Are Prices Enough? The Economics of Material Demand Reduction*

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February 2017

Abstract

Recent policy proposals to achieve carbon targets have emphasized material demand reduction strategies aimed at achieving material efficiency. We provide a bridge between the way economists and engineers think about efficiency. We use the tools of economics to think about policies directed at material efficiency and to evaluate the role and rationale for such policies. The analysis highlights when prices (or taxes) can be used to induce changes in material use and when taxes may not work. We argue that the role of taxes is limited by concerns about their distributional consequences, by international trade and the lack of international agreement on carbon prices, and by investment failures.

Keywords: Material efficiency; economic efficiency; policy choices, CO_2 reductions.

1 Introduction

The focus of policies to meet carbon reduction targets has until now been on changing the way that energy is produced, and this has led to subsidies to the use of renewable energy, as well as subsidies to innovation in renewable technology. Attempts to put in place carbon prices have had only limited success, and there is no sign of any international agreement on a market for carbon. Even if there were such an agreement, as pointed out by Sorrell (2015), there is a strong correlation between energy demand and economic

*We would like to thank Julian Allwood, Sandy Skelton, Ian Gough and two reviewers for constructive discussions and feedback.

growth: energy demand is likely to keep on growing and this growth in demand lies at the heart of the environmental problem. Against this backdrop, Allwood et al. (2011, 2013) have proposed alternative policy interventions to reduce the demand for energy. These policies have focused on reducing the demand for materials that are used in production and also on reducing the materials used in providing the services that consumers demand.

Materials embed large amounts of energy but there is very little physical capability to improve the efficiency with which that energy is used in the production of materials such as steel or concrete. On the other hand, Allwood et al. (2011) argues that there are considerable inefficiencies in the way materials themselves are used in the production of goods and services. The first aim of a reduction in material demand is to shift the input mix in the production of final (and intermediate) goods away from processes that are material intensive towards processes using other inputs with a lower carbon footprint, such as skilled labour. The second aim is to shift final goods away from material intensive goods towards less intensive goods.[1]

Our focus in this paper is on the desirability of policies to reduce material demand and what those policies might look like, and we do not consider directly the market for energy. This paper therefore has three aims. First, we provide an accessible way into how economists think about efficiency and material efficiency in particular, and to provide a bridge between the way economists think and engineers think about efficiency. Second, we want to use these tools of economics to think about policies directed at material efficiency. Third, we want to evaluate the role and rationale for such policies directed at material efficiency within the context of an encompassing climate change strategy.

There are often misconceptions about what the underpinnings are of standard economic analysis, and in particular there is often a conflation of the use of economic analysis with particular value judgments on specific economic systems. Economic analysis does not rule out market failures, nor does the use of economics require a belief that all markets should be free. What underpins economic analysis is the idea of *individual* decision making and that individuals make decisions to best satisfy their preferences. There is no prescription about what form those preferences should take - there is nothing in economic theory that stops individuals being altruistic or caring about the environment, for example. A second important underpinning of economic analysis is the specification of the economic constraints, markets and opportunities that individuals face. Again, there is no prescription that the markets work or that there is a market for everything that individuals want. The reality is that there are some things which individuals like which would be damaged by being traded on markets (like friendship), and there are other

[1]For some materials, e.g., steal, it may be possible to substitute primary materials for secondary (reused) materials and in that way to keep the amount of materials constant while reducing the carbon footprint.

things which should be traded which have not been (like pollution).[2] What economics can offer, therefore, is a framework of individual decision making given the economic constraints and opportunities faced.

Part of the value of this economic approach is that it clearly and explicitly specifies all underlying assumptions. The approach is to start with the simplest set of assumptions to set a benchmark, and then to consider how alternative assumptions affect the conclusions in the benchmark. This makes the role of particular assumptions transparent.

This paper is written by economists but is intended explicitly for non-economists and to build a bridge between economic analysis and other approaches. It is also intended to be stand-alone without the need for further economics reading to understand the arguments and approach. The paper proceeds as follows. Section 2 presents the basic economic framework for understanding notions of efficiency, individual rationality, market allocations and market failure. We relate these concepts to the notion of material efficiency in Allwood (2011). Section 3 discusses potential public policy interventions, and especially the guiding principles that can inform policy decisions. Section 4 discusses the limitations of market based solutions for dealing with carbon emissions and whether or not there is an economic case for using material demand reduction as an instrument itself. Section 5 offers new empirical evidence on the degree of substitution possibilities between materials and other inputs. Section 6 concludes.

2 Efficiency, rationality and market failure

Language is used in different ways by different disciplines. This is particularly the case when economists talk about the concepts of efficiency, of rationality and of market failure. Further, understanding these concepts is crucial to understanding economic arguments concerning the use of market instruments compared to, say, direct regulation. The purpose of this section therefore is to review these concepts as used by engineers and economists, and in particular to explain why market failure introduces inefficiencies (as understood by economists) in the allocation of resources in a market economy.

2.1 Efficiency concepts

Allwood et al. (2011) define *material efficiency* as all changes that result in decreasing the amount of engineered and processed materials used to produce one unit of economic

[2]Similarly, when economists talk about costs, there is no necessity for those costs to be exclusively monetary. The cost of a policy may be the direct impact on well-being or welfare. On the other hand, it is useful when discussing costs to have a unit of account to measure costs, and this is often money, implying that all costs are measured in common units.

output or used to fulfill human needs more broadly. Economists, on the other hand, say that a production plan is efficient if there is no technologically feasible way to produce more output with the same inputs or to produce the same output with less inputs. We shall refer to this as *economic efficiency* in the rest of this paper. Although related, the two concepts of efficiency are not identical.

To see this more clearly, it is useful to model a simplistic economy. The model is far from an accurate description of the economy but it is a very useful abstraction to illustrate the points we want to emphasize and to clarify concepts. The economy has two final goods sectors (indexed by $i \in \{1, 2\}$). Each sector has many similar firms producing outputs. We focus for now on a representative firm in each sector. The production technology for producing output in sector i is described by a production function of the following type:

$$y_i = F_i(l_i, m_i)$$

where l_i is the amount of labour input and m_i is the amount of materials input.[3] The production function describes the maximum amount of output that can be produced from a given combination of the two inputs.[4] Figure 1 plots the output (or production) in sector 1 as a function of the materials employed for a given amount of labour. Allocations on and below the production function are feasible and are within the production possibility set.

The two inputs, labour and materials, can substitute for each other in production and so there exist many different combinations of the two inputs that can produce a given amount of the output. The different combinations of inputs to produce a given amount of the output is represented by an "isoquant" which is defined as

$$Q(y_i) = \{(l_i, m_i\} \in \mathbb{R}^2 : y_i = F\left(l_i, m_i\right)\}.$$

The slope of the isoquant at a given input combination captures the potential substitution allowed by the production technology.[5] Figure 2 plots an isoquant for sector 1. The

[3]We focus on the case with two inputs only. It is easy to generalize to more inputs. It is also possible introduce an intermediate sector which produces materials from raw inputs, energy, capital and labour. These complications are introduced as they are needed.

[4]It is standard to assume that the marginal products (i.e., the increase in production from increasing an input marginally: $\frac{\partial F_i}{\partial l_i}$ and $\frac{\partial F_i}{\partial m_i}$) are positive but declining.

[5]These are referred to as the *marginal rate of technical substitution* or MRTS and are defined as

$$MRTS^i(m_i, l_i) = \frac{\frac{\partial F_i}{\partial m_i}}{\frac{\partial F_i}{\partial l_i}}.$$

production function and the isoquants are simply descriptions of technical possibilities available to the firm.

