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### Author for correspondence:

Julian M. Allwood  
e-mail: [jma42@cam.ac.uk](mailto:jma42@cam.ac.uk)

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# Transitions to material efficiency in the UK steel economy

Julian M. Allwood

Department of Engineering, University of Cambridge,  
Trumpington Street, Cambridge CB2 1PZ, UK

Steel production is energy intensive so already has achieved impressive levels of energy efficiency. If the emissions associated with steel must be reduced in line with the requirements of the UK Climate Change Act, demand for new steel must be reduced. The strategies of 'material efficiency' aim to achieve such a reduction, while delivering the same final services. To meet the emissions targets set into UK law, UK consumption of steel must be reduced to 30 per cent of present levels by 2050. Previous work has revealed six strategies that could contribute to this target, and this paper presents an approximate analysis of the required transition. A macro-economic analysis of steel in the UK shows that while the steel industry is relatively small, the construction and manufacturing sectors are large, and it would be politically unacceptable to pursue options that lead to a major contraction in other sectors. Alternative business models are therefore required, and these are explored through four representative products—one for each final sector with particular emphasis given to options for reducing product weight, and extending product life. Preliminary evidence on the triggers that would lead to customers preferring these options is presented and organized in order to predict required policy measures. The estimated analysis of transitions explored in this paper is used to define target questions for future research in the area.

## 1. Introduction

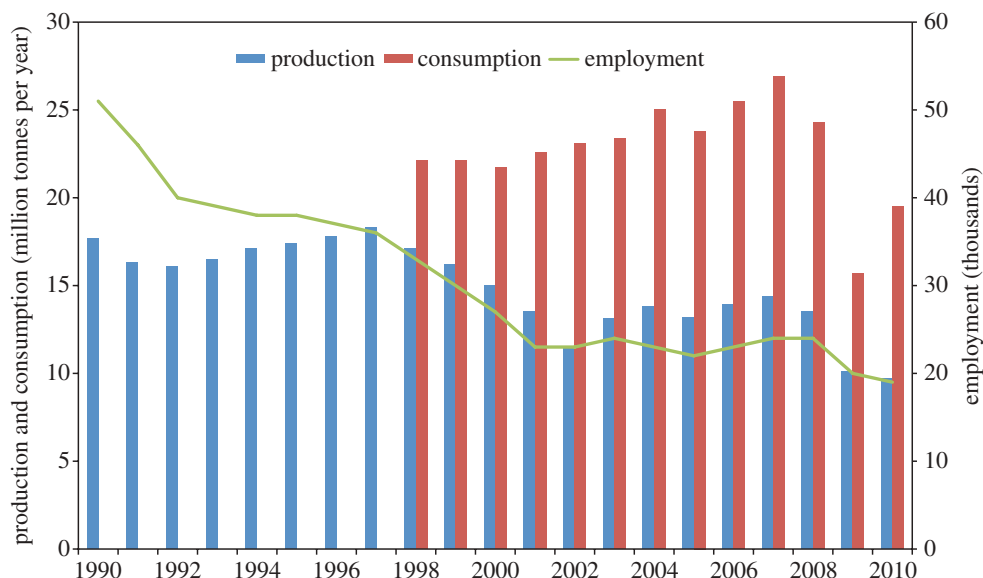
In previous work, we have shown that implementing energy and process efficiency measures is insufficient to meet scientific or government targets for industrial emissions reductions, because the energy-intensive (material producing) industries are already remarkably efficient [1]: we estimated that the technical potential for

future energy efficiency in the steel industry would lead to a maximum reduction of 34 per cent of current energy use per tonne of new steel, and this would require extraordinary international focus on implementation. This limit to future process efficiency motivates the pursuit of material efficiency, which we define by the ratio of material service delivered over new material produced. Thus, material efficiency aims to deliver the same services provided by materials today, but with less new materials production. In a 'white paper' on the topic based on a comprehensive literature review, we attempted to set out the broad range of strategies that could be deployed to achieve material efficiency, to identify barriers to their adoption and anticipate means to overcome the barriers [2]. In parallel, through a major UK Government funded research programme 'WellMet2050', working in close co-operation with a large industrial consortium, we have aimed to give reality to the potential for material efficiency in the energy-intensive materials production sectors, particularly for steel and aluminium. This work has led to a book *Sustainable materials: with both eyes open* [3] which identifies six ways of reducing demand for new materials production while delivering the same 'material services'.

- *Light-weight design.* Most products could be 25–30% lighter if they were optimized, but we currently use excess material to exploit economies of scale, as insurance against uncertain loads, and to support loads experienced during installation.
- *Reducing yield losses.* 25 per cent of all liquid steel and 40 per cent of all liquid aluminium produced globally each year is never used in final products, but becomes production scrap and is recycled. The resulting perpetual loop of scrap could be reduced significantly through a co-operative effort between design and production.
- *Diverting manufacturing scrap.* Some opportunities exist to divert production scrap away from re-melting and into alternative fabrication processes, to avoid the high melting energy of recycling.
- *Re-using metal components.* Larger components from end-of-life products, particularly steel I-beams from old buildings, could be re-used directly without recycling. This is currently inhibited by the need for rapid demolition of old buildings and the lack of an agreed standard for re-certifying old steel, but is already profitable for a number of small operators.
- *Delaying end-of-life.* Most buildings and products are replaced long before their physical end-of-life owing to changed user requirements or competition from new designs. Alternative design strategies could be deployed to achieve a much longer life for high-embodied-energy structural components, while allowing more frequent replacement of components that deliver style or functions. Although in some cases this delay might delay adoption of efficiencies in product use, in most cases we currently replace goods earlier than would be required to minimize total energy requirements.
- *Using products more intensively.* Most office buildings are unoccupied for around 100 h of each 168 h week, and the 28 million 5-seat cars licensed in the UK are used for 4 h per week each by an average of 1.6 people. More intensive use of products would reduce total required capacity.

