Energy sufficiency and rebound effects

Concept paper

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Executive Summary

The concept of **energy sufficiency** is gaining increasing attention as a potentially promising approach to mitigating climate change. However, there is no single agreed definition of energy sufficiency. Some authors consider energy sufficiency to be a particular *level* of energy service consumption that is consistent with human well-being and environmental limits. Others consider it to be a *reduction* in energy service consumption that has the effect of reducing the energy and environmental impacts of that consumption - an interpretation that is similar to the older concept of energy conservation. Example energy sufficiency actions include turning lights off in unoccupied rooms, lowering thermostats, avoiding air travel and cycling rather than driving to work. While both definitions have their merits, the former is more contentious and is harder to operationalise. As a result, this report primarily uses the latter definition.

The potential for energy sufficiency to reduce energy use and emissions is gaining increasing attention. One reason is that improvements in energy efficiency have not reduced energy consumption by as much as anticipated. This is partly due to various *rebound effects* – namely behavioural responses to improved energy efficiency that offset some of the potential energy and emission savings. For example, people may take the benefits of improved insulation in the form of warmer homes rather than reduced energy consumption (a direct rebound effect), or they may spend the cost savings on other goods and services that also require energy and emissions to provide (an indirect rebound effect). The evidence on the size of such rebound effects has grown substantially over the last decade and their importance for energy and climate policy has become increasingly recognised.

This report explores the relationship between rebound effects and energy sufficiency. Specifically, the report: a) identifies the source and magnitude of rebound effects from improved energy efficiency; b) suggests ways in which energy sufficiency actions could reduce these rebound effects and thereby increase energy and carbon savings; and c) investigates how energy sufficiency actions can lead to rebound effects of their own. This leads to some conclusions on the effectiveness of energy sufficiency actions and the implications for public policy. The report combines insights from economics and social psychology and argues that both of these perspectives are required to fully understand the relevant issues. The main findings of the report are as follows:

First, the rebound effects from energy efficiency improvements are frequently large and should be taken into account by public policy. For example, studies of measures affecting vehicle fuel use suggest that the direct rebound effect averages around 32% in the long run, implying that one third of the expected energy savings will not be achieved. While the majority of empirical studies focus on the direct rebound effect, the indirect and other effects can be comparable in magnitude and will further erode the energy and emission savings.

Second, it is wrong to conclude that rebound effects are undesirable, since the mechanisms involved contribute to improved societal welfare. Whether rebound effects are a problem in particular instances will depend upon the size of the associated welfare benefits relative to the environmental costs of the 'lost' energy savings. This is a difficult judgement to make, particularly when energy prices do not adequately reflect the external costs of energy consumption.

Third, consumers may limit the rebound effects from improved energy efficiency by restricting their consumption of the relevant energy service(s) and/or ensuring that the cost savings are spent on non-energy-intensive goods and services. For this to be effective, consumers must be highly motivated to reduce their environmental footprint and have a good understanding of relative impacts of different activities. However, effective measures to reduce rebound effects may also be incentivised or enforced by public policy.

Fourth, energy sufficiency actions are themselves associated with indirect rebound effects as a consequence of re-spending the associated cost savings. Evidence suggests that these effects are modest (e.g. 10%) for actions affecting electricity use and heating, larger (e.g. 20-40%) for those affecting transport fuels and very large (e.g. 60-100%) for those affecting food products. Shifting to a vegetarian diet, for example, could potentially contribute to an increase in global greenhouse gas emissions. The evidence also suggests that indirect rebound effects are larger for low-income groups and proportional to the level of taxation on the energy carrier. However, estimates of the size of these effects are highly uncertain and sensitive to the methodology and metric employed (e.g. energy use, carbon emissions or GHG emissions) and to the national context (e.g. average carbon intensity of electricity generation).

Fifth, studies of the psychological drivers of sufficiency actions show that if people engage in environmentally-friendly actions in one area they may consider that they have 'moral licence' to be less environmentally responsible in other areas. This provides an additional source of rebound effect and one that is potentially important. This type of rebound effect is more commonly labelled 'negative spill-over' and appears more likely to occur when people have weak environmental values, when the initial action is relatively easy, and when that action is motivated by either guilt or financial gain. Conversely, negative spill-overs appear less likely to occur when people have strong environmental values, when the initial action is relatively difficult and when that action is motivated in part by concerns about environmental identity. In the latter circumstances, a 'positive spill-over' may be observed instead - namely where an environmentally responsible behaviour in one area encourages a subsequent environmentally responsible behaviour in another area. The balance between positive and negative spill-overs will have an important influence on the effectiveness of sufficiency actions.

Sixth, a more comprehensive approach to energy sufficiency is voluntary 'downshifting': that is, reducing household income through either moving to a lower paid (but more satisfying) job or reducing working hours. Downshifting should reduce household consumption and thereby the environmental impacts of that consumption. But

downshifting will also shift expenditure and time-use patterns in complex ways that could lead to a less than proportionate reduction in energy use and emissions. Also, widespread adoption of downshifting will lead to reductions in energy prices which in turn will encourage other groups to increase their energy consumption, as well as having complex and potentially negative impacts on the broader macro-economy. These considerations point to the limitations of a voluntary, bottom-up approach to energy sufficiency and to the corresponding importance of collective action.

Finally, the most effective way to mitigate rebound effects is likely to be through some form of carbon pricing. In principle, this could incentivise efficiency improvements and sufficiency actions, while at the same time mitigating any associated rebound effects and protecting low-income groups. The preferred approach would be an economy-wide scheme with revenue recycling that incorporates border carbon adjustments to capture the emissions embodied in traded goods. But carbon pricing schemes need to be supplemented by other policy instruments, including energy efficiency regulations and information programs. There is scope for designing these in such a way as to provide a disincentive to certain types of rebound effects.

Energy Sufficiency

european council for an energy efficient economy

Table of Contents

Figures

Tables

1 Introduction

The concept of **energy sufficiency** is gaining increasing attention as a promising approach to mitigate climate change. However, there is no single agreed definition of energy sufficiency. Some authors consider energy sufficiency to be a particular *state* or outcome defined by a *level* of energy service consumption that is consistent with both human well-being and environmental limits, while others consider it to be a *direction* defined by *reduction* in energy service consumption that also reduces the associated environmental impacts. In this report, we use the latter approach and define energy sufficiency as: *reductions in the consumption of energy services, that have the aim of reducing the energy use and environmental impacts associated with those services*. Examples include turning lights off in unoccupied rooms, lowering thermostats, avoiding air travel and cycling rather than driving to work. As such, energy sufficiency is analogous to what used to be termed 'energy conservation'. Since we assume that energy sufficiency is motivated by environmental values, it may also be considered a particular form of 'pro-environmental behaviour' [1]. Sufficiency actions may be undertaken by individuals or organisations, and may be either encouraged or obstructed by public policy.

This report is one of a series of reports on the topic of energy sufficiency prepared for European Council for an Energy Efficient Economy (ECEEE), with the help of funding from the KR Foundation. The current report examines the relationship between *energy sufficiency and rebound effects*. The term rebound effect normally refers to various behavioural responses to improved energy efficiency, whose net result is to reduce the energy savings achieved [2]. For example, people may take the benefits of improved insulation in the form of warmer homes rather than realising the full potential reductions in energy consumption. One aim of this report is to describe the nature and magnitude of rebound effects from energy efficiency improvements and to assess the potential for energy sufficiency actions to *limit* those effects and thereby to increase energy savings. But a second aim is to explore the potential for rebound effects *from* the energy sufficiency actions themselves. For example, the money saved from giving up air travel may be spent on other goods and services that also require energy and emissions to provide, thereby offsetting some of the global energy and emission savings. Hence, while energy sufficiency actions may mitigate rebound effects, rebound effects may reduce the environmental benefits of energy sufficiency actions.

A key objective of this report is to combine insights from economics and social psychology and to show how both perspectives are required to fully understand the determinants and consequences of sufficiency actions. While economic studies use the term *rebound effects*, psychological studies use the term *negative spill-overs* [3]. There are overlaps between these two concepts, but also important differences. Moreover, both rebound effects and spill-overs may be associated with either energy efficiency improvements or energy sufficiency actions - a distinction that is summarised in Table 1.

Table 1. Rebounds and spill-overs

	Energy efficiency improvement	Energy sufficiency action
Economic perspective	Efficiency rebounds	Sufficiency rebounds
Psychological perspective	Efficiency spill-overs	Sufficiency spill-overs

Rebound effects and negative spillovers reduce the energy savings from both energy efficiency improvements and sufficiency actions, and thereby their associated environmental benefits. As a result, they are frequently judged negatively - as something to be minimised. But this view is misleading since it ignores the wider benefits provided those improvements and actions. For example, insulation improvements in low-income households may be associated with relatively large rebound effects since the occupants may take the benefits in terms of warmer homes rather than energy savings. But the improved insulation may nevertheless improve aggregate social welfare since the occupants are longer cold and ill. Whether rebound effects are judged to be a problem in particular instances will therefore depend upon the size of the benefits to consumers and producers relative to the environmental costs of the 'lost' energy and emission savings.

The following sections explore the sources of rebound effects and spill-overs, the different mechanisms involved, the factors influencing their magnitude and the available evidence on their importance in different contexts. The report focuses entirely on sufficiency actions by households, since the literature on sufficiency actions by firms and other organisations is very limited. While most of the discussion relates to actions affecting the direct consumption of energy by households (e.g. for heating and lighting), the report also discusses broader actions that have indirect consequences for energy use and emissions, such as shifting to a vegetarian diet.

The report is structured as follows. Section 2 describes the sources, types and drivers of rebound effects from energy efficiency improvements and summarises the evidence on their magnitude. Section 3 introduces the concept of energy sufficiency, provides examples of sufficiency actions, discusses whether such actions can reduce the rebound effects from energy efficiency improvements and presents some broader evidence on the psychological drivers of sufficiency actions. Section 4 examines the potential for both rebound effects and spill-overs from sufficiency actions, including the drivers and determinants of those effects and the limited evidence that is available on their magnitude. Section 4 concludes by highlighting some relevant policy implications.

2 What are rebound effects?

2.1 Introduction

Complex systems exhibit adaptive and emergent behaviour that is difficult to capture with scientific models – and much less with the simple 'mental models' that guide everyday decision-making. While our models of system behaviour are frequently static, reductionist and linear; the systems themselves are dynamic, path-dependent and non-linear, with behaviour driven by multiple interdependencies and time-delayed feedback loops. As a result the long-term consequences of actions and interventions may differ radically from those that were intended or expected - and the system responses may confound the original objectives [4]. For example, roadbuilding programmes designed to reduce congestion may lead over time to greater car use and more congestion. Vehicle safety measures may encourage people to drive more aggressively, thereby offsetting their benefits. Large-scale use of pesticides and herbicides may encourage the evolution of resistant pests. And so on [4].

These types of outcome are highly relevant to individual or collective action to promote sustainability – especially when (as is commonly the case) attention is focused upon local impacts over the short term when what matters is the regional or global impacts over the long-term. Improving energy efficiency to reduce energy use and carbon emissions is a primary example. Such improvements can lead to a variety of responses - termed *rebound effects* - whose net result is to reduce the energy and emissions 'saved' relative to a counterfactual where such responses do not occur [2]. Indeed, the introduction of certain types of energy efficient technology in the past appears to have contributed to an overall *increase* in energy consumption - the so-called Jevons' paradox [5].

The following sections describe the sources, classification and determinants of these rebound effects from improved energy efficiency, and summarises the available evidence on their magnitude in different contexts.