We can use the two figures to illustrate the concepts of efficiency in engineering and in economics. Material efficiency is where the production process uses the minimum amount of material to produce y^i. Economic efficiency is where the production process minimises the cost of producing y^i. Consider first Figure 1. Point A below the production function is neither efficient in the engineering sense nor in the economic sense, while point B satisfies both definitions. Thus, in this case the two concepts coincide. Moreover, as long as materials have a positive purchase price, it is not in the interest of any profit maximizing firm to allow for inefficiencies of type A to persist. In short, material inefficiencies of the type indicated by type A are not consistent with basic optimization principles and are unlikely to be a common feature of real-world economies with profit-maximising firms.

Second, now consider Figure 2. The isoquant is drawn to allow for the realistic possibility that the exists a minimum amount of material that is needed (with a given technology) to produce sector's 1 output: below that minimum – denoted m_1^{min} – no matter how much labour (and other inputs) are used, the firm will be unable to produce the quantity of the output, y^1 shown. The material m_1^{min} represents the engineering estimate of the least amount of material with which the given amount of output can be produced (when combined by the amount of labour l_1^*. The condition for material efficiency is uniquely satisfied at point E. The input ratio at point E also satisfies the condition for economic efficiency (at some set of prices). However, crucially, so does any other input combination (such as point D) on the isoquant. In this case, we observe that material and economic efficiency are not *necessarily* the same.

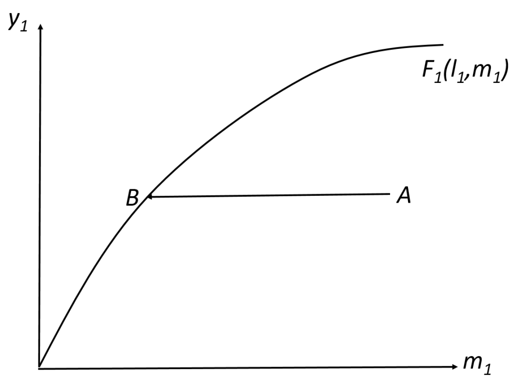
2.2 Rational choices

Producers. Production functions and isoquants describe technical possibilities available to the firm, and allow us to characterise whether or not the allocation in an economy is efficient. On its own, this does not explain what firms will decide to do. Whether firms chose to employ an input combination such as that associated with point D in Figure 2 or the material efficient combination at point E depends on the incentives and prices they face as well as the decision making process. The basic assumption of economic analysis of firm behavior is that firms minimize the cost of producing a given amount of output and choose the level of output to produce to maximize profit.[6] The cost minimizing choice

We use the convention to define the MRTS as a positive ratio, so strictly speaking, the MRTS is the absolute value of the slope of an isoquant at a given point.

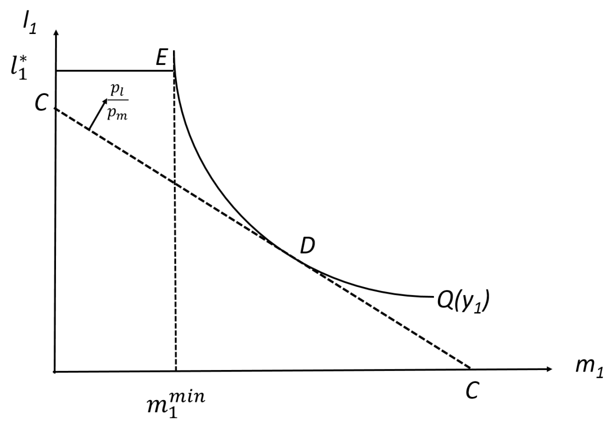
[6]There is, however, now a large literature in organizational economics showing that these assumptions may fail because of transaction costs within the firm and the agency problems that arise from this (Milgrom and Roberts 1992).

Figure 1: The production technology



Notes: The figure graphs the production function in sector 1 as a function of the material input for a fixed amount of labour input.

Figure 2: An isoquant for sector 1



Notes: The figure graphs an isoquant for sector 1 (the convex curve) and an isocost or price line (the dotted straight line).

that firms make of how to select what input ratio of materials and labour to produce y^1 depends on the relative price of the two inputs, according to the simple principle that the marginal rate of technical substitution (MRTS), at the chosen input ratio, is equal to the relative price of the inputs.[7] In Figure 2, given the relative price (or isocost) line $C - C$ shown (the downward sloping, dotted line), firms in sector 1 select the input ratio associated with point D. This is the point that minimises their cost of producing y^1 and so this choice is efficient in the economic sense, although not in the material efficiency sense.

To see intuitively why this condition must hold, imagine a scenario in which it fails, and, say, the price ratio is 1 but the MRTS is 2. In this case, if the firm buys one extra unit of labour, it will be able to produce the same output as before but using two units of materials less. As the relative price is 1, costs will be lower. Since the technology differs between sectors, firms in the two sectors will, despite facing the same relative input price, rationally select different input ratios. Sector 1 could, for example, employ a much more material intensive product technique than sector 2. Importantly, there is *no* presumption that any of them will select the material efficient input mix at point E: the choice will depend on the relative prices faced and the substitution possibilities. The minimized cost associated with producing a given amount of output at the prevailing input prices is called the cost function and can be written as $c_i(p_l, p_m, y_i)$ where p_l and p_m are the price of labour and materials, respectively. The marginal cost is the derivative of this function with respect to output.[8] The profit maximizing choice of output depends on market conditions in the output markets. Under the assumption of perfect competition, firms will take the price of their output as given. To maximize profits, they will produce up to the point where the marginal cost of producing another unit is equal to the price they can get for that unit in the market.

Analogous to this analysis of the production of final goods using materials and labour, we can analyse the production process of an intermediate good sector that produces

[7] Mathematically,

$$MRTS^i(m_i, l_i) = \frac{\frac{\partial F_i}{\partial m_i}}{\frac{\partial F_i}{\partial l_i}} = \frac{p_l}{p_m},$$

where p_l and p_m are the market price of labour and materials, respectively.

[8] The ratio of the marginal cost in the two sectors is called the *marginal rate of transformation* (MRT) because it shows how output in one sector (by a cost minimizing reallocation of inputs) can be expanded at the sacrifice of a contraction in the other sector. Formally, the marginal rate of transformation is defined as

$$MRT(y_1, y_2) = \frac{\frac{\partial c_1}{\partial y_1}}{\frac{\partial c_2}{\partial y_2}}.$$

materials from labour, raw materials r (which we can think of as including energy). This requires defining a material production function:

$$m = G(l_m, r),$$

where l_m denotes the labour input used in the material producing sector and m is the total amount of materials produced in the economy. To maximize profits, the material producing firm hires labour until the value of the marginal product of labour is equal to the price of labour (the wage rate):

$$p_m \frac{\partial G}{\partial l_m} = p_l.$$

Consumers. Consumers do not maximise profits. Instead, the starting assumption is that consumers make choices to satisfy their preferences as well as they can given the prices they face and their income levels. We describe the preferences of the consumer over the two goods and over leisure using a utility function which indexes the well-being of the consumer as a function of the quantity of the two goods and of leisure enjoyed. Leisure is included because this is what the consumer must sacrifice to earn income. Assuming that all consumers are the same,[9] we can write the utility function as $u(x_1, x_2, L - l)$ where x_i is the amount of good i consumed, l is the amount of labour suppled to the market, and L is the total endowment of leisure time. Insofar as consumers make rational choices, they will select the consumption bundle that maximizes their utility subject to their budget constraint.[10]

It is important to be clear here on what is meant by rational behaviour by individuals. The economists definition of a *rational choice* is where an individual makes a choice that is consistent with their own preferences. It is a definition of *consistency*, asking whether or not different choices by an individual are consistent with each other. This definition does not make any judgement about whether the individual's preferences are "reasonable". An alternative definition of rationality is synonymous with *conformity*: does an individual's choice conform to an external judgement about what is reasonable. This alternative definition leads to individuals being judged as irrational even if that individual is completely content with their choice. Paternalistic interventions onto consumer behaviour rests on this external judgement of what is reasonable.

