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The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand

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In this paper, we review the energy requirements to make materials on a global scale by focusing on the five construction materials that dominate energy used in material production: steel, cement, paper, plastics and aluminium. We then estimate the possibility of reducing absolute material production energy by half, while doubling production from the present to 2050. The goal therefore is a 75 per cent reduction in energy intensity. Four technology-based strategies are investigated, regardless of cost: (i) widespread application of best available technology (BAT), (ii) BAT to cutting-edge technologies, (iii) aggressive recycling and finally, and (iv) significant improvements in recycling technologies. Taken together, these aggressive strategies could produce impressive gains, of the order of a 50–56 per cent reduction in energy intensity, but this is still short of our goal of a 75 per cent reduction. Ultimately, we face fundamental thermodynamic as well as practical constraints on our ability to improve the energy intensity of material production. A strategy to reduce demand by providing material services with less material (called 'material efficiency') is outlined as an approach to solving this dilemma.

1. Introduction

Humanity's use of materials is immense, growing and quite unequal between the rich and the poor. For example, Graedel & Cao [1] point out that there is a correlation between rates of metal usage and gross domestic product ($R^2 = 0.7964$), with *per capita* metal use in high-income countries (approx. US$12.5 k per cap) larger than the use in low-income countries (approx. US$1 k per cap) by a factor of about 30. Our collective anthropogenic material flows are now a geological force, equalling in magnitude other natural geological phenomena [2], and often dominating or perturbing natural material budgets and cycles for many of the elements [3,4]. The power required to make these materials and their associated products, and the carbon emissions associated with this production are also huge, completely dominating the world industrial sector that requires of the order of one-third of the total worldwide primary energy use per year, and contributes a similarly large proportion of global anthropogenic carbon emissions from fuels and processing [5–7].

In this paper, we examine the determinants of these large energy requirements, and look to potential future reductions, and in particular, potential constraints on these reductions. We approach this problem by focusing on the largest energy users among the many materials, and then on the most energy-intensive operations of their production processes. We frame the problem by using a simple mathematical identity, which states that the energy use for a particular material E is equal to the quantity of material produced Q multiplied by the average energy intensity for that material e,

$$E_i = Q_i \cdot \mathrm{e}_i, \tag{1.1}$$

where E_i is the energy use per year for material 'i' (J), Q_i is the material production per year (mass), and e_i is the energy intensity (MJ kg^{-1}). Our total energy use then is just the sum $E_{\mathrm{T}} = \Sigma E_{\mathrm{i}}$.

First, we look at the energy intensity of material production (e) and review the reasons for the high values and the steps that can be taken to reduce these values. Second, we look at the determinants of demand (Q) and identify mechanisms that could be used to reduce demand.

As a point of reference, we are looking to reduce our energy use in the material sector, even while we allow demand to grow. For example, sustainability guidelines for energy and carbon emissions suggest that we need to halve our energy use from 2000 to 2050.[1] At the same time, to allow developing countries to 'catch up' to the developed world, we would need to allow for a doubling of demand [5,8,9]. Taken together, this would require that the energy intensity of material production in 2050 be only one-quarter of that in 2000. In other words, we are looking into the possibility of obtaining a 75 per cent reduction in the average energy intensity of material production. We set aside potential complications such as price effects and rebound, and proceed as if we are operating in a world where the incentives exist to encourage this goal.

If one looks at the hundreds of materials that humanity produces, the associated energy requirements are dominated by just a few material categories. This simplifies the analysis. Here, we look at the materials used to make physical goods. Figure 1 shows a Pareto-type plot rank ordering the energy requirements for these materials. Figure 1 shows that just a few materials dominate material production, and if we track just the 'top five' (steel, cement, paper, aluminium and aggregated plastics), then these alone dominate the entire world material production sector whether measured by energy used or carbon dioxide emitted (see electronic supplementary material and Allwood *et al.* [5] and US Energy Information Administration [11]).

[1]For example, the Intergovernmental Panel on Climate Change recommends reducing CO_2 by 50–80% by 2050 [8]. Among the options available: (i) energy efficiency, (ii) development of a renewables electricity grid and electification of material production, and (iii) carbon capture and storage, we focus on the first, which appears to have significant near-term and scalability advantages over the other two options.