2.2 Types of rebound effect

Rebound effects are commonly analysed from the perspective of orthodox economics. This considers the primary source of rebound effects to be the response of individuals and organisations to the economic opportunities offered by cheaper energy services such as more efficient heating and lighting. These responses involve a number of different economic mechanisms operating at different levels and over different periods of time. As an illustration, consider some possible responses to improvements in the average fuel efficiency of passenger cars (**Error! Reference source not found.**):

1. *Direct effects*: fuel-efficient cars make car travel cheaper, so people may be encouraged to buy more cars and to drive those cars further and/or more often [6];
2. *Indirect effects*: fuel-efficient cars may lead to reduced expenditure on road fuels, but the cost savings will be spent on other goods and services whose provision necessarily involves energy use and emissions at different stages of their global supply chains [7-9];
3. *Embodied effects*: fuel-efficient cars may embody technological improvements such as lightweight materials that can be more energy intensive to produce, with the result that the life-cycle energy savings may be less than the operational energy savings [7];
4. *Service quality effects*: technical improvements such as better aerodynamics and more efficient engines may encourage the purchase of larger, heavier, more powerful and more comfortable cars, rather than more fuel-efficient cars [10,11];
5. *Energy market effects*: widespread adoption of fuel-efficient cars may reduce fuel demand, thereby reducing fuel prices which in turn will encourage increased fuel consumption within national and global markets [12];
6. *Secondary effects*: widespread adoption of fuel-efficient cars will induce changes in prices, investment, production and trade in multiple markets, which will have

corresponding impacts on energy consumption both within the national economy and along international supply chains [13,14];

7. *Transformational effects*: widespread adoption of fuel-efficient vehicles may make car travel increasingly attractive relative to other transport modes, thereby deepening the 'lock-in' to the car-based transportation system and triggering associated and reinforcing changes in infrastructure, land use patterns, institutions, regulations, supply chains and social practices [5,15].

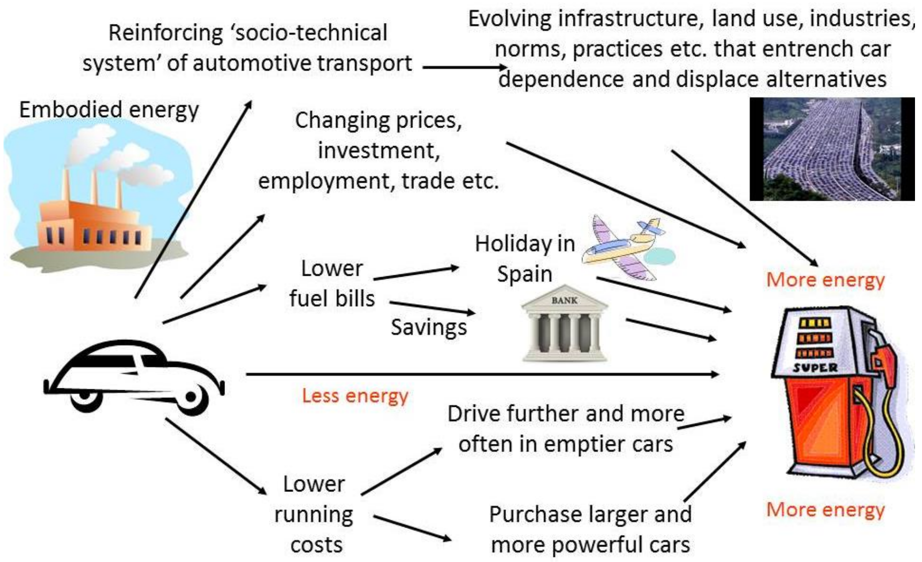

Figure 1. Rebound effects from more fuel-efficient vehicles

Although these mechanisms are complex, they by no means exhaust the range of possibilities - not least because factors that are neglected by orthodox economics may also play a crucial role. For example, people may have environmental motivations for purchasing a fuel-efficient car, since it should reduce their transport-related carbon emissions. But evidence suggests that if people engage in environmentally responsible behaviour in one area (e.g. purchasing a fuel-efficient car) they may consider that they have 'moral licence' to engage in less environmentally responsible behaviours in other areas (e.g. more flying). These broader mechanisms are termed *negative spill-overs* by environmental psychologists and they both *overlap* with the mechanisms discussed above and provide an *additional* source of rebound. They are discussed further in Section 4.

Beginning with Khazzoom [16], a growing number of studies have sought to estimate or model one or more of the above effects in different circumstances using a variety of techniques [2]. Quantification is challenging, however, and the causal linkages become increasingly difficult to establish as the time horizon extends and spatial boundaries expand. Most studies focus solely upon direct rebound effects, with the determinants and magnitude of other effects receiving less attention. Studies also focus primarily upon consumer behaviour, although a comparable set of responses will result from energy efficiency improvements by producers. Since the latter can improve productivity, boost economic output and encourage economic growth, they may potentially be associated with *larger* rebound effects [2,5]. But this report will focus solely upon rebound effects for consumers, as these are better understood and more relevant to the topic of energy sufficiency.

2.3 Classifying rebound effects

The rebound effect (R) is commonly defined as the gap between the *potential* (PES) energy savings from an energy efficiency improvement and the *actual* energy savings (AES):

$$R = \left[1 - \frac{AES}{PES}\right] \quad (1)$$

Potential energy savings are estimated *ex ante* under the assumption that there are *no* behavioural responses to the efficiency improvement, while *actual* energy savings are measured or estimated *ex-post* and include one or more of the behavioural responses indicated above. So for example, a rebound effect of 20% (R=0.2) means that one fifth of the potential energy savings have been 'taken back' by one or more of the above responses.

It is common to distinguish between *direct* and *indirect* rebound effects:

Direct rebound effects derive from increased consumption of the energy service, such as heating or lighting, whose effective price has fallen as a result of improved energy efficiency. For example, the availability of energy efficient washing machines may encourage people to buy more washing machines, to buy larger machines, to use them more frequently and/or to reduce the size of the average load. As a result, energy consumption will be larger than in a counterfactual scenario in which none of these behavioural responses occur. The magnitude of these effects is likely to depend upon both the size of the energy-related costs and the 'visibility' of those costs to the consumer. So for example, we may expect a larger direct rebound effect from energy efficient vehicles than from energy efficient vacuum cleaners since the energy costs of the former are both larger and more visible to the consumer. At the same time, the direct rebound effect may be inversely proportional to the level of consumption of the energy service, since the marginal utility from that service will fall with increased consumption. So for example, we may expect a smaller direct rebound effect among high-income households since these tend to be nearer to saturation in their consumption of (at least some) energy services. Note further that increased demand for energy services may either derive from *existing* users of that service or from *new* users who were previously unable or unwilling to purchase the relevant equipment. So for example, improvements in the energy efficiency of space cooling may encourage some households to replace their existing equipment and to use the new equipment more intensively, as well as encouraging other households to purchase space cooling equipment for the first time.

Indirect rebound effects derive from re-spending the cost savings from energy efficiency improvements on *other* goods and services (e.g. leisure, clothing) that also require energy to provide (e.g. from production of materials, manufacture of products, shipping, road freight, retail), and hence also lead to greenhouse gas (GHG) emissions. For example, the cost savings from more energy efficient lighting may be put towards the purchase of a laptop that has been made in China and shipped to the UK. Alternatively the money could be saved, but it will ultimately lead to energy use and emissions through deferred spending. In principle, we expect higher direct rebound effects to be associated with lower indirect rebound effects, and vice versa.

Most estimates of indirect rebound effects are 'economy-wide' in that they relate to energy use and emissions throughout the national economy, and frequently along global supply chains as well. These effects are typically estimated with the help of input-output (I-O) models that are calibrated to the structure of the national or global economy. However, I-O models are 'static' in that they do not allow for price adjustments in the relevant product, labour and capital markets. Perhaps the most important of these adjustments will occur in energy markets, where the widespread adoption of energy efficiency improvements can reduce regional and global energy prices and thereby encourage increased energy consumption. But other adjustments may also occur, such as increased consumption of non-energy goods that raises the price of those goods and encourages increased investment by producers. These broader macroeconomic adjustments are sometimes labelled ***secondary effects*** and will also affect energy use and emissions at both the regional and global level.

It is important to make the following distinctions:

- *Energy versus total costs*: Energy efficiency improvements reduce the *energy* cost of energy services, but not necessarily the *total* cost since this also includes capital,

maintenance and non-energy operational costs.[1] For example, LED lighting is more energy efficient than traditional lighting and cheaper to run, but the individual lightbulbs may be more expensive to purchase. Whether the lifetime costs of LED lighting are lower than traditional lighting will depend upon the relative intensity of use of each technology (hours per year) and the relevant discount rate. The magnitude of rebound effects will therefore depend upon the total cost of the energy efficient technology and how decisions about purchasing and operating that technology are influenced by different components of that cost. This in turn will depend upon whether the adoption of the energy efficient technology is voluntary, or whether it is incentivised or mandated by public policy [17].

- *Efficiency versus other attributes:* Energy-efficient technologies may also differ in in other respects from inefficient alternatives. For example, the quality of lighting from LEDs may be better than that from traditional lightbulbs; or fuel-efficient cars may be smaller and less comfortable than inefficient cars. In principle, changes in these broader attributes could make an energy-efficient technology either more or less attractive, and the response to the adoption of that technology will depend upon whether and how these other attributes have changed and the value placed on those attributes relative to that placed on energy costs [18]. In addition, it is possible that improvements in the energy efficiency of particular technologies will encourage increased demand for these broader attributes. For example, improvements in efficiency of car engines may encourage the purchase of larger and more powerful cars, since these now cost no more to run than smaller cars did in the past. This may be considered another form of rebound, jointly determined by producers and consumers, and one that is relatively little explored in the empirical literature [10,19].
- *Energy versus emissions:* Both direct and indirect rebound effects may be estimated in terms of energy consumption, carbon dioxide (CO2) emissions, GHG emissions or some other environmental metric, such as NOx emissions or water use [20]. The magnitude of the rebound effect will therefore depend upon the metric used. As the carbon/GHG-intensity of economies change over time, the relative magnitude of carbon/GHG rebound effects will also change – and in some circumstances, rebound effects may be small in energy terms but large in carbon/GHG terms, or vice versa.
- *Direct versus embodied:* Households use significant amounts of energy 'directly' in the form of electricity2, heating fuels and vehicle fuels, but they also use energy 'indirectly', since energy is used at each stage of the supply chain for most goods and services. This life-cycle energy use is commonly termed embodied energy while the associated emissions are termed embodied emissions. While most studies focus upon direct energy use and emissions, embodied energy use and emissions are also important. For example, the savings from an energy-efficient heating system may be spent upon more heating (direct rebound, direct energy), more lighting (indirect rebound, direct energy) or more furniture (indirect rebound, embodied energy).
- *Narrow versus wide:* Estimates of rebound effects will depend upon the spatial boundaries of both the potential and actual energy savings in Equation 1 [21]. For example, should the estimate of potential energy savings relate solely to the direct energy use by the household, or also to the energy used along the supply chain for the relevant energy commodity (e.g. the energy used to extract and refine crude oil and to deliver heating oil to households)? Similarly, should the estimate of actual energy savings relate solely to the host country, or also include the energy embodied in imported goods? If our primary interest is global climate change, it would seem appropriate to measure rebound effects in terms of carbon or GHG emissions and to have a spatial boundary for both the potential and actual emission savings that encompasses the entire world (i.e. tracking the impacts of the efficiency improvement along all relevant global supply chains). But many empirical studies measure rebound

[1] Opportunity costs may also be relevant. For example, increasing refrigerator size may not be the best use of available space.

[2] Emissions associated with electricity end use are commonly labelled as direct, even though they occur at the power station.

effects in terms of use of energy use rather than emissions and have a narrower system boundary for energy/emission savings since these are easier to estimate. Moreover, the system boundary used for estimating potential savings is often different from that used for estimating actual savings (Figure 2) [22].

- *Short versus long term:* It is equally important to specify the temporal boundaries of the potential and actual energy savings. Rebound effects may be larger or smaller over the long-term as a greater range of behavioural responses become available - such as changes in land-use patterns following the greater availability of more energy-efficient and hence lower cost car travel. But long-term effects can be more difficult to estimate.
- *Ex post versus life cycle:* Rebound effects are normally understood as an ex post response to an energy efficiency improvement. But in some circumstances it may be appropriate to take a life cycle perspective, and to also consider the energy used to manufacture and dispose of the relevant energy-efficient equipment [7]. If the energy-efficient equipment has more 'embodied' energy, this will subtract from its operational energy savings.3 This component is sometimes labelled the embodied effect [7], but this is easy to confuse with the embodied energy that forms part of the indirect rebound effect. It is also important to recognise that the embodied effect relates to energy use (or emissions) prior to rather than following an efficiency improvement.