Analysis in [3, §19] of the potential for applying these six strategies across the full catalogue of steel and aluminium using products showed that light-weight design, delayed end of life and more intensive use are the three most effective options to reduce emissions as they all lead to reduced demand for production of primary material. The other three strategies divert material from recycling, but as this is already less energy intensive than primary materials production, they have less overall effect.

Our work to date has focused on the motivation for material efficiency, and assessment of the potential material efficiency strategies that could be implemented in practice. This has provided clear evidence that material efficiency offers sufficient options to achieve targets for industrial emissions reduction [3, §19] but as yet has not explored the means to bring it about. This paper therefore aims at a preliminary exploration of the transition to material efficiency,



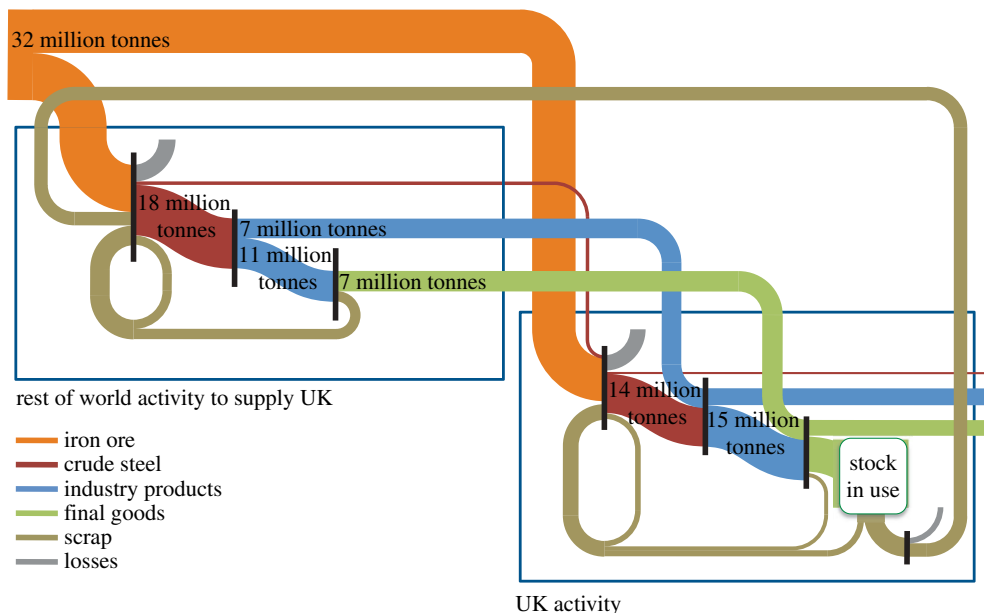
**Figure 1.** UK production, consumption and employment since 1990 (adapted from UK Steel [5]). (Online version in colour.)

through anticipating the operation of a future UK steel economy. The next section provides a macro-economic view of material efficiency in the UK steel economy. Section 3 translates this macro-economic view into requirements for specific exemplar products, and §4 estimates the customer and producer triggers that might bring about the necessary transition in order to anticipate relevant policy options. The paper is developed out of the analysis and case studies of the WellMet2050 research programme and overtly uses estimates in order to give some definition to the key research questions that underpin future transitions towards material efficiency.

## 2. The UK steel economy now and with material efficiency

This section aims to characterize the UK ‘steel economy’ now and in 2050, assuming that the 80 per cent emission reduction targets of the UK Climate Change Act [4] are met. The phrase ‘steel economy’ is used to describe the complete sequence of physical and economic activities required to deliver final services from the use of steel in the UK. Because the transformation required by the Climate Change Act is so dramatic, only an approximate characterization of the UK steel economy is required in order to identify the scale of the challenge. This requires firstly a physical and secondly an economic description.

The recent history of the UK steel economy is summarized in figure 1. UK steel production, which is mainly primary production from ore owing to the legacy of assets constructed 50 years ago, declined dramatically in the early 1980s, and figure 1 then shows a steadier decline in the past 20 years from approximately 15 million tonnes per year to 10 million tonnes per year in 2010 [6]. Employment has declined in proportion to output, but the graph shows that the UK’s demand for steel has (until the financial crisis of late 2008) steadily grown, serviced by increased imports. Although UK climate policy is currently restricted to emissions on UK territory, figure 1 clearly demonstrates how this is artificial. Barrett *et al.* [7], using input–output tables to predict the UK’s true emissions based on consumption, show that in contrast to national figures showing a small reduction in UK production emissions since signing the Kyoto protocol in 1990, UK emissions driven by consumption have in reality risen by 20–30% in the past 20 years. The difference between the two figures is because of the ‘carbon leakage’ implied by figure 1: our demand for steel (and the outputs of other energy-intensive industries) is increasingly met by producers in other countries.

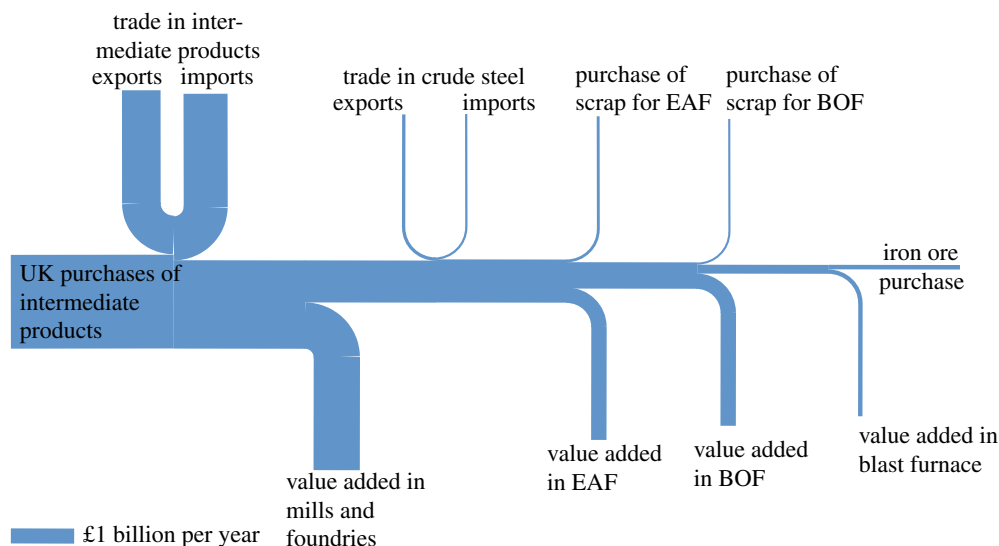


**Figure 2.** Mass flow analysis of UK steel consumption. (Online version in colour.)

The most recent published analysis of the detailed steel flows through the UK is that of Dahlström & Ekins [8] using 2001 data and their numbers have been used to construct the right-hand side of figure 2. The figure shows the transformation of imported iron ore and domestic steel scrap into new liquid steel, intermediate stock steel products (bars and coils of strip steel, for example) and final goods (cars or domestic appliances, for example). Dahlström and Ekins' analysis aimed to characterize flows only within the borders of the UK, so to illustrate the artifice of 'carbon leakage' the left-hand side of figure 2 connects Dahlström and Ekins' import requirements to an estimate of the activity in the rest of the world required to supply the UK.

The figure assumes that all scrap exported from the UK is used to supply UK imports, and assumes that yields in upstream steel production (the ratio of useful steel produced over total steel produced in the furnace) are the same as those in the UK. However, the figure assumes that yields in manufacturing are lower than those within the UK, because much of the steel imported to the UK (particularly in cars) is fabricated from sheet rather than long products. In a detailed analysis of yields along steel supply chains, Milford *et al.* [9] show that globally around 25 per cent of all liquid steel produced each year is cut off during production and internally recycled. Using results from Hatayama *et al.* [10] also, this ratio results from a combination of lower losses (approx. 5–15%) for long products (such as steel sections and reinforcement bars) and higher losses (approx. 35–50%) for components made from sheet steel. Accordingly, the estimate in figure 2 assumes that total production scrap in the rest of the world is equal to the total mass of steel in final goods imported to the UK—and hence the total offshore production required to service UK consumption is greater in figure 2 than that reported in figure 1, and similar to the 32 million tonnes predicted in [7].

Dahlström & Ekins [8] complement their analysis of mass flow for UK steel with an estimate of the monetary value of the steel flows, and these money flows are summarized in figure 3. Figure 3 shows the consequences of £6.2 billion UK spending on intermediate steel stock products in 2001, confirms the balance of trade in both stock products and crude steel seen in figure 2 and shows how this spending is used to add value to around £300 million of iron ore imports. However, in anticipating how the UK steel economy might change towards material efficiency, this figure is insufficient, because the outputs of the steel industry are all intermediate and not final products.



**Figure 3.** Value flow for UK steel production and trade in 2001. EAF, electric arc furnace; BOF, basic oxygen furnace. (Online version in colour.)

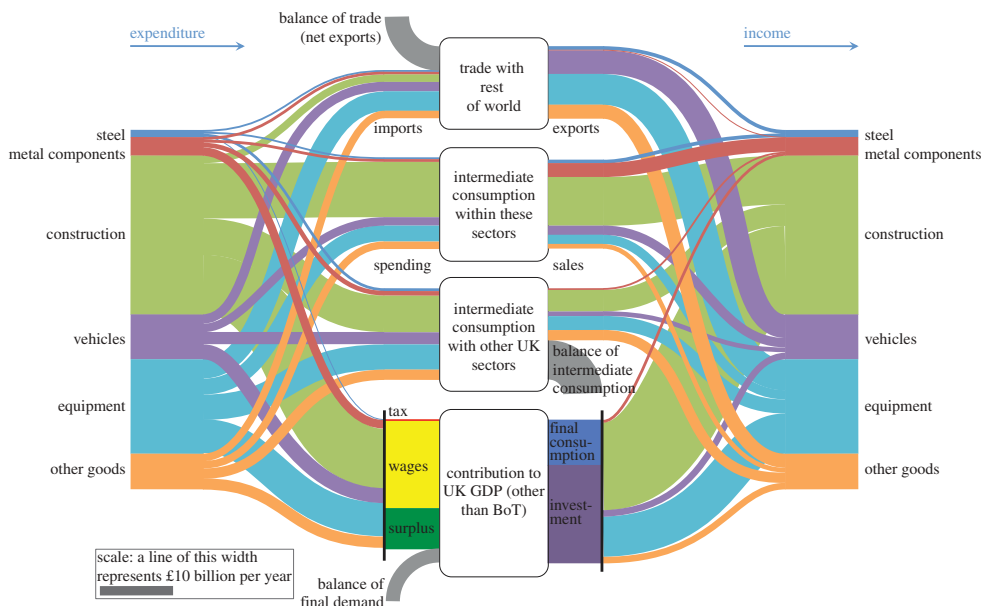
The analysis must continue forward through other sectors, until the steel has become part of final demand, in order to understand the role of steel in the UK economy.