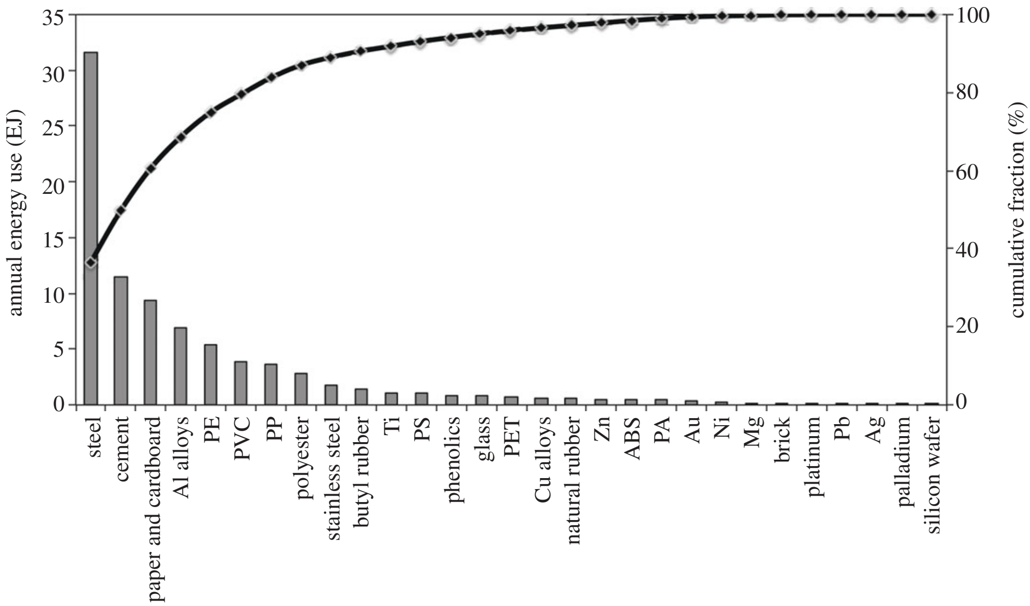

Figure 1. Annual primary energy used for the production of 29 materials worldwide, cumulative scale on the right. PE, polyethylene; PVC, polyvinyl chloride; PP, polypropylene; PS, polystyrene; PET, polyethylene terephthalate; ABS, acrylonitrile butadiene styrene; PA, polyamides. Adapted from Ashby [10].

2. Energy intensity '*e*'

The energy intensity (or embodied energy) is defined as the energy required to produce a material from its raw form, per unit mass of material produced. The energy is usually measured as the lower heating value of the primary fuels used plus any other primary energy contributions. These energy requirements are dominated by two main steps: (i) harvesting and (ii) refining. For metals from minerals, this would involve the mining, crushing, washing and separation of the ore from the surrounding material (called gangue), and the chemical-reduction process that produces the refined material from its ore (called smelting in metal processing). Many of the important metal ores are either oxides or compounds with sulfur that, in turn, are converted into oxides during processing. The reduction step for these oxides uses a reducing agent, usually carbon, which yields a final output, including refined metal and carbon dioxide gas. Hence, the reduction process can produce a certain amount of carbon dioxide (of the order of 1 mol of carbon dioxide per mol of metal) in addition to the carbon dioxide associated with the energy requirements (which depends critically on the nature of the energy source). The ratio of carbon dioxide emitted by the carbon reduction reaction to that from energy use varies by material and technology, but is generally in the range of 1 : 1 (some cement operations) to 1 : 10 (some aluminium operations). In general, however, the carbon dioxide intensity of material production is dominated by the energy intensity of production and the implied fuel usage, with a very strong correlation between the two, as shown in figure 2.

Early material production processes were relatively simple, requiring only harvesting, as for stone and timber, and mixing and heating as for bricks and concrete. These materials are still in use today and are generally produced much more efficiently than in early days, with energy intensities of the order of 1–5 MJ kg^{-1}. Newer materials, extracted from dilute ores, and involving a reduction step, are much more energy intensive. For example, the energy intensities for a variety of metals are plotted in figure 3 versus the dilution (reciprocal of the ore grade or mass concentration '*c*' of the metal at the mine).

While there is a considerable scatter in the plot, it does show that these materials are quite energy intensive compared with earlier materials, and that above a certain dilution, energy

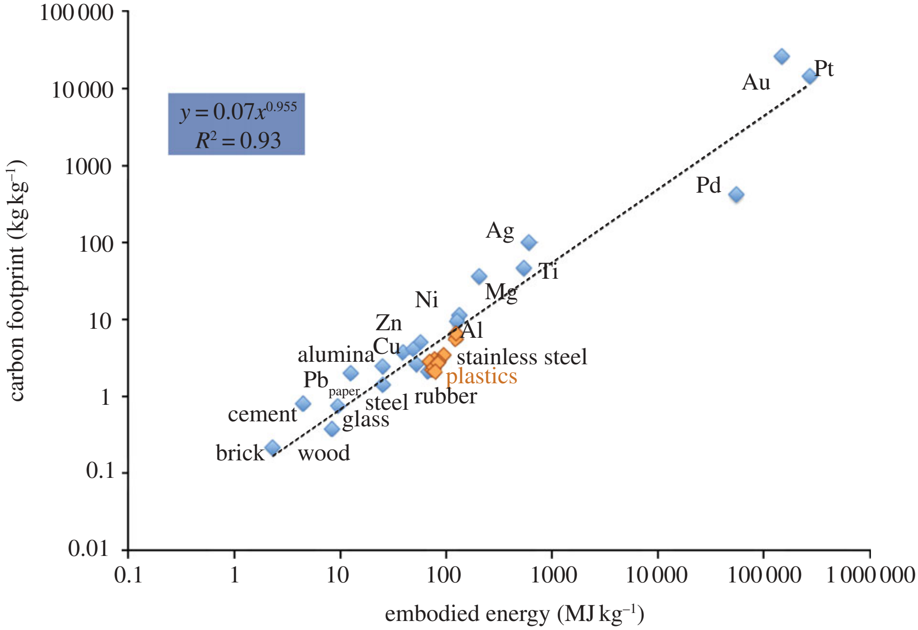

Figure 2. The carbon emission in kilograms of CO_2 per kilogram of material produced versus the embodied primary energy. Data adapted from Ashby [10].