[9]This assumption rules out distributional issues, but it is a simple matter to build that into the model.

[10]The principle that governs this choice is that the *marginal rate of substitution* (MRS), defined as the ratio of the marginal utility of, say, the two produced goods, is equal to the relative prices that the consumer faces in the market for the two final goods.

The point to take from this discussion is that consumers acting to satisfy their own preferences will make choices between the materially intensive and the materially non-intensive good depending on the relative price of the two goods. In thinking about interventions, we need to be clear about whether we are intervening because of a judgement about the preferences of individuals, or to achieve the objective of reducing carbon emissions through reduced material use.

2.3 Aggregate Efficiency and the Market Allocation

Two central question are: how *should* resources be allocated and how *are* resources allocated in a market economy. The discussion of rational choice by firms and consumers above provides the starting point for thinking about these questions and about whether or not economy-wide economic efficiency as understood by economists corresponds to the notion of material efficiency as understood by engineers.

To fix ideas, let us suppose that the economy has a fixed amount of raw materials (r) and fixed labour available.[11] These scarce resources should be allocated efficiently between the two final sectors and the material producing sector. An allocation of resources is efficient if it is impossible with the given technology and total endowments of labour and raw materials to reallocate the inputs to make more output or to change the output mix of final goods to deliver higher welfare to consumers. Economists often refer to this as Pareto efficiency. In our simplified economy, a Pareto efficient allocation must satisfy two conditions: production and product mix efficiency.[12]

Production efficiency: It should not be possible to reallocate the available resources between production in the three sectors in such a way as to increase the output from one sector without reducing the output from another. This requires that the marginal rate of technical substitution (MRTS) between labour and materials in the two final goods sectors are the same and that this common MRTS, in turn, is equal to the marginal product of labour in the material producing sector:

$$MRTS^1(m_1, l_1) = MRTS^2(m_2, l_2) = \frac{\partial G}{\partial l_m}.$$

Intuitively, suppose that this condition does not hold. Then, it would be possible either to reallocate labour and materials across the two final goods sectors in such a way as to keep the output from one sector fixed, while increasing the output from the other; or it would be possible to reallocate labour from the final goods sectors to the material producing sector and increase the amount of total final goods produced. This definition

[11] The basic points we make below do not depend on this simplification but some of the details do.
[12] Consumption efficiency is not an issue under the maintained assumption of identical consumers.

of production efficiency assumes a closed economy. In an open economy, production efficiency also requires that the marginal rate of transformation in domestic production is equal to that in other countries, an issue that we return to in section 4 below.

Product mix efficiency: It should not be possible to change the output mix of the economy in such a way as to make consumers better off. This requires that the marginal rate of transformation (MRT) in production is equal to the marginal rate of substitution in consumption (MRS). A simple contradiction argument shows why.

It remains, of course, to be seen if the optimizing behavior of the firms and consumers will actually deliver a market allocation that matches these conditions. The so-called First Welfare Theorem says it will (under some conditions). To see why, return to the optimality conditions that we discussed above. First, production efficiency is achieved because firms in the two final goods sectors hire the cost minimizing input mix, i.e.,

$$MRTS^1(m_1, l_1) = \frac{p_l}{p_m} = MRTS^2(m_2, l_2)$$

and the representative material producing firm hires labour till $\frac{\partial G}{\partial l_m} = \frac{p_l}{p_m}$.

As long as all producers face exactly the same prices and wages (which, amongst other things, rules out certain types of taxes) and take those as given (which rules out monopoly behaviour), their individually optimal choice to minimize cost and maximize profit results in an overall market allocation of resources which is production efficient. Product mix efficiency is assured by the market allocation because consumers optimize their consumption mix by equating the marginal rate of substitution (MRS) between the two final goods to the relative market prices and because firms produce till their marginal cost equates the market price for their output. As long as consumers and firms face the same prices, this guarantees that the MRS in consumption is equal to the marginal rate of transformation (MRT) in production. The basic insight from this fundamental result of welfare economics is that market prices send signals about the relative scarcity of resources and these signals induce agents to act privately in a way that leads to an aggregate outcome that is efficient.

How does the efficient market allocation relate back to the notion of material efficiency? Again, the market allocation could be compatible with the material efficient input mix in the two final goods sectors, but most likely it will not be: this depends on which relative input price prevails in the input markets. The deeper reason for the likely discrepancy is that the market allocation brings together technology and resource constraints, preferences and optimizing behavior; material efficiency zooms in on what is technologically possible, but does not consider what is desired by consumers and what is profit-maximising for firms. This discussion makes another important point clear. If one wanted to change the market allocation, for example, with a view to move towards the material efficient input mix or try to shift consumption patterns towards outputs which are less material intensive in their production, then this can be done. And the way to do it, is to manipulate the prices that firms and consumers face in order to induce them to make a different set of choices.

2.4 Market failure

In practice, there are many reasons why the First Welfare Theorem – the statement that the market allocation is Pareto efficient – does not apply. Economists talk about market failures. The three most important sources of market failure are: monopoly (or other types of non-competitive market imperfections), information asymmetries, and externalities. This also include information and capacity constraints that prevent agents from appreciating existing inefficiencies or mean that they lack the managerial or institutional capacity to implement solutions. Imperfections in financial markets can lead to inefficiencies in the allocation of risks.[13] Market failures can also be caused by government policy such as taxes, subsidies and regulation.

Allwood et al. (2011) suggest that there are two main reasons why a society may want to reduce material demand and move to achieve material efficiency:

1. Finite availability of natural resources (e.g., raw materials such as ion ore).

2. Environmental externalities (primarily carbon emissions).

The first of these does not, however, by itself constitute a market failure.[14] While it is true that many of the key raw materials that are used heavily in the production of processed materials are finite in supply, they are, typically, traded in markets and their current and future prices reflect their relative scarcity. This enables the market to allocate their use efficiently over time and space. Therefore, over the long term as the fixed stocks are run down, the relative price will trend up, thus reducing demand and encouraging substitution in production into less costly alternatives long before the resources in a physical sense runs out. In short, the market, in this case, provides the right signals for "demand reduction".[15]

The second reason, in contrast, is both valid and important: the production of processed materials such as steel and cement are major contributors to carbon emissions.

[13] For a discussion of how uncertainty influences the regulation of externalities, see Pindyck (2007).

[14] Insofar as there are monopoly or monopsony in the relevant markets for these resources, then there is a market failure. The source, however, is not the finiteness of the resources traded in these markets but the industrial structure.

[15] Soderholm and Tilton (2012) provides a good discussion of this in the context of the material efficiency debate.

Economists define an externality as an unintended consequence of an action taken by a firm (or consumer) that has a *direct* positive or negative effect on the welfare of other consumers or on the cost of production of other firms. Environmental externalities introduce inefficiencies (in the Pareto sense discussed above) in the allocation of resources. In the context of our model economy, we can see this by assuming that each unit of materials produced causes CO_2 emission which has a negative impact on consumers. Specifically, environmental damage, $D(m)$, may be an increasing, convex function of the total amount of materials produced (and used in the two final goods sectors). The utility of a representative consumer, therefore, becomes $u(x_1, x_2, L - l) - D(m)$.[16] By definition neither the producers of materials nor the producers of final goods take into account that each unit of materials they produce or use causes harm to consumers. Similarly, the consumers do not take into account that their demand for, say, the more material intensive final good contributes to the carbon problem. They all behave exactly as above in the previous subsections.

The problem is that the material price p_m – the private valuation/cost – no longer reflects the social benefit of employing an extra unit of labour to produce an extra unit of materials. From a social point of view, the "correct" allocation of labour to that sector is governed by

$$\frac{\partial G}{\partial l_m} p_m = p_l + \frac{\partial D}{\partial m} \frac{\partial G}{\partial l_m},$$

where the last term on the right-hand side reflects the carbon externality which has not been "priced in".