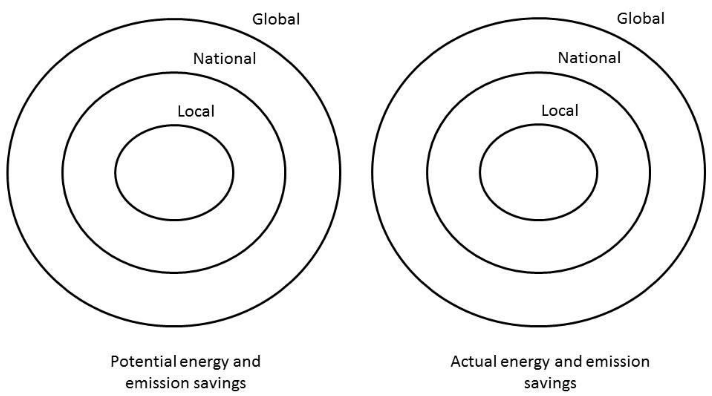

Figure 2. Choice of system boundary for potential and actual energy/emission savings

Figure 3 provides one way of summarising the different effects described above. The total (or economy-wide) rebound effect is shown here as the sum of the direct, indirect, secondary and embodied effects. These subtract from the potential energy savings to give the actual energy savings. As discussed in the next section, both the direct and indirect effects may in turn be decomposed into income and substitution effects. However, this type of classification can be misleading since the individual effects are not necessarily additive. This applies in particular to the indirect and secondary effects: these both reflect economy wide impacts, but calculate those impacts in a different way (i.e. with and without allowing for price adjustments). Moreover, in some circumstances individual components of the rebound effect can be negative, so they add to rather than subtract from the potential energy savings. For this reason, it is theoretically possible for the overall rebound effect to be negative (i.e. *AES*>*PES*) - an outcome that has been called 'super conservation' [23].

The total rebound effect is therefore the net result of multiple mechanisms that sometimes reinforce and sometimes offset one another. The relative size of these different effects may vary widely from one situation to another and from one system boundary to another and will also change over time. Estimating the magnitude of these different effects can be challenging even when good data is available - which is rarely the case. And since empirical

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3 In contrast, if the energy-efficient equipment has *less* embodied energy over its life-cycle than the inefficient equipment, this will *add to* the operational energy savings.

estimates depend upon the choice of efficiency measure, spatial boundary, temporal boundary and rebound metric; there is a risk of comparing apples and oranges when contrasting the results of different studies.

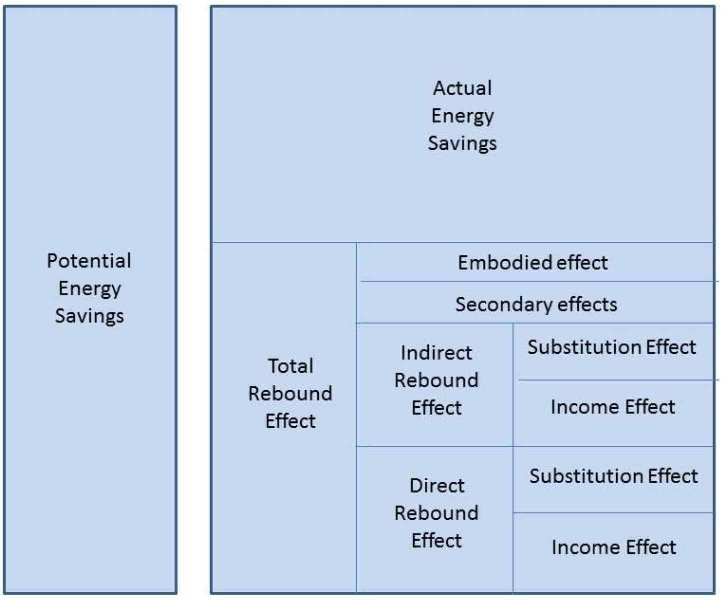

Figure 3. Classifying rebound effects

2.4 Economic drivers of rebound effects

2.4.1 Rebound effects and economic welfare

Since rebound effects reduce the environmental benefits of energy efficiency improvements, they are usually judged negatively - as something to be minimised. But this view is misleading since it ignores the benefits provided by energy efficiency improvements. From an economic perspective, the contribution of energy efficiency improvements to aggregate social welfare is given by the sum of the costs and benefits they provide to consumers, producers and all other affected parties. This includes the environmental costs associated with the energy used to deliver the relevant energy service.

For example, improvements in the energy efficiency of domestic boilers will make heating cheaper and households may take advantage of this by enjoying higher levels of thermal comfort. This will increase their 'consumer surplus'[4] which contributes to aggregate social welfare. Energy consumption will normally still be reduced, but not by as much as it would have been in the absence of the increased demand for heating (the direct rebound effect). Since energy consumption contributes to climate change, it imposes costs on other people both now and in the future. These 'external costs' must be set against the benefits to consumers of warmer homes.

In practice, it is unlikely that all relevant costs and benefits can be monetised and compared in this way - and there are philosophical difficulties in attempting to do so. Nevertheless, it is clear that a judgement that rebound effects are 'bad' and something to be minimised must rest upon the assumption that the external costs of energy use are very high - and hence, in this example, that the costs associated with any increase in heating demand outweigh the benefits to consumers of warmer homes. In practice, this need not be the case. For example, direct rebound effects in low-income households may be relatively high, but may contribute a major increase in welfare since the occupants are no longer cold and ill.

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[4] Consumer surplus is the difference between what people are willing to pay for a good and what they actually pay.

Also, the external costs of energy use will depend in part on the carbon intensity of the relevant energy carriers.

2.4.2 Direct and indirect rebound effects

Rebound effects may be analysed and estimated with the standard tools of micro and macroeconomics. Although most of these approaches rely upon restrictive assumptions about consumer decision-making (i.e. utility maximisation under constraints), they can nevertheless offer valuable insights - as well as forming the basis of the majority of empirical work in this area.

Figure 4 provides a standard microeconomic illustration of rebound effects. It shows the trade-off between consumption of an energy service (*S*) by a household and consumption of a basket of other goods (*Z*). Consumers are assumed to maximise their 'utility' (*U*), or satisfaction, from consuming some combination of *S* and *Z* subject to a 'budget constraint'. It is assumed that greater consumption provides more utility, but the satisfaction obtained from each additional unit of consumption is less than that obtained from the previous unit (declining marginal utility). 'Indifference curves' such as U_1 and U_2 represent different combinations of the two goods that provide equal utility to the consumer ($U_2>U_1$). The diagonal line from Z_0 to S_0 indicates the initial budget constraint. Given current income (*X*) and the relative prices of *S* (P_s) and *Z* (P_z), the consumer can purchase any combination of *S* and *Z* that lies along this line, whose slope is given by: $-P_z/P_s$.

At one extreme, the consumer could choose to consume $S_0=X/P_S$ of the energy service and none of the other goods, while at the other extreme she could consume $Z_0=X/P_Z$ of basket of goods and none of the energy service. Prior to the energy efficiency improvement, the 'optimum' mix is given by (S_1, Z_1), where the budget constraint is tangential to the indifference curve U_1. At this point, utility is maximised. A energy efficiency improvement reduces the effective price of the energy service ($P'_s<P_s$) and allows greater consumption of the energy service ($S'_0=(X/P'_S)>S_0$). The optimum mix is now given by (S_2, Z_2) where the new budget constraint is tangential to the indifference curve U_2 which represents the maximum amount of utility that can be obtained from the new level of 'real income' (nominal or money income is unchanged). Hence, consumption of the energy service increases ($S_2>S_1$), consumption of the basket of goods decreases ($Z_2<Z_1$) and the consumer obtains a higher level of utility ($U_2>U_1$).

The analysis highlights the fact that increased consumption of the energy service ($S_2>S_1$) contributes to improved consumer welfare ($U_2>U_1$) and that the drivers of improved welfare are also the drivers of the rebound effect (e.g. households benefiting from warmer homes). At the same time, the additional energy consumption may have external costs, in the form of environmental impacts. The net contribution to societal welfare will be given by the difference between the increase in consumer welfare associated with the additional energy service consumption and the increase in external costs associated with the additional energy consumption. This calculation involves some difficult trade-offs, but it cannot be assumed that the additional external costs will always outweigh the improvement in consumer welfare.

Figure 4 also decomposes the response into a substitution effect and an income effect. The *substitution effect* is defined as the change in consumption that would result from the change in relative prices *if* income were adjusted to keep utility constant. In effect, the change in consumption is artificially restricted to a movement along the original indifference curve. But since the energy service is cheaper, the consumer's total purchasing power, or 'real income' has increased. This allows a shift from one indifference curve to another (higher utility). The *income effect* is defined as the change in consumption that would result exclusively from this change in real income, holding prices and nominal income constant. Standard microeconomic techniques (the Slutsky equation) allow the two effects to be individually estimated, with the income effect being derived from income elasticities[5] and the substitution and total effect being derived from price elasticities.

[5] Economists tend to estimate expenditure elasticities rather than income elasticities, partly because data on expenditures is easier to obtain than data on incomes. But the term 'income elasticity' will be used in this report.

Note that, in Figure 4, the substitution (S_S-S_1) and income (S_2-S_S) effects for the energy service *reinforce* one another and lead to *increased* consumption ($S_2>S_1$), while the substitution (Z_s-Z_1), and income (Z_2-Z_S) effects for the basket of goods *offset* one another and lead to *decreased* consumption ($Z_2<Z_1$). But in practice there will be multiple goods and services, and these outcomes will not hold for each. Consumption of some goods may increase following the energy efficiency improvement while consumption of others may reduce. The former are said to be *complements* to the energy service while the latter are said to be *substitutes*. For example, the consumption of home entertainment could increase following insulation improvements (since people are spending more time at home), while the consumption of alcohol in pubs could decrease. Note further that the analysis assumes a *costless* improvement in energy efficiency. The inclusion of capital costs would reduce the income effect but not the substitution effect.

Annex 1 develops this analysis more formally, deriving expressions for the different effects that allow them to be estimated empirically.

