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Material efficiency: providing material services with less material production

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Introduction

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Material efficiency, as discussed in this Meeting Issue, entails the pursuit of the technical strategies, business models, consumer preferences and policy instruments that would lead to a substantial reduction in the production of high-volume energy-intensive materials required to deliver human well-being. This paper, which introduces a Discussion Meeting Issue on the topic of material efficiency, aims to give an overview of current thinking on the topic, spanning environmental, engineering, economics, sociology and policy issues. The motivations for material efficiency include reducing energy demand, reducing the emissions and other environmental impacts of industry, and increasing national resource security. There are many technical strategies that might bring it about, and these could mainly be implemented today if preferred by customers or producers. However, current economic structures favour the substitution of material for labour, and consumer preferences for material consumption appear to continue even beyond the point at which increased consumption provides any increase in well-being. Therefore, policy will be required to stimulate material efficiency. A theoretically ideal policy measure, such as a carbon price, would internalize the externality of emissions associated with material production, and thus motivate change directly. However, implementation of such a measure

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has proved elusive, and instead the adjustment of existing government purchasing policies or existing regulations— for instance to do with building design, planning or vehicle standards— is likely to have a more immediate effect.

1. Introduction

This Discussion Meeting Issue of the *Philosophical Transactions of the Royal Society A* is the result of a meeting held at the Royal Society in London, UK, on 30–31 January 2012. The proposal for this meeting arose out of preparation by the present authors of 'Material efficiency: a White Paper' [1], which was written with the aim of surveying the area and hoping to stimulate interest. The design of the meeting was overtly inter-disciplinary, aiming to draw insights from economics, sociology, design and policy as much as from environmental or technical analysis, in reaction to the questions raised in the White Paper. This overview paper is structured to present a brief summary of the White Paper, and to show how the 15 papers presented at the meeting and other work arising in the academic literature in the past 2 years has taken the subject forwards.

The argument of the White Paper is that, with a growing population and increasing wealth, demand for material extraction and processing is likely to double in the next 40 years. The environmental impacts of the required processing will become critical. In particular, the industrial sector drives nearly one-third of global energy demand, with most of this energy used to produce bulk materials. This requirement for energy will grow with increasing demand for materials, and the increasing energy intensity of production as ore concentrations decline. Most energy is produced by combusting fossil fuels, so materials processing is a major driver of carbon emissions and hence climate change. However, there will be significant limits to future improvements in process efficiency, because energy costs have already driven key processes near to their technical limits [2]. Therefore, a key component of mankind's response to global warming must be to produce less new material. For some materials, this goal can be achieved by increasing recycling, which is the primary goal of discussions around the phrase 'circular economy', although this is constrained by the availability of scrap or end-of-life material, and many practical difficulties associated with collection, sorting and separation [3].

However, in addition to pursuing energy efficiency and recycling, we could also reduce our total demand for material by pursuing the idea of 'material efficiency'—which is to continue to provide the services delivered by materials, with a reduction in total production of new material. This could be achieved by many technical strategies including maintaining existing products for longer, using them more intensely, re-using components from unwanted products or designing products with less material through light-weight design or dematerialization. There are economic, commercial, regulatory and social reasons why these strategies have not been deployed to date, although potentially they could be overcome through policy, new business models or consumer choice.

2. Motivations for material efficiency

Reducing requirements for production of new material would lead to reduced rates of extraction of natural resources, reduced energy demand, reductions in emissions and other environmental harms, and potentially has national political advantages through offering a reduced dependence on imports and increased self-reliance. However, the core motivation for examining material efficiency in this Discussion Meeting Issue arises from its potential as an emissions abatement strategy: materials production is both energy intensive and already largely energy efficient. There are remaining opportunities for efficiency, but they are not sufficient to meet the very ambitious emissions reductions targets proposed by climate scientists. Therefore, unless there exist less CO_2 intensive substitute materials with comparable performance available in comparable quantities, or unless a new low-carbon energy supply replaces the use of fossil fuels, or unless CO_2 can be captured and stored safely, the ambition to reduce industrial emissions can be translated into an aim to reduce our total requirement for materials production. A review of published analyses of emissions intensities (emissions per tonne of material produced) of the five most emitting materials (steel, cement, plastic, paper and aluminium), which have already been subject to 100 years of improvement efforts motivated by costs, suggests that they could further improve by at most around 25–40% [2]. Gutowski *et al.* [4] using estimates of future technical innovations in both primary and secondary production, and accounting for an increased contribution from recycling, predict a slightly greater improvement potential to 50 per cent. This would allow a doubling of global materials output with no increase in emissions, which would be a remarkable achievement. However, climate scientists (for example through the Intergovernmental Panel on Climate Change [5, Table 3.10, p. 229]) and resulting policies [6] propose that we must achieve an absolute reduction in emissions of at least 50 per cent by 2050, regardless of this anticipated doubling of demand.