There are, of course, other rationales that one could invoke to make the case for material efficiency policy interventions based on a demand reduction strategy. Soderholm and Tilton (2012) point out that non-environmental externalities can arise through supply chain interactions. For example, the production choices of upstream producers may make it difficult for downstream firms to recycle or reuse certain materials. Another example is imperfections in the innovation process. Technological progress could, for example, by itself induce less material intensive input mix choices in production and in that way reduce the environmental externality. However, such innovations may be under-provided by the market because the positive spill-over effects that are typically associated with them are not taken into account by the innovators. But the core rationale for an intervention is the presence of significant environmental externalities in the production of key materials (steel and cement being two important examples).

[16] This treats the externality as a non-depletable (public bad) flow externality. This formulation is often used to capture global warming, but, of course, sidesteps complex issues related to stocks and time.

3 Public Policy Interventions

The starting point for thinking about material demand reduction policies is the possibility, emerging from from engineering research, that it is feasible to produce (many) goods with half as much materials, and to use produced goods for twice as long. We can think of this as defining m_i^{min} in section 2.1 above. It is clear that such a change in production processes would reduce material demand and help to achieve carbon savings but also that it will requires a policy intervention to induce firms and individuals to carry out the change. The rationale for any such intervention is to correct the environmental externality (the underlying market failure), rather than the achievement of material efficiency or a material demand reduction per se. A host of different policy instruments can potentially help achieve this. We can make a distinction between price or tax instruments and direct regulation. The tax instruments include a tax on carbon (a carbon price) that would correct the environmental externality and would do so partly through a reduction in material demand, a tax on the use of materials as inputs that would induce substitution away from materials, and a tax on the final consumption or production of material intensive goods. In terms of regulations, a requirement that, say, half of all steel used in construction should be from recycled steel would be an alternative instrument.

Given the view of efficiency outlined above, the economics approach to public policy interventions is based on two central ideas. The first is that a market failure that causes an inefficiency in the allocation of resources provides a rationale for a correcting policy intervention. The second is that if there is no market failure but there is a desire to redistribute income, then the intervention must be chosen to maximize a social welfare function that weighs up winners and losers.[17] However, this welfare function respects the choices that individuals and firms make as being what is best for them given the constraints and options they face.[18]

This approach to public policy provides (at least) three useful guiding principles that can inform the choice of policy instrument. These principles are flexibility, targeting and unintended consequence. We discuss these in turn.

3.1 Flexibility

A given market failure, such as the carbon externality in our model economy, can, as noted above, be fixed in many different ways; that is, there are many competing policy instruments that can fix the problem. Some of these allow firms and consumers greater

[17] This would also apply if the correction of the market failure creates winners and losers.

[18] This starting assumption is challenged by recent work in behavioral economics (e.g., Shogren and Taylor 2008) and the whole idea of a benevolent government trying to maximize social welfare has long been under critical review by public choice scholars (e.g., Buchanan and Musgrave 1999; Mueller 2003).

flexibility in what they want to do than others and flexibility has value. It is useful to make a distinction between two types of flexibility: "how to do" and "what to do" flexibility. "How to do" flexibility describes whether the firm that is subject to the regulation can decide itself how to comply, whereas "what to do" flexibility is about whether there are specific targets set of what must be achieved (e.g., in terms of pollution reduction). For example, suppose the objective of a policy intervention is to reduce the total amount of material demand in an economy to reduce carbon emission by a certain amount. One approach – a command-and-control approach – is to force all users of materials to reduce their use of material per unit of output by a given amount (e.g., by regulating that all firms must reduce the gap between point D and point E by 50% in figure 2). This allows no "what to do" flexibility. If, on top of this, the regulation also required that the target be achieved by light-weighting product designs, then there would be little "how to do" flexibility either. By contrast, a carbon tax levied on the output from the material producing sector would put a price on carbon and increases the price of materials. Alternatively, the instrument could be a tax on material production regardless of the carbon input. Either instrument creates the incentive for the material users in the two output sectors to economize and substitute materials for labour.[19] This offers maximum flexibility: no-one is told what or how to do it. Of course, the effectiveness of a given price change in reducing material demand depends on the elasticity of substitution in production: the slope of the isoquant. If there is little scope for substitution, then the price increase needed will be substantial. However, if there is little option for substitution, then the cost to producers of moving to the materially efficient point will be substantial.[20] The actual degree of substitution is an empirical issue that we return to in section 5.

The welfare economics approach to public policy offers a strong case for favoring flexible regulation and policies. First, the same social benefits can be achieved at lower cost to firms and consumers. This is because the regulated firms can comply with the regulation in the least costly way and adopt the particular response that suits them the best (Baumol and Oates 1988, chapter 10). Each firm can explore all types of "material efficiency options" and pick the ones that cost the least given its particular circumstances. In short, a direct intervention aimed, say, at extending the life time of a product or requiring light-weighting of cars that prescribes what to do and how to do is

[19] Skelton and Allwood (2013) point out that the incentives for material efficiency caused by a carbon price can be offset by the disincentives to material efficiency caused by labour taxes. The argument we are making here is that for a given labour tax (in the model equal to zero), a carbon price, ceteris paribus, make material relatively more expensive and that will, depending on the size of the substitution elasticity, reduce the demand for materials.

[20] The cost of moving to a more materially efficient point can be calculated by looking at the slope of the isoquant at the new point: this slope must equal the new relative price of inputs $\frac{p_m(1+\tau)}{p_l}$. The cost is then approximately the cost of purchasing the original bundle of inputs at the new prices, and so the increase in cost is $m_D \tau p_m$.

not, in general, the best option unless one is 100% sure that the intervention is the best option for everyone. In a constantly changing world of uncertainty and with significant heterogeneity across firms and consumers, it is hard to know what is best and a policy intervention that allows flexibility is, typically, better. Second, flexibility gives firms an ongoing incentive to seek out innovations that can reduce the cost of compliance. This dynamic incentive to innovate or to fund research and development is absent if they are simply told what to do and how to comply.

3.2 Targeting

In thinking about which intervention might best address a particular market failure, a useful starting point is to look for the source of the problem and to ask which of the many different instruments target the source most directly. If you need to screw a screw in the wall, then you can, of course, use a hammer, but a screwdriver would, in most cases, be a better tool for the job. Likewise, in many cases, with policy instruments (Bhagwati and Srinivasan 1983, chapter 13): in our model example, the source of the problem is that too much carbon is emitted and the reason for this is that material demand is too high or, put the other way around, too many "material goods" are being produced. The most targeted instrument would be to levy a tax equal to the social marginal damage on each unit of materials traded in the economy, thus increasing the price of each unit of material traded i.e.,

$$\tau_m = \frac{\partial D}{\partial m} \frac{\partial G}{\partial l_m}. \tag{1}$$

Such a so-called Pigouvian tax would internalize the externality and incentivize firms to use (and produce) the socially optimal and efficient amount of materials. The theory of tax incidence shows that (in a competitive market) it does not matter from whom the tax is collected, so it could either be a tax paid by the producers of materials or by the users. What will happen in either case is that the economic cost of the tax will be shared between the two sides of the market. As a consequence, the price of materials relative to labour will increase and this will induce firms in the two final goods sectors to reduce demand for materials and seek out innovations that allow them to economise on the use of the materials.[21] The cost of producing the two final consumption goods will obviously increase with the increased cost of inputs, and will increase more so in the sector that uses materials more intensively. As a consequence, the relative price of the output from

[21] The substitution away from materials will not necessarily be in the same for the two firms because they have different elasticities of substitution.

that sector will go up and induce consumers to buy less of the material intensive good and more of the other.