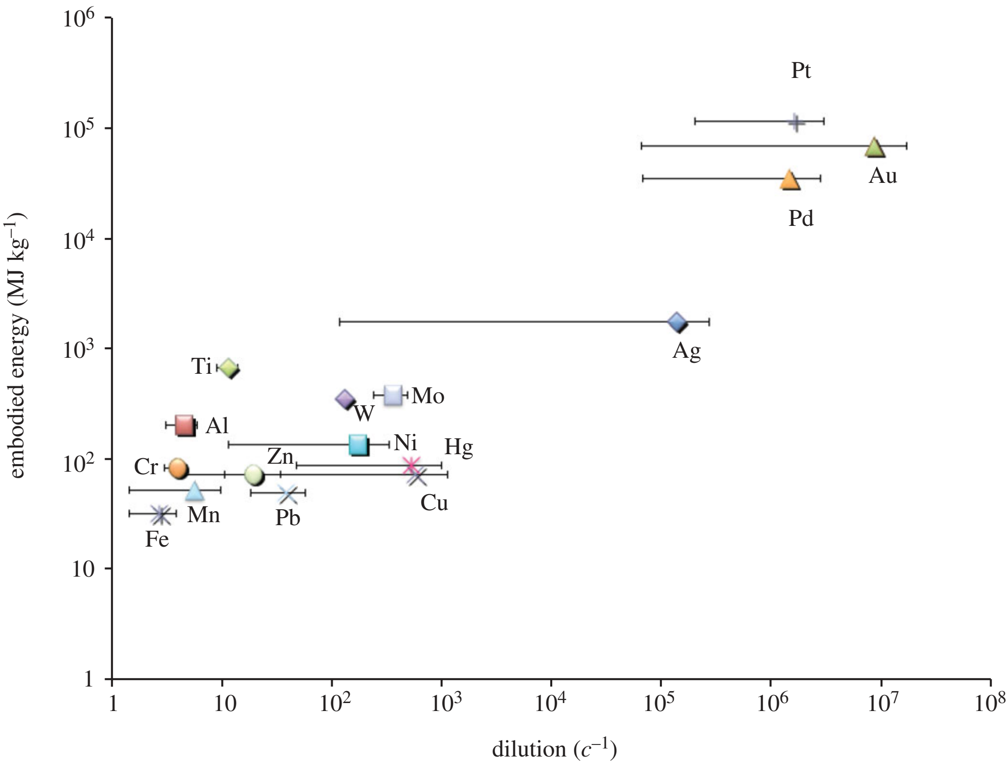

Figure 3. Embodied primary energy of 16 metals [10] plotted against the dilution, or inverse of concentration, of the common ores used to produce the metals [12].

intensity e increases with dilution ($1/c$). The shape of the observed trend can be explained by the change in the dominating energy step. In the lower dilution range, particularly for materials such as iron and aluminium, the energy requirement for production is dominated by the chemical-reduction step. At the other end of the figure, for those metals that are highly dilute (and generally less reactive), such as gold and platinum, the energy requirements are dominated by the mining and separation steps, and generally increase with increasing dilution of the ore. The scatter in the low-dilution area can be explained in part by the differences in the thermodynamic requirements for the chemical-reduction process. This can be estimated by looking at the magnitude of the standard Gibbs free energy of formation for the common ores used to make these metals. For example, looking in the low-dilution area of the figure, the Gibbs free energy for the ores for titanium (TiO_2) and aluminium (Al_2O_3) is relatively large (18.9 and 29.5 MJ kg^{-1}, respectively) compared with the Gibbs free energy for the ores used to produce iron (Fe_2O_3) and manganese (MnO2) (6.7 and 8.9 MJ kg^{-1}, respectively) [13]. Other major differences, which affect the embodied energies, are the quality and availability of the ore, the ore matrix, the complexity of the smelting and production processes, the age of the technology used, and the degree of purity required in the final output. Because these factors can vary considerably around the world, each data point in figure 3 could actually be represented by a cluster of points around a mean value that could easily vary by ±20 per cent or more. See Ashby [10] and Craig & Hammond [14] and the electronic supplementary material. Note that unlike the engineering properties of a material, such as strength or stiffness, which can be obtained under well-specified conditions, the embodied energy is a function not only of the material itself, but also of a larger system that surrounds the material and is often not well defined. Hence, this level of uncertainty is somewhat inherent to the type of large boundary analysis we are performing.

Historical data show that industry has made significant reductions in the energy intensity of materials, particularly for those produced in high volumes. Figure 4 gives time-series data for average worldwide production of pig iron and aluminium. Figure 4 shows e plotted against Q for the chemical-reduction step only, which dominates for the two cases, with a few dates marked to indicate the progression of time. The energy-intensity data for pig iron correspond to the coke used in blast furnaces, whereas the energy-intensity value for aluminium corresponds to the electricity used in the smelting of aluminium (the so-called Hall–Héroult process). The pig iron data show an almost one order of magnitude reduction in the energy intensity over a time period of about 200 years. The aluminium data show an equally impressive reduction over about a century. The average annual improvements for the energy intensity for these technologies have been in the range 1.0–1.5%. The plots also show the theoretical minima for these operations. These minima are approximated by the standard Gibbs free energy of formation for the ores (Fe_2O_3 and Al_2O_3). It is readily apparent that while there is still room for improvement, new improvements will be constrained by thermodynamics. Generally, as one approaches a thermodynamic limit, progress slows down, and the performance levels off near to, but never obtaining the limit. Figure 5 shows a breakdown of the energy intensity for aluminium smelting by major regions of the world over the time period 1980 to 2005. The data show the variation in the world data as well as the world average, marked with the dashed line in the middle. Taken together, figures 4 and 5 suggest two important strategies to further reduce the world average energy intensity of material production. The first would be to move the world average down to the best available technology (BAT) and the second would be to move further towards the theoretical minimum.[2]

The constraints on the first strategy are primarily financial. Material production facilities require large capital investment. Once these costs are sunk, there is a large incentive to continue operation for decades. In fact, looking closely at figure 5 reveals that some of the least energy-efficient facilities are actually operated in the developed world where the installations are older, whereas the newer more energy-efficient facilities are in the developing world. This pattern is repeated for other materials as well, see results for world cement production [7]. After

[2]Our efficiency improvement calculations are based on final energy. More details and alternative calculations schemes are discussed in the electronic supplementary material.