An obvious first response to this challenge is to examine options to reduce emissions, while meeting market demand for materials, through energy and process efficiency. This ambition has already driven strong interest in the pursuit of four major options:

— Increased recycling: recycling metals, paper and some plastics can save energy, compared with producing new material from ore, biomass or oil. However, in addition to the technical challenges of recycling [3], the potential for recycling to contribute to industrial emissions abatement is constrained by the volume of material available for recycling. Even if perfect collection were possible, the availability of material from end-of-life products is limited by the time delay between initial production and subsequent discard of products [7]: while overall demand is growing, a closed-loop or 'circular' material economy is not possible. Prediction of the potential impact of recycling, therefore, depends on analysis of future requirements and existing stocks. This has given rise to a literature on the analysis of material stocks, including steel stocks in various nations [8], steel in the building stock [9] and materials in housing [10]. Evidence that *per capita* requirements for steel stocks saturate at around 10 tonnes per person [8] suggests that developed economies such as the UK could feasibly operate a closed-cycle for steel, whereas developing economies such as China and India cannot do this until their stocks have grown further.

— Material substitution: Ashby [11] provides an evidence base for examining the potential for using materials other than those commonly used today. As well as considering material properties, substitution depends on the availability of sufficient volumes of material—and as we currently produce 200 kg of steel and 400 kg of cement each year for every person alive on the planet [12], it appears that stone and wood are the only viable substitutes for cement and steel, if measured by both property performance and availability. However, these two materials are considerably more difficult to use, so broadly we can conclude that there are no significant opportunities for substituting the bulk structural materials whose production dominates industrial energy demand figures.

— Powering industry with low-carbon electricity: MacKay [13] explores the potential for a low-carbon energy supply from renewable sources, and shows several options for powering UK industry with renewable electricity. None of these options is easy—owing to the large scale of implementation required for renewables (MacKay reflects this by giving estimates of total land areas required) or the large number of nuclear power stations required. However, the problem is even worse than this, because industry is just one of three major sectors of final demand for energy (the other two are the use of buildings and the use of vehicles), and these sectors are also hoping to use low-carbon electricity supplies in future. Furthermore, the political and infrastructural challenges of implementing such a large-scale change in our energy supply system are difficult. Smil [14] describes the relatively slow transformation of energy systems owing to the complex planning and regulatory developments required to allow changes in supply infrastructures. Beyond this argument about implementation speed, Fouquet & Pearson [15], introducing a special issue on the theme of transitions, recognize that, unlike past energy transitions, the hoped-for transition to low-carbon energy may not show the private benefits to producer and consumer that drove past transitions. The literature on transformations suggests that it would be highly risky to depend on a single technical 'fix' without exploring alternatives, including material efficiency.

— Carbon capture and storage: carbon capture and storage of industrial emissions is also technically possible, but although several technologies for separating CO_2 from other gases are now well established (Meijer *et al.* [16] describe options for separating CO_2 from other gas streams in steel making), even a first large-scale demonstration project of the combination of both capture and storage is as yet far ahead. The technology is also likely to be expensive: potentially one-third of the output of a traditional power station would be required to drive the process. (Sathre & Masanet [17], in a review of current literature on this point, report that the energy penalty of CO_2 capture, defined as the percentage decrease in electricity output per unit of fuel input, ranges from 12% to 48%.) Therefore, as with the pursuit of low-carbon electricity, this approach cannot be treated as a single safe solution for industrial decarbonization.

These four approaches have attracted considerable interest, but while the limits to their implementation over the next four decades cannot be predicted with accuracy, it seems extremely unlikely that these measures alone will allow a halving of emissions over this short period, while material output doubles. Therefore the strategies of material efficiency—delivering material services with less overall material production—must form part of the portfolio of mitigation options for industrial CO_2 emissions.

The motivation to pursue material efficiency as an emissions abatement strategy applies equally to many of the other environmentally harmful impacts of production, including emissions of other greenhouse gases and the release of particulates, acids and other toxics in air, soil and water: many of these problems arise at the most energy-intensive stages of production, so a reduction in overall volumes of material production will reduce their impact. However, this Discussion Meeting Issue also reports on two other motivations. First, Ayres & Talens Peiró [18] examine the potential importance of material efficiency in discussions about rare and critical metals: the rate at which metals become critical would clearly be reduced if the strategies of material efficiency were applied to reduce demand for new production. The issue of criticality has received considerable attention in the past 5 years, but remains a contested area: Erdmann & Graedel [19] review several methodologies for defining 'criticality', and there remains doubt about whether there is a significant risk of absolute scarcity or whether the challenge is more that as high-quality ore deposits are used up, more energy will be required to extract critical metals from less good ores. Ayres & Talens Peiró [18] discuss the consequences of critical metals occurring mainly as 'hitch-hikers' to common attractor metals such as iron or copper, in particular in disconnecting price and supply, and review current applications and recycling processes. At present, apart from precious metals such as gold and platinum, recycling rates for critical metals are very low: Graedel *et al.* [20] estimate that they are under 1 per cent in most cases, largely because these metals are used for alloying (so are difficult to separate), or are dispersed in products that use them only in very small quantities (so are difficult to collect). The pursuit of material efficiency in the design of products containing these critical metals could support more efficient use over longer periods, and new approaches to design for separation at end of product life.