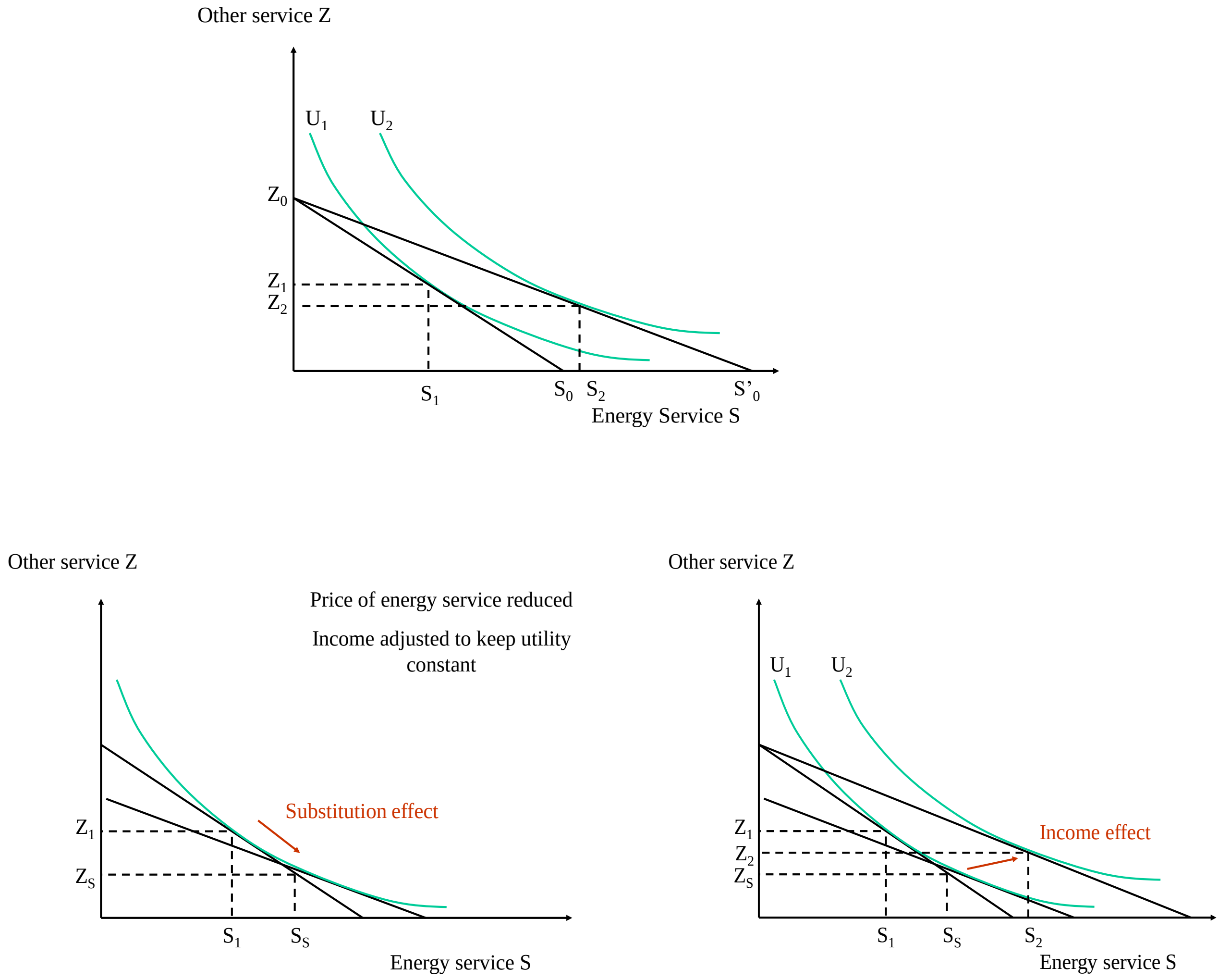

Figure 4. Decomposing rebound into income and substitution effects

2.4.3 Secondary effects

The analysis of secondary effects is more complex as these involve adjustments in multiple markets (i.e. general rather than partial equilibrium). Fortunately, the most important secondary effect is likely to be through changes in energy prices, which can be analysed in a straightforward manner as indicated in Figure 5. This illustrates the supply (S) schedule for

the relevant energy commodity, together with the demand schedule both before (*D*) and after (*D'*) the energy efficiency improvement. Initially, a quantity Q_1 of energy is sold at price P_1. The energy efficiency improvement shifts the demand schedule to the left, leading to new equilibrium of Q_3, P_3. If there were no price response, energy consumption would fall further to Q_2. Hence, the potential energy saving is given by Q_1-Q_2, the actual energy saving is given by Q_1-Q_3 and the 'energy market' rebound is given by: $1-\left[\frac{(Q_1-Q_3)}{(Q_1-Q_2)}\right]$. This is *additional* to the direct and indirect rebound effects discussed above.

The size of the energy market effect will depend upon the relative slope of the supply and demand curves for the relevant energy commodity – as measured by their price elasticities. Higher rebounds will occur when supply is inelastic (steep curve) and demand is elastic (shallow curve). Both supply and demand tend to be more elastic over the long-term.

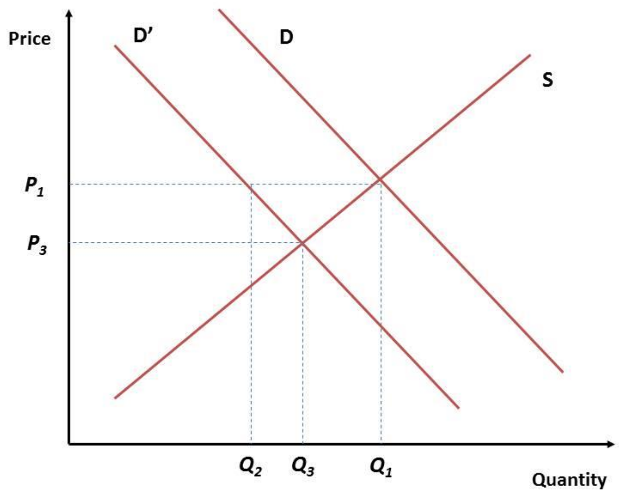

Figure 5. Energy market effect

The secondary effects do not stop with adjustments in energy prices. The increased spending power will increase demand for a range of goods and services, thereby increasing economic activity and putting upward pressure on the prices of those goods. Over time this may encourage investment in new production capacity, thereby expanding supply and mitigating those price increases. Higher demand may also lead to higher wages, as well as lower unemployment, increased imports and reduced competitiveness of export industries. The demand for energy (and for goods that are complements to energy) may fall, potentially leading to 'disinvestment' by energy producers such as oil refineries [24]. This in turn will put an upward pressure on energy prices and reduce the energy market rebound indicated above. In other words, energy efficiency improvements by households can trigger a host of macroeconomic adjustments that will affect energy consumption in complex ways throughout the regional and global economy. Some of these adjustments will add to the rebound effect and some will subtract, and their relative importance will change over time as markets adjust. These responses are too complex to measure, but can be simulated with the help of macroeconomic models [13,25].

2.5 Evidence on rebound effects

Sorrell [2] provides a comprehensive summary of the empirical evidence on rebound effects as it stood in 2007. This review was subsequently updated by Jenkins *et al* [26] and Azevedo [21]. In the intervening years there has been an explosion of empirical research, including an increasing number of studies from China. There has yet to be a comprehensive review of this new evidence, but the conclusions of most studies appear broadly consistent

with the 2007 review. Only a brief summary of these results will be provided here - with the methods used to produce these results being summarised in Annex 2.

2.5.1 Direct rebound effects

By far the best studied area for the direct rebound effect is **car travel** – in part because good data is available on both fuel consumption and distance travelled. Most studies estimate the rebound effect from elasticities of distance travelled with respect to either fuel efficiency, fuel cost per kilometre or fuel prices [18], but they vary considerably in terms of the data used and specifications employed. A recent meta-analysis [27] of 76 studies containing 1138 estimates suggests a direct rebound effect for car travel of **~12% in the short run and 32% in the long run**. But the results depend upon the elasticity measure used and the most direct of these measures - the efficiency elasticity of distance travelled - was typically found to be insignificant or close to zero. A variety of factors may explain this, including a negative correlation between fuel efficiency and other vehicle attributes (such as power and spaciousness) that may be complements to distance travelled [28]. Results also vary between countries and over time, with lower per capita GDP being associated with larger rebound effects [27] and with some evidence of declining rebound effects within the OECD [6]. This is plausible, since many industrialised countries are experiencing a saturation or even decline in car travel per capita whereas car travel is 'taking-off' in developing countries [29].

The next best studied area for direct rebound effects is household **heating**. Several studies use a quasi-experimental approach which involves measuring energy consumption before and after an energy efficiency improvement. However, most of these studies are methodologically weak and they rarely include a control group [30]. The results suggest that engineering models typically overestimate the energy savings from heating/cooling improvements by around **one half**—and potentially by more than this for low income households. But changes in internal temperature only account for a portion of this shortfall and behavioural change by the occupants only account for a portion of the change in internal temperature [30].

Other studies employ econometric analysis of household survey data to estimate rebound effects for heating, but these vary widely in terms of the demographic groups covered, the definition and measurement of the relevant variables, the extent to which various factors are controlled for and the methodologies employed [30].[6] Sorrell and Dimitropoulos compared the results of nine pre-2007 studies and found estimates in the range 10–58% for the short-run effect and 1.4–60% for the long-run effect. More recent studies also provide results in that range, but are much more robust. For example, Aydin *et al* [31] analyse data on the energy efficiency, energy consumption and socio-demographic characteristics of 563,000 Dutch households and estimate a rebound effect of **27%** amongst homeowners and **41%** amongst tenants - with higher rebound effects for low-income groups. Volland [32] conducts a similar analysis of 11,500 US households and estimates a mean rebound effect of **30%**, with higher rebounds for households facing higher prices for heating fuels.

There are relatively few estimates of the direct rebound effect for **other household energy services**, owing largely to lack of data. Rebound effects may be low for many energy services (e.g. home entertainment, vacuuming), since energy costs are small - both in absolute terms and relative to other costs - and tend to be relatively invisible to the consumer. Also, other attributes of the energy service may play a much larger role in decision-making. One of the few robust studies in this area is by Davis [33] who analysed the results of a field trial of energy-efficient washing machines among 98 US households. Demand for clean clothes increased by **5.6%** after the new machines were installed, but this reflects responses to savings in water and detergent costs as well as energy costs.[7] Davis also led the evaluation of a Mexican program that subsidised the replacement of 1.9 million refrigerators and air-conditioners. By combining program, participant and energy billing

[6] A number of elasticity measures could be used as a proxy for the direct rebound effect for heating and cooling and the size of the effect may be expected to vary widely depending on the measure chosen [30].

[7] Davis estimated that the opportunity cost of time forms 80–90% of the total cost of washing clothes, which would constrain the size of any direct rebound effect.

data, Davis *et al* [34] estimated that the refrigerator replacement achieved only one quarter of the forecast energy savings while the air conditioner replacement led to an **increase** in energy consumption. While the refrigerator results may largely be explained by higher specifications and over-optimistic engineering estimates, the air conditioning results most likely reflect price-induced rebound.

2.5.2 Direct and indirect rebound effects

Estimates of **combined direct and indirect rebound effects** are commonly obtained by combining estimates of the income or price elasticity of different categories of household expenditure with estimates of the energy/emission intensity of expenditure on those categories (e.g. in tCO_2/£). So for example, the studies use income and price elasticities to estimate how households distribute the cost savings from efficiency improvement between different commodities, and use expenditure intensities to estimate the associated energy use and emissions. Elasticity estimates can be obtained from the econometric analysis of household expenditure data, while expenditure intensity estimates can be obtained from environmentally-extended input-output models. A key distinction is between studies that only capture the income effects from energy efficiency improvements (using income elasticities) and those that capture both income and substitution effects (using price elasticities). While the latter should in principle provide more accurate estimates, this may not be the case in practice owing to various methodological difficulties [35].

There is a small but growing evidence base in this area, with the most prominent studies being listed in Tables 2 and 3. The estimated effects cover a remarkably wide range, from the very small (4%) to the extremely large (300%). While most studies focus on improved energy efficiency in electricity, heating or personal travel, others examine sufficiency measures, such as reducing car travel or food waste. The latter are discussed further in Section 4. Different studies estimate rebound effects in energy, CO_2 and GHG terms, but no study estimates and compares all three.

The diversity of results, combined with methodological limitations [see 35] and the limited use of sensitivity tests make it difficult to draw any firm conclusions. However, the studies demonstrate that: first, the combined direct and indirect rebound effects may sometimes exceed 100%; second, the indirect rebound effect is inversely proportional to the direct effect; third, direct and indirect effects appear to be larger for measures affecting car travel than for measures affecting electricity or heating fuels - in part because road fuels tend to be subject to higher levels of taxation; fourth, rebound effects within a country tend to be larger for low-income groups in that country; and finally, rebound effects vary widely between different countries owing to differences in energy prices, commodity prices and taxation regimes (Figure 6) [36].