It is possible to see the wider role of steel in the UK economy by exploring money flows between the steel industry, its immediate downstream sector (component manufacture), the four major end-use sectors of construction, equipment manufacture, vehicle manufacture, other metal goods (including domestic appliances for example)—and a seventh ‘rest of economy’ sector. These flows are shown in figure 4 with, on the left, flows showing how each sector distributes its revenue through purchasing, paying wages and taxes and generating a surplus, and on the right, the sources of revenue flowing into each sector. (The data used to construct figure 4 come from the most recent set of UK input–output tables created with 2004 data by Turner [11] based on [12]. The numerical basis of figure 4 is given in the electronic supplementary material.)

Figure 4 is designed to illustrate the sources and destinations of the turnover of the six sectors of interest. The magnitudes of the flows at the extreme right- and left-hand sides of the figure are identical: all income is expended. In the centre of the diagram, four categories of exchange are defined. The two middle categories show intermediate consumption—trade between sectors. The upper category shows trade between the six sectors and the rest of the world. The fourth category shows two indicators of how these sectors contribute to UK gross domestic product—with the income approach on the left and the expenditure approach on the right. (Figure 4 uses 2004 data, while figures 2 and 3 use 2001 data. Steel prices vary rapidly as it is a globally traded commodity, and during the period 2000–2009, the price of new steel sections in the UK varied between £200 and £750 per tonne. This reinforces the need to take only an approximate view of money and mass flows when anticipating the future of steel in the UK, as the sector is so strongly influenced by activity elsewhere.)

Figure 4 demonstrates several key features of the UK steel economy.

- The income to the steel sector on the right-hand side of the diagram and almost all income to the metal components sector arise not from final demand, exports or ‘other UK sectors’ but from within the six selected sectors. This confirms that these sectors are the ones required to represent the UK ‘steel economy’.
- The steel sector is small compared with the downstream sectors which depend on it.
- The UK has a positive balance of trade for these six sectors, particularly through exporting equipment and vehicles, although with no export related to construction.



**Figure 4.** The UK steel economy in 2004. GDP, gross domestic product; BoT, balance of trade. (Online version in colour.)

- The gross value added by these sectors to the national economy (tax plus wages plus surplus) is less than their total income from other sectors; however, they contribute a substantial net consumption of intermediate goods within the UK—they have a considerable ‘knock-on’ effect within the economy.

The most important message of figure 4 is that because the output of the steel sector is entirely consumed as intermediate consumption by construction and manufacturing, UK steel demand can be cut only if these downstream sectors can continue to function well, with much less new steel. Evidence in [3,13] makes clear that there are no viable substitute materials that can replace steel without increasing emissions, so a reduction in national steel demand requires that the (much larger) downstream sectors change their designs, their production processes or their customer offerings, to require one third less steel without themselves shrinking.

Figures 2 and 4 now give a basis for defining a target for the UK steel economy in 2050, within the requirements of the UK Climate Change Act. Müller *et al.* [14] have shown that developed economies reach a stable stock of steel per person, beyond which further increases in wealth do not lead to increased steel ownership. The UK reached this position in around 1975, so current demand of around 530 kg per person per year is mainly to replace existing goods. Even though the UK population is expected to increase by 15 per cent by 2050 [15], for the sake of simplicity, we will assume that demand in 2050 is approximately the same as today. In [3, §10] we conducted a comprehensive analysis of every possible energy and process efficiency measure that might be applied to existing production of steel. The mid-range of our forecast is that by 2050, recycling rates will reach 90 per cent of all end of life steel, all existing primary processes will be 14 per cent more energy efficient, electric motors in downstream fabrication will be 50 per cent more energy efficient, 20 per cent of all electricity production will be decarbonized, and there will be some adoption of novel processes linked to carbon capture and storage. In total, this strongly optimistic projection would lead to reducing the total emissions of existing production to 65 per cent of current levels. The UK Climate Change Act mandates a reduction to 20 per cent of current levels, so in addition to all known energy and process efficiencies, this requires that our demand for new steel must be reduced to 30 per cent of present levels.



Can the UK economy function well, while reducing our steel demand from today's level of 530 kg per person per year to this target level of 160 kg per person per year? The next section will examine this question for four representative products, but the evidence presented in this section shows that such a change would have repercussions across many sectors of the economy. Reducing steel output will lead to a loss of employment both in the steel industry and its suppliers, although this could potentially be reduced by policies to replace some imported steel with domestically produced material. However, the downstream sectors which use steel as an input are crucial to UK welfare, and cannot be allowed to shrink in proportion to steel output. This is therefore a rich area for future study: if downstream sectors including construction and manufacturing shift from current dependence on new steel to applying the material efficiency strategies listed in the introduction, what will be the consequences for prices and employment, and what will be the knock-on effects for other sectors?

The key research question arising in this section is therefore about redeployment: at present, construction and manufacturing businesses are mainly driven by sales growth related to delivery of new goods. Can these businesses transform to achieve equivalent sales, with similar employment, while using one third of the new steel required at present? More specifically:

- Having given priority to light-weight design, more intensive use and longer lasting products in the review of §1, is it possible to deliver these strategies in construction and manufacturing without significant job losses? Are there other value-adding activities that do not require significant material inputs that could absorb spare labour from construction and manufacturing? For example, will customers pay for the increased costs of labour producing 'heritage standard' buildings to compensate reduced overall rates of new building? Is there a viable business model for servicing cars over 30 years, with a similar ratio of income to labour as in producing new cars at present that might last for around 15 years?
- What other knock-on and dynamic effects would a reduction of steel consumption have within the economy? Which other sectors currently benefiting from the 'balance of intermediate consumption' shown in figure 4 could or could not adjust to lower steel output?
- Are there missing national statistics that would illuminate material flows more clearly, and that would in turn help to inform and motivate customers and businesses towards material efficiency strategies?
- Can the UK's current balance of trade in steel and steel-intensive goods be adjusted to provide some economic comfort to compensate for reduced overall steel demand?
- Are there new policy opportunities for national governments to regulate emissions from onshore material efficiency rather than trying to negotiate treaties that influence emissions elsewhere associated with offshore production?