Second, Vasara *et al.* [21] discuss a more general phenomenon than the coupling of 'critical' to 'energy' concerns detected by Ayres and Talens Peiró. The development of biofuels as an alternative to fuel oils clearly depends on the (large-scale) availability of fertile land and fresh water for irrigation. Similarly, the conversion of coal to liquid fuel requires water, and most means to overcome water shortages demand increased energy input. Vasara *et al.* [21], therefore, describe what they term 'resource convergence'—recognizing that many resource stresses and responses to those stresses are coupled to stresses and responses for other key resources (including energy, water, land, metals, chemicals and biomass). Material efficiency is, therefore, likely to become a priority strategy in the wider area of responding to resource stresses other than energy and emissions.

Where Vasara *et al.* [21] focus on the connections between key materials such as steel and cement with other resource systems, Lifset & Eckelman [22] discuss the role of these key materials as components within complex multi-material products. They consider the motivation for exploring material efficiency, by asking at which scale of decision-making it is most likely to be valuable. For those seeking to determine policy or broad corporate strategy, the ideas of material efficiency offer a new set of strategies in discussion of industrial emissions policy. However, for the designers of individual and multi-material products, material efficiency, while providing guidance on sensible strategies, cannot be applied blindly—as the full environmental impacts of design choices will depend on the relative environmental intensity of different materials, and the interaction between impacts in production and those in use. These are the well-known concerns of 'life cycle' thinking, which considers trade-offs in product design choices over the lifespan of the product. For example, increased use of renewable energy supply options might in the short term justifiably increase demand for specific materials, as the infrastructure is constructed. Gutowski *et al.* [23] discuss this issue with detailed data for 25 different product cases, asking whether remanufacturing old products would show a net benefit compared with replacing them with new products—in effect examining the trade-off between embodied energy in products and the energy required during their use. The results showed that remanufacturing was a beneficial strategy for products with low use-phase energy, or low rates of technology improvement, but a poor one when technical improvements allowed more efficient product use. Intlekofer *et al.* [24] report similar findings from case studies of domestic white goods and computers. For product designers, therefore, the application of the strategies of material efficiency must be appropriate to the particular context.

3. Technical options for implementing material efficiency

The White Paper identified four broad strategies for implementing material efficiency, expanded to six here [12]:

— Light-weight design: Carruth *et al.* [25] derive a set of technical principles for designing light-weight products, and then test them on five commercial case studies, with detailed evaluation within the current supply chain. Their evidence suggests that, on average, one-third of all material use could be saved if product designs were optimized for material use rather than for cost reduction, because downstream production (and design) costs are generally dominated by labour and not materials. In addition, manufacturers are motivated to use excess material by an asymmetry in the costs of product failure compared with the costs of over-specification, and by the fact that many products experience higher loads prior to use (in installation or transport) than in use.

— Reducing yield losses: individual manufacturing companies are typically confident that their management of yield losses (generally measured as the difference between mass of material purchased and the mass of material eventually used in products) is well under control. However, Milford *et al.* [26] report a series of case studies examining yield losses along the entire supply chain—from liquid metal to final products—and show remarkably high accumulated losses. In particular, for goods made from sheet metal, approximately half of all liquid metal becomes scrap (which is then recycled in most cases) *en route* to the final product. The worst losses occurred in blanking (10% for sheet metal, with similar losses found for the printing and packaging industry) and trimming after stamping (15–30%), and appear to have had little attention. New technologies could potentially address these issues. For example, in the clothing industry, sheets of fabric are laser-cut into pieces prior to sewing, allowing better tessellation and lower yield losses [27]. With the right technology development, light-weight design can be combined with reduced yield losses. For example, a novel technology for rolling variable-section I-beams for use in construction can create beams using one-third less metal than standard I-beams, providing identical service but without additional yield losses [28]. This is a rich area for further innovation.

— Diverting manufacturing scrap: a consequence of the high yield losses of blanking at present is that the residual 'skeleton' of the sheet could—if well managed—be used as the source for further smaller blanks. Allwood *et al.* [12] report case studies of businesses that perform this task, and that have more demand than can be met with available supply. This is a limited opportunity, and would be reduced if more effective blanking procedures were introduced, so not a target area for further research. For aluminium scrap, a specific opportunity for scrap diversion is made possible by the technology of solid bonding, allowing machining chips to be recycled via extrusion without melting [29].