Now, consider an alternative instrument: levying a tax on the material intensive final good. Again, this induces substitution in consumption away from the materially intensive good, but it does not create direct incentives for firms to adjust their input mix. Overall, fewer materials may be produced and traded and, as a consequence, less carbon may be emitted from the material producing sector. However, to get the same carbon benefit as with the direct tax on the use of materials or on carbon, the final consumer prices need to be distorted considerably more than the relative price change induced by the direct tax on material inputs. This increases the cost of correcting the externality.[22]

3.3 General equilibrium effects

All policy interventions create economy-wide ripples, or what economists call general equilibrium effects (e.g., Goulder et al. 2016). These can be important, and can either reinforce or neutralise the intended effect of the policy. With a command-and-control intervention that stipulates that all firms have to become more material efficient (by light-weighting say), the forced reduction in demand for materials leads to a price fall in the market price of materials. The firms that use materials most intensively benefit the most from this price fall, and the price of materially intensive final goods may well fall, leading to an expansion in demand for materially intensive goods. There will be a reduction in carbon emission but by less that one might have thought. By contrast, with a direct tax on materials, the cost of production of the material intensive good has gone up, the price of the material intensive good will rise and demand will fall.

3.4 Distributional Consequences

Policies targeted at material efficiency are not intended as instruments to improve or worsen the distribution of income and welfare. Nonetheless, such policy interventions inevitably have consequences for distributional outcomes (e.g., Bento et al. 2009). A policy that corrects a market failure generates economic surplus and, in principle, can make everyone better off but only *if* a complementary policy to compensate the losers

[22]This argument about targeting assumes that the government has sufficient (independent) policy instruments to correct all distortions in the economy. This is, typically, not the case in practice and there will be market failures or policy-induced distortions coming via the tax system that cannot be corrected. This means governments are operating in what economists call a second best world: a situation where some market failures or policy-induced distortions must be taken as given. This makes the policy problem harder and introduces new trade offs. We return to this below.

with some of the winners' surplus is put in place (e.g., Hicks 1939).[23] The reality is that these distributional outcomes are often not compensated for by the tax or benefit system. Furthermore, since any tax or benefit system is distortionary, it may not be optimal to fully compensate for distributional consequences. In these cases, the distributional consequences need to be weighed up in an evaluation of the effects of the policy intervention. However, this weighing of (incidental) distributional *consequences* of a policy is distinct from thinking of the policy as having distributional *goals* independent of the carbon reduction goals.

3.5 Summary

The general message emerging from the welfare economics approach to public policy is in a nutshell a recommendation for flexible, targeted policy solutions that allow firms and consumers the maximum freedom to explore different (material efficiency) solutions and give them the strongest possible incentive to do so. There is a clear rejection of inflexible and prescriptive interventions that single out specific technological solutions. Particular technological solutions that can reduce material demand, enhance recycling or extend the life-span of products – all of which can contribute to a reduction in environmental externalities and can help economize on the use of non-renewable resources – can be part of the solution that firms can choose to use. However, the welfare economics approach to public policy favors market interventions through price changes (such as a carbon price or a material tax) that creates the incentives for firms and consumers to internalize the externality by adopting different approaches which may well include some or all of the specific technological solutions highlight by engineers.

4 The Economic Case for Specific Material Demand Reduction Interventions

The discussion above suggests that a properly designed carbon price (or a market for carbon pollution permits, as the one used in Europe) can, in principle, provide the solution to the carbon problem *(*and) that such a policy does trigger, through the adjustment of the relative prices throughout the economy, reduction in the demand for materials. The demand reduction happens in two ways. First, producers using materials in production face a higher relative price of materials and will substitute away from materials and will

[23]Such a policy is called a Kaldor-Hicks improvement because those that are made better off could hypothetically compensate those that are made worse off and this would then lead to a Pareto-improving outcome. A situation is said to be Kaldor-Hicks efficient if no potential Kaldor-Hicks improvement from that situation exists.

seek out product, process and technological innovations that can help them economise on materials. Second, the increase in the relative price of material inputs will hit the material intensive sectors the most. This will shift the relative final consumer prices against material intensive products and in that way induce a reduction in the demand for materials.

Against the background, is there an economic case to be made for adopting specific material demand reduction strategies or for adopting specific technological solutions through direct regulation. We argue that there are a number of reasons why demand reduction strategies could be part of a comprehensive climate policy package as a supplement to a carbon pricing policy, and these reasons also suggest why carbon pricing has had limited success. The arguments are based on political economy constraints, on the need to shift from production-based to consumption-based carbon counting, on constraints imposed by international trade, and on fixed-costs of innovation. All these arguments are based on what economists call second best considerations where some key aspect of the situation cannot be directly influenced by the policy intervention under consideration and, therefore, must be treated as a constraint.

Before discussing the three reasons for direct intervention, we want to highlight two rationales for intervention aimed at reducing material demand which have less credence: first, the argument that individuals are "mistaken" in their demand for materially intensive goods; second, the argument that individuals and firms are not able to optimise properly and, as a consequence, are mistaken in not using less materially intensive products or production processes. The first of these arguments is based on the premise that consumers do not know what is in their best interest: it rests on the belief that there is something intrinsically wrong about a preference for, say, a large or heavy car, or that such preferences are false or contrived. While it may be a valid argument that individuals have preferences that have been manipulated or are counter-productive to long-term happiness, such an argument is not relevant to the debate on how to solve the carbon problem. It is an argument for intervention in individual choices to achieve a different objective: to increase true well-being. Again, the instrument to achieve this objective should adhere to the basic principles outlined above. The second argument that individuals or firms are not correctly optimising is discussed above: if firms are not profit maximising, then, as in Figure 1, there are opportunities for new entrants to make positive profits. If consumers are not optimising and not making the decisions that they themselves would prefer, there is, again, an argument for a government intervention to increase welfare, but this is not relevant to correcting the over-consumption of materials to reduce carbon use.

4.1 Political economy constraints on carbon pricing

Over the past 20 years, many countries have made progress putting a price on carbon emission (Sterner 2002; Pollitt 2015). Carbon taxes were introduced in many Scandinavian countries already in the 1990s, the climate levy in the UK dates back to 2001, and the European Carbon emission scheme started trading in 2005 (Ellerman et al. 2010). Despite this progress, there is still a long way to go to achieve the international commitments agreed in Kyoto and, more recently, in Paris and to meet the national goals set by individual countries, including the United Kingdom.

A major obstacle to getting the "carbon price" right are political (Schneider and Volkert 1999). First, in practice, carbon taxes and markets for tradeable carbon permits tend to increase the relative price of electricity and gas heating. The incidence of such taxes is regressive because electricity and heating costs constitute a relatively larger expenditure share for poor than for rich households (e.g., Grainger and Kolstad 2010). This distributional impact and the "fuel poverty" it may cause impose a political acceptability constraint on how far democratically elected governments are willing go toward implementing an efficient carbon price. Internalising the carbon externality creates, as already noted, economic surplus and with that comes the possibility of a Kaldor-Hicks improvement. In particular, if the carbon externality were the *only* market failure in the economy, it would be possible to create a compensation package (through the tax-transfer system) that would make all consumers better off and avoid "fuel poverty". However, since the tax-transfer system in itself introduces multiple distortions in consumer and producer choices, the carbon externality is, in practice, not the only distortion and it interacts with multiple others. Under such circumstances, there is no guarantee that a package that would make everyone better off is, in fact, technically feasible (e.g., Goulder 1995). Second, producers, in particular in the energy sector, are likely to lobby against environmentally motivated regulation in general and carbon taxes in particular (Fredriksson 1997; Aidt and Dutta 2004). Again, it is possible to use the tax revenue (or any initial allocation of tradeable permits) to compensate producers/polluters (Bovenberg et al. 2008; Hepburn et al. 2013) and in that way to reduce political opposition to the carbon price policy (Aidt 2010). However, using the revenue from a carbon tax in this way will make it even harder to devise a compensation package that would neutralise some of the distributional side-effects of the policy.