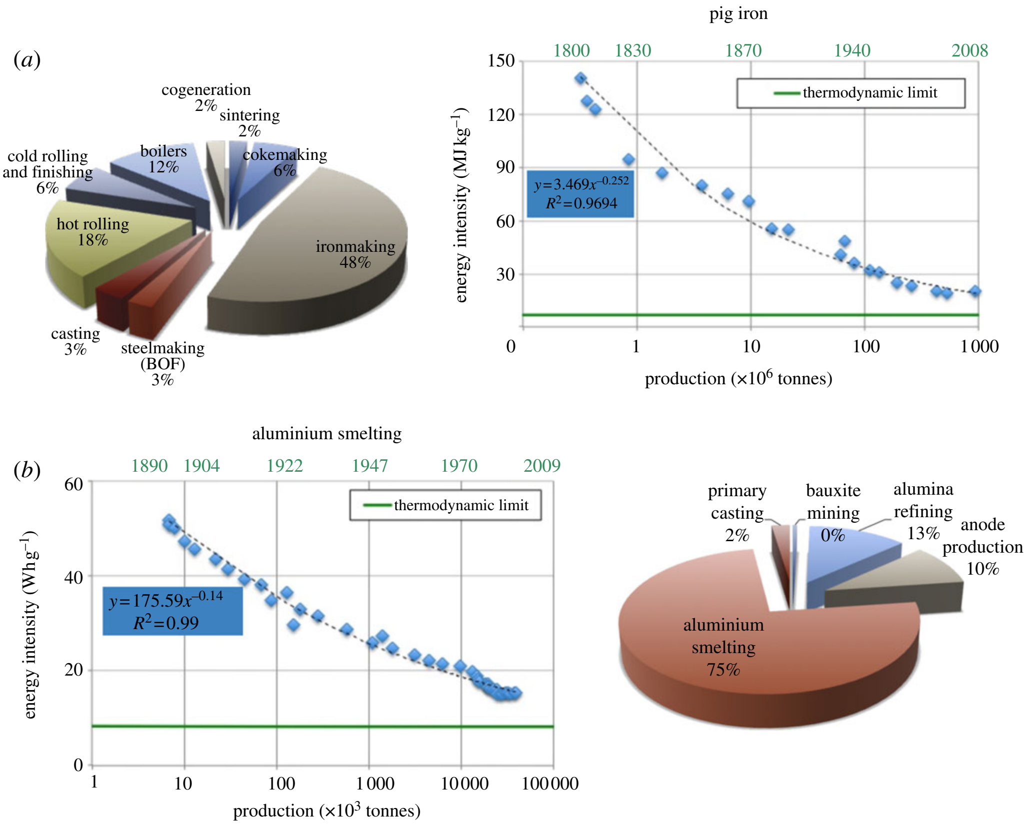

Figure 4. (*a*) Historic trends in global average energy requirements for production of pig iron from ore (coke use), and (*b*) for aluminium smelting (electricity use), versus the respective global production volumes (mass). The corresponding years are labelled above the chart. Also included are the theoretical minimum values for the two processes. Data for iron energy intensity are adapted from Smil [15] and that for aluminium are adapted from Choate & Green [16]. Production data are adapted from the *Mineral yearbooks* [17]. Pie chart data are adapted from Choate & Green [16], Worrell *et al.* [18] and de Beer *et al.* [19]. BOF, basic oxygen furnace.

reviewing the data for the so-called top five materials, we estimate that a worldwide move from today's average to BATs[3] would result in an overall energy reduction of about 18 per cent. This agrees with detailed estimates made by us and others, including the International Energy Agency (IEA) [5–7]. Some of the technologies involved in these improvements would include worldwide implementation of by-product gas recovery from steel production and thin slab casting, retrofitting of aluminium smelters and point feeders, continuous digesters and dry sheet forming for paper production, wet to dry kilns for cement, as well as fuel and clinker substitution and improvements in cracking and distillation for plastics. In addition, widespread implementation of combined heat and power and more efficient electric motors are assumed. Data used in our calculations are provided in the electronic supplementary material.

Additional energy reductions can be made with research breakthroughs and by implementing cutting-edge technologies. Each of the top five materials already have technology roadmaps with key energy challenges identified and funded research and scale up on going [11]. At the same time, the major energy-intensive steps for the top five materials are already in the vicinity of 60 per cent efficient (relative to their thermodynamic limits). If we make the fairly aggressive

[3]BAT is as given by International Energy Agency (IEA). BAT in many cases can be the same as best practice technology that is best available and economical, but can be different when a new technology has emerged. Saygin *et al.* [20] in their work distinguish the two for several industries.

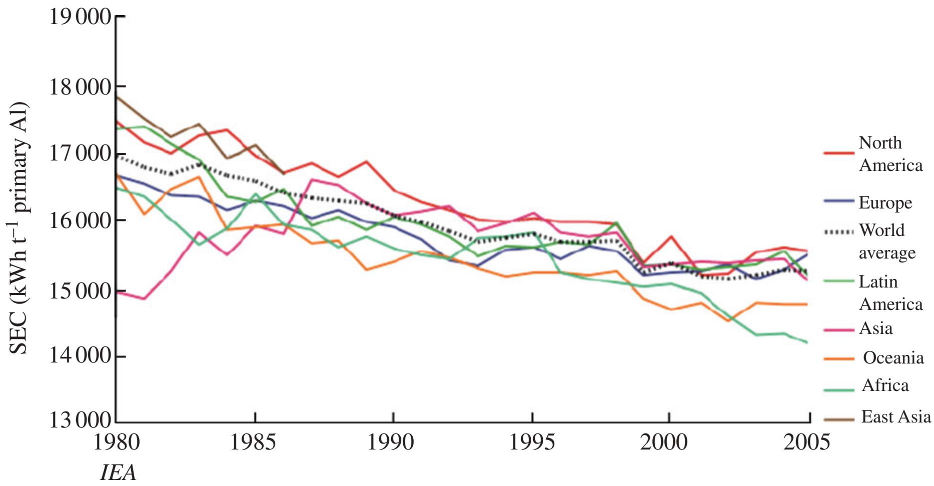

Figure 5. Historical regional data for the energy (electricity) intensity of aluminium smelting. SEC, specific energy consumption. Reproduced with permission from IEA [7]. Tracking industrial energy efficiency and CO_2 emissions © OECD/IEA 2007, figure 8.1, page 211.