— Re-using components: generally when owners decide to replace products, the decision is driven only by performance of a few components within the product, so the remainder could be re-used. A clear example of this is in steel-framed buildings, where steel does not degrade in use, and building replacement is typically driven by changed user requirements or planning policies: some buildings have been made with re-used steel [30], but these remain rare. To examine the potential for re-use as a material efficiency strategy, Cooper & Allwood [31] create a catalogue of all current steel- and aluminium-using products, and conduct expert interviews about the potential for component re-use for each product type. Their results suggest that around 30 per cent of all components by mass could be re-used at the end of product life, with the key opportunities arising in construction, large vehicles and industrial equipment. As yet reuse is rare, owing to incompatibility between past and present designs, and the relatively high cost of product disassembly and used-component management.

— Longer-life products: public concern about the 'throwaway society' has led to much discussion, but as yet little action. Cooper [32] presents 17 papers exploring why this is the case for consumer products, but most materials are used in construction, equipment or vehicles, and this area has had little attention. Steel products are most commonly replaced because a subset of critical components are degraded. These critical components typically account for a small share of the steel mass within products, and potentially products could be used for longer if these components were replaced [12].

— More intense use: a broad body of work in the area of 'product service systems' aims mainly to explore the commercial opportunity of leasing rather than selling goods, and potentially this may have the environmental benefit of reducing the total number of goods (and hence requirements for material production) needed to deliver a required level of service. However, Tukker [33], reflecting on a European Union (EU)-wide network activity in this area, reports only marginal benefits owing to changed user behaviour with different contracts of ownership. As yet there is a shortage of evidence on how more intense product use can reduce material requirements. However, an interesting business model aiming to deliver energy efficiency is that of 'energy service companies' (ESCos), which for example might charge building tenants for the supply of energy services (such as heat and light) rather than for utilities. Thus the profit of the ESCo depends on reducing energy purchases while delivering a required level of service—for example, through intelligent light switching and improved insulation. (Sorrell [34] describes these companies, and explores the conditions in which they would be attractive to clients.) These companies therefore have a clear profit motivation to develop skills and implement appropriate technologies to reduce energy purchase costs. Potentially, some material services could be provided similarly [35].

Each of these strategies merits much further research effort, to identify the scope of their mitigation potential, and to find the means to overcome present-day barriers to their implementation. A feature of the technical pursuit of material efficiency is that the six strategies above may conflict with each other, and three such conflicts require further investigation:

— The optimization of component mass through light-weight design may inhibit future component re-use, unless the architecture in which the component is used is standardized, and may inhibit use over a longer lifespan, if optimization inhibits future changes of use.
— Reducing yield losses cuts the availability of scrap for diversion or recycling. This strategy, therefore, does save energy, but is less effective than pursuing light-weight design or product life extension, because it reduces both the supply and demand for material flowing through (less energy intensive) secondary production.
— Maintaining an energy-using product in use over a longer life may delay the opportunity to adopt technology improvements which lead to reduced energy requirements in use. This trade-off has been subject to several studies (including [23,24] mentioned above) which are reviewed by Skelton & Allwood [36], who go on to develop a model of the total energy implications of product ownership. Using a range of assumptions regarding product characteristics and the typical timing of product failure, they show that early replacement can cause as much excess energy use as delayed replacement.

4. Economics and material efficiency

A key component of economic discussion of *energy* efficiency has been consideration of the 'rebound effect', also known as the Jevons [37] paradox:

> It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.

In other words, if technology improvements allow delivery of some function with reduced energy input, the cost of the function reduces, so stimulating increased demand and, as a result, total energy requirements do not reduce. Jevons made this statement from his analysis of British use of coal in the nineteenth century, and Wrigley [38] sets this in context by describing the self-regulation of the 'organic economy' in Britain prior to its dependence on coal: without coal, the only source of available energy arises from photosynthesis, so biomass was required for food, fuel and materials. Production of iron was, therefore, inherently limited, as it required high inputs of biomass for energy, and, once most productive land was under management, this could only be supplied at the cost of reducing food and other materials. Population growth was, therefore, constrained (or eventually would be prevented) by the limits of the total net primary productivity of the land. This perspective provides helpful context for discussion of material efficiency—and a similar self-regulation might occur if supplies of ores and minerals were equally constrained. However, as discussed above, the problems of material production are not that we face an input constraint, but rather that the unwanted outputs of production—emissions of CO_2 in particular—place strain on the carrying capacity of the Earth's natural sinks. Feedback of the input constraint in the organic economy was instantaneous—food shortage in any year would immediately affect the whole population. However, the feedbacks of global warming have a relatively long time delay—and a key challenge to implementing material efficiency is to find economic justification today for actions that will benefit the population in future.