The consequence of these political economy considerations is that, even leaving aside issues to do with international trade and the global nature of the carbon problem, which we return to in the next section, the actual carbon price policy that emerges as the equilibrium outcome of the game between politicians, voters and lobby group is likely to be substantially below the "efficient" level (τ in equation (1)) and will not be sufficient to reduce emission down to the set targets. In principle, so long as there is some potential substitution away from carbon producing inputs, there will be a carbon tax that reduces emissions from domestic production, but in practice, given the limited substitutability, the implied carbon price is infeasible.

We can think of these political issues as an additional constraint on the optimisation problem facing the government - the economy is in a second-best world. We can then ask if, given this state of affairs, there is a case for specific material demand reduction policies that can help reduce emissions towards the desired targets without running into the same political acceptability constraints. From a political economy point of view, an instrument that targets directly the material used in the production process, such as a tax on the material input, or differentiating the final goods tax by materials used, might attract less opposition. This is partly because the industries, firms and consumer groups affected by such policies are likely to be more diverse, making it harder for them to organize effective lobby groups (Olson 1965). Moreover, while it is possible that the incidence of a "material tax" may be regressive, it is likely to be less regressive than the carbon tax. This is because material intensive goods (e.g., heavy cars) are not necessarily goods that are predominately consumed by low-income households and which constitute a large share of their budgets. This will alleviate some of the distributional objections to such a tax.

Instruments operating explicitly through material demand reduction are, however, not the only set of second best policy interventions one could consider. Another possibility is subsidies to renewable energy.[24] In this context, "reducing demand" may be a more difficult message to sell politically than the message "invest in green energy supply". The opposition to a carbon price compared to subsidies to renewable energy will have a similar basis to the opposition to a tax on material use. The social costs and benefits along with the scope for actual carbon reduction of these various options must be weighed up to close the case for demand reduction policies as the second best response.

4.2 Consumption-based carbon reduction targets

The emissions reduction targets embodied in international agreements as well as the national targets set by various governments share the feature that they are production-based. The aim is to reduce emission from domestic production (including transportation) sectors by a given amount within a set time frame relative to some baseline. An alternative to this is to set consumption-based carbon reduction targets ((Peters 2008), (Wiedmann

[24]MacKay (2013) discusses the possibility of converting industrial energy demand to electricity and switching to renewable electricity sources and highlights that significant infrastructure investments would be required.

2009), (Davis and Caldeira 2010)): to count the carbon content of the final consumption goods demanded in the economy and then set the targets in terms of a reduction in the carbon content of the aggregate bundle of final goods consumed in the economy. In a closed economy (i.e., one without any international trade), it does not make a difference which way the target is defined. In the model economy above, for example, the carbon emission is generated by the production of materials, but these get embodied in the final consumption goods. We can, therefore, calculate the carbon content per unit of final good i denoted C_i as[25]

$$C_i = \frac{m_i}{m} G_m \frac{1}{x_i}. \tag{2}$$

A policymaker can, then, define the reduction target either as a reduction in $\sum C_i$ or in the amount of emission coming from the production of material G_m and achieve the same total reduction. Crucially, however, the two ways of defining the target are not the same when goods can be traded internationally. The reason is that a production based target can, in principle, be satisfied by moving all domestic production abroad and (for as long as there are foreign reserves to fund it) simply import the goods from abroad. This would achieve the production-based target while keeping the carbon content embodied in the consumption bundle unchanged and therefore do very little to reduce global carbon emission.

Reallocation of production would not be a major problem if all countries imposed the efficient carbon price. In that case, the global price structure would reflect the carbon externality and global emission would be cut to the efficient level. However, there is no global carbon price regime.[26] This introduces another second best constraint on the policy problem and provides a rationale for moving to emission reduction targets that are consumption-based. A consumption-based carbon reduction target will take into account the carbon embodied in imported goods and the carbon embodied in exported goods would be counted abroad.

A consumption-based target system suggests that the “source” of the carbon problem is the level and mix of final consumption goods. This, in turn, suggests that demand reduction policies should play a direct role in implementing them. The demand reduction instrument in this case would be a correcting set of carbon taxes levied on final consumption goods in proportion to their carbon content. Such a set of taxes, along the lines of Sandmo (1976), could be part of an optimally chosen policy package aimed at implementing consumption-based carbon reduction target in an open economy with

[25]In practice it is, of course, much harder to calculate the carbon content. Barrett et al. (2013) show how it could done for the UK economy.

[26]Parry (2016) argues that even in the absence of an international pricing system, it makes sense for individual countries to impose significant carbon taxes/prices because they would reduce emission of local polluting substances (and not just the emission of CO_2).

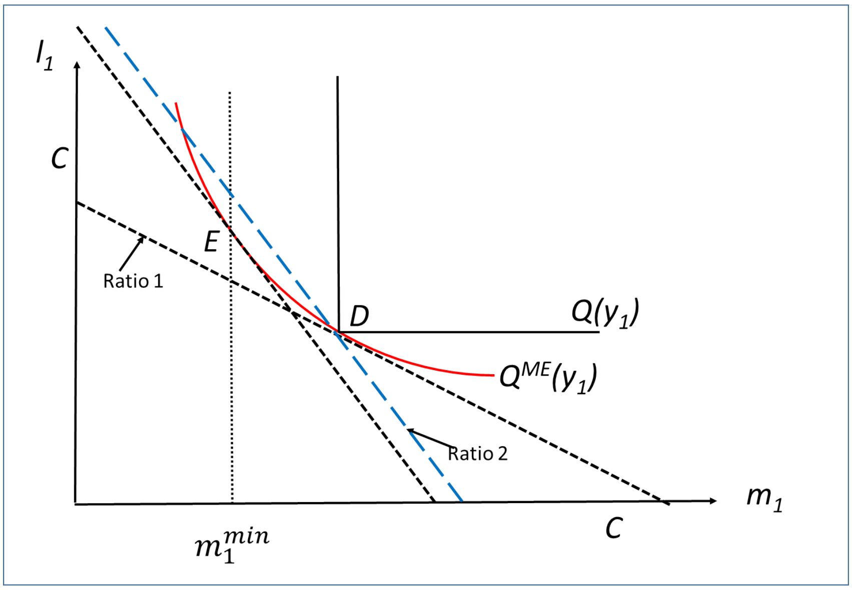
international trade. There remains, as with the carbon tax discussed above, the issue of political economy constraints and who actually bears the cost (Grasso 2016). Implementation of such a consumption carbon tax could be through a system analogous to the UK Value-Added-Tax system, with each firm in the production process paying for the additional carbon produced at that stage of the production process. This system is equivalent to the consumers paying for all the carbon used in the production of the goods they consume.

4.3 Technological innovation: Marginal Changes vs Large Jumps

A final reason for specific demand reduction strategies that regulate the implementation of changes to material use comes from the process of technological innovation. Conceptually, we think of changes to the price of materials as inducing a movement to the left along the isoquant in Figure 2. The shape of the isoquant embodies the existing techology that firms use. This analysis is essentially analysis of marginal changes. It may be however that changes in technology are not continuous. If there are few substitution possibilities in existing technology, price changes will have limited effects: marginal changes may not be enough. This possibility is captured in Figure 3. The initial isoquant is labelled $Q(y_1)$ with initial price line "ratio 1" and production at point D. The isoquant is drawn without any substitution possibilities to make the point clear: changing the price line to "ratio 2" will not change the use of inputs at all, and the input mix will remain at point D. With this technology, price changes will not induce a move to a more materially efficient point. Instead, there needs to be investment to change the technology to the isoquant labelled as $Q_{ME}(y_1)$ where there are possibilities for substitution and where subsequent changes in price can move the input mix towards the materially efficient point. With this technology, the change in relative prices from "ratio 1" to "ratio 2" shifts input use to point E. This highlights that changes in carbon use requires changing technology in a discrete way to move onto a different isoquant. In other words, the reason why firms cannot be induced to be at a more materially efficient point is because moving there requires a non-marginal amount of investment to jump to the new technology. This does raise two questions: first, what is the market failure that is preventing firms from taking these large investments; second, what policies could the government adopt to help incentivise the investments.

Market failure may arise in this context if not all the returns to the innovation are captured by the firm doing the innovation. A further reason may be because the return to the investment is highly uncertain and dependent on the regulatory environment or because of capital market failures. Sterni (2015) discusses further reasons for such market failures in this context. In any case, the issue is that changes in price may not lead to carbon reduction if carbon reduction can only take place through large jumps in technology. This seems to be an argument for putting in place regulations restricting the use of materials to ensure this investment takes place. Alternatively, the instrument could be a subsidy towards the adoption of a specific new technology.

Figure 3: Non-Marginal Changes in Production



Notes: The figure graphs an initial isoquant for sector 1 (the black 90° curve $Q(y_1)$), an isoquant following a discrete investment (the red convex curve $Q^{ME}(y_1)$), an initial price line ("ratio 1") and a new price line ("ratio 2").

5 Evidence on Substitution between Materials and Other Inputs

The elasticities of substitution between materials and other inputs in production in different sectors is the key to judging the impact of changes in the relative price of materials on demand for materials, and in that way reducing carbon emissions. These elasticities describe how easy it is for producers to replace materials with other inputs in the light of a relative price increase while maintaining output at a constant level. More precisely, the so-called Hicks-Allen substitution elasticity between, for example, materials and some other factor of production (labour, capital or energy) is defined as the percentage change in the demand of materials relative to that other input when the price of the other input relative to materials increases by one percent. If this elasticity is positive, the two inputs are substitutes in production: an increase in the price of materials leads to an increase in demand for the other input. The larger the (positive) elasticity elasticity of substitution, the more responsive materials are to price changes and the easier it is to replace materials with the substitute input. If the elasticity is negative, the inputs are complements: it is not possible to replace materials with such complementary inputs.

To get a sense of how big these elasticities are in practice, we make use of the sectoral input-output database developed by Dale W. Jorgenson and his colleagues (Jorgenson et al. 1987). The database contains 35 economic sectors in the USA. For each sector, it includes data on the value and the price of labor, capital, materials and energy and the value and the price of output between 1960 and 2005. These data allow us to estimate a translog cost function for each sector and calculate the Hicks-Allen partial substitution elasticities as in Salgado-Banda and Bernal-Verdugo (2011). We focus on six major metal-using sectors: construction, primary metal, fabricated metal, non-electronic machinery, electronic machinery and motor vehicles.

Row 1 of Table 1 reports the own price elasticity: how does the use of materials respond to changes in the price of materials, by sector. Rows 2 to 4 report the Hicks-Allen cross price substitution elasticities capturing how the use of capital, labour or energy respond to changes in the relative price of materials. As expected, we observe that when the price of materials goes up, the demand for materials goes down. With respect to the cross price substitution elasticities, a number of facts stand out. First, labour and energy are substitutes for materials in all but one sector (fabricated metal). Second, there is a great deal of heterogeneity in the degree of substitution: the difference between primary and fabricated metal is particularly stark with energy being a close substitute for materials in primary metal but not in fabricated metal. Third, capital is not a strong substitute for materials; in fact, in several sectors, the two inputs are complements. Taken together, these estimates show the opportunities and pitfalls of trying to achieve carbon reduction through changing material prices. In construction, for example, a higher price of materials leads to less materials being used, and to less capital, with output being maintained through greater use of labour, but also with the negative consequence of greater energy being used directly. In other words, a rise in the price of materials motivated by the need to reduce carbon emissions can be counterproductive to the extent that the direct use of energy increases.

We can use these estimates to illustrate the scope for material demand reduction through input substitution. We set the policy objective to be a reduction in material demand by 5%, 10% or 20%. For a given desired reduction, the first question is by how much does the relative price of materials in each sector have to increase (e.g., by imposing

Table 1: Responses to Changes in the Price of Materials

	Construction	Primary metal	Fabricated metal	Non-electronic machinery	Electronic machinery	Motor vehicles
Material	-0.69*	-0.84*	-0.60*	-0.89	-0.95	-0.37*
Capital	-0.53*	0.21*	-0.24*	0.36*	1.17*	0.67*
Labour	0.88*	1.45*	1.02	1.15*	0.92*	1.48*
Energy	3.10*	3.51*	-0.25*	2.02*	1.71*	0.64

Note: * significant at 5% level. The numbers represent the percentage change in use of the different inputs following a percentage change in the price of materials. A positive coefficienct indicates an increase in the use of, for example, labour in response to an increase in the price of materials.

a material tax) to achieve the reduction target in that sector.[27] The second question is by how much does the cost of production in each sector (of a given amount of output) go up as a consequence of this price increase.[28] Table 2 reports the answers to these two questions, with the top panel showing the required increase in the (relative) materials price and the lower panel showing the implied increase in total production cost for the firms in each sector.

These numbers indicate the scale of the challenge in reducing material demand through price changes. First, the price increases required to reach the reduction targets are substantial. For example, to cut back material use by 20% in the fabricated metal industry, a 35% increase in price is needed. Second, there are marked differences across sectors. For example, to achieve a 10% reduction in demand for materials in the construction sector, the price of materials would have to rise 15% and this would increase the cost of

[27] We calculate the required increase in the price of materials to achieve a given reduction in material use within each sector using the formula:

$$\frac{dP^M}{P^M} = \frac{-\frac{dM}{M}}{\frac{s^K}{s^M}\varepsilon^K_{PM} + \frac{s^L}{s^M}\varepsilon^L_{PM} + \frac{s^E}{s^M}\varepsilon^E_{PM}} \tag{3}$$

where C is total cost and we have defined:

$$\varepsilon^j_{PM} = \frac{dj/j}{dP^M/P^M} \qquad and \qquad s^j = \frac{P^j j}{C} \qquad \forall j \in \{K, L, E\}$$

[28] To calculate the increase in cost within each sector, we first calculate the cost elasticity with respect to the price of materials:

$$\frac{dC/C}{dP^M/P^M} = s^K\varepsilon^K_{PM} + s^L\varepsilon^L_{PM} + s^E\varepsilon^E_{PM} + s^M\left(1 + \varepsilon^M_{PM}\right) \tag{4}$$

then multiply this elasticity by the size of the required price change in equation (3).

Table 2: Required Increase in Material Price and Implied Increase in Costs

Target reduction	Construction	Primary metal	Fabricated metal	Non-electronic machinery	Electronic machinery	Motor vehicles
			Required Increase in Price			
5%	7%	9%	15%	17%	18%	48%
10%	15%	17%	30%	34%	35%	97%
20%	29%	35%	60%	68%	71%	193%
			Implied Increase in Production Costs			
5%	4%	6%	8%	9%	9%	37%
10%	8%	11%	16%	18%	18%	73%
20%	16%	22%	31%	36%	37%	147%

production by 8%. At the other extreme, to achieve a 10% reduction in material use in the motor vehicle sector, the price of materials would have to almost double, and costs would rise 73%. This reflects the weaker substitution options in the motor industry. It is clear that a one-size-fits-all policy is unlikely to be optimal. Third, the magnitudes of the implied increases in the production cost (in the lower panel of the table) give a sense of the direct economic cost of adopting a carbon-motivated material reduction strategy. These costs, which as already noted vary substantially across sectors, will have to be measured against the costs of other carbon reduction strategies to evaluate the desirability of say a "carbon" tax on materials. The caveat to these numbers is that the calculations are based on marginal changes, effectively moving along the existing isoquant. As argued in section 4.3, there may be opportunities to make non-marginal changes to production, shifting into different production processes which are more flexible with regard to input prices.

6 Conclusion

The purpose of this paper was to explain the economic issues surrounding material demand reduction. Standard economic arguments focus on market based instruments, such as prices or permits, because of the flexibility that such market instruments give firms and because of the incentive to innovate. These instruments will achieve material demand reduction as part of the mechanism for reducing carbon emissions. On the other hand, the economy is subject to non-economic constraints: there are political constraints due to the distribution of winners and losers, the economy is an open-economy and there is no international agreement on prices for carbon. These considerations mean that using price changes to achieve material demand reduction may be constrained, especially if these price changes or taxes are imposed on producers in tradeable sectors. There is more scope if targets for carbon reduction are consumption based. However, in this second best world, it is not clear what the right instrument is.

Direct regulation of the use of materials (such as imposing restrictions on car weight or material use in buildings) to reduce their use relies on the government knowing, for each firm, the optimal technology for that firm to use to contribute to the carbon target. It is the information requirement on government and the stifling of incentives for further innovation that underpins the economic arguments for using market mechanisms even in this context. The economic approach is to identify the objective, the relevant market failure and find the most efficient instrument that targets that failure rather than trying to pick winners amongst a large set of technical solutions. There remains an argument for subsidising investment and research in technical solutions to improve material efficiency if there are large fixed costs of investment or changing technology, but this is different from requiring firms to switch.

At the heart of this economic approach is a distinction between objectives, instruments and incidental outcomes. In the context of this volume, the objective is the end goal of reducing the output of carbon. Instruments are policies that the government can put into place to achieve this objective. Instruments could include market mechanisms, direct regulation or simply providing information. Market mechanisms include price mechanisms, such as carbon prices, or quotas, or subsidies. Direct regulation of production or consumption could include the proposals to restrict directly the amount of steel used in construction or to regulate the weight or fuel consumption of cars. Providing information could involve providing innovative production techniques that improve the efficiency of materials use. Incidental outcomes might be changes in the amount of goods, cars or houses that individuals consume or demand. We call these outcomes incidental because they simply describe the mechanism through which policy instruments achieve the desired objective. Material demand reduction, for example, is not in itself either an objective or an instrument. On the other hand, the advantage of thinking about policies that operate through reductions in material demand is to contrast with policies that operate through changes in the supply of energy or demand for energy directly. The reason why, as economists, we talk in terms of objectives and instruments is that whatever instrument is used, there is likely to be changes to demand and to supply, but the particular split is not important compared to the outcome of lower carbon.

References

Aidt, T. (2010). Green taxes: Refunding rules and lobbying. *Journal of Environmental Economics and Management 60*(1), 31–43.

Aidt, T. and J. Dutta (2004). Transitional politics: Emerging incentive-based instruments in environmental regulation. *Journal of Environmental Economics and Management 47*(3), 458–479.

Allwood, J., M. Ashby, T. Gutowski, and E. Worrell (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling 55*(3), 362–381. cited By 126.

Allwood, J., M. Ashby, T. Gutowski, and E. Worrell (2013). Material efficiency: Providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371*(1986).

Barrett, J., G. Peters, T. Wiedmann, K. Scott, M. Lenzen, K. Roelich, and C. Le Quere (2013). Consumption-based ghg emission accounting: A UK case study. *Climate Policy 13*(4), 451–470.

Baumol, W. J. and W. E. Oates (1988). *The theory of environmental policy.* Cambridge, UK: Cambridge University Press.

Bento, A., L. Goulder, M. Jacobsen, and R. Von Haefen (2009). Distributional and efficiency impacts of increased US gasoline taxes. *American Economic Review 99*(3), 667–699.

Bhagwati, J. N. and T. N. Srinivasan (1983). *Lecture on international trade.* Cambridge, MA: RFF Press.

Bovenberg, A., L. Goulder, and M. Jacobsen (2008). Costs of alternative environmental policy instruments in the presence of industry compensation requirements. *Journal of Public Economics 92*(5-6), 1236–1253.

Buchanan, J. M. and R. A. Musgrave (1999). *Public finance and public choice. Two contrasting visions of the state.* Cambridge,MA: MIT Press.

Davis, S. and K. Caldeira (2010). Consumption-based accounting of co2 emissions. *Proceedings of the National Academy of Sciences of the United States of America 107*(12), 5687–5692.

Ellerman, A. D., F. J. Convery, and C. de Perthuis (2010). *Pricing Carbon: The European Union Emissions Trading Scheme.* Cambridge, UK: Cambridge University Press.

Fredriksson, P. (1997). The political economy of pollution taxes in a small open economy. *Journal of Environmental Economics and Management 33*(1), 44–58.

Goulder, L. (1995). Environmental taxation and the double dividend: A reader's guide. *International Tax and Public Finance 2*(2), 157–183.

Goulder, L., M. Hafstead, and I. Williams, R.C. (2016). General equilibrium impacts of a federal clean energy standard. *American Economic Journal: Economic Policy 8*(2), 186–218.

Grainger, C. A. and C. D. Kolstad (2010). Who pays a price on carbon? *Environmental and Resource Economics 46*(3), 359–376.

Grasso, M. (2016). The political feasibility of consumption-based carbon accounting. *New Political Economy 21*(4), 401–413.

Hepburn, C., J.-H. Quah, and R. Ritz (2013). Emissions trading with profit-neutral permit allocations. *Journal of Public Economics 98*, 85–99.

Hicks, J. R. (1939). The foundations of welfare economics. *The Economic Journal 49*(196), 696–712.

Jorgenson, D. W., F. M. Gollop, and B. M. Fraumeni (1987). *Productivity and US Economic Growth*. Cambridge, MA: Harvard University Press.

MacKay, D. (2013). Could energy-intensive industries be powered by carbon-free electricity? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 371*(1986).

Milgrom, P. and J. Roberts (1992). *Economics, Organization and Management*. New York: Pearson.

Mueller, D. C. (2003). *Publilc Choice III*. Cambridge, UK: Cambridge University Press.

Olson, M. (1965). *The logic of collective action: Public goods and the theory of groups*. Cambridge, MA: Harvard University Press.

Parry, I. W. (2016, June). Reflections on the international coordination of carbon pricing. Working Paper 5975, CESifo Munich.

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics 65*(1), 13 – 23.

Pindyck, R. S. (2007). Uncertainty in environmental economics. *Review of Environmental Economics and Policy 1*(1), 45.

Pollitt, M. G. (2015). A global carbon market? *MIT Center for Energy & Environmental Policy Research (CEEPR) Working Papers 2015-016*.

Salgado-Banda, H. and L. E. Bernal-Verdugo (2011). Multifactor productivity and its determinants: an empirical analysis for mexican manufacturing. *Journal of Productivity Analysis 36*(3), 293–308.

Sandmo, A. (1976). Optimal taxation. *Journal of Public Economics 6*(1), 37 – 54.

Schneider, F. and J. Volkert (1999). No chance for incentive-oriented environmental policies in representative democracies? A public choice analysis. *Ecological Economics 31*(1), 123–138.

Shogren, J. and L. Taylor (2008). On behavioral-environmental economics. *Review of Environmental Economics and Policy 2*(1), 26–44. cited By 68.

Skelton, A. and J. Allwood (2013). The incentives for supply chain collaboration to improve material efficiency in the use of steel: An analysis using input output techniques. *Ecological Economics 89*, 33–42.

Soderholm, P. and J. Tilton (2012). Material efficiency: An economic perspective. *Resources, Conservation and Recycling 61*, 75–82.

Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews 47*, 74–82.

Sterner, T. (2002). *Instruments for Environmental and Natural Resource Management*. Washington, DC.

Sterni, N. (2015). *Why Are We Waiting? The Logic, Urgency, and Promise of Tackling Climate Change*. Cambridge, MA: MIT Press.

Wiedmann, T. (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics 69*(2), 211 – 222.