Table 2. Studies estimating combined direct and indirect rebound effects for households – income effects only

Author	Region	No. of expenditure categories	Measure	Area	Rebound metric	Estimated rebound effect (%)
Lenzen and Day [37]	Australia	150	Efficiency & Sufficiency	Food, heating	Energy & GHGs	45-123%
Alfreddson [38]	Sweden	300	Sufficiency	Transport, electricity, heating, food	CO_2	7-300%
Thomas and Azevedo [39]	US	428	Efficiency	Transport, electricity, heating	Energy and GHGs	15-27%
Murray [40]	Australia	36	Efficiency & Sufficiency	Transport, lighting	GHGs	4–24%
Chitnis *et al* [7]	UK	17	Efficiency	Electricity, heating	GHGs	5-15%
Freire-Gonzalez [41]	EU-27	163	Efficiency	Transport, electricity, heating	Energy	30-300%
Bjelle *et al* [42]	Norway	12	Efficiency & Sufficiency	Transport, electricity, heating, food, waste, other	GHGs	40-58%

Table 3. Studies estimating combined direct and indirect rebound effects for households – income and substitution effects

Author	Region	No. of commodity categories	Measure	Area	Rebound metric	Estimated rebound effect (%)
Brannlund *et al* [27]	Sweden	13	Efficiency	Transport; utilities	CO_2	120-175%
Mizobuchi [43]	Japan	13	Efficiency	Transport; utilities	CO_2	12-38%
Lin and Liu [44]	China	10	Efficiency	Transport; utilities	CO_2	37%
Kratena and Wuger [45]	Austria	6	Efficiency	Transport; heating; electricity	Energy	37-86%
Chitnis and Sorrell [46]	UK	12	Efficiency	Transport, heating, electricity	GHGs	41-78%

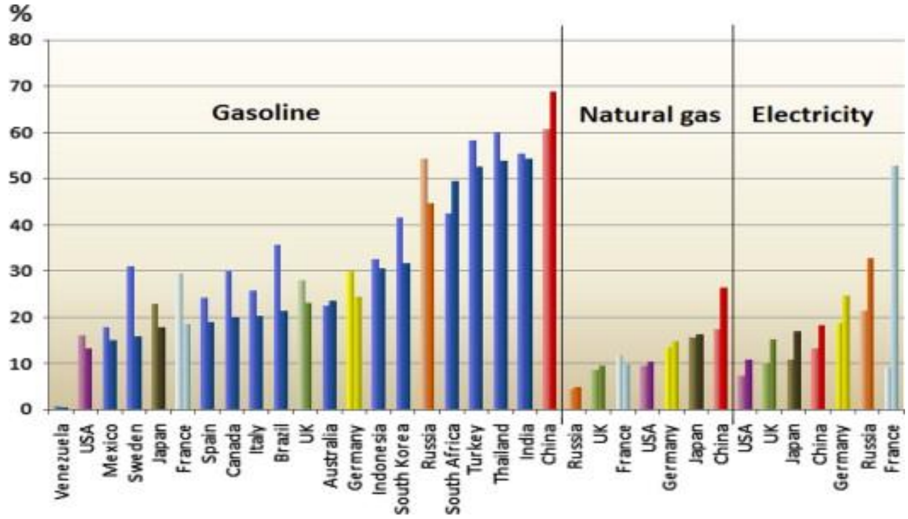

Figure 6. Estimates of direct and indirect rebound effects in different countries - income effects only
Source: Antal and van den Bergh [36].
Note: Average re-spending rebounds for energy (first columns) and carbon dioxide emissions (second columns) for three energy carriers (2009). Colors denote countries. Standard blue is used if data was only available for gasoline.

2.5.3 Secondary effects

The **energy market rebound** can be estimated from the own-price elasticities of supply and demand for the relevant energy commodity. As an illustration, a demand elasticity of -0.4 and a supply elasticity of +1.0 would lead to an energy market rebound effect of 30% [12]. If the demand elasticity was higher (e.g. -0.6) and/or the supply elasticity was lower (e.g. +0.2) the rebound effect would be larger (e.g. 75%). Although the energy market rebound is necessarily less than 100%, it may be significant in some cases and it will *add* to the direct and indirect effects described above.

The total rebound effect includes the direct, indirect, energy market and **other secondary effects**. While the first three may be estimated individually, other secondary effects are best estimated with the help of a macroeconomic model. However, nearly all modelling studies of rebound effects focus upon energy efficiency improvements by producers rather than consumers. Two exceptions are a study by Lecca *et al* [13] for the UK and a follow up study by Figus *et al.* [47] that model the impact of a costless improvement in the efficiency of all types of household energy use. Such studies incorporate a range of macroeconomic adjustments that may either amplify or reduce the rebound effect, and hence may lead to a higher or lower estimate of the rebound effect than studies that ignore those adjustments. However, it is common for such studies to produce *larger* estimates of rebound effects that are obtained from studies of direct effects alone. For example, both Lecca *et al* [13] and Figus *et al* [47] estimate a long-term, economy wide rebound effect that exceeds **50%**.

The results found by Lecca *et al* [13] and Figus *et al* [47-49] are not directly comparable to those in Tables 2 and 3 because the system boundary for potential energy savings is wider (e.g. economy wide rather than direct energy use) while the system boundary for actual energy savings is narrower (e.g. excluding the energy embodied in imported goods) [22]. This demonstrates the difficulty of comparing studies that use different definitions, metrics and/or system boundaries.

2.6 Summary

This section has described the sources of rebound effects from energy efficiency improvements, classified these effects, elaborated on their drivers and summarised the available evidence on their magnitude in different contexts. There are three main conclusions:

First, is misleading to talk about a single rebound effect. Instead, rebound effects are the net result of multiple mechanisms that sometimes reinforce and sometimes offset each other, and their magnitude varies widely between different situations and over time. While attention frequently focuses solely upon direct rebound effects, the indirect and secondary effects may be equally if not more important in many cases.

Second, from an economic perspective, the drivers of rebound effects are the same as the drivers of improved welfare, in that rebound effects reflect increased consumption of both energy and energy services relative to a counterfactual in which no adjustments occur. Hence, rebound effects should only be considered undesirable if the external costs of the increased energy consumption exceed the welfare benefits of the increased energy service consumption – along with those from the associated economy-wide adjustments. This in turn will depend upon the relative weight given to the different categories of costs and benefits.

Third, the empirical evidence suggests that rebound effects are frequently large and therefore should not be ignored in either energy modelling studies or policy appraisals. It is common to find estimates of direct or combined direct and indirect rebound effects that exceed 30%, especially for energy efficiency improvements by low-income groups - and the limited evidence from macroeconomic models suggest that economy-wide effects could be larger still. However, since it is rare to find estimates of rebound effects that exceed 100%, the majority of energy efficiency improvements should still lead to energy and emission savings.

3 Energy sufficiency, and its potential to mitigate rebound effects

3.1 Introduction

This section examines the concept of energy sufficiency and its relationship to rebound effects. We distinguish between *energy sufficiency actions* that focus on particular energy services, and broader attempts to live a more 'frugal' lifestyle through *downshifting*. The literature on energy sufficiency is relatively small, since the term is relatively new. However, energy sufficiency can be considered a particular type of *pro-environmental behaviour* (PEB) by households, and there is a large literature on the nature and determinants of such behaviours from within social psychology [1], as well as older literature on energy conservation [50]. This section therefore summarises some of the lessons from this broader literature, as well as suggesting ways in which energy sufficiency actions can offset the rebound effects from improved energy efficiency.

3.2 What is energy sufficiency

There is no single agreed definition of energy sufficiency (Box 1). Some authors consider energy sufficiency to be a particular *level* of energy service consumption that is consistent with human well-being and environmental limits. Others consider it to be a *reduction* in energy service consumption that has the effect of reducing the energy and environmental impacts of that consumption. We adopt the second interpretation in this report and define energy sufficiency actions as *reductions in the consumption of energy services, with the aim of reducing the energy use and environmental impacts associated with those services*.

One difficulty with this definition is the ambiguity of the term 'energy services'. At the household level, these are normally interpreted as services that require *direct* energy consumption for their provision, such as heating and lighting. But as discussed in Section 2, all goods and services are associated with *indirect* energy consumption along their supply chains and these may also be an appropriate target for sufficiency actions. For example, reduced consumption of meat and dairy products can have a major impact on total (i.e. direct plus indirect) household energy use and GHG emissions.

A further difficulty is that energy services are subjective, difficult to measure and have multiple attributes or dimensions. For example, the energy service of personal cleansing may be achieved with a 'monsoon' shower with a high water flow rate or with a smaller shower with a lower flow rate, but the subjective experience (and utility obtained) will be very different. Similarly, the energy service of thermal comfort will depend upon internal air temperature, but also upon radiant temperature, air velocity, humidity, activity levels, clothing, external temperature and social conditioning. The same energy service may also be delivered by different types of energy carrier (e.g. gas boiler or electric immersion heater) or with no or very little direct energy use at all (e.g. thermal comfort in a passive house). Hence, 'reducing' energy service consumption can mean different things depending upon how those services are defined, provided and measured. But we assume that the underlying objective is to reduce the environmental impacts associated with providing that service.

Box 1. Competing definitions of energy sufficiency

Energy sufficiency as a vision for the future

Energy sufficiency as an outcome can be thought of as an 'energy safe space' where everyone's basic needs are met and we enjoy a range of energy services. Access to these energy services is more equitable than it is today, and total energy demand is

no more than can be supplied within the limits of the environment's carrying capacity. To move towards this energy safe space, a number of things can happen:

- We can increase access to energy services for those whose basic needs are not currently met
- We can decrease energy demand whilst maintaining the same energy services through energy efficiency improvements
- We can decrease energy demand through energy sufficiency actions
- We can meet energy demand through more sustainable supply options, thus increasing the level of demand that can be met within environmental limits.

Energy sufficiency as an action

Energy sufficiency actions are actions that reduce energy demand, taking us towards this 'safe space' through changing the quantity or quality of the energy services demanded. These actions can be categorised in a number of ways, including changing/reducing the way we use an energy service; better sizing of energy using equipment to match people's needs; and choosing a different energy service.

Source: ECEEE

3.3 Examples of energy sufficiency

3.3.1 Energy sufficiency actions

Energy sufficiency actions can be carried out in many domains and may affect both direct and embodied energy use and emissions. While attention normally focuses upon direct energy use, embodied energy may form a larger proportion of a household's total 'energy footprint'.

The areas that offer the most potential for sufficiency actions are transport, heating, electricity use and food, [51-54]. For example, Benders et al [55] estimates that these four categories account for three quarters of Dutch household GHG emissions. However, food consumption accounts for a larger proportion of household GHG emissions than it does of household energy use - highlighting the importance of whether our focus is energy use, CO_2 emissions or GHG emissions.

A commonly advocated sufficiency action is to walk and cycle for short journeys – an option that also has significant health benefits. For example, some 22% of UK car trips are of less than two miles and account for ~3% of total car mileage and ~4.9% of total car emissions. An equally effective but less commonly advocated measure is to reduce flying. While aviation accounts for only ~5% of GHG emissions for an average UK household, the proportion is larger for high-income groups [56] and flying is one of the fastest-growing sources of emissions. For illustration, a return flight from London to New York generates approximately the same GHG emissions as heating an average EU home for a year [57]. But while offsetting aviation emissions is becoming increasingly popular, very few people appear prepared to restrict their flying [58].

Measures to reduce space heating demand can be very effective, as this category accounts for around 15% of household carbon emissions [59]. A commonly advocated measure is to reduce thermostat settings[8], or to turn off radiators in unoccupied rooms. For example, the UK Government suggests that 'Turning your thermostat down by 1°C could reduce CO_2 emissions and cut your fuel bills by up to 10 per cent' [60]. Since 1970, the average internal temperature of UK homes has risen from 13.7°C to 17.7°C during the winter period - a figure that is probably lower than in many other European countries [61]. Hence, although

[8] See, for example, http://www.energysavingtrust.org.uk/ .

millions of low income households continue to endure cold homes, a larger number of households enjoy relative thermal comfort and therefore should have scope for this type of sufficiency action.

A related but less frequently advocated measure is to limit the floor area of dwellings [62,63], as this is strongly correlated with heating and total energy use. However, income growth and changing demographics (e.g. more single person households) is creating strong pressures in the opposite direction, with average floor space per capita in the EU growing from $15.2m^2$ in 1990 to 18.6 m^2 in 2010 [64]. In contrast to this general trend, a reduction of floor area can be popular with older people, those wishing to reduce their ecological footprint or those seeking to reduce their housing costs [63]. Limiting the floor area of dwellings could be enforced through regulations or incentivised through taxation. However, such policies may be politically difficult owing to shrinking real incomes, growing inequality, and the fact low-income households spend a larger share of their income on housing than high income households.

The most commonly advocated sufficiency actions for electricity consumption are switching off standby appliances, switching off lighting in unoccupied rooms and washing clothes at lower temperatures - although each of these have a relatively modest impact on energy use and emissions [65]. Measures that conserve hot water can reduce both energy and water bills, as well as mitigating water shortages and reducing upstream energy consumption (e.g. for pumping) - although these upstream impacts are usually ignored.

With food consumption, the most popular sufficiency actions are to reduce food waste and shift away from meat and dairy products. An average UK household throws away one third of their food purchases [66], and there have been high profile campaigns to reduce this waste [67].[9] Reducing consumption of meat and dairy is commonly advocated on both environmental and health grounds and can have a very large impact on GHG emissions [65]. Options range from complete elimination of animal products to treating meat as the garnish rather than the centrepiece of a dish [68-70]. However, as discussed in Section 4, this type of sufficiency action may be particularly prone to rebound effects.

In classifying these actions, it is useful to make the following distinctions:

- **Restraint versus substitution:** Many sufficiency actions are associated with some form of restraint. For example, in the travel domain, an action based on restraint might start by asking: 'do I need to undertake this car journey'? True restraint would renounce the journey altogether. On the other hand, less energy-intensive substitutes might be considered, such as travelling by public transport, or replacing the journey with a video conference. Whether restraint or substitution involves loss of utility will depend upon a variety of factors, including trade-offs between different values and goals and the extent to which the relevant options are facilitated or obstructed by various technical, infrastructural, economic and social variables. For example, travelling by public transport in the UK is often less convenient, slower and more expensive than travelling by private car.
- **Voluntary versus enforced:** Although sufficiency actions such as walking and cycling involve individual choice, they may be enabled and encouraged by public policy. For example, walking and cycling can be encouraged by high-density land-use developments, dedicated cycle lanes and adequate cycle parking, whereas car travel can be discouraged by high parking charges and rising fuel taxes. It is misleading, therefore, to view sufficiency actions as solely an individual choice - they depend upon the broader infrastructural, technical, economic and social context and may be specifically incentivised or required by public policy. Prescriptive policies such as banning car use in city centres, or regulating floor areas tend to be unpopular and hence are rarely used - although there are exceptions such as the regulation in North Rhine-Westphalia that limits the maximum floor space (m^2/person) for people receiving housing allowances [71]. More common are information and education programmes, including energy

[9] See https://www.lovefoodhatewaste.com/

saving tips, feedback on energy consumption and social comparisons of energy consumption.

- **Individual versus collective**: Most sufficiency actions are taken by individuals, but people are more likely to adopt such actions if they feel social pressure to do so, if they act in collaboration with others (e.g. neighbourhood groups) or if they identify with a broader social trend or social movement [72]. For example, changes in social norms in areas such as recycling can encourage individual action which in turn can reinforce those changes in social norms. Similarly, something like the voluntary simplicity movement can help to normalise sufficiency lifestyles [73].

3.3.2 Downshifting

Most people taking sufficiency actions will continue to work and to earn as much as before – and simply spend their money in a different way. But an alternative approach is to voluntarily reduce household income - commonly known as *downshifting*. For example, people may choose to work less, take a pay cut and reduce their aggregate consumption. Downshifting is widely advocated as an effective means of alleviating time pressures and improving quality of life while at the same time reducing environmental impacts. For example, it has been estimated that if everyone in the UK were to downshift to the Minimum Income Standard as defined by Bradshaw *et al* [74], then average household GHG emissions would fall by 37% [75]. Importantly, the Minimum Income Standard is based on what the public think people need for an acceptable minimum standard of living: it includes "*more than just, food, clothes and shelter. It is about having what you need in order to have the opportunities and choices necessary to participate in society*" [76]

Evidence suggests that - after adjusting for household composition - the environmental impacts from household consumption are strongly correlated with household income [77-81]. For example, Nassen and Larsson [48] estimate the income elasticity of Swedish household GHG emissions to be 0.84, while Kerkhof *et al* [49] estimate a similar figure for Dutch households. As an illustration, Figure 6 shows the total GHG emissions for different income groups in the UK. This suggests that the wealthiest households have disproportionately high emissions, partly as a consequence of regular flying, greater car use, more dwelling space and higher appliance ownership [7]. This relationship implies that downshifting households are likely to reduce their GHG emissions, regardless of whether they take any specific actions to reduce their use of particular energy services (e.g. less flying). Hence, downshifting should have environmental benefits. If downshifting households choose to reduce their consumption of transport, heating and electricity by proportionately more than their consumption of other goods, those benefits may be amplified.

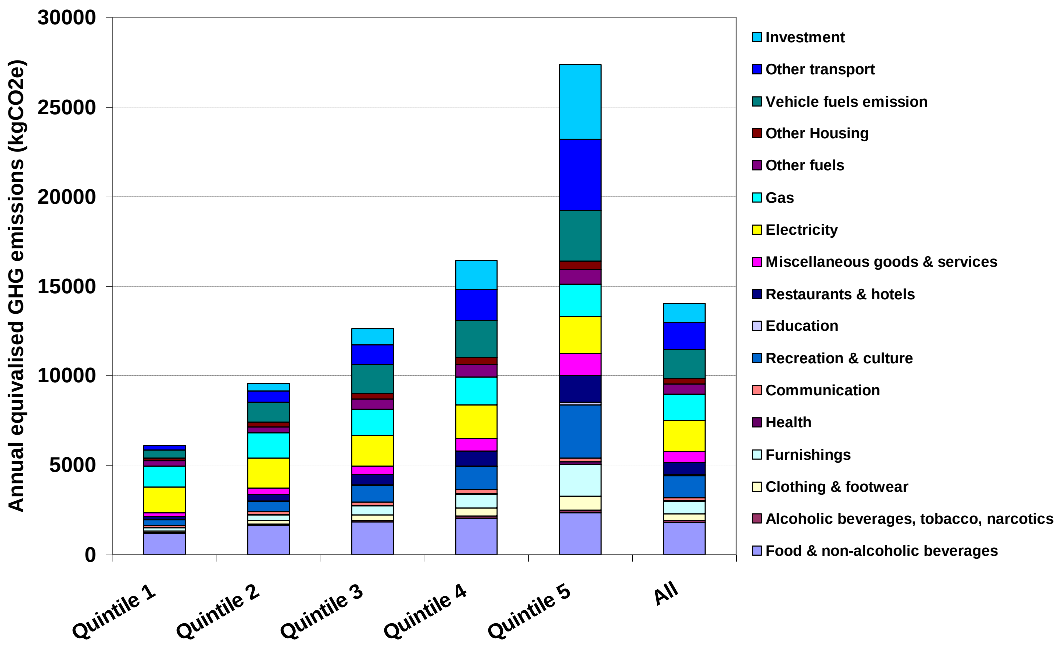

Figure 7. Estimates of GHG emissions for different income groups in the UK
Source: Chitnis et al Figure 4 [7].

To downshift, you must begin with a level of income that it is feasible to downshift from without jeopardising subjective (and possibly other types) of wellbeing. Hence, it is primarily an option for those who are relatively wealthy. But with increasing income inequality, rising housing costs, growing debt burdens and falling real wages [82], the proportion of people with the ability and/or inclination to downshift may be both relatively small and declining. A key problem is that many people are economically or psychologically "locked-in" to current consumption patterns and find it difficult to change. Relevant factors here include: land-use patterns and physical infrastructures that constrain choice in key areas (e.g. travel and heating); non-income related tax obligations; the rapid obsolescence of consumer goods, (creating a need for regular expenditure on replacement); the search for status through the acquisition of symbolic 'positional goods'; and the rapid adaptation of aspirations to higher income levels [83-86]. Downshifting, in other words, is difficult and may only be an option for a few. It also has broader macroeconomic consequences that influence both the feasibility of such changes and their environmental effects. These are discussed further in Section 4.

3.4 Using energy sufficiency to mitigate rebound effects

In some circumstances, sufficiency actions may mitigate the rebound effect from improved energy efficiency. We provide some illustrative examples below, looking first at mitigation of direct rebound effects and then indirect rebound effects.

As explained in Section 2, direct rebound effects occur when energy efficiency improvements reduce the effective price of energy services, thereby encouraging increased consumption of those services. Sufficiency actions may prevent this outcome, through an environmentally motivated decision to *limit* consumption of those services. For example, people may choose not to drive further than previously despite purchasing a more fuel-efficient vehicle. Such decisions become easier when energy service consumption already exceeds a certain level – with further consumption providing little additional utility and/or the sufficiency action reflecting a normative choice that this level of consumption is 'enough'.

In some circumstances, these decisions could be facilitated or enforced through technical or policy intervention. For example, the 2.38 million households in England that suffer from

fuel poverty [87][10] are eligible for government subsidies to improve the thermal efficiency of their dwellings. When such measures are carried out, it is common for the benefits to be taken in the form of warmer homes rather than energy savings. An energy sufficiency strategy to complement such measures could be to constrain indoor temperatures to, say, 20°C by installing temperature-limiting thermostatic controls in tandem with energy efficiency measure. To the extent that households would have increased internal temperatures beyond 20°C in the absence of the controls [89], such a measure would reduce the direct rebound effect whilst at the same time allowing an 'adequate' level of thermal comfort. Similar measures could be applied in high-income households, whose average pre-retrofit temperatures are already around 20°C, thereby allowing the direct rebound effect to be eliminated altogether.

Thus energy sufficiency strategies could mitigate the direct rebound effect. The additional savings on heating bills would be spent on other goods and services, thereby creating an indirect rebound effect. But the total energy and carbon savings are likely to be larger than in the absence of such controls. It is worth noting, however, that there are only a few energy services where this type of measure would be technically feasible. And since such interventions would severely restrict individual choice (e.g. preventing households from enjoying higher internal temperatures), they seem unlikely to be politically feasible.

Indirect rebound effects are more challenging to address. This is because the provision of all goods and services involves energy use and emissions at different stages of their supply chains. Thus any re-spending of the cost savings from energy efficiency improvements will necessarily lead to *some* indirect rebound effect. However, the size of that effect can vary widely depending upon the particular pattern of re-spending. To minimise the indirect rebound effect, it would be necessary to target re-spending on goods and services that have a relatively low energy or emission intensity. Options include goods and services that are relatively expensive (e.g. fine artwork, organic food) and those that are inherently low impact (e.g. evening classes). Other options include spending the cost savings on additional energy efficiency improvements, on renewable energy investments or on carbon offsets. The last of these could be a particularly effective option: for example, if a small proportion of the cost savings from efficiency improvements were used to purchase and retire EU ETS carbon allowances, the avoided carbon emissions would greatly exceed those from increased consumption of the energy service. In other words, the emission savings could be amplified rather than reduced.

Downshifting should reduce aggregate energy consumption, but may not reduce the direct and indirect rebound effect from energy efficiency improvements. Indeed, since rebound effects tend to be larger for low-income groups [8], it is possible that they will be also larger in downshifted households. But again, these rebound effects could be minimised if the household chose to restrict consumption of relevant energy service(s) and to re-spend any cost savings on goods and services that are less energy/emission-intensive. This in turn would require households have a good understanding of the relative energy/emission intensity of different goods and services - which appears unlikely to be the case.

3.5 Psychological drivers of energy sufficiency

3.5.1 Energy sufficiency as pro-environmental behaviour

In our definition, energy sufficiency is motivated by environmental concerns and is therefore a form of *pro-environmental behaviour*. This section summarises some of the lessons from the psychological literature on pro-environmental behaviour - much of which focuses on behaviours relevant to energy consumption.

Whereas energy efficiency is associated with "doing more with less", energy sufficiency is associated with "enough". The concept therefore has a strong normative dimension. The term energy sufficiency is rarely used in environmental psychology, primarily because it is

[10] The UK government considers a household to be in fuel poverty if: a) they have above average 'energy requirements' (the national median level); and b) were they to spend that amount, they would be left with a residual income below the official poverty line. [88]

considered inappropriate for researchers and policy makers to make judgements about what is enough. However, it is widely acknowledged that there is a need to reduce the environmental impact of household consumption. As such, much of the environmental psychology literature focuses on Western households and aims to understand the variables that influence people's willingness to voluntarily adopt behaviours that are beneficial for the environment.

In environmental psychology, the term pro-environmental behaviour is sometimes defined as: 'behaviour that harms the environment as little as possible, or even benefits the environment' [90]. This definition includes behaviour that is beneficial for the environment but is not necessarily (or exclusively) motivated by environmental goals. Studies using this definition often focus upon the *outcomes* of behaviour such as energy use (via meter readings: [91]) or waste production (via bin weighing [92]) rather than the *causes* of those outcomes. Hence, they reflect environmental impacts but do not identify the specific behaviours underlying those impacts.

The more common definition of pro-environmental behaviour is "behaviour that consciously seeks to minimize the negative impact of one's actions on the natural and built world" [93]. This definition excludes behaviours motivated by other goals as well as those that are environmentally damaging [90]. Studies typically focus on specific behaviours such as recycling [94], transportation mode choice [94,95] or political activism. Pro-environmental behaviour may also be labelled environmentally friendly behaviour [96], ecological behaviour or conservation behaviour [97].

Since most research in this area focuses on intentions rather than outcomes, it can be difficult to determine the contribution of psychological variables to actual environmental impacts [98]. First, behaviour measures frequently rely on self-reports, which are sensitive to response bias and may not reliably reflect actual behaviour [99-101]. Second, behaviour measures are rarely weighted by their relative environmental impact and the most environmentally significant behaviours can be overlooked. Indeed, someone may be labelled pro-environmental because they adopt several relevant behaviours, even if those behaviours have limited impact. Third, people typically have limited knowledge of the relative environmental impact of different behaviours, with the result that 'good' intentions may lead them to adopt 'bad' behaviours. For example, Gatersleben, Steg and Vlek [98] found that people were unaware that their (direct and indirect) energy use for home heating and holidays was much larger than that for clothes washing and home entertainment.

Much of the social psychological literature focuses on combinations of behaviours. Typically, people are asked to indicate how frequently they adopt a number of different behaviours which are then analysed to identify behavioural 'clusters'. Such analyses tend to find clusters associated with waste avoidance, energy use, transport and political activism [96,102-104], suggesting that people are more likely to behave consistently within these clusters than between them. The number and type of clusters identified will depend upon the behaviours included, but since there are no standard measures of pro-environmental behaviour it can be difficult to compare the findings of different studies.

3.5.2 Determinants of pro-environmental behaviour

The social psychological determinants of pro-environmental behaviour are commonly classified into two categories: those associated with rational 'cost-benefit' decision-making and those driven by environmental values. The literature employs a number of behavioural models, including the Theory of Planned Behaviour [105] which is an individual cost-benefit model and the Norm Activation Model which is a normative model. There are also models that combine the two approaches, including the Value Belief Norm model [106].

There is a vast body of literature examining the variables that influence pro-environmental behaviour. Most of this work is correlational and examines the variables most strongly associated with a range of self-reported behaviours. Experimental studies are less common and tend to examine the influence of one or more specific predictors on one or more specific outcome measures. The latter are more likely to include measures of actual, rather than intended or self-reported behaviour.

Individual cost-benefit studies

Individual cost-benefit models assume that behaviours are influenced by perceptions of likely outcomes and the value people attach to those outcomes. Relevant outcomes may include both individual instrumental costs and benefits (such as financial costs and benefits, time and effort) and social rewards and punishments (being accepted, praised or reprimanded by others).

The Theory of Planned Behaviour (TPB) [105] suggests that planned or reasoned behaviour is influenced by: a) attitudes towards that behaviour (expectations of outcomes and valuations of those outcomes); b) perceptions of behavioural control (expectations about how easy or difficult it is to do); and c) social norms (expectations of what other people think is the appropriate or right thing to do). The model has been shown to be useful in explaining a range of pro-environmental behaviours including water saving [107], recycling [108] and reduced car use [109]. But many studies add additional variables to the model, making it difficult to draw conclusions about its validity. In their meta- analysis of 23 transport studies, Gardner and Abraham [109] found strong support for the predictive utility of the TPB, but also found that habits (i.e. non-reasoned behaviour) played an important role.

Two types of social norms are distinguished in the literature: *descriptive* norms (perceptions of what other people do) and *injunctive* norms (perceptions of what other people see as the right thing to do) [110]. Several studies have demonstrated that giving people information about what other people do can be useful in promoting pro-environmental behaviours such as energy conservation and towel reuse in hotels [91,111]. However, if people are motivated to act in line with others, they may also increase their energy use if they realise they are using less energy than others - another type of rebound effect. However, adding an injunctive message that conveys social approval or disapproval can eliminate this effect [91]. The desire to gain social approval has also been shown to promote conspicuous ecological consumption where those who were made more concerned about their status were shown to be more likely to choose green over non-green consumer products, but only if the green alternative was more expensive [112].

Normative studies

The majority of studies examining pro-environmental behaviour treat such behaviour as primarily morally motivated. The underlying idea is that such behaviour tends to be costly to individuals here and now, but beneficial for the environment, for distant others and for future generations. Therefore such behaviour cannot be motivated by selfish concerns but needs to be treated as moral behaviour. Most of this work is based on the Norm Activation Model [113] which was developed to explain why people sometimes act selflessly for the benefit of others. The model proposes that altruistic behaviour is associated with people's awareness of the consequences of their behaviour for others and their ascription of responsibility for those consequences. These two factors can activate a personal norm which can result in altruistic action. A range of studies have demonstrated that such a personal norm (often measured as guilt) is associated with pro-environmental behaviour. Many of these studies incorporate personal norms into the theory of planned behaviour to improve its predictive value - thereby linking the cost benefit and normative dimensions [114-117]. A meta-analysis conducted in 2007 [118] confirmed the importance of both self-interested and altruistic motives. The analyses demonstrated that, in line with the TPB, the relationship between each of the psycho-social variables on behaviour was mediated by intention. Intention explained 27% of the variance in actual behaviour, and this in turn, was significantly predicted by attitude, behavioural control and personal moral norms (explaining 52% of the variance).

Schwartz & Bilsky [101] propose that human values can be usefully described along two dimensions: self-enhancement versus self-transcendence and conservatism versus openness to change. The first dimension distinguishes people who are more concerned about aspects such as power, control and hedonism (self-enhancement) from those more concerned about altruism, protecting the environment and a world at peace (self-transcendence). There is considerable evidence that those with more self-transcendent

values report stronger environmental concern and behaviour [119-123]. Materialism, on the other hand has been associated with stronger self-enhancement values and less environmental concern and behaviour [124].

Identities also influence behaviour because people are motivated to act in line with how they see themselves and strive to achieve a positive, coherent sense of self [125]. Environmental or green identities have been shown to be strong predictors of pro-environmental behaviour over and above other variables such as attitudes and norms [126-130].

3.5.3 Intervention studies of pro-environmental behaviour

There is a large literature that evaluates interventions to encourage pro-environmental behaviour, with the majority of these focusing upon information interventions. These rely on the assumption that people weigh up the costs and benefits of their behaviours, so the provision of information on costs and benefits can encourage behavioural change.

However, a range of other interventions have also been shown to be effective in promoting pro-environmental behaviours. Abrahamse*, et al.* [131] reviewed 38 studies and showed that, although information interventions tend to result in changes in knowledge and attitudes, this does not always translate into behavioural change. They also found that the positive effects of rewards tended to be short lived. Frequent feedback was also shown to have potential for behaviour change, but studies rarely examined the long-term persistence of those changes. In a more recent meta-analysis Osbaldiston and Schott [132] reviewed intervention studies of a broader range of pro-environmental behaviours. They concluded that the most effective interventions were linked to cognitive dissonance (making people aware of the discrepancy between their behaviours and their attitudes), goal setting, social modelling (providing some sort of demonstration) and regular prompts. In addition they suggested that different interventions may be effective for different behaviours: for example, a combination of treatments can help promote recycling, setting goals is beneficial for reducing gasoline use and social modelling works best for home energy conservation.

A meta-analysis of information interventions on energy use [133] found that such interventions reduced electricity consumption by 7.4%, on average. Tailored information such as home energy audits were more effective than historical or peer comparison feedback, but pecuniary feedback and incentives could result in increased rather than reduced energy use. Some more recent studies have confirmed these findings and there is an increasing amount of research that suggests that financial appeals and incentives may not only be ineffective in promoting pro-environmental behaviour but can even be counter-productive - perhaps by crowding out altruistic motives [134-137].

Many intervention studies focus on small respondent numbers and are insufficiently linked to motivation theories - thereby making it difficult to draw clear conclusions about the key variables motivating pro-environmental behaviour. People do not appear to behave consistently pro-environmentally across different domains and the same motivational goal (doing something beneficial for the environment) may motivate different people to undertake different behaviours. However, based on the evidence to date it can be concluded that *environmental concerns* are important for understanding and promoting pro-environmental behaviour (although environmental concern does not always translate into action) and that giving people *tailored information* on what they can do to reduce their environmental impact, together with *frequent feedback* on their actions, especially *comparative feedback* (e.g., how close they are to achieving their energy conservation goal or how much they recycle compared to neighbours) can assist that behaviour.

3.6 Summary

This section has examined the nature and drivers of energy sufficiency, drawing in particular on the literature on pro-environmental behaviour. There are five main conclusions:

First, there is no single definition of energy sufficiency, but it is useful to distinguish between energy sufficiency as an *action* relevant to a *single* energy service, and energy

sufficiency as a *goal* relevant to *all* energy services. While the latter would have more far-reaching impacts, it is harder to defend, operationalise and achieve.

Second, for energy sufficiency as an action, it is useful to distinguish between actions involving restraint and those involving substitution. Care must also be taken with the definition of energy services, since these need not involve direct energy consumption. While most energy sufficiency actions focus upon highly visible energy services, such as car travel, the embodied energy/emissions associated with other goods and services can form a large share of the total energy/emission footprint of a household. In addition, some commonly advocated actions such as turning lights off in unoccupied rooms may have only a marginal impact on energy use and emissions, while less popular measures such as reducing flying may have a much greater impact.

Third, for energy sufficiency as a goal, both the total amount of household expenditure and the targeting of that expenditure become important. Since total environmental impacts are strongly correlated with household income, *downshifting* to a lower level of income can potentially reduce a household's total environmental impact. But since various physical, economic and social factors obstruct downshifting, the proportion of people with the ability to downshift may be relatively small - and the proportion of people with both the ability and inclination may be smaller still.

Fourth, to reduce the rebound effects from energy efficiency improvements, households must limit consumption of the relevant energy service(s) (minimising the direct rebound effect) and re-spend the cost savings on less energy-intensive goods and services (minimising the indirect rebound effect). In other words, they must complement the energy efficiency improvement with informed sufficiency actions across all areas of consumption. This requires strong motivation, a desire for consistency and a good understanding of the relative environmental impacts of different goods and services.

Fifth, the social psychological literature suggests that energy sufficiency actions are primarily motivated by environmental values, but also by self-interest. Awareness of the environmental impact of different actions tends to be limited, with the result that people may not prioritise the most effective actions. Relevant enablers of sufficiency actions include tailored information and frequent and comparative feedback, but financial incentives may in some circumstances be counter-productive.

4 Can energy sufficiency create rebound effects?

4.1 Introduction

The previous two sections have summarised the nature and magnitude of rebound effects from energy efficiency improvements, introduced the concept of energy sufficiency and investigated how sufficiency actions could potentially mitigate rebound effects. But it is essential to recognise that sufficiency actions have rebound effects *of their own* that can offset the energy and emission savings from those actions. Building upon the concepts introduced in earlier sections, this section summarises the mechanisms underlying these 'sufficiency rebound effects', the evidence that is available on their magnitude following different types of sufficiency action and the conditions under which they may be larger or smaller. The following section discusses the rebound effects from sufficiency actions, while Section 4.3 discusses the rebound effects from downshifting. Section 4.4 examines the additional psychological factors that may generate sufficiency rebounds - commonly grouped under the heading of negative spill-overs.

4.2 Rebound effects from sufficiency actions

4.2.1 Drivers of rebound effects from sufficiency actions

As discussed in Section 3, sufficiency actions involve voluntary reductions in the consumption of energy services, such as turning lights off in unoccupied rooms (less lighting), cycling to work rather than taking the car (less car travel) or wearing clothes for longer (less clothes washing). In contrast to improving energy efficiency, sufficiency actions do not reduce the effective price of the energy service, do not require investment in durable goods and do not entail capital or operating costs. But they will lead to savings in energy costs - and in some cases may also lead to savings in other types of costs, such as car maintenance, replacement light bulbs and detergents.

Sufficiency actions can be analysed using the simple microeconomic framework introduced in Section 2. This disaggregated the behavioural response to an energy efficiency improvement into an *income* effect and a *substitution* effect. Unlike efficiency improvements, sufficiency actions should not be associated with any substitution effects, since the effective price of the relevant energy service (e.g. lighting) remains unchanged. However, they will be associated with income effects since the savings in energy costs will be available for re-spending on other goods and services. Hence, *sufficiency actions will lead to indirect rebound effects*.

The savings in energy costs may be treated in a similar manner to an increase in real income - with the qualification that the additional income is not spent on the relevant energy service. If consumer preferences remain unchanged, the pattern of re-spending will be similar to historic patterns and can therefore be estimated from econometric evidence on the income elasticities of different categories of goods and services (i.e. the percentage increase in consumption following a 1% increase in household income).[11] Normal goods will be associated with a positive indirect rebound effect and inferior goods will be associated with a negative indirect rebound effect (Annex 1).[12] The overall effect will depend upon the distribution of re-spending between different goods and services, together with the relative energy/emission intensity of those goods and services. Note that the re-spending may be

[11] The correct approach to estimating the pattern of re-spending uses the *marginal* propensity to consume different goods and services (as indicated by income elasticities) rather than the *average* propensity (as indicated by the current distribution of expenditure). So for example, overseas holidays may form a small proportion of current expenditure, but may form a larger proportion of marginal (i.e. additional) expenditure. UK data suggests that, for households with a median level of income, marginal expenditure is less emission-intensive than average expenditure.

[12] Consumption of normal goods increases with income (positive income elasticity) while consumption of inferior goods decreases with income (negative income elasticity). An example of the latter could be 'value' food products that are replaced with high quality products as income increases.

associated with both direct energy use/emissions (e.g. spending the cost savings from more efficient heating on more lighting) and with embodied energy use/emissions (e.g. spending the cost savings on more ready-meals). In contrast to energy efficiency improvements, the use of income elasticities should provide an unbiased estimate of the sufficiency rebound effect. This is because, in the absence of any price changes, there is no substitution effect.

This approach assumes that the sufficiency action is confined to the relevant energy service and that preferences otherwise remain unchanged. But in practice, preferences may well change, especially if (as we assume) the sufficiency action is motivated by environmental concerns. For example, it is possible that individuals will reduce their consumption of other environmentally damaging goods and services ('spill-over'). However, is also possible that individuals will increase consumption of those goods and services if they consider that the sufficiency action gives them a 'moral license' to do so. These contrasting outcomes are discussed in Section 4.4.

Given the large differences in the energy/emission intensity of different categories of goods and services, the size of the sufficiency rebound effect will be highly sensitive to the particular pattern of re-spending. So for example, goods with low energy/emissions intensity may nevertheless contribute a large indirect rebound effect if they constitute a large share of total re-spending. To illustrate, Figure 8 compares the GHG-intensity of expenditure ($tCO2_e$/£), the share of total expenditure (%) and the share of total GHG emissions (%) of 17 categories of goods and services for an average UK household [8]. This shows that spending £1 on electricity and gas creates up to ten times more GHG emissions than spending £1 on other commodities. But the emission intensity of energy commodities is offset by their small share of total expenditure, with the result that direct energy consumption only accounts for 41% of an average UK household's 'GHG footprint', split between 29% domestic energy (i.e. electricity, gas and other fuels) and 12% vehicle fuels.

Figure 8 aggregates household expenditure into only 17 categories which understates the variation in energy and emission intensity between individual products. For example, some food products (e.g. beef) are far more emission-intensive than others (e.g. potatoes) and products that are similar in terms of GHG emissions can vary widely in price (e.g. farmed versus wild salmon). In addition, some products may be relatively emission-intensive (e.g. beef owing to methane emissions from livestock) but less energy-intensive, and vice versa. As a result of these variations, the size of the indirect rebound effect will depend upon the distribution of re-spending both within and between the expenditure categories in **Error! Reference source not found.** as well as upon the metric used.

The rebound effect may also be larger for sufficiency actions that reduce other costs. For example, if a household gives up car travel altogether, they will save on maintenance, insurance, and vehicle tax as well as on road fuels. These additional cost savings will also be available for re-spending, thereby amplifying the rebound effect. Put another way, *the greater the economic benefit from the sufficiency action, the larger the indirect rebound effect* [40]. In addition, since expenditure on car insurance and maintenance is less energy and emission-intensive than expenditure on road fuels, the rebound effect associated with the former will be proportionately larger than that associated with the latter.

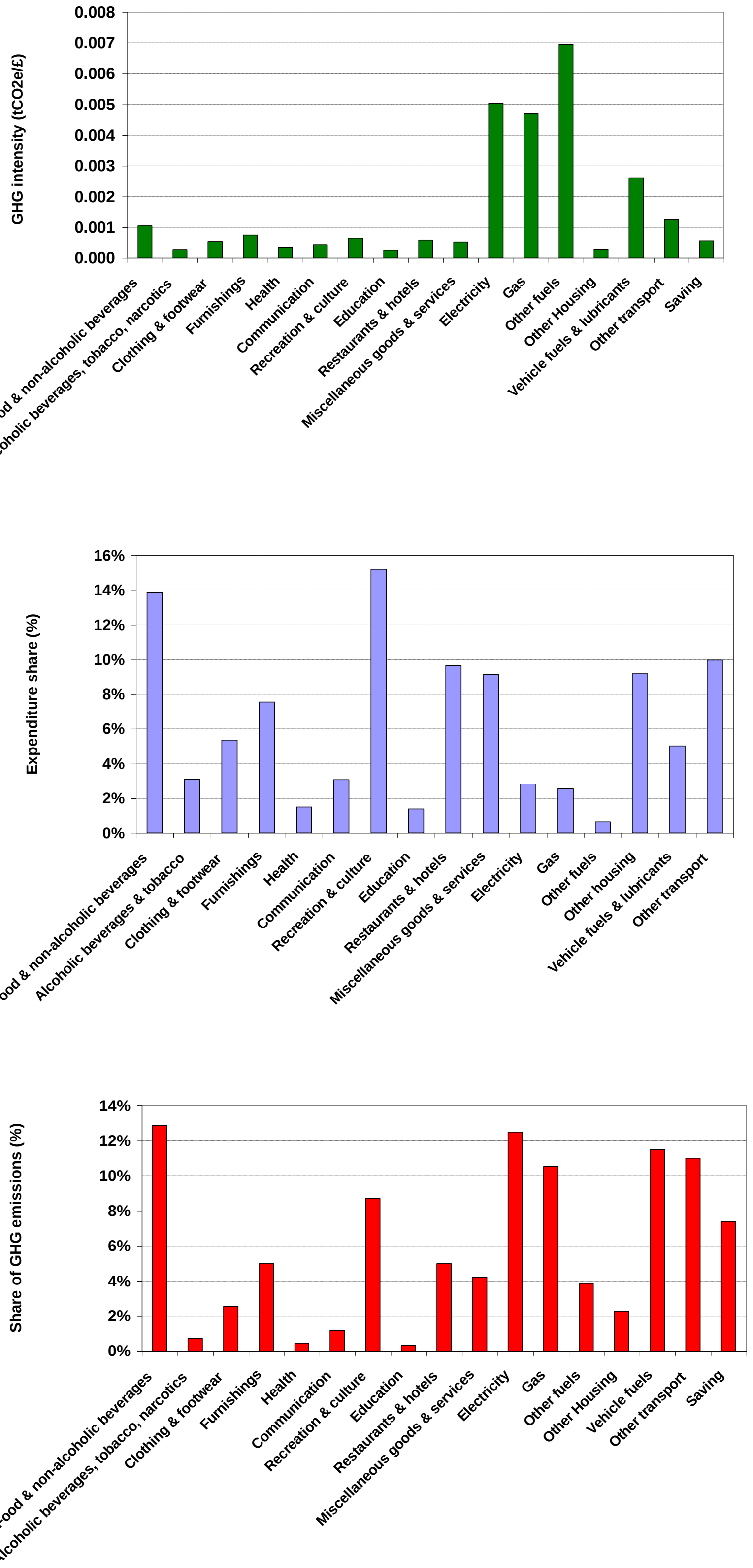

Figure 8. Estimates of the GHG-intensity of expenditure, share of total expenditure and share of total GHG emissions by category for an average UK household
Source: Druckman et al [9].
Note: Estimates include both direct and embodied emissions and allow for the variation of product taxation between categories. The latter contributes to the comparatively low emission intensity of vehicle fuels compared to electricity and gas.

Re-spending the cost savings from sufficiency actions may also lead to various *secondary effects*. In particular, sufficiency actions, if widely adopted, will lower energy prices that will

in turn encourage increased energy consumption (see **Error! Reference source not found.**). Effectively, the choice of *some* people to *reduce* their energy (service) consumption will trigger a reduction in energy prices that will in turn encourage *other* people to *increase* their energy (service) consumption [138]. Similar impacts may occur in markets for goods that are complements to the relevant energy carrier, but there may be offsetting impacts in markets for goods that are substitutes to the energy carrier.

Depending upon both the number of people adopting sufficiency actions and the structure of the relevant markets, these effects may occur at the local, national, regional or global level. Since energy is a necessity, the fall in energy prices should benefit low-income groups. But there may be offsetting price increases for substitute goods, and any reductions in energy prices will also benefit high-income groups (e.g. making it cheaper for the wealthy to heat their swimming pools). Moreover, if the energy carrier is used for multiple energy services (e.g. electricity), it is possible that the same people who chose to reduce consumption of one energy service (e.g. electric heating) will be encouraged to increase their consumption of another energy service (e.g. lighting) to take advantage of the lower energy prices. This last outcome may be of limited importance if the relevant energy services are price-inelastic, and may be mitigated if the energy sufficiency actions are comprehensive - that is, consumers restrict their use of a wide range of energy services.

4.2.2 Estimates of indirect rebound effects from sufficiency actions

There is a small but growing body of literature that estimates the magnitude of indirect rebound effects from sufficiency actions, but none that estimate secondary effects. Most studies employ estimates of the income elasticity and energy/emission intensity of different categories of goods and services (see Annex 1 and 2), but they vary widely in their methodological approach, level of disaggregation of household expenditure and choice of sufficiency actions. The most prominent studies are summarised below.

A pioneering study in this area is Alfredsson [139], who investigates a mix of energy efficiency improvements and sufficiency actions in food, travel and utilities (heating and electricity) by Swedish households. Alfredsson estimates that a shift towards ‘green’ diets would reduce food-related energy consumption by 5% and food expenditure by 15%, but re-spending the cost savings would lead to rebound effect for carbon emissions of ~200%. This high rebound results from the fact that food products have a lower GHG-intensity of expenditure than domestic energy and transport fuels, and a proportion of the re-spending is directed towards the latter. The green travel and green housing scenarios are estimated to have rebound effects of 15% and 20% respectively, while combining all three scenarios leads to a rebound effect of 35%. The latter involves a comprehensive set of actions, but only reduces energy use by 8% and carbon emissions by 13%.[13]

Carlsson-Kanyama *et al* [140] use a similar approach to Alfredsson, but find that a shift to ‘green’ food consumption reduces overall energy consumption. This result follows in part from their assumption that ‘green’ diets are more expensive (owing to the higher cost of locally produced organic food), thereby leading to a negative rebound effect.[14] The importance of variations in the price and quantity of individual products is also emphasised by Girod and de Haan [141], who find that Swiss households with low GHG emissions spend more on high-quality goods and services. But while shifting towards higