance of disposal charges. However, except in the case of temporary structures (such as exhibition pavilions) construction with substantial use of reclaimed components remains challenging because:

- The supply chain is not developed, so sourcing reclaimed parts requires individual search and negotiation and contractors are cautious about engaging in re-use. In the UK, health and safety legislation and time pressure from land-owners both strongly favour demolition over deconstruction at present, thus limiting the supply of parts for re-use.
- Use of reclaimed components generally increases project complexity, design fees are typically higher when a design must be built around existing components, and some repair or modification costs may be incurred.
- It may be necessary to re-certify reclaimed components prior to re-use. Generally, reclaimed components are not sufficiently well documented for re-use without testing, and testing is currently expensive.

Component re-use, particularly in construction, is an effective emissions abatement strategy and depending on the split between scrap and new prices for materials, can be profitable in developed countries. However it operates only at very small scale at present, principally due to a lack of supply. This could be changed with relatively simple interventions.

3.4. Using less material to provide the same service

Extending product life, upgrading products and re-using components are all material efficiency strategies applied at the end of the product's first life. The final option identified through Eq. (2) relates to product design prior to first construction: the impacts of material use in providing a service can be reduced if less material is used. This might occur if the existing material properties are upgraded, if existing materials are substituted by others giving less impact, if the amount of material used is reduced by design optimisation or if the service provided by the material can be dematerialised.

The properties of a given material can be *upgraded* either when improved processing can give improved properties, or when the properties are locally controlled within a product as part of a manufacturing process. An example of the first kind is in the recent invention of Bainitic steels which can have strengths up to 2500 MPa compared to conventional steel around 700 MPa, without a significant change of energy required in processing. If strength is the key design limit on some component, this implies a substantial embodied-energy benefit. As an example of the second kind, surface engineering is widely practised to enhance component life through increased wear resistance, for instance in rail track. The development of 'functional segregation' remains an exciting avenue for manufacturing engineers, but it is unclear how much material could be saved.

In specialised applications, for instance the use of platinum in catalytic converters, or rare earth elements in super-conductors, material *substitution* is difficult. However, in more general (and therefore higher volume) applications, most engineering materials do have substitutes with similar properties, so for example it is possible to construct houses, tower blocks and even cars out of wood. Could such substitutions lead to a substantial reduction in the impacts of material services? Fig. 3.3 shows that, of the five materials prioritised by Fig. 2.4, stone and wood are candidate substitutes for concrete and steel with reduced embodied energy although this would be 'back to the future': construction with concrete and steel is current because it is easier. For paper, plastic and aluminium – which are typically selected for other properties – no obvious substitutes exist. Where aluminium is used because of its low density (for instance in aerospace), it is increasingly substituted by composites. However, as yet, recycling of composites is not possible (highly toxic processes can be used to extract fibres, but the energy intensive matrix materials are lost) so this substitution is unlikely to give a net benefit.

'Light-weighting' involves *reducing* the amount of material required to provide a service. For consumable materials, intelligent application may allow significant savings without reduction of service. For example, Worrell et al. (1995b) demonstrate that a 44% reduction in fertiliser use in the Netherlands can be achieved simply by applying the fertiliser only in the required location, at specified dosage. For non-consumable materials used to create products or structures, the subject of topology optimisation (e.g. Sigmund, 2000) aims to minimise the mass of material required to deliver a given service. For materials which are 'cast' from liquid to final form in a single process, particularly for polymers, such optimisation is practical and widely used. However, for materials such as metals or wood which are machined as part of production, such optimisation generally reduces the mass of the final part, without reducing the mass of material required to create the product. One response to this has been to propose use of 'additive' manufacturing techniques, in which complex parts are additively built up from powder or liquids. However, Fig. 3.4 demonstrates that processes related to novel materials, and those which build up material at small scale, lead to the highest rates of energy use. (This also reaffirms the point made in Table 2.2, that there is more scope for energy efficiency in the processing of less commonly produced and more specialised materials.) In addition, more optimised products may be less robust in use, it may be harder to reuse or recycle optimised parts and complex components may be harder to separate at end of life. As yet there appears to be little effort applied to optimising the total mass of produced material required to deliver a final service.

In examining *dematerialisation*, Ayres and van den Bergh (2005) discuss three mechanisms of economic growth: substitution of fossil fuels for labour to reduce costs; scale economies and learning by doing to reduce costs; substitution of information/knowledge leading to increased value to customers. This vision of dematerialisation is alluring, but elusive, and several false claims based on 'Environmental Kuznets Curves' have been published (Dinda, 2004) arising from misinterpretation of the shift of production from high to low labour cost countries leading to an apparent swing to a service economy when trade is ignored. Enthusiasm for dematerialisation has often focused on the use of digital technologies to provide information services without other media – 'the paperless office', online newspapers, directories etc. However, evidence of real dematerialisation is scarce, and as Hogg and Jackson (2009) report in a study of digital music, the material impact of the newly required electronic equipment can be a greater burden than that of the replaced media. In order to have a significant impact, dematerialisation would be required in major material using sectors: it

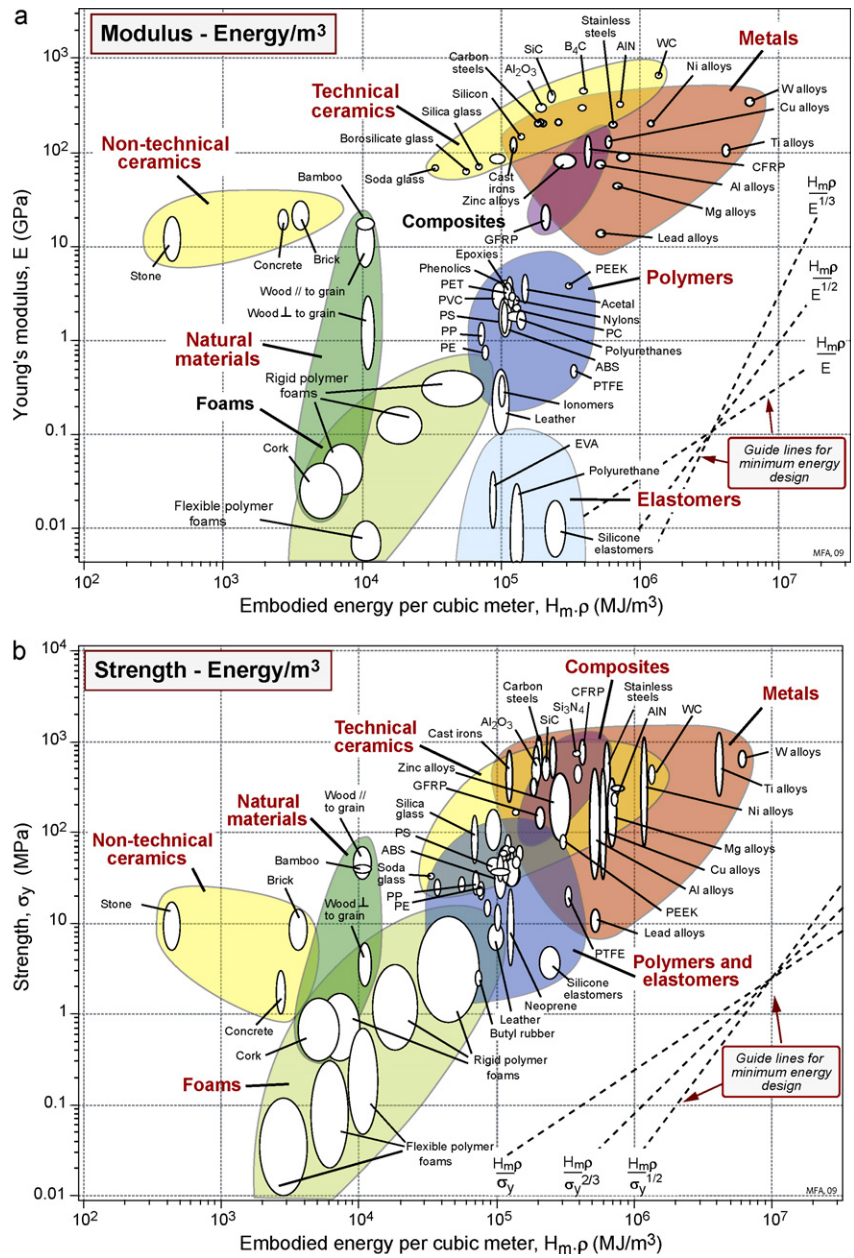

Fig. 3.3. Materials selection options through comparing performance and embodied energy (from Ashby, 2009). (a) Stiffness against embodied energy. (b) Strength against embodied energy. The charts can be used to identify material substitutions with lower embodied energies. For applications in which stiffness or strength is a key attribute, these two charts demonstrate the attractiveness (low embodied energy) of stone and wood.

is unclear whether dematerialisation of construction is possible, although many buildings (houses/offices) are empty for more than half of each day, so there is potential for design for multiple use; a shift from private to public transport would lead to relative dematerialisation; redesign to avoid over-specification of equipment and appliances could lead to significant savings.

There appear to be many options for reducing the mass of material required to deliver material services, but this area has had little exploration. Material substitution is unlikely to deliver step-change reductions in total impacts, because the key materials are required in high volumes. Development of improved properties in materials is normal practice, but as yet we do not understand the trade-offs for instance, between re-using an older steel truss, or melting it to allow re-alloying for improved properties. Dematerialisation is elusive, but design for less material consumption has substantial scope, limited by the trade-off of increased manufacturing costs with component specialisation against reduced material purchasing.

3.5. Open questions

This section has demonstrated four key material efficiency options which are technically possible, but under-deployed. The reasons for this will be examined in the next section, but as yet we do not have a clear understanding of the technical potential of the strategies: for which products/sectors/consumers are each of the four strategies most appropriate, and what are the key trade-offs created by adopting more materially efficient behaviour? These uncertainties generate the open questions in Table 3.4.

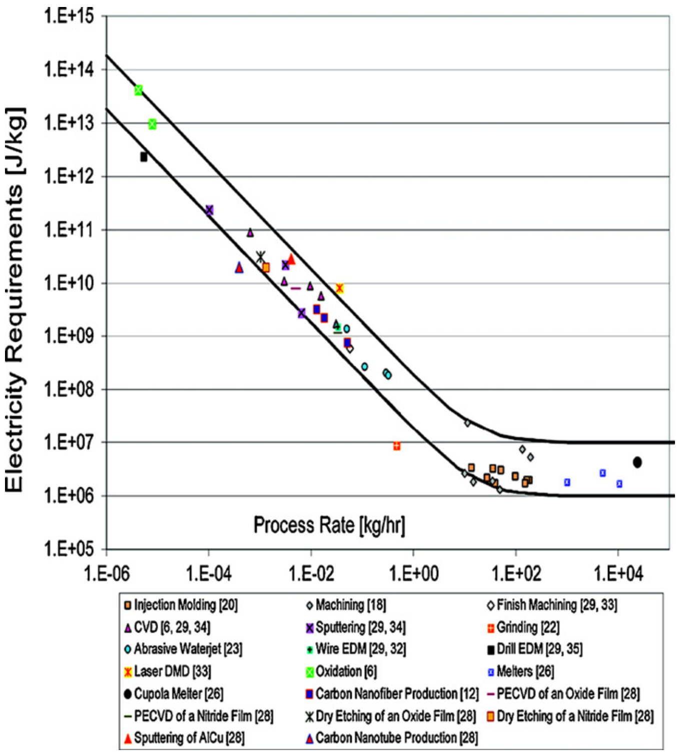

Fig. 3.4. Electricity used per unit of material processed for various manufacturing processes as function of processing rate.
From Gutowski et al. (2009). Reference numbers in the legend refer to the original publication.

4. Barriers to adopting material efficiency strategies

If the material efficiency options of Section 3 are technically feasible, but commercially deployed only at small scale if at all, there are clearly barriers limiting their adoption. This section categorises these barriers as economic, regulatory and social, and aims to provide an overview of current understanding, leading to discussion in the next section of how they might be overcome.

4.1. Economic and business barriers

Directly, we have not found an economic analysis of material efficiency as defined in this paper. There is a substantial body of work examining 'resource economics', initiated by Hotelling (1931) who aimed to understand the market response to finite resource constraints. The 'Hotelling rule' suggests that the value of a mine will increase at some interest rate, so the owner will extract material only if the price of the ore is growing at least at the same interest rate. The publication of 'Limits to Growth' in 1972 led to a reawakening of interest among economists on this theme, and Solow (1974) provided a widely quoted re-statement of Hotelling's original rule. However, the discussion of Section 2.1 has shown that resource scarcity is less of a problem than threats arising from the impacts of resource extraction. Simpson et al. (2005) refer to this as the 'new scarcity', but as yet it appears that economists have not examined the material efficiency options which are the focus of this paper and which might be adopted to address this new scarcity.

The strategies of Section 3 motivate the following economic questions:

- Under what conditions would it be preferable for businesses in developed economies (with less new demand than replacement demand) to derive revenue from servicing the existing stock of goods rather than aiming to replace it?
- When is it commercially attractive to use reclaimed modules or components in constructing new goods, and how can this attractiveness be increased?
- How do the additional capital and labour costs of manufacturing materially efficient products contrast with the benefits of reduced material purchasing and user benefits of lighter weight products?

Figs. 4.1 and 4.2 provide some evidence about how decisions are currently taken in response to the last of these questions. Fig. 4.1 suggests that material demand may only be weakly influenced by energy prices. A key driver of material efficiency from Section 2.2 is to reduce energy demand, and higher energy prices should apparently reduce demand for energy intensive materials. However, although Fig. 4.1b shows that higher energy prices will lead to higher prices for the operation of transport and buildings, energy prices are only weakly linked to the price of final goods because so much other labour is required to transform raw materials into goods (Hannon, 1975).

Fig. 4.2 shows that historically energy prices have been level, while material prices have steadily declined and purchasing power (in richer countries – the illustration is for the UK) has risen dramatically. The consequence of Fig. 4.2, with wages rising in parallel with purchasing power, is that production decisions for commodity materials will usually be driven by the need to reduce labour costs – and any opportunity to substitute excess material use for reduced labour is likely to be attractive.

Further barriers to the adoption of materially efficient strategies arise because:

- Businesses which have invested heavily in the equipment and systems of mass production may be locked into these legacy assets that were developed in an era of cheap and abundant energy. If older assets are now written off, making new capital expenditure to reduce material purchasing may be particularly unattractive. As an example of this, most metals production involves uncoupled thermal cycles which could be combined, but the assets involved are old and physically separated, and the cost of investing in new integrated production lines would be prohibitive.
- Most of the costs associated with the environmental impacts of material and energy production, the so-called externalities, are not reflected in the price of materials.
- Re-use and recycling would compete for the same stream of material. If more material is diverted to re-use this may lead to a

Table 3.4
Open questions about material efficiency strategies.

OQ6	Given that most goods can be maintained indefinitely if cost is no object, what drivers would promote more intense use, maintenance, repair and re-sale rather than disposal and under what conditions would this not be advantageous?
OQ7	A key driver of profit in product companies has been increased differentiation, yet design for re-manufacturing and re-use would favour standardisation. How can these needs be resolved?
OQ8	Where would the greatest future benefits from remanufacturing occur, and how would they be promoted?
OQ9	What might drive demand for component re-use, and how would the required supply chain operate profitably?
OQ10	What would be the consequences of a return to stone and wood in place of concrete and steel, and are there any other significant material substitutions that reduce the impacts of materials?
OQ11	How much material can be saved if topology optimisation is linked to the total mass of material required to make a part, and not just to the mass of the part?
OQ12	Are there opportunities for significant dematerialisation of material services and if so, how can they be promoted?

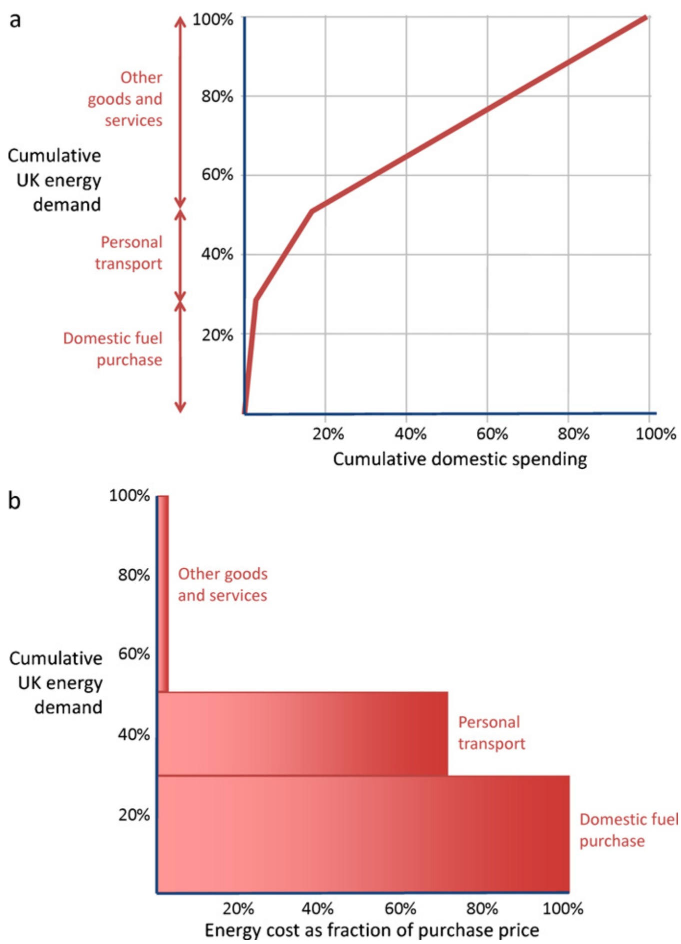

Fig. 4.1. Fuel costs are strong drivers of personal fuel purchase but weak drivers of the prices for other goods and services: (a) more than 50% of UK energy demand requires only 15% of spending; (b) the purchase price of final goods and services is largely insensitive to energy price. Numbers estimated from the 2004 UK input–output tables created by Wiedmann et al. (2008) and other UK government statistical reports on energy consumption.

supply shortage in recycling, and hence an increase in the price offered for recycling, and thus a reduced incentive for re-use.

All current economic systems are predicated on growth and Pearce (2005) shows that it is almost impossible to imagine a different system emerging. As a result, business models in production companies are oriented towards growing sales volumes, so are strongly motivated to increase product replacement rates and hence to build in 'planned obsolescence' to product designs. Thus, material efficiency which may be opposed by material producers as a threat to the volume of sales of their commodity products, will also be opposed by upstream businesses unless they can reclaim value through some other activity.

Finally, the result of a material efficiency improvement could be a cost reduction for a given service or product, and this could trigger the so-called 'rebound effect'. The logic of the rebound effect is that the cost reduction gives purchasers more disposable income, so they will buy more of the service, and thus overcome the efficiency gain. There is a continuing debate on the validity and the size of the rebound effect in the assessment of energy efficiency (see e.g. Schipper and Grubb, 2000; Herring, 1998) and little empirical analysis of the rebound effect (Sorrell et al., 2009). With respect to material efficiency no empirical studies exist. As shown by Fig. 4.1, material costs are limited in the costs of most goods or services. This suggests that the potential rebound effect arising

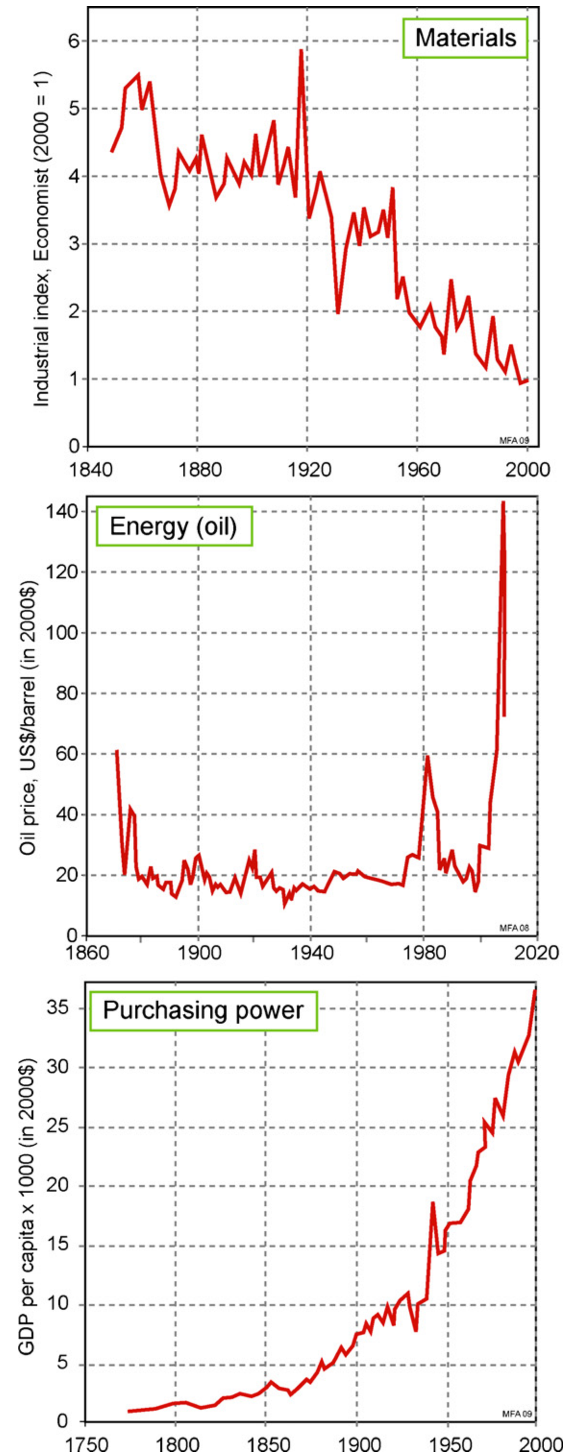

Fig. 4.2. History of energy and material prices and spending power. From Ashby (2009).

from material efficiency may be small, but as yet it has not been examined.

4.2. Regulatory and legal barriers

If markets reflected all costs accurately and immediately, then in response either to material scarcity or to harmful impacts created by material production and processing, prices would rise and this would curtail demand and stimulate a search for substitutes and technology improvements. For goods which are privately owned and traded without 'externalities', markets have proved effective at achieving this, but for 'public' goods – such as the atmosphere, oceans or biodiversity – the costs of harm do not affect prices unless the costs are added due to policy. Historically, according to Pearce (2005), rather than identifying a target standard of performance, policy makers typically identify a current best technology and set in place measures to promote its adoption. This approach, also known as 'picking winners' has the attraction of feasibility, but will lead to slow change if a stimulus is needed to develop technologies to a higher standard.

The imposition or acceptance of policy clearly depends on social pressure – in turn depending on both facts and the perception of facts – and this may only develop when an environmental impact has reached a critical level. In this case, policy makers must move rapidly to create change by any rapid means, rather than taking what Pearce claims would be the more rational approach of developing market based instruments such as fuel or effluent taxes, or tradeable permits on air pollution, which allow the market to identify the most efficient ways to curb unwanted effects. The pressure to create policy is also dampened by the lobbies of those most likely to be economically influenced by change – who can be pervasive, and closely allied with the government bodies that set regulation.

These remarks apply to all environmental policy, but in the area of material efficiency it is possible to identify some specific barriers within existing policy:

- Changes to UK health and safety regulations so that demolition employees work mainly at ground level have significantly reduced the availability of construction steel for re-use in the past 10 years (Allwood et al., 2010a).
- Governments may give support to materially inefficient practices for manufacturing, energy or resource extraction sectors for instance through scrappage schemes or favourable tax reductions. van Beers and de Moor (2001) claim that these sectors receive over £1 trillion in subsidies.
- Standards bodies assume that all materials are new – and there is in general a lack of government certification for reused materials.
- Lack of information and poor system design places a high burden on individuals to identify optimum disposal routes for every item being discarded. (Different solutions are currently required in the UK for kettles, clothing, fridges, batteries, televisions etc.).
- Standards which prescribe a certain material composition instead of a material performance inhibit material substitution or re-use. This is for example, a barrier for blended cement in road construction in large parts in the US.
- Legislation on producer responsibility persists beyond first ownership, so that, for example UK charity shops now do not sell electrical goods. Clarification on this responsibility is required to support extensions to product or component life.

It appears that, because the value of material efficiency is not well known and therefore it has not been a priority in policy making, some existing regulations unintentionally act as a barrier to the efficient use of materials.

4.3. Social barriers

'Consumerism' or 'materialism' is much-discussed as contemporary ills, but greed is not in any sense new. Kasser (2002) quotes the Chinese philosopher Lao Tzu from 500 BC saying 'chase after money and security, and your heart will never unclench' and, in the first known book, as he repents of his war-like behaviour, Gilgamesh is told by the holy man Utanapishtim to 'abandon wealth and seek living beings! Spurn possessions and keep alive living beings!' (Anon, 2010). Greed appears to be part of our makeup, and apart from major recessions, it is difficult to identify any period in which a prosperous nation has chosen to reduce or constrain its habit of material acquisition. Even among those who proclaim values that imply self-control against social norms, it appears that our ability for restraint is limited by a so called 'value-action' gap: in Darley and Batson's (1973) study, of 40 seminary students at Princeton who were asked to give a short talk on the Biblical parable of the Good Samaritan in a nearby room, only 40% stopped to help an apparently distressed man in their way. Hannon (1975) and Druckman and Jackson (2008) show that household energy use grows in proportion to disposable income, and this pattern appears to be independent of householders' stated ethical values.

The origin of consumerism as a particular form of greed, with ownership of goods leading to social status, is often linked to the time of the industrial revolution (De Vries, 2008). Adam Smith's statement (Smith, 1776) that 'consumption is the sole end and purpose of all production' appears to suggest that production exists only to satisfy consumer desires, but the rest of his writing makes clear that in fact the rise of efficient production (supply) has the effect of stimulating demand by moving unattainable luxury goods into mass markets. De Vries (2008) argues that in fact the transition to consumerism began 100 years earlier, from the mid-seventeenth century, when members of households increasingly spent time working in employment outside the home, in order to purchase external services, such as children's education, that would previously have been provided within the home. This dependence on purchased goods, and hence monetary income, provides a beginning for consumerism, but its manifestation in wealthy economies where basic needs for security, health and comfort have been met is now far broader:

- Fashion rather than form or function determines the end of life of many goods, and while technical reasons for the end of physical life can generally be overcome by design, it is difficult to change the symbolic role of a product without replacing its material content. This focus on 'conspicuous consumption' suggests that goods made from re-used material, or designed for future re-use, may be seen as less desirable if they symbolise thrift.
- Convenience has become a major driver of consumption, leading to considerable excess in capacity for service provision: individual car or washing machine ownership leads to national capacity for personal transport and clothes washing far in excess of requirements.
- Cultural attitudes to waste have moved from moral disapproval to complete acceptance, so the 'throw-away' society treats as normal the discard of materials with re-use value.
- De Vries (2008) reviews work arguing that the pervasiveness of marketing and media images of idealised lifestyles ensures that it is the anticipation of consumption that is at the core of today's hedonism, and the fact that the reality cannot live up to the dream drives the immediate craving for further consumption.

The use by governments of GDP figures as an indicator of economic well-being directly supports the pursuit of policies that aim to increase spending, and hence consumerism. In turn this drives the production and processing of much more material than is necessary to meet basic human needs, and leads to a waste stream rich in perfectly functioning products discarded for a lack of desirability rather than any lack of function.

5. Mechanisms to promote material efficiency

The motivation to pursue material efficiency for environmental benefit set out in Section 2 is compelling. What might promote it? One generic answer is that 'copying' and 'fear of being left behind' appear to be much more powerful weapons than legal

Table 5.1
Classification of instruments to improve material efficiency and stakeholder interaction. The table depicts the (key) stakeholders in the life-cycle of materials that are directly addressed by the instrument.

Instrument	Examples	Region	Material life-cycle impact				
			Extraction	Production	Manufacture	Use	End of life
Information	Recycling programs	Various				X	X
	Environmental performance labeling for vehicles	EU				X	
	IPPC LCI guidelines	Various			X	X	
Certification and standards	Blue Angel	Germany		X	X	X	
	Building codes/performance standards	Various		X	X	X	
	BREEAM environmental standards for buildings	UK			X	X	
	Appliance efficiency standards	US			X	X	
	ISO environmental standards	Various	X	X	X		
	Energy using products directive	EU			X	X	
Preferential Purchasing	Government procurement	Netherlands				X	
	Corporate procurement	Various			X	X	
	Tesco green club card points	UK				X	
Voluntary programs	Packaging covenant	Netherlands			X	X	X
	Recycling targets	Sweden		X			X
	Aluminium for future generations (IAI)	Global		X			
Ownership	DSD system for packaging	Germany			X		X
	WEEE Directive	EU			X		X
	End-of-life vehicles Directive	EU			X		X
	Deposit return beverage containers	Various					X
Subsidies and incentives	Feed in tariffs	Germany		X			
	Renewable energy investment and production tax credits	Various		X			
	Subsidised cavity wall insulation	UK				X	
Taxes and charges	Packaging tax	Norway, Netherlands			X		
	Landfill tax	Various					X
	Fuel price escalator	UK				X	
Permitting	Banning free plastic bags	China, Cities USA				X	
	Banning recyclables in landfill	EU					X
	Limited permitting landfills/incinerators	Various					X
Research and development	Design for Environment	USA			X		
	Academic research councils (e.g. EPSRC in the UK)	Various	X	X	X	X	X

agreements. The Chinese 11th five year plan, which included a commitment to a 20% reduction in energy consumption per unit of GDP between 2006 and 2010 based on adopting best available practice from elsewhere is an example of this (China, 2006), as is China's commitment to match European performance (CEC, 2007) by supplying 15% of all its electricity generation from renewable sources by 2020 (NDRC, 2007). All developed governments seek to ensure by R&D investment that they are well-placed in future technology races, so fear of being left behind is a powerful motivator – and this applies at individual, business and governmental levels. This section aims to collect evidence of other potential drivers of change.

5.1. Business opportunities

The case studies described earlier in this paper suggest that new business opportunities related to material efficiency may occur through:

- New revenue streams, such as primary metals producers developing a 'second-hand' supply chain (for instance reconditioning, re-certifying and re-selling used I-beams) exactly as car makers aim to control their re-sale chains.
- Leasehold as a new business model – taking the example of Rolls Royce 'power by the hour' contracts for aero-engines, or Xerox's leasing of copiers, to retain materials on the balance sheet and hence nurture their value.
- Brand benefits of environmental leadership, as currently being pursued by large UK retail chains for example (Jones et al., 2007).
- Vertical integration providing the ability to draw value from business streams other than growth in physical output.
- Embodied energy becoming a higher priority as use-phase energy efficiency improves – for instance as buildings become more passive and vehicles more efficient, so their production energy becomes a higher priority.
- Learning lessons from developing countries – where the ratio between labour and energy/material costs is different.
- New supply chain partnerships – for instance between design and demolition in buildings, or design, repair and end-of-life in appliances.

Despite institutional barriers and a lack of infrastructure, it appears that there can be a first-mover advantage for businesses to lead materially efficient behaviour, particularly when added brand value can compensate for increases in cost.

5.2. Government interventions

Table 5.1 summarises policy instruments that have been used to promote material efficiency around the world. Generally, these are relatively conservative measures – aiming to support change more than banning or taxing unwanted behaviour. Combining insights into policy mechanisms from implementation of energy efficiency and waste management from work by Lilja (2009a,b) from experience in preparing a National Waste Plan for Finland, Peck and

Chipman (2007) reporting to the United Nations on industrial development for sustainability, Hekkert et al. (2000a,b) and Worrell et al. (1995a):

- Resource taxes and waste taxes have been fiercely opposed by the industrial establishment although landfill taxes are now widespread and rising in Europe.
- Finland is now moving towards a resource tax and Norway has a tax on packaging.
- Where regulations banning certain behaviour have been implemented, they mainly concern waste regulation, such as: reduced permits for landfill sites and permits for new incinerators; restrictions on waste disposal – for instance on lead acid batteries in landfill; banning free distribution of plastic bags in shops; aluminium cans and PET bottles in Sweden must hit 90% recycling or be banned; CAFÉ regulations on fleet average consumption.

Brewer and Mooney (2008), in looking for models for new Australian policy on construction and demolition waste, report on good practice in Denmark and the Netherlands including landfill levies, landfill material bans, material segregation and certification leading to very low landfill rates. European end-of-life legislation is a powerful prototype for driving materially efficient strategies, and by seeking to harmonise waste policies across the EU, has aimed to avoid 'leakage' whereby waste is exported to exploit regulatory differences.

A measure widely supported by industry in Finland is the development of negotiated environmental agreements – negotiated between government and business units to support the process of constructing a mutually shared policy frame for promoting waste prevention in the industrial sector (Lilja, 2009b). Generally these agreements do not include sanctions or quantitative goals, but are used to promote implementation of new legislation. They have been popular in the fields of waste management, energy efficiency and climate policy – and have an extensive literature. Other laws designed to promote behaviour, for instance requiring that government departments buy products with a certain proportion of recycled material have also been adopted, including: a requirement that drinks be sold in refillable bottles in Denmark; the Japanese construction recycling act requires sorting of debris from demolition; several EU states have imposed a mandatory separation of household waste (Peck and Chipman, 2007). As yet the potential for material efficiency strategies as a stimulus to increase employment has not been explored, although potentially job creation in material efficiency could offset job losses from declining production.

5.3. Consumer drivers

Despite the strong human urge to consume discussed in Section 4.3, a growing body of literature suggests that increased materialism (continuing to purchase goods beyond some threshold of satisfying basic needs) reduces human well-being. At its simplest, this evidence is provided by numerical measures of 'happiness' plotted against income, either within a social group, nationally, or internationally, and the graphs generally show no increase of happiness above some level of income. In more detail, Kasser (2002) presents evidence from a wide range of behavioural psychology surveys demonstrating a link between materialism and unhappiness: individuals focused on materialistic values have lower well-being, poorer psychological health, greater insecurity, poorer relationships, are less generous to others and even if they attain some target level of affluence are rapidly dissatisfied so set increased targets. Jackson (2005) in an extensive survey on consumption, reviews this and other related evidence, and sets it in context of other analyses of consumption examining the symbolic drivers of consumption as an indicator of status, and therefore part of the basic human needs to find a high-quality mate. In this primitive sense, aiming to develop greater status (to consume more) is a basic biological urge, which will over-ride the collective benefits of reduced consumption, and is therefore very difficult to counter. Layard (2006) however provides compelling evidence about happiness being related to relative wealth, income or consumption rather than some absolute level. From this, he draws a significant distinction between 'valued consumption' and consumption aiming to improve social rank, pointing out that for a society as a whole, the sum total of rank is constant. Therefore, 'performance related' rewards, that focus on achieving rank, make no contribution to societal well being, and tend to promote a false link between increased working hours (and increased spending) and more happiness.

The literature of sustainable consumption is still relatively young, so mainly focused on understanding behaviour rather than on identifying mechanisms for change. Jackson (2005) briefly mentions contemporary social movements such as 'ethical consumption', 'downshifting' and 'voluntary simplicity' but with little optimism. An inspiring possibility described by Fletcher (2008) demonstrates that when commodity goods, such as clothing, have become part of an individual's 'life-story' they move from disposable to permanent: a garment given by a particular person at an important time, or one that was partly made or personalised by a friend cannot be discarded so lightly as one purchased anonymously from a supermarket. There is also evidence that employees value a shift towards more sustainable behaviour (Remmen and Lorentzen, 2000), that wide-ranging changes in social behaviour are possible (smoking and avoiding seat-belts have become 'unsocial' in the UK) and in some cases materially efficient solutions (re-filling rather than replacing) could be more convenient for consumers.

5.4. Open questions

Even though plenty of technical options exist for developing material efficiency, developed economies have not adopted it and even appear to pursue greater inefficiency in the interest of GDP growth. However, the evidence of Section 2 showed that in order to reduce the impacts of production while serving a globally growing demand, material efficiency is vital – and the evidence of this section suggests that there are some credible options for promoting it.

The fact that currently developed economies have failed to pursue material efficiency begs the question of whether it could form a component of future economic growth in developing economies. Eq. (2) describes a separation between new demand (from first time consumers) and replacement demand, and in developed economies, where most demand is for replacement goods, existing business models aim for ever faster replacement of well functioning goods, by creating dissatisfaction with current performance, style or functionality. Is this an inevitable goal for economic development, or is it possible to pursue a development path in which material efficiency, and the associated development of jobs that nurture rather than replace the value of engineered materials, can be a driver of growth?

The discussion of this and the previous section on barriers to material efficiency and mechanisms to overcome them leads to the set of open questions in Table 5.2.

6. Discussion

In delivering material services we will not run out of (low cost) materials, but if we are concerned about the environmental impacts of materials production, this paper has shown that there is a rationale to analyse the contribution that material efficiency can provide beyond energy-related efficiency.

Table 5.2
Open questions about the implementation of material efficiency.

OQ13	How can businesses in high labour-cost countries promote material efficiency if it requires more local labour, while material and energy are small contributors to the costs of mass production?
OQ14	How should upstream materials processing businesses by compensated, or what new business opportunities can they pursue, if material efficiency leads to lower physical volumes of sales?
OQ15	Which governmental measures are inhibiting the adoption of materially efficient practice?
OQ16	What measures can governments implement today to support material efficiency, and what measures should they begin to negotiate with industry and voters?
OQ17	Under what conditions, if any, will affluent consumers opt for materially efficient solutions?
OQ18	Will the rebound effect be an important factor to account for in the assessment of the potential contribution of material efficiency improvement?
OQ19	Which laws, particularly related to producer responsibility, inhibit material efficiency, and how can they be modified to support it?
OQ20	Is it possible for developing economies to build material efficiency into their development path?

The tension between 'what can we do' and 'what must we do' has been a constant theme in the narrative of this paper. According to Bleischwitz et al. (2009), the guiding question for economics is 'can companies and industries spur their competitiveness, and can countries as a whole enhance their prosperity through improving material efficiency?' The equivalent back-casting question is 'given what we know about the capacity of ecosystems for absorbing the effects of production, what level of material efficiency must we achieve, and how do we bring it about?' We have demonstrated that opportunities exist to improve the efficiency with which we use materials, and despite the obstacles to adopting this behaviour, there are many mechanisms that might be deployed to promote it. Yet material efficiency within the field of climate change mitigation has received limited attention since the first studies in the mid 1990s.

The purpose of this paper is not to provide answers. Instead it has aimed to frame the field of material efficiency, provide directions for research, and challenge the research community to explore this field.

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References

Akerlof GA. The market for 'lemons': quality uncertainty and the market mechanism. The Quarterly Journal of Economics 1970;84(3):488–500.
Aleklett K, Hook M, Jakobsson K, et al. The peak of the oil age – analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy 2010;38(3):1398–414.
Alexander C, Smaje C. Evaluating third sector reuse organisations in the UK: case-studies and analysis of furniture reuse schemes. Resources, Conservation and Recycling 2008;52:719–30.
Allwood JM, Cullen JM, Milford RL. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environmental Science and Technology 2010;44(6):1888–94.
Allwood JM, Cullen JM, Cooper DR, Milford RL, Patel ACH, Carruth MA, et al. Conserving our metal energy: avoiding melting steel and aluminium scrap to save energy and carbon. University of Cambridge; 2010a, ISBN 978-0-903428-30-9.
Allwood JM, Laursen SE, de Rodriguez CM, Bocken NMP. Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. University of Cambridge; 2006, ISBN 1-902546-52-0.
Anon. The epic of Gilgamesh. www.ancienttexts.org/library/mesopotamian/gilgamesh; 2010 [accessed September 2010].
Ashby MF. Materials and the environment: eco-informed material choice. Burlington, MA, USA: Butterworth-Heinemann; 2009.
Asolekar SR. Status of management of solid hazardous wastes generated during dismantling of obsolete ships in India. In: Proceedings of in the International Conference on "Dismantling of Obsolete Vessels"; 2006.
Ayres R, Ferrer G, van Leynseele T. Eco-efficiency, asset recovery and remanufacturing. European Management Journal 1997;15(5):557–74.
Ayres RU, van den Bergh JCJM. A theory of economic growth with material/energy resources and dematerialization: interaction of three growth mechanisms. Ecological Economics 2005;55:96–118.
Babbitt CW, Kahhat R, Williams E, Babbitt GA. Evolution of product lifespan and implications for environmental assessment and management: a case study of personal computers in higher education. Environmental Science and Technology 2009;43:5106–12.
Behrendt S, Jasch C, Kortman J, Hrauda G, Pfitzner R, Velte D. Eco-service development: reinventing supply and demand in the European Union. London, UK: Greenleaf Publishing; 2003.
Bentley RW, Mannan SA, Wheeler SJ. Assessing the date of the global oil peak: the need to use 2P reserves. Energy Policy 2007;35(12):6364–82.
Bleischwitz R, Welfens PJJ, Zhang Z. Introduction. In: Bleischwitz R, Welfens PJJ, Zhang Z, editors. Sustainable growth and resource productivity. Sheffield: Greenleaf Publishing Ltd.; 2009. p. 1–12.
Bogue R. Design for disassembly: a critical twenty-first century discipline. Assembly Automation 2007;27(4):285–9.
Boyer RR. Attributes, characteristics, and applications of titanium and its alloys. Journal of Materials 2010;62(5):21–4.
Brewer G, Mooney J. A best practice policy for recycling and re-use in building. Proceedings of the Institution of Civil Engineers. Engineering Sustainability 2008;161(ES3):173–80.
Bulkeley H, Gregson N. Crossing the threshold: municipal waste policy and household waste generation. Environment and Planning A 2009;41:929–45.
Castellano PJ, Volk TA, Herrington LP. Estimates of technically available woody biomass feedstock from natural forests and willow biomass crops for two locations in New York State. Biomass and Bioenergy 2009;33:393–406.
Chadha A. From carbon to carbohydrates: corporate strategies for biopolymer technology development. Journal of Commercial Biotechnology 2010;16:159–67.
China. The 11th five-year plan. Available online from: www.gov.cn; 2006 [accessed September 2010].
Choate WT, Green JAS. U.S. energy requirements for aluminum production: historical perspective, theoretical limits and new opportunities, 2003. Available from: www1.eere.energy.gov/industry/aluminum/pdfs/al_theoretical.pdf [accessed August 2008].
Commission of the European Communities (CEC). Renewable energy road map renewable energies in the 21st century: building a more sustainable future. Brussels: CEC; 2007, COM(2006) 848 final.
Cooper T. Slower consumption: reflections on product life spans and the 'throwaway society'. Journal of Industrial Ecology 2005;9(1–2):51–67.
Counsell TAM, Allwood JM. Meeting the 2050 carbon target for paper by print removal. CIRP Annals – Manufacturing Technology 2008;57(1):25–8.
Da Rocha CG, Sattler MA. A discussion on the re-use of building components in Brazil: an analysis of major social, economical and legal factors. Resources, Conservation and Recycling 2009;54:104–12.
Dahmus JB, Gutowski TG. What gets recycled: an information theory based model for product recycling. Environmental Science and Technology 2007;41(21):7543–50.
Darley JM, Batson CD. From Jerusalem to Jericho: a study of situational and dispositional variables in helping behaviour. Journal of Personality and Social Psychology 1973;27(1):100–8.
de Almeida P, Silva PD. The peak of oil production – timings and market recognition. Energy Policy 2009;37(4):1267–76.
De Vries J. The industrious revolution: consumer behaviour of the household economy, 1650 to the present. Cambridge: Cambridge University Press; 2008.
DfT (Department for Transport). National travel survey. Available online from: www.dft.gsi.gov.uk; 2009 [accessed September 2010].
Diamond J. Collapse: how societies choose to fail or survive. London, England: Penguin Books; 2006.
Dinda S. Environmental kuznets curve hypothesis: a survey. Ecological Economics 2004;49(4):431–55.
DoETR (Department of the Environment, Transport and the Regions). Making waste work; a strategy for sustainable waste management in England and Wales. London: HMSO; 1995.
Druckman A, Jackson T. Household energy consumption in the UK: a highly geographically and socio-economically disaggregated model. Energy Policy 2008;36(8):3177–92.
Eggert RG, Carpenter AS, Freiman SW, Graedel TE, Meyer DA, McNulty TP, et al. Minerals, critical minerals and the US economy. Washington: National Academy Press; 2008.
Eide A. The right to food and the impact of liquid biofuels (agrofuels). Right to food studies. Rome: Food and Agricultural Organization of the United Nations (FAO); 2008, Available online at www.fao.org/righttofood/ [accessed April 2010].
Ericsson M. Will the mining industry meet the global need for metals? In: Bleischwitz R, Welfens PJJ, Zhang Z, editors. Sustainable growth and resource productivity. Sheffield, UK: Greenleaf Publishing; 2009.

Ferrer G, Ayres RU. The impact of remanufacturing in the economy. Ecological Economics 2000;32:413–29.
Ferrer G. The economics of personal computer remanufacturing. Resources, Conservation and Recycling 1997b;21:29–108.
Ferrer G. The economics of tire remanufacturing. Resources, Conservation and Recycling 1997a;19:221–55.
Fisher B, Nakicenovic N. Issues related to mitigation in the long-term context. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Climate change 2007: mitigation: contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change;. Cambridge, UK: Cambridge University Press; 2007.
Fletcher K. Sustainable fashion and textiles: design journeys. London: Earthscan; 2008.
Geiser K. Materials matter: toward a sustainable materials policy. Cambridge, MA: The MIT Press; 2001.
Goeller HE, Weinberg AM. The age of substitutability: what do we do when the mercury runs out? Science 1976;191(4228):683–9.
Gorgolewski M. Designing with reused building components: some challenges. Building Research and Information 2008;36(2):175–88.
Graedel TE, Allwood JM, Birat J-P, Buchert M, Hagelüken C, Meskers CEM, et al. The recycling of metals: a status report. Under review. Journal of Industrial Ecology 2010.
Graedel TE. Defining critical materials? In: Bleischwitz R, Welfens PJJ, Zhang Z, editors. Sustainable growth and resource productivity. Sheffield, UK: Greenleaf Publishing; 2009.
Gronostajski JZ, Kaczmar JW, Marciniak H, Matuszak A. Direct recycling of aluminium chips into extruded products. Journal of Materials Processing Technology 1997;64(1–3):149–56.
Gutowski TG, Branham MS, Dahmus JB, Jones AJ, Thiriez A. Thermodynamic analysis of resources used in manufacturing processes. Environmental Science and Technology 2009;43:1584–90.
Hannon B. Energy conservation and the consumer. Science 1975;189(4197):95–102.
Hekkert MP, Joosten LAJ, Worrell E, Turkenburg WC. Reduction of CO_2 emissions by improved management of material and product use: the case of primary packaging. Resources, Conservation and Recycling 2000a;29:33–64.
Hekkert MP, Joosten LAJ, Worrell E. Reduction of CO_2 emissions by improved management of material and product use: the case of transport packaging. Resources, Conservation and Recycling 2000b;30:1–27.
Herring H. Does energy efficiency save energy: the economists debate. EERU Report No. 074. Energy and Environment Research Unit, The Open University; 1998.
Hogg N, Jackson T. Digital media and dematerialization an exploration of the potential for reduced material intensity in music delivery. Journal of Industrial Ecology 2009;13(1):127–46.
Hotelling H. The economics of exhaustible resources. Journal of Political Economy 1931;39:137–75.
Huang GQ, editor. Design for X: concurrent engineering imperatives. 1st edition London: Chapman & Hall; 1996.
Hujbregts MAJ, Rombouts LJA, Hellweg S, Frischknecht R, Hendriks AJ, van de Meent D, et al. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environmental Science and Technology 2006;40(3):641–8.
IAI (International Aluminium Institute). Aluminium for future generations 2007 update; 2007 [accessed April 2010] www.world-aluminium.org/cache/fl0000189.pdf.
IEA (International Energy Agency). Tracking industrial energy efficiency and CO_2 emissions. Paris: OECD/IEA; 2007.
IEA (International Energy Agency). Energy technology perspectives 2008: scenarios & strategies to 2050. Paris: OECD/IEA; 2008a.
IEA (International Energy Agency). World energy outlook. Available from: http://www.worldenergyoutlook.org/S.103-107; 2008 [accessed September 2010].
Jackson T. Life better by consuming less: is there a 'double-dividend' in sustainable consumption? Journal of Industrial Ecology 2005;9(1–2):19–36.
Jones P, Comfort D, Hillier D. Sustainable development and the UK's major retailers. Geography 2007;92(1):41–7.
Kasser T. The high price of materialism. Cambridge, MA: MIT Press; 2002.
Kaya Y. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. Paris: IPCC Energy and Industry Subgroup. Response Strategies Working Group; 1990.
Kerr W, Ryan C. Eco-efficiency gains from remanufacturing: a case study of photocopier remanufacturing at Fuji Xerox Australia. Journal of Cleaner Production 2001;9:75–81.
Klee RJ, Graedel TE. Elemental cycles: a status report on human or natural dominance. Annual Review of Environment and Resources 2004;29:69–107.
Layard R. Happiness: lessons from a new science. Penguin; 2006.
Lilja R. From waste prevention to promotion of material efficiency: change of discourse in the waste policy of Finland. Journal of Cleaner Production 2009a;17:129–36.
Lilja R. Negotiated environmental agreements in promoting material efficiency in industry – first steps in Finland. Journal of Cleaner Production 2009b;17:863–72.
Mackay DJC. Sustainable energy – without the hot air. Cambridge, England: UTT Press; 2009.
Matsumoto M. Business frameworks for sustainable society: a case study on re-use industries in Japan. Journal of Cleaner Production 2009;17:1547–55.
Mazzanti M, Zoboli R. Waste generation, waste disposal and policy effectiveness. Evidence on decoupling from the European Union. Resources, Conservation and Recycling 2008;52:1221–34.
Meadows DH, Meadows DL, Randers J, Behrens WW. The limits to growth: a report for the club of Rome's project on the predicament of mankind. London: Earth Island Ltd; 1972.
Mulero R, Layton B. Two-dimensional Minkowski sum optimization of ganged stamping blank layouts for use on pre-cut sheet metal for convex and concave parts. Journal of Manufacturing Systems 2007;26:44–52.
National Development and Reform Commission (NDRC). Medium and long-term development plan for renewable energy in China. People's Republic of China. Available online from: www.chinaenvironmentallaw.com; 2007,[accessed September 2010].
Navon R, Berkovich O. Development and on-site evaluation of an automated materials management and control model. Journal of Construction Engineering and Management 2005;131(12):1328–36.
Parto S, Loorbach D, Lansink A, Kemp R. Transitions and institutional change: The case of the Dutch waste subsystem. In: Parto S, Herbert-Copley B, editors. Industrial innovation and environmental regulation: developing workable solutions. Tokyo: United Nations University Press; 2007.
Pearce D. Environmental policy as a tool for sustainability. In: Simpson RD, Toman MA, Ayres RY, editors. Scarcity and growth revisited: natural resources and the environment in the new millennium. Washington, DC: Resources for the Future; 2005.
Peck M, Chipman R. Industrial energy and material efficiency: what role for policies? In: Industrial development for the 21st century: sustainable development perspectives. United Nations Division for Sustainable Development; 2007, Online at www.un.org/esa/sustdev/publications/industrial_development/full_report.pdf.
Pimm SL. The world according to Pimm: a scientist audits the earth. New York: McGraw-Hill; 2001.
Prettenthaler FE, Steininger KW. From ownership to service use lifestyle: the potential of car sharing. Ecological Economics 1999;28:443–53.
Remmen A, Lorentzen B. Employee participation and cleaner technology: learning processes in environmental teams. Journal of Cleaner Production 2000;8:365–73.
Rubin ES, Chen C, Rao AB. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 2007;35:4444–54.
Schipper L, Grubb M. On the rebound? Feedback between energy intensities and energy uses in IEA countries. Energy Policy 2000;28:367–88.
Seitz MA. A critical assessment of motives for product recovery: the case of engine remanufacturing. Journal of Cleaner Production 2007;15:1147–57.
Shiklomanov IA. World water resources and their use – a joint SHI/UNESCO product. UNESCO International Hydrological Programme; 2010 [accessed March 2010] webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml.
Sigmund O. Topology optimization: a tool for the tailoring of structures and materials. Philosophical Transactions of the Royal Society of London A 2000;358:211–27.
Simpson RD, Toman MA, Ayres RY. Introduction: the 'new scarcity'. In: Simpson RD, Toman MA, Ayres RY, editors. Scarcity and growth revisited: natural resources and the environment in the new millennium. Washington, DC: Resources for the Future; 2005.
Smil V. Energy in nature and society – general energetics of complex systems. MIT Press; 2008.
Smil V. Energy transitions: history, requirements, prospects. Praeger Publishers; 2010.
Smith A. An inquiry into the nature and causes of the wealth of nations, bk. 4, ch. 8. Available online from: www.gutenberg.org; 1776 [accessed September 2010].
Smith VM, Keoleian GA. The value of remanufactured engines. Journal of Industrial Ecology 2004;8(1–2):193–221.
Solow RM. The economics of resources or the resources of economics. American Economic Association 1974;64(2):1–14.
Sorrell S, Dimitropoulos J, Sommerville M. Empirical estimates of the direct rebound effect: a review. Energy Policy 2009;37:1356–71.
Subramoniam R, Huisingh D, Chinnam RB. Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs. Journal of Cleaner Production 2009;17:1163–74.
Sundin E, Bras B. Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production 2005;13:913–25.
Sutherland JW, Adler DP, Haapala KR, Kumar V. A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. CIRP Annals – Manufacturing Technology 2008;57(1):5–8.
Szargut J. Chemical exergies of the elements. Applied Energy 1989;32:269–86.
Szargut, J. Egzergia, Widawnictwo Politechniki Slaskiej, Gliwice; 2007 [in Polish].
Tilwankar AK, Mahindrakar AB, Asolekar SR. Steel recycling resulting from ship dismantling in India: implications for green house gas emissions. In: Proceedings of second International Conference on "Dismantling of Obsolete Vessels", during 15–16 September; 2008.
Truttman N, Rechberger H. Contribution to resource conservation by re-use of electrical and electronic household appliances. Resources, Conservation and Recycling 2006;48:249–62.
Tsiliyannis CA. Parametric analysis of environmental performance of reused/recycled packaging. Environmental Science and Technology 2005;39:9770–7.
Tukker A, Jansen B. Environmental impact of products: a detailed review of studies. Journal of Industrial Ecology 2006;10(3):159–82.

USGS. Mineral commodity summaries 2010: U.S geological survey. USGS; 2010, 193 p.
van Beers C, de Moor A. Public subsidies and policy failure. Aldershot, UK: Edward Elgar; 2001.
van Nes N, Cramer J. Product lifetime optimization: a challenging strategy towards more sustainable consumption patterns. Journal of Cleaner Production 2006;14:1307–18.
Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA. Human appropriation of the products of photosynthesis. BioScience 1986;36(6):368–73.
Wang T, Müller DB, Graedel TE. Forging the anthropogenic iron cycle. Environment Science and Technology 2007;41:5120–9.
Watson B, Radcliffe D, Dale P. A meta-methodology for the application of DFX design guidelines. In: Huang GQ, editor. Design for X: concurrent engineering imperatives. 1st edition London: Chapman & Hall; 1996. p. 441–62.
Whelan C, Sassano E, Kelley J. Management of electric motor repair. IEEE Industry Applications Magazine 2006;12(May–June (3)):74–83.
Wiedmann T, Wood R, Lenzen M, Minx J, Guan D, Barrett J. Development of an embedded carbon emissions indicator – producing a time series of input–output tables and embedded carbon dioxide emissions for the UK by using a MRIO data optimisation system. London: DEFRA; 2008.
Worrell E, Faaij APC, Phylipsen GJM, Blok K. An approach for analysing the potential for material efficiency improvement. Resources, Conservation and Recycling 1995a;13:215–32.
Worrell E, Martin N, Anglani N, Einstein D, Khrushch M, Price L. Opportunities to improve energy efficiency and reduce greenhouse gas emissions in the U.S. pulp and paper industry. Available from: www.osti.gov/bridge/servlets/purl/790009-AERaSR/native/790009.pdf; 2000 [accessed April 2010].
Worrell E, Meuleman B, Blok K. Energy savings by efficient application of fertilizer. Resources, Conservation and Recycling 1995b;13:233–50.
Yuan Z, Bi J, Moriguchi Y. The circular economy: a new development strategy in China. Journal of Industrial Ecology 2006;10(1-2):4–8.
Zwolinski P, Lopez-Ontiveros M-A, Brissaud D. Integrated design of remanufacturable products based on product profiles. Journal of Cleaner Production 2006;14:1333–45.