The word 'efficiency' always refers to a ratio, but can have several different definitions, and this leads to significant confusion when examining the economic implications of strategies aiming at efficiency. As intended by the authors of this paper, 'material efficiency' is a physical measure—how many tons of material are required to deliver some level of final service, such as passenger transport or appropriate space for working and living. However, in economics, the denominator of measures of efficiency is usually money—how much material is required to deliver each money unit of revenue or gross domestic product (GDP). Thus, economists equate an increased consumption of material and energy services with increased economic welfare, where the physical view would be that the welfare arises from the service provided by the energy and materials, and not their consumption *per se*. Equation (4.1) relates these two measures by use of a third ratio, which is the price consumers are willing to pay for material services,

$$\frac{\text{Materials required}}{\text{Service provided}} = \frac{\text{Materials required}}{\text{Money spent}} \times \frac{\text{Money spent}}{\text{Service provided}} \Leftrightarrow$$
$$\text{Physical material efficiency} = \text{Economic material efficiency} \times \text{Price of service.} \tag{4.1}$$

The intention of the physical definition of material efficiency is to draw attention to the physical inputs required by society, which in turn define the industrial emissions arising from production. The intention of the economic definition is to relate material demand to other economic activities and motivations. However, equation (4.1) demonstrates that it is quite possible for economic material efficiency to improve (for the ratio to decrease) while physical material requirements remain static, or even increase, if the price of the service delivered by the materials increases. The pursuit of economic material efficiency may not, therefore, lead to any reduction in the environmental consequences of industrial production, and, at worst, the economic definition can be used to create an entirely artificial impression of 'decoupling' of economic and physical activity: if rich countries such as the UK pursue policies to reduce onshore materials production and manufacturing, they will apparently show a shift to a more service-based economy, their economic material efficiency will apparently improve and their onshore CO_2 emissions will apparently reduce. To illustrate this, Wiedmann *et al.* [39] show a rapid divergence between the UK's emissions as reported to the United Nations Framework Convention on Climate Change (production-based) and those from consumption since 1990: the UK's consumption-based emissions are now more than 30 per cent greater than reported production-based figures. This difference is entirely due to the offshore materials production and manufacturing required to meet the physical demands of UK consumption. Thus, any reported gain in UK material efficiency, measured by the economic ratio, would disguise the true worsening of the UK's physical material efficiency. Davis *et al.* [40] demonstrated that this phenomenon is not limited to the UK, and report the balance of trade of CO_2 for 11 countries, strongly re-inforcing the conclusion that production-based figures are a poor indicator of a nation's environmental impacts.

A further complication from the difference between economic and physical measures of material efficiency arises when the word 'material' is used to describe the intermediate inputs of production, rather than physical materials. Baptist & Hepburn [41] stated this difference as follows:

> Engineers and scientists have tended to define 'materials' to mean physical inputs such as iron ore and steel, often measured in units of mass. In contrast, economists often do not differentiate between 'materials' and other intermediate inputs aggregated together, partly because it can be difficult to distinguish 'raw' materials from other processed physical components—even materials such as cotton and timber require labour and capital to be produced.

Baptist and Hepburn proceed with the economic definition, and, by fitting production functions to data related to a broad set of manufacturing sectors in the USA, demonstrate that firms with lower 'material' (intermediate) inputs have higher total factor productivity (that part of output which cannot be explained after accounting for the application of defined inputs including capital and labour). This analysis—the first we have found to examine material efficiency in the economic literature—is dependent on the economic definition of 'material', and for example shows that a design consultancy with few intermediate inputs has greater total factor productivity than an assembly line with many. This carries an interesting policy message—supporting the logic of 'decoupling' that more labour-intensive businesses have lower material impacts. However, this message must be interpreted carefully, because the beneficiaries of these productive service businesses will continue to spend their income on physical goods, which must be made somewhere. Furthermore, the intermediate inputs to individual firms are themselves the outputs of other firms, and eventually all intermediate spending is converted to wages, tax and profits, once sufficient transactions have been taken into account. Unpicking the connections in this chain of transactions is one of the contributions to material efficiency possible through input–output analysis. Hannon [42] summarizes the work of his group in Illinois using this approach in the 1970s. The analysis proceeds by disaggregating national energy consumption among the sectors represented in an economic input–output table, either in the ideal case by direct sectoral analysis of energy purchasing and use, or more commonly by assuming that energy consumption within the sector is strictly proportional to money flow. (This is clearly a big assumption, when energy prices may vary independently of the quantity of energy purchased, pricing may be different for different sectors and so on.) The Leontief inverse is then used to attribute responsibility for energy consumption to final demand. The approach can be used to estimate the energy consequences of different means to the same end—for example contrasting the use of disposable or refillable drinks containers.

The simplistic assumption of linearity—that money flow and energy use are always proportional—strongly influences the conclusions possible from this form of analysis. At an aggregate level, the assumption tends towards suggesting that the main way to reduce national energy use is to reduce total national income, because efficiency measures in one sector will release additional spending in another, and similarly because structural change (more activity in one sector, less in another) will have less effect than expected, as income in one sector turns into spending in others. At an individual level, the assumption creates a difficulty for one person seeking to reduce their ‘energy footprint’: choosing to purchase less energy-intensive goods has less effect than expected, because individuals must spend their money somehow, so it will remain in the economy, and be ‘re-spent’ by the providers of those goods, who—on average—will follow national preferences for energy-intensive goods. This argument would be closely mirrored in equivalent analysis of materials. The technical strategies set out in the previous section aim to reduce the ‘material intensity’ of the manufacturing and construction sectors—and input–output analysis could be used to demonstrate how this would change costs, and, therefore, influence demand, although this must account for cross-border coupling—to avoid the illusions of production-based accounting demonstrated above [39]. There is opportunity for valuable research in this area.

Within the framework of input–output analysis, if all manufacturing, construction and the steel industry were treated as a single sector, a national economy would suffer no knock-on effects from a transition to material efficiency (less steel production in this case) if the combined sector delivered the same total output, with the same contribution to employment, taxes and profit, and the same requirement for other intermediate consumption. This hypothetical requirement is the basis for a preliminary exploration of a transition to material efficiency in the UK steel economy [43]. UK steel consumption is currently around 530 kg steel per person per year and should be reduced to 160 kg per person per year to meet the requirements of the UK Climate Change Act [6]. For four case study products, the technical strategies described above provide sufficient options to deliver similar services within this required reduction for steel [43]. The manner in which steel-bearing goods are delivered today requires labour, largely in making new goods in manufacturing or construction, and potentially this labour could be re-deployed into maintenance, servicing, upgrade and transfer of existing goods, rather than making replacement goods. Detailed analysis is required to examine the economic potential and consequences of this re-deployment, but it would be brought about rapidly if customers or producers preferred it, and government policies in future could be designed to support this preference.

5. Sociology and material efficiency

In a crisis, individual behaviour can change rapidly to support a national goal: in the UK in the Second World War, householders gave up their iron railings to supply material for armaments, and in the summer of 2011, following the Tsunami on 11th March that year, Japanese households voluntarily reduced electricity consumption by up to 15–20% compared with the previous year [44]. There is also an emerging consensus that, even though there is a well-established linear correlation between individual income and total energy requirements [45], beyond some threshold, increasing wealth does not lead to increasing well-being—for example in studies by Kasser [46] or Layard [47]. However, despite this consensus, in the absence of a crisis, are there mechanisms by which individuals, communities or societies can be brought to prefer material efficiency options?

As yet, it has proved difficult to find such mechanisms, without which the hope of societal change remains unhelpful 'wishful thinking' rather than something we can actively pursue. However, a valuable contribution is to recognize the current existence of alternatives to 'Western consumerism' and then to explore whether there are features of other social structures that could be adapted and adopted. Urry [48] argues that a 'powered down' society must meet several criteria to be socially stable and attractive: there must be reasonable levels of well-being, as measured by social (rather than GDP) indicators of societal health; there must be reasonable social equality—not too great a divide between the 'haves' and 'have-nots'; the 'heroes' or 'role models' of such a society should be 'local' rather than being exemplars of high mobility and consumption, as with Western celebrities at present; such a society should be more local and operating at smaller scale. Urry describes two demonstrations of some of these characteristics: the recent development in Cuba of organic agriculture, agro-ecology, small markets, worker co-operatives and urban gardens; the community-led transition to a fossil-free future in the Swedish city of Växjö.

In contrast to this societal view of consumption, Harrod [49] examines the emotional relationships between individuals and materials or objects, through a rich survey of artists, sculptors and writers. From Ruskin's concerns about cast iron being an emotionally hollow simulation of hand-forged wrought iron, through emotional responses to wood, to the use of consumer waste as the raw material for sculptures, Harrod draws our attention to the (largely lost) meaningfulness of materials and the objects made from them. Fletcher [50], aiming to underline a similar message, notes that a garment from a 'fast-fashion' chain can be discarded after one outing as cheaply as it was bought, whereas something made or enhanced by a friend at a time of crisis cannot be discarded at all, as it has become 'emotionally durable' and part of an individual's life-story. The emotional permanence of buildings and objects has been a constant of many societies, and only under the mass availability created by industrial production has it been lost. While not yet providing a mechanism for change, Harrod's writing is a valuable pointer to material value and consequent well-being that has been hidden as a result of mass production.

Heritage is greatly valued in several countries with longer histories, and there are pointers in both Urry's and Harrod's papers to the possibility that societal well-being, apparently no longer increasing with GDP in developed economies, could actually be increased in a less material hungry society. So far, this possibility carries with it the danger of nostalgia—a return to an imagined golden past, where people were happier while consuming less. We are short of visions of a technologically advanced future with reduced consumption: the 'paperless office' is yet to emerge, despite 40 years of personal computing, and as yet we have no data to support the (marketing) concept that e-readers and other portable devices reduce total environmental impacts. Much further thinking and research is required to begin to develop and translate such visions into proposals for action.

6. Policy and material efficiency

The goal of material efficiency potentially creates two challenges to conventional political aims: does it destroy jobs and does it deny growth? The exploration of policy interest in material efficiency must, therefore, provide reassurance to these two concerns, while also searching for policy mechanisms that are politically acceptable.

In a broad response to the authors' White Paper on material efficiency, Söderholm & Tilton [51] state that

> policy makers should opt for policy measures that target the relevant market failures (e.g. environmental damages) as closely as possible. This normally means avoiding policies that directly encourage specific material efficiency options... . This is because ex ante it is difficult for policy makers to know in what ways and by how much to alter material production and use.

The most widely discussed such measure is the imposition of a 'carbon price' or 'carbon tax'—on the grounds that carbon emissions are an un-priced 'externality', so pricing them appropriately will change cost structures so that the free market finds the optimal solution to a lower carbon future. (There are also many other environmental effects such as air pollution in developing economies which are external to current prices.) This has been the basis for most international negotiation over climate change to date, but has proved largely unsuccessful: without the agreement of an international carbon price, it is possible to impose carbon prices more regionally, for example in the EU emissions trading scheme. However, such schemes can implement only very low carbon prices, to avoid creating an impossible competitive disadvantage for industries within that region which must compete in global markets. Indeed, Victor [52] argues that the ambition to develop a universal, international, legally binding agreement that national governments will then translate into domestic policy is fundamentally flawed in the case of greenhouse gas emissions: such an agreement must always be constrained to the lowest common denominator of commitment, so will fall short of the level of action required to make a big difference. Instead, Victor proposes that progress is more likely through 'clubs'—small groups of countries, possibly regionally connected, edging forwards their abatement commitments in response to each other's actions, and sharing the benefits of progress among themselves.

In addition to the general difficulty of international agreement, a specific problem arises when considering the effect of a carbon price on demand for materials: materials are an intermediate good, and generally contribute only a very small part of the total cost of producing final goods—for example, of all the costs of making a typical steel-framed office building, steel purchase contributes around 4 per cent [12]. The dominant cost in making buildings and goods is labour—so even a very high carbon price will have only a relatively small effect on the price of the final goods. Similar cost structures in other industries mean that there are weak incentives for actors at the end of supply chains—such as car companies, food companies and construction sector clients—to instigate material efficiency measures upstream. A carbon price would change the relative cost of different materials and so offer greater incentives for material efficiency within individual companies upstream, but, as discussed above, there are few if any substitutes for the bulk materials which drive most industrial emissions and upstream measures such as light-weighting and yield improvement require collaboration along supply chains [26]. Therefore, the idea that a carbon price will act to bring about the form of material efficiency discussed in this paper is doubly unlikely: politically, it is very unlikely that an international carbon price will be agreed; even if it were agreed, it is unlikely to result in the collaborative effort across supply chains that is required to fully exploit the opportunities for greater material efficiency.

Skelton & Allwood [53] use multi-regional input–output analysis to explore the effect of a carbon price on the incentives for material efficiency along the supply chains of five key steel-intensive sectors. They show that the composition of input expenditure in these supply chains is such that greater weight is placed on labour cost reduction than on steel cost reduction: average expenditure on labour is 12 times greater than expenditure on steel in the production of these five products. Even a high carbon price does little to raise the priority given to steel. More importantly, the incentives offered by a carbon price are dwarfed by the disincentives to greater material efficiency caused by labour taxes (the combination of taxes on income, profits and social security contributions), which deter the substitution of labour for steel. The net result of policy, even with a high carbon price, remains an incentive to substitute more material for less labour.

This is the opposite effect than would be required to promote material efficiency, and reinforces the suggestion long-made by Stahel [54] that governments should shift the burden of taxation away from the renewable resource of labour, and onto the non-renewable resources of materials and fossil fuels. Baptist & Hepburn [41] re-echo this suggestion, but as yet it remains largely hypothetical, and has not entered political thinking or implementation. In fact implementation could be extremely difficult: given the current high ratio of labour tax to energy/material taxes, a new tax on materials would have to be set at an extremely high level in order to maintain net government income, and this would give a significant first-mover disadvantage to industries in any country beginning the switch.

It appears therefore that, while it would be preferable to develop simple policies that target market failures as closely as possible, there are sufficient difficulties in achieving this to suggest that in many cases other, less perfect, means may well be easier to implement. Government policy in all countries already includes widespread publicly accepted regulation—for example on planning permission, building standards, vehicle standards, health and safety and so on. So potentially there is a much more immediate intervention available to governments through adjusting existing regulation rather than dreaming of an idealized, yet unattainable, incentive. In parallel, governments exert significant influence on markets as purchasers (in the UK, government purchasing accounts for approx. 30% of all final demand), so modification of existing purchasing policies to stimulate markets for material efficient delivery of goods is a powerful weapon available to policy-makers. Allwood [43] anticipates a broad range of measures that might stimulate a move towards material efficiency, by identifying two main features of possible intervention: where there is insufficient experience of the implementation of material efficiency, governments can act to stimulate awareness and innovation; where there is a lack of motivation to adopt material efficiency, governments can stimulate both business and customer preferences.

However, interventions that are not based around a single incentivizing measure must be applied well to be effective. Worrell *et al*. [55] provide a detailed case study of packaging policy in The Netherlands over the period 1991–2012, showing that it achieved a reduction in packaging volumes until 2000, but thereafter volumes have consistently grown. They deduce that this has occurred primarily owing to a lack of consistent national policy over time, lack of well-defined and monitored targets, the lack of national public statistics on packaging, and a failure to communicate about options for more materially efficient packaging. Clearer obligations on reporting, particularly about mass of material used nationwide, would help stimulate effective reduction.

Cramer [45] provides a political perspective on policy for material efficiency, examining the transition process of implementation that must occur even once an agreed policy approach has been identified. She emphasizes key lessons from transition management—that all actors be involved in the change process, that changes must occur at many levels (for example with innovative experiments, in practice, informing changes at regime level) with a long-term vision guiding short-term actions—and deduces that:

> the role of government is not restricted to formulating policies and then leaving it to other actors to implement them. Instead, [government involves] a continuous interplay between the different actors during the whole implementation process.

In the absence of a single 'pure' policy measure based around a single incentive, it seems likely that policy to bring about material efficiency must be a process of the type described by Cramer, based on a long-term vision (with a clear metric as Worrell suggests) and worked out through the normal broad complex of government measures.

7. Discussion

The need for material efficiency as a component of industrial emissions abatement is inevitable, if demanding targets for emissions reductions are to be achieved. Sufficient technical options exist to deliver current levels of material service with significantly less material, many of which could be implemented immediately if so demanded by customers, and some of which could be made cheaper by technical innovations. However, cost structures have long promoted a substitution of more material for less labour, so there is relatively little incentive for businesses to lead a transition to material efficiency, unless required to do so either by customers or by policy. Although a 'perfect' policy initiative built around pricing the externality of emissions would be attractive to politicians, it might not be effective for products (where costs are dominated by labour and not energy) and there is as yet no indication that governments are likely to adopt such measures. Without doubt, those pursuing material efficiency have much to learn from the history of energy efficiency regulation, and the iterative adjustment of existing regulations has the potential to create significant incentives for material efficiency. For example, in the short term, adjusting policies around construction and planning has significant potential for reducing total requirements for material associated with buildings, although such regulation is local in nature so would require many initiatives to lead to rapid change.

Interest in discussing material efficiency is growing, and this Discussion Meeting Issue aims to stimulate a broader engagement across the whole range of disciplines involved, but, to bring it about in practice, leadership is required. A particular priority at present—identified by Cramer [45] in her suggestion that innovative experiments should inform regime change—is to find 'lead users' who, through personal motivation or brand-values associated with environmental leadership, will pioneer the implementation of the technical strategies described earlier. In parallel, material efficiency must be brought into policy discussions—to raise awareness of its real potential, and begin the process of transition required for policy design to recognize the consequences of material consumption.

The journey towards achieving significant physical material efficiency is a long one, albeit urgent if emissions abatement targets are to be achieved. The long history of bulk (energy-intensive) materials being traded as low-priced commodities has created a materially inefficient system, but this can be changed. Stahel's [54] call for taxing resources rather than labour strikingly emphasizes the scale of change required to redirect the economic system towards material efficiency, but perhaps a more immediate commercial motivation arises by an analogy identified by Wrigley [38]: the industrial revolution in Great Britain occurred not because of British coal mining, but because of Britain's use of coal to deliver new higher value products and services. Potentially, this could be an inspiration to the business leaders and policy-makers whose decisions direct material use: future economic well-being may depend much more on the value created by materials than from trading them as commodities, and the pursuit of this value would inevitably coincide with a pursuit of material efficiency.

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