### 3. Material efficiency for steel-intensive products

The review of previous work in §1 demonstrated that the most effective material efficiency strategies are to reduce material demand per unit of service (through light-weight design or more intensive use) or to reduce replacement rates by maintaining goods for longer. In this section, we will examine the implementation of these approaches to meet the target from §2—to reduce UK demand for new steel to 160 kg per person per year. In order to explore this challenge, table 1 translates the current macro-economic figures of §2 into *per capita* equivalents of current use and then demonstrates the physical significance of these through an approximate translation of these numbers into four representative products. The intention of table 1 is to give some physical reality of the material efficiency targets of §2, not to make precise numerical predictions, and the justification for the data in the table is provided in the electronic supplementary material.

**Table 1.** UK material efficiency targets translated into representative products. (Product data mainly taken from [3], production yield data from [9,10]. Further details of the origin of numbers in this table are given in the electronic supplementary material. The letter labels of each row, shown in the second column, are used to demonstrate how the calculated rows arise from the data rows.)

		construction	equipment	vehicles	other goods
<b>UK figures</b>					
mass flow (million tonnes per year)	a	18	5	4	5
total spend (£billion per year)	b	170	48	100	38
average pay in sector (£ per hour)	c	11	18	18	18
<b>per capita figures</b>					
mass (kg per year)	a/0.06	300	83	67	83
spend (£ per year)	b/0.06	2800	800	1700	630
<b>representative product</b>		<b>office block</b>	<b>rolling mill</b>	<b>car</b>	<b>refrigerator</b>
mass of steel in product (kg)	d	1 000 000	5 000 000	960	50
estimated yield ratio in production	e	94%	80%	50%	80%
capacity (persons served by product)	f	630	200 000	2.2	3
mass of liquid steel (kg per person)	$g = d/(e*f)$	1700	31	870	21
lifespan before replacement (years)	h	40	18	15	8
mass of liquid steel (kg per person per year)	$j = g/h$	43	1.7	58	3
price (£) (for whole product)	k	14 000 000	20 000 000	20 000	300
annual spend (£ per person per year)	$m = k/(f*h)$	560	6	600	13
equivalent labour (hours per person per year)	$n = m/c$	50	0.3	33	1
<b>material efficiency limits</b>					
minimum steel mass (kg)	p	700 000	4 500 000	300	25
maximum possible lifespan (years)	q	100	30	20	40
maximum possible capacity	r	940	250 000	3	3
limit of liquid steel (kg per person)	$s = p/(e*r)$	790	23	200	10

The ‘representative product’ category of table 1 introduces several interesting measures of steel consumption. The mass of steel in the product is the mass over the lifespan—reflecting the fact that the ‘work rolls’ in rolling mills wear out in operation, and must be replaced approximately every 2 years, and the lifespan of the mill is therefore averaged over its components. The ‘capacity’ measure indicates the number of people in the UK served by each product—for example, we have an average of one car per 2.2 people. This allows derivation of two *per capita* measures of steel use. ‘Mass of liquid steel (kg per person)’ is a measure of stock, and ‘mass of liquid steel (kg per person per year)’ is a measure of annual consumption. For example, the table shows that out of the 530 kg per year of liquid steel each person in the UK consumes, 58 kg per year is used to make cars. The row ‘equivalent labour (hours per person per year)’ translates average annual per person spending on each product into an equivalent labour input, using estimated UK labour rates: on average, each person in the UK pays for 33 h of labour in vehicle manufacturing each year.

The penultimate three rows of table 1 estimate the probable limits to the three key material efficiency strategies reviewed at the beginning of this section.

— *Light-weighting.* Steel framed buildings could be produced with around 30 per cent less steel than at present by optimization [16]. It is difficult to reduce the mass of rolling mills,



which is determined by the loads they experience. Car mass can be reduced significantly, as low as 300 kg [17], and refrigerators could be smaller and hence lighter.

- *Increased lifespan.* Office and commercial buildings in the UK are typically designed for 50 year lifespans, but 100–200 years is routinely possible. However, they are replaced after 40 years because of changes in user requirements, or changes in mechanical or electrical technology (ventilation, insulation, Internet, etc.) but this could be overcome through reconfigurable design [3, §16]. The rolls in rolling mills are currently wholly replaced when the surface is worn, but replaceable sleeves might allow great extension in the life of the bulk of the embodied material [18]. It seems unlikely that the lifespans of cars can be increased significantly, while car technology is changing rapidly, but refrigerator specifications change slowly, and refrigerators could be designed for maintenance to allow very significant life extension.
- *More intensive use.* Office buildings are largely unoccupied for at least two thirds of each week—outside ‘office hours’—so plausibly could be used more intensively. It would be difficult to change the number of people served by each refrigerator—inevitably each household will require a refrigerator, and the table assumes only a modest possible increase in car utilization—equivalent to a reduction to one car per household.

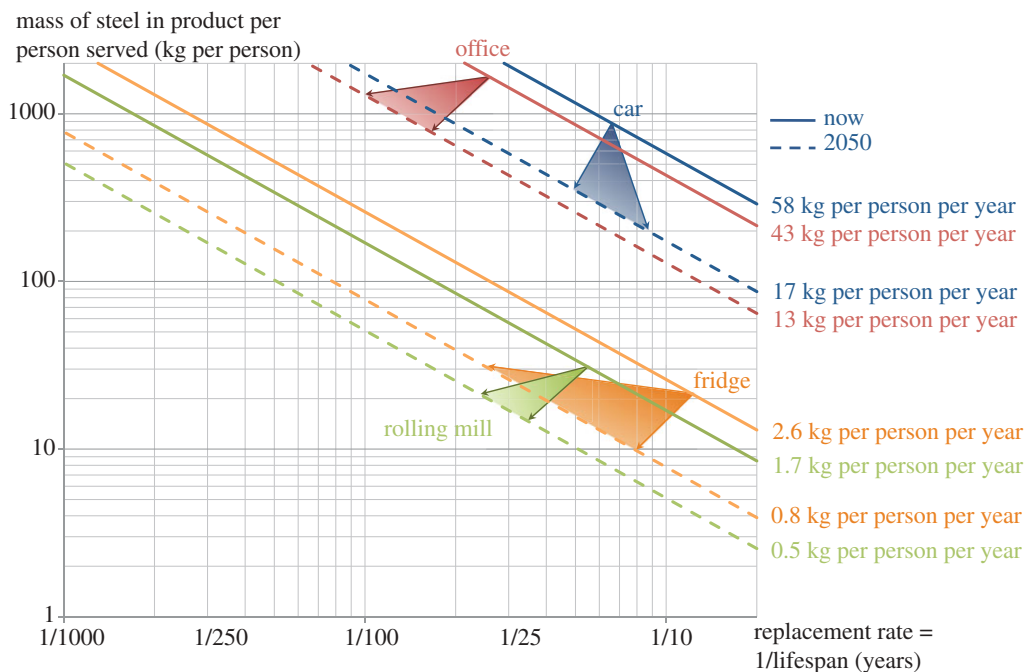
The final row of table 1 shows how the options to reduce product weight and those to allow more intensive use combine to reduce the total mass per person required by each product. These numbers are scaled back to mass of liquid steel, assuming no change in manufacturing yield. The intention of table 1 is to provide only illustrative data, and more detailed analysis would be required to evaluate the material efficiency strategies for each product in realistic detail: for example, it is probable that there may be trade-offs between different strategies, which limit their total impact.

The targets to achieve material efficiency—to reduce the requirement for new steel per person per year to 30 per cent of present levels—are now illustrated for the four products of table 1 on the graph of figure 5: the  $x$ -axis has been chosen as the replacement rate ( $1/\text{lifespan}$ ) so that contours with constant values of mass-per-person times replacement rate (shown as straight lines as both axes are logarithmic) show rates of steel demand per person per year.

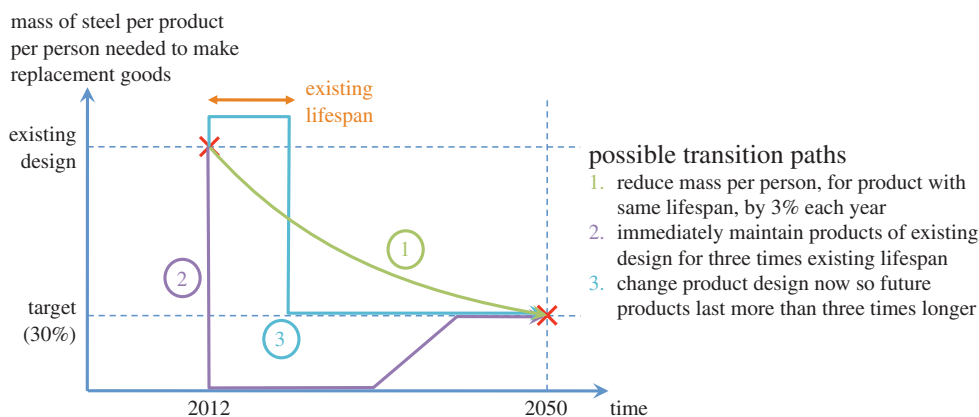
The solid contours show existing personal demand rates for the four representative products, from table 1, and the dashed lines show the corresponding material efficiency targets at 30 per cent of these levels. For each product, a triangle is shown—with the upper right vertex showing current use, and the other two vertices defining the limits to life extension and mass per person defined by the last rows of table 1. Any combination of life extension and mass per person reduction along the dashed line meets the 2050 target. In most cases a reduction in both measures is required. However for the car, sufficient weight saving is possible, that in the limit, a car with 300 kg of steel with a reduced lifespan of around 11 years would meet the target. Also for the refrigerator, if the lifespan was extended from 8 years to the limiting value of 40 years proposed, the mass per person could increase by up to 50 per cent. For the office and the rolling mill, both weight reduction and life extension are required. (For some products, there will be a relationship between mass and energy required in use, and this is explored further in [3, §16].)

Figure 5 is static—and shows options to ensure that by 2050 all products have shifted from current parameters to those of the material efficiency targets on the dashed contours. However, this ignores the existing stock of products and their lifespan. For any product category, there will be some distribution of remaining lifespans for the UK’s current stock, so it is possible that some of the current stock will not be replaced before 2050. This effect provides a further ‘boundary condition’ on the transition to material efficiency, and is illustrated in figure 6, which shows three illustrative pathways from current to future products.

Pathway 1 shows a smooth transition based on reducing the mass of steel per person required as each product is replaced. If the mass is reduced—either by light-weight design or more intensive use of products—at a rate of approximately 3 per cent per year, the requirement will have dropped to 30 per cent by 2050. Pathway 2 illustrates a possible transition if existing products



**Figure 5.** Plausible targets for material efficiency for representative products. (Online version in colour.)



**Figure 6.** Three transition paths for achieving 2050 material efficiency target. (Online version in colour.)

are kept for three times longer. If this is possible—it is probably what would happen automatically in a crisis such as war—without any change of product design, it could be implemented at any time between now and 2050, so for illustration, the figure shows an instant change. Demand for replacement steel drops to zero in the short term, as products due to be replaced now would be maintained for a two further lifespans, and then rises to an average of 30 per cent of previous levels. Pathway 3 assumes that in order to maintain products for substantially longer, their design must be changed—perhaps even requiring more steel than used at present. Thus steel requirements initially increase, until the existing stock has been replaced. For refrigerators and cars, with current lifespans less than 38 years, this is possible before 2050—but for buildings it cannot be applied. Therefore, the range of transitions illustrated in figure 5 may not all be feasible for products with a longer lifespan. Figure 6 is in effect a template for any ‘roadmap’ of transition.

Table 2 gives specific examples of implementation related to the discussion of this section, showing for each of the representative products of table 1 examples of the physical requirements

for each of the three key material efficiency strategies and commenting on the business implications of the change.

This section has demonstrated that it is possible to find technical options to achieve the mass savings specified in §2, and to envisage business models for some if not all of these options. However, to date, there has been no move in this direction, so the next section of the paper discusses the triggers that might initiate the required transition.

The key research question arising from this section is about business models: for all major steel-intensive products, is there a plausible business model in which current employment can be maintained, while reducing the required mass of steel per unit of service to 30 per cent of current levels? With more detail:

- Table 2 gives examples based on estimates. What specific options exist for each major steel using product, and is there a business case for each option?
- What design principles lead to products requiring less steel per unit of service, while delivering sufficient robustness to allow long life?
- How can existing longer-life product designs (such as buildings) be upgraded for longer life most effectively?
- At present the cost of steel is generally low compared with the cost of labour: are there production technologies, design strategies or business models that can help us to overcome current diseconomies of scale in producing optimized light-weight components?
- What co-benefits would customers find sufficiently attractive to motivate a switch to light-weight or long-life designs?
- Current asset and project valuation methods based on discounting rates appear to remove all accounting benefit from investing in future longevity: would other valuation methods give a higher priority to longer-life assets?
- If we assume unchanged spending rates (product price divided by lifespan) for major product types, what repair or upgrades can be achieved with the available money (labour) and can this be improved?

## 4. Triggers for the transition to material efficiency

The previous section aimed to give specific examples of strategies that would bring about material efficiency for four representative products. To summarize the different motivations identified in table 2, table 3 summarizes the triggers that might lead to either purchasers or producers opting for material efficiency over current practice.

However, at present, neither purchasers nor producers are pursuing these options and we have few if any examples of where socially motivated behaviour choice alone has led to a significant reduction in demand, even when—as in the case of smoking—continued consumption causes direct personal harm. It is therefore probable that some policy intervention is required to trigger material efficiency, and two features of this intervention can be deduced from tables 2 and 3:

- there is as yet insufficient motivation for businesses and their customers to opt for material efficiency and
- we lack experience of the implementation of material efficiency, so there is low awareness of its potential and value.

Figure 7 uses these two features to structure a set of possible policy opportunities that might promote a transition to material efficiency. Figure 7 is speculative, but demonstrates a range of policy opportunities, based on our estimated purchaser and producer triggers in table 3. The key research question arising from this discussion is about policy: what triggers would drive businesses and individuals to prefer material efficiency options? More specifically:

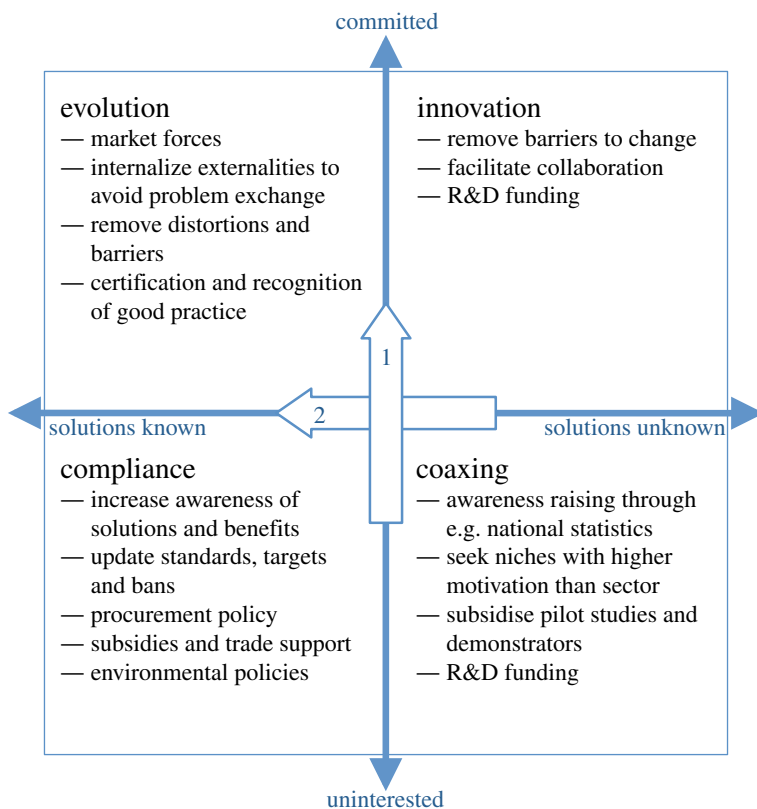
**Table 2.** Examples of physical (in italics) and business implementation of the three material efficiency strategies for the four representative products.

	lighter weight design	more intensive use	longer life
office block	<p><i>up to 30% of current steel use can be saved through avoiding over-specification and optimizing components</i></p> <p>steel purchasing is a small fraction of construction costs, and reducing steel use will increase labour. This could be cost-neutral if clients choose (or are obliged) to pay a higher price, but gives no benefit except for 'branding'. Would be more attractive if it gave 'co-benefits' such as rapid construction, increased flexibility or longer life</p>	<p><i>most offices are currently unoccupied for 60–70% of the hours in a week, so could be designed with 'shifting furniture' for multiple uses</i></p> <p>although a few schools now double their capacity utilization with a morning and afternoon shift of pupils, this strategy is rare. It could increase rents for the owner, if office furniture and partitions could be rapidly 'folded away' and replaced by for example restaurant or entertainment, or if offices and apartments were combined</p>	<p><i>office buildings are currently replaced after approximately 40 years, and there is no technical barrier to maintaining them for 100 years or more</i></p> <p>office buildings are replaced due to changing user needs or changed planning permission so life extension would be attractive if a building had heritage value or could be reconfigured with different capacity. Refurbishment and new build have similar costs, so potentially cost-neutral if retrofit/ upgrade occurs at the same rate as replacement now</p>
rolling mill	<p><i>there are some opportunities for optimizing mill design, but probably more options for reducing the mass of associated material handling kit</i></p> <p>much industrial equipment is over-designed, to provide a high degree of robustness. Delivering more optimized products would increase labour and cost extra, and clients currently see no benefit</p>	<p><i>mill utilization is around 60%, but having excess capacity allows for flexibility in the range of products being rolled</i></p> <p>owners are already motivated to maximize utilization, so little opportunity to increase. Global capacity currently increasing, and old mills are re-sold and moved to areas with growing demand</p>	<p><i>the mill stand lasts for a long time, but work rolls have a shorter life. Replaceable sleeves [18] may be feasible in future</i></p> <p>the labour and cost of having replaceable wear surfaces, rather than replacing whole parts, are probably comparable, but may be attractive for convenience and speed</p>

(Continued.)

Table 2. (Continued.)

	lighter weight design	more intensive use	longer life
car	<p>lightweight design is key to improved future fuel economy, and there is potential to reduce to 25% of current mass</p> <p>customers might prefer light-weight cars if fuel costs rise rapidly, regulation promoted them and safety concerns are addressed. Little change to labour requirements or price, which is dominated by design not material purchasing</p>	<p>car sharing and preferential 'car-pool' lanes have been tried widely, with little effect, but future self-driving cars may help</p> <p>manufacturers will resist more intensive use, as it would cut total sales. Car users currently prefer the convenience of ownership to the cost saving of sharing, although this would change with a big escalation of fuel prices</p>	<p>no technical difficulty to repair cars indefinitely, but this misses the opportunity to upgrade for better performance or style</p> <p>new car production exploits economies of scale very effectively, so an hour of labour in repair shops is less productive than one in manufacture. If fuel economy reaches a plateau, re-design for easy repair and style upgrade could help</p>
refrigerator	<p>options exist to use less metal in existing refrigerators, and as refrigerator capacity has grown rapidly, it could be reduced with little inconvenience</p> <p>refrigerator price and production complexity do not scale strongly with capacity (prices are more about style) so a shift to lighter or smaller refrigerators would not significantly reduce employment</p>	<p>little opportunity to serve more people, as there is one refrigerator per household. If size is reduced, capacity used more intensively</p>	<p>refrigerators currently have short lifespan which could easily be extended by better design and manufacturing control</p> <p>leasing (at approx. £13 per person per year) could be attractive to consumers and suppliers. However, repair costs are currently high, due to strong diseconomy of scale, so re-design is needed to allow simple exchange of modules</p>



**Figure 7.** Possible policy interventions that might support material efficiency. (Online version in colour.)

**Table 3.** Summary of potential triggers for material efficiency.

triggers for purchasers	triggers for producers
<ul style="list-style-type: none"> <li>● changes in costs (taxes) related to product ownership, material purchase or disposal</li> <li>● co-benefits (e.g. faster construction, better performance, speed of repair, convenience)</li> <li>● reduced purchase price or costs of use</li> <li>● use of different asset valuation models—based on replacement not initial outlay, leading to different risk assessment</li> <li>● heritage status—valuing products beyond their replacement costs</li> <li>● leasing models to allow for changes in capacity or performance</li> <li>● trend/fashion for material efficiency</li> <li>● crises such as war or recession</li> </ul>	<ul style="list-style-type: none"> <li>● regulation (planning, bans, standards)</li> <li>● production technology innovations to reduce costs of optimization</li> <li>● customer preference or specification</li> <li>● material scarcity or (substantial) material price increases</li> <li>● business models that reduce search costs for one-off customers</li> </ul>



- For each key steel-intensive product, where is it currently positioned in figure 7, and therefore what specific policy measures are required to move towards the upper left quadrant?
- Are there over-arching national policy measures that would support a widespread shift in business motivation along the vertical axis of figure 7?
- How can solutions identified for particular products, such as those discussed in the previous section, be generalized to provide a solutions manual for material efficiency across sectors and materials?

## 5. Conclusion

This paper has aimed to provide a broad overview of the transition to material efficiency required if the emissions associated with UK steel consumption are to be reduced in line with the targets set into law in the UK Climate Change Act. Most of the evidence gathered in the paper is estimated, so is not intended to provide precise predictions, but has been used in an attempt to give reality to the required transition. Relating national targets to four representative products has shown that government policy aiming to support material efficiency is unlikely to be a single broad-brush measure, but instead more subtle measures can be used to find intersections in the triggers that would drive purchasers and producers to prefer material efficiency solutions. The paper has proposed a research agenda by which the estimates for the UK steel economy used in this work can give much more detail and then be generalized across materials and sectors to provide national guidance.

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