assumption that these can be further improved to within half the remaining distance to the theoretical limit (approx. 80% efficient), then we estimate an additional overall reduction in total energy requirements for material production of about 19 per cent, for a total of 37 per cent when combining both strategies. Some of the breakthrough technologies considered here include increased direct carbon injection in blast furnaces, direct smelting of iron ore using coal, black liquor gasification for paper, inert anodes for aluminium and other cutting-edge technologies, some of which may not have been discovered yet. Again, additional details can be found in our work and that of others, as well as in the electronic supplementary material of this study [5–7,11,18,21–23]. The magnitude of this improvement may seem smaller than expected to some. The reason is that this improvement applies only to primary production, not secondary (recycled) production, which in some cases already represents a significant fraction of supply. We discuss recycling next.

Another way to reduce the energy requirements for material production would be to look to a new material source with a lower energy intensity e. This could be to harvest the already processed materials in end-of-life products. That is, because recycling generally avoids many of the energy-intensive steps in primary production (e.g. chemical reduction, mining and separation, etc.), it is well known for having a lower energy requirement when compared with primary production. For example, the production of secondary aluminium may require only of the order of 10 per cent of the energy intensity of primary aluminium. And for steel, it may be only 50 per cent of the primary energy intensity [10]. The problem here is that while we know that we can generally make the energy intensity of secondary production small compared with primary production, there are serious constraints on the quantity of secondary materials that can be captured and processed. This problem is particularly apparent for emerging countries while they are building their infrastructure, which adds materials to stocks rather than making them available for recycling [24].

To explore this effect, we use a relatively simple model that focuses on post-consumer discards, an area with the most potential for improvement.[4] Consider the total demand Q_T subdivided into Q_p (primary production) produced with energy intensity e_p, and Q_s (secondary production)

[4]The other discards come from industrial scrap, which is essentially a form of inefficiency. While industrial scrap has been a sizable component of recycled materials in the past, constant improvement and slower growth will diminish its importance in the future.

produced with energy intensity e_s. The total energy E_T for a given material is then

$$E_T = Q_p e_p + Q_s e_s, \tag{2.1}$$

$$E_T = Q_T[(1-r)e_p + re_s] = Q_T\bar{e} = Q_T e_p(1-m), \tag{2.2}$$

$$m = r\left(1 - \frac{e_s}{e_p}\right) \tag{2.3a}$$

and

$$r = \frac{Q_s}{Q_T}, \tag{2.3b}$$

where $\bar{e}$ is the average energy intensity, r is the fraction of secondary material in the supply and m controls our potential energy savings. Because the general situation is $r \le 1$ and $e_s < e_p$, with $0 < m < 1$, our goal then is to make m as close to 1 as possible.

We state the constraints on Q_s as

$$Q_s < Q_{\text{discards}} < Q_T. \tag{2.4}$$

That is, our secondary supplies must be less than the end-of-life discards owing to difficulties in collection, separation and losses. Let us say

$$Q_s = fQ_{\text{discards}}, \tag{2.5}$$

where $0 \le f \le 1$ is the fraction of discards that becomes available to satisfy demand. Second, the discards must be less than demand because, in general, the discards have come out of the system after 'n' years of product lifetime, whereas demand has continued to grow at rate 'i'. Putting this together gives us an expression for r,

$$\frac{Q_s}{Q_T} = r = f(1+i)^{-n}. \tag{2.6}$$

In other words, r is constrained by the efficiency of the recycling system as well as by the parameters of growth. Furthermore, as we move forward to improve our recycling in an effort to reduce energy use and carbon emissions from material production, we will run into the realization that some materials such as steel, paper and aluminium are already recycled at fairly high levels. At the same time, there is no known route to efficiently recycle cement, and the recycling of plastics is difficult. The challenges plastics present to recycling are the flip side of the advantages they provide for product design—they are almost infinitely changeable. That is, we can alter their colour, properties and performance by a vast array of pigments, additives and fillers, only to greatly complicate the problem of material identification and separation at the end of life. At the same time, some improvements in technology and labelling in Europe do seem to be helpful in improving the recyclability of plastics.

If we now assume a fairly aggressive effort to increase the fraction f and apply estimates for the relevant recycling parameters given in table 1, we estimate a net additional reduction in the world energy intensity required to produce materials at about only 7 per cent of current usage (increased recycling decreases the primary material fraction and thus diminishes the savings from BAT and cutting-edge strategies). Note that this percentage depends on the order of implementation of our proposed energy saving strategies (current to BAT to cutting edge). If recycling were implemented before any of the other improvements (using column 5 instead of column 6), then the percentage change would have been 20 per cent. Nevertheless, the total combined savings would remain the same, at about 44 per cent, regardless of the order. Finally, we implement yet a further recycling improvement by assuming an additional reduction by 50 per cent in the energy intensity of secondary material production, e_s. Many of these secondary processes have not yet been optimized, often for practical reasons related to the collection and sorting of incoming scrap. By uniformly assuming this 50 per cent reduction for all materials, we are still quite far from any thermodynamic limits, for example, the melting of the metals and thermoplastics only requires of the order of 10–20% of our assumed values. This provides still more improvement, raising our total potential savings to 56 per cent. Note that this improvement step appears quite large

Table 1. Recycling parameters for top five materials. Cur, current average; CE, cutting edge; *r*, recycling rate as a fraction of supply. Details are provided in the electronic supplementary material.

material	*n* (years)	*r*2005 (%)	*r*2050 (%)	$[1\text{-}e_{s,Cur}/e_{p,Cur}]$ (%)	$[1\text{-}e_{s,Cur}/e_{p,CE}]$ (%)	$[1\text{-}e_{s,CE}/e_{p,CE}]$ (%)
steel	19	37	69	64	29	65
aluminium	15	30	65	94	89	95
cement	50	0	0	—	—	—
paper	1	45	80	47	34	67
plastic	5	4	28	55	37	68

because we have already implemented aggressive increases in recycling rates in the previous improvement. This is just about as far as we can go with energy efficiency, even using very optimistic assumptions, and yet we are still substantially short of our goal of 75 per cent.

3. Material substitutions

Material substitution presents another potential method for reducing material energy requirements. The idea would be to substitute a material with a lower energy intensity, for a material with a higher energy intensity. For example, substituting concrete, bricks or wood for steel in buildings and infrastructure, or steel for aluminium or plastics in vehicles. A look at figure 6 reveals that if these materials could be substituted kilogram for kilogram, then they would reduce the energy to make these products. Furthermore, owing to the strong correlation shown in the figure between material price and energy intensity, this substitution could also save money. Unfortunately, while potentially simple in concept, the idea of material substitution is much more complicated than substituting recycled (secondary) material for primary material. The main problem is that the material properties of the two substitutes may differ significantly, leading to very different designs. Hence, any analysis to determine the potential energy savings would require a full life-cycle assessment. For example, Ashby has shown how the development of new materials (i.e. alloys, composites, etc.) has led to better properties for construction materials. That is, progressing from natural materials (i.e. stone, timber, etc.) to these new modern materials, one sees that material strength and elastic modulus have increased by about one to two orders of magnitude, whereas the energy requirements to make these new materials has increased by about three to four orders of magnitude (see figs 9.14 and 9.15 in Ashby [10]). Furthermore, materials that we may think of as substitutes may also act as complements. For example, reinforced concrete uses steel reinforcing as well as other steel components in the structure. And steel buildings usually have reinforced concrete foundations. The result is that the findings of various life-cycle assessment studies comparing alternative material designs are quite mixed, often with no clear winner or loser by energy and environmental measures [25,26].

One reoccurring complication in these studies is that energy use and carbon emissions are often not dominated by the embodied energy of the materials to make the product. This is true for buildings where heating, cooling or lighting dominate, and for vehicles where fuel use dominates. In fact, there are many studies showing that lighter weight and more energy-intensive materials such as advanced composites and aluminium can be substituted for lower energy-intensive materials in vehicles and aircraft with overall net savings in total energy use [10,27].

And finally, because material price and energy intensity correlates so closely, it can be assumed that price-based material substitution has already led to significant reductions in the energy requirements for materials. For example, in figure 7, the energy intensity, *e*, versus world production, *Q*, for many materials of construction are plotted. Figure 7 reveals that, in general, many of the high production volume materials are already the low-energy-intensity materials. Of the top five, steel, paper and concrete are near the bottom of the energy-intensity scale. Although

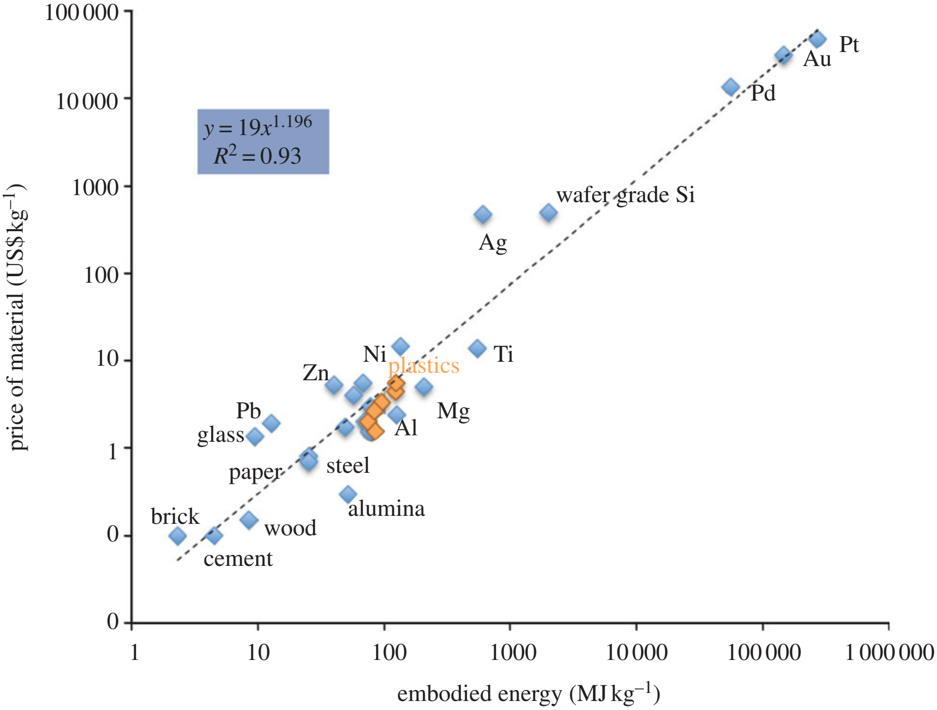

Figure 6. Price of various materials plotted against the embodied energy of the materials. The data for embodied energy comes from Ashby [10], for material prices for metals from the *Mineral yearbooks* [17], plastics from IDES [28] and brick, wood and glass from Ashby [10]. Plastic prices are for year 2011, and all others are for 2009.

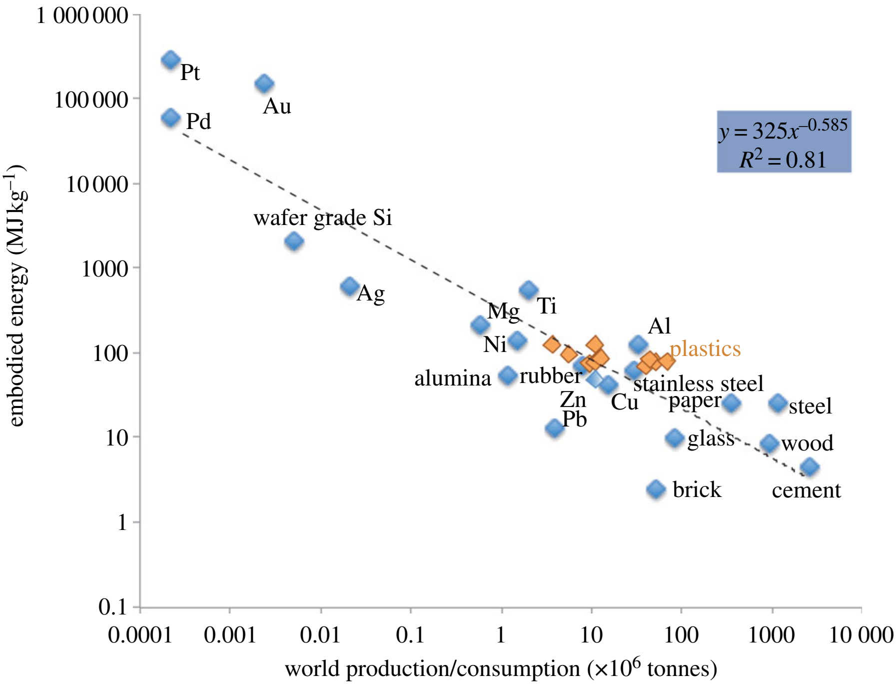

Figure 7. Energy intensity *e* versus world production *Q* for various materials of construction. Adapted from Ashby [10].

it is possible that some opportunities for the substitution of concrete, brick and wood for steel do likely still exist, we do not see material substitution, as characterized here, as a major strategy to reduce material energy requirements. In fact, the expected trends are just the opposite, as discussed in §4.

In summary, we have looked at the possibility of reducing the energy intensity of material production by 75 per cent by 2050, and found that this appears very unlikely. An analysis that includes significant new breakthroughs in production technology and recycling systems as well as deployment worldwide falls short of this mark, providing only about 56 per cent reduction. The essence of this problem is that material production energy is dominated by a small group of materials that have been in production for some time, and have already become quite efficient. Iron and steel, cement, concrete, paper and aluminium have all been in production for at least a century. Plastics, which are newer, will be reaching a century in production just a decade or two from now. Hence, while future gains in energy efficiency for these materials are still expected, major improvements are restricted in part by the laws of thermodynamics.

An alternative way to interpret this result is to observe that if we can obtain the energy-intensity improvement of 56 per cent as just calculated (i.e. $e_{2050} = 0.44e_{\text{today}}$), then we can still meet our original target of $E_{2050} = 1/2E_{\text{today}}$ by restricting growth in demand to only a 25 per cent increase rather than a doubling. This would be a reduction from a 100 per cent increase in demand to just a 25 per cent growth.[5] Is such a reduction possible? And what would be the consequences for the world? We address the issue of demand reduction in §4.

4. Potential for demand reduction

Forecasting future demand for materials is based upon developing plausible scenarios on how the world will develop. A popular working hypothesis is that the developed world has nearly saturated in its *per capita* demand for many of the basic energy dominating materials, whereas the developing world is growing, and may well aspire to the same high levels of materials used currently by the developed world.

The best developed case to support the so-called ‘saturation hypothesis’ is for iron and steel.[6] To understand the salient points of this case, one must differentiate between materials stocks, the total quantity of the materials currently being used by society, and material flows, the annual inputs or flows of materials to society. In studies of iron and steel used in industrialized countries, it has been observed that these stocks tend to plateau after a certain level of *per capita* income. The general idea is that society has adequate supplies of durable goods and infrastructure and, in fact, adding more might be difficult. Müller *et al.* found this plateau level for iron and steel stocks to be about 10 t per cap. After this level is reached, society maintains a certain level of material consumption required to replace and maintain this stock level. This level is estimated to be in the vicinity of 500 kg per cap per year. For comparison, current global average *per capita* iron and steel stocks are estimated to be about 2.7 t per cap, and global average iron and steel flows are about 200 kg per cap per year [24,31,32]. It is interesting to take these numbers and estimate the amount of iron and steel required to move the world from its current average values, to the levels of the developed world. In order to build world stocks of iron and steel to an average value of 10 t per cap for a population of 9×10^9, total production of at least 71 Gt of new primary material would be required, assuming that all existing stocks are recycled in a closed loop. To accomplish this goal, annual primary steel production would (if growing linearly) have to increase by a factor of 2.7 in parallel with growth in secondary steel production. This estimate underscores the enormity of the task: achieving a worldwide ‘saturation’ stock level of 10 t per cap requires that we mine and refine most of the 79 Gt of identified ore from which usable iron can currently be economically and legally extracted [24]. This is not impossible, iron is one of the most abundant elements in the

[5] Note that there is an interaction between demand growth rate and energy intensity because growth affects the recycling fraction of supply (see equation (2.6)).

[6] Evidence for saturation in concrete can be found in Sahni [29] and Aïtcin [30].

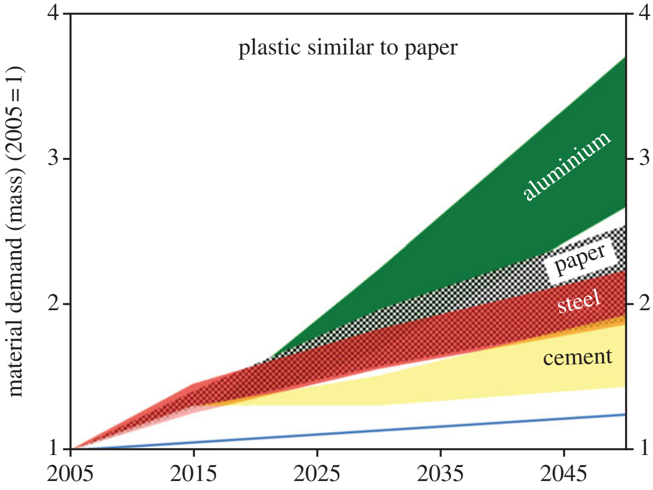

Figure 8. The range of future demand for aluminium, paper, steel, plastic and cement constructed from forecasts provided by the IEA [7]. Plastics demand projection adapted from Allwood *et al*. [5]. The bottom curve (blue) leading to 1.25 in 2050 shows the maximum demand allowed in order to meet the goal of halving the world's energy use by materials with a 56% improvement in energy intensity (see text).

Earth's crust and we will not run out. But understandably, the potential complications involved for a task of this scale are clearly beyond what can be fully taken into account in any forecast. Note also that the nominal growth rate shown in figure 8 for steel (a doubling in demand) would not result in raising the current world average (200 kg per cap per year) to the current level of iron and steel consumption in the developed world (500 kg per cap per year). To accomplish this goal, steel would have to increase by a factor of 3.2 (assuming a world population of 9×10^9) rather than 2.0.

In general then, the approach to a problem of this complexity is to develop alternative scenarios with both high and low estimates that attempt to take into account potential known problems that this development may face. In figure 8, you will find these estimates as developed by the IEA. Figure 8 shows that from 2005 to 2050, aluminium is estimated to grow between a factor of 2.6 and 3.5; paper between 1.8 and 2.4; steel between 1.8 and 2.2; and cement between 1.4 and 1.7. Note that the median for steel is exactly a doubling in demand over this time period. For comparison, we have drawn a line on the bottom of the figure showing what a 25 per cent increase would be. This is meant to represent the scenario where we obtain all of our projected improvements in energy intensity (i.e. 56% improvement) and then limit growth to 25 per cent in order to obtain our goal of cutting our material-related energy in half. This line helps only to underscore the difficulty of the task we have set for ourselves in this study.

Note that in the electronic supplementary material, we have repeated the improvement scenario calculations using the more detailed forecasts given in figure 8, rather than our previous assumptions of a simple doubling in demand for each material. Under these conditions, the resulting total energy-intensity improvement is noticeably less than 56 per cent; using the lower demand values for each material, the total improvement is now 51 per cent, and for the higher demand values, 50 per cent. This reduction in improvement potential can be explained by the shift in composition of the materials that make up our global materials diet. Society is moving towards more energy-intensive materials. This is shown in figure 8 with the materials with higher energy intensities (aluminium, paper and plastics) growing faster than the materials with the lower energy intensities (cement and steel). This trend seems to work against any notion that the material sector can reduce energy usage by substitution. It is, in fact the very opposite that is taking place.

5. Material efficiency

At the beginning of this paper, we asked the question: could the world's material production halve its energy use while doubling demand, based on a programme of energy-intensity improvement? Here, we have argued that the answer to this question is no, even with very aggressive improvement scenarios. Furthermore, fundamental barriers stand in our way, so allowing more time beyond 2050 will not help.

However, we could greatly reduce material energy requirements if we could reduce demand. This would require new thinking about how we use materials. Could the developed world work towards a goal of reducing their basic material requirements by half, while allowing the developing world to catch up to this new level? This is decidedly not a business-as-usual scenario, but is worth looking into in more detail. If feasible, such a programme of 'material efficiency' could greatly help in meeting our energy goals for materials. Material efficiency means providing material services but using less material, and is reviewed in more detail in the editorial paper for this issue [33]. The result would have to lead to a reduction in material demand. That is, material production would have to be reduced, whereas material efficiency activities would have to be increased. The essence of material efficiency is to be more efficient in how materials are used in the design of new products, to make products last longer and to optimize the operational intensity of the material goods (e.g. serve more people with a given product—to share). By themselves, these ideas are not new ideas. But they have not yet been explored in any depth as a means to reduce our global energy use and carbon emissions. New thinking in this area to address not only engineering challenges but also policy challenges is sorely needed. To start the discussion on this topic, one of us (J.A.) has already written a book with a colleague on this topic [31], and four of us (J.A., M.A., T.G. and E.W.) have recently written a white paper [34]. Furthermore, this entire issue of the *Philosophical Transactions of the Royal Society A* is devoted to the many aspects of this idea. While we see this approach as technically possible, we believe that many of the barriers will be behavioural, requiring significant inputs from the social sciences. Of course, at the same time, other avenues such as the development of renewable energy sources, and carbon capture and storage technologies should also be pursued. We do believe, however, that some aspects of material efficiency could be implemented quickly, and at low cost if consumers were motivated to do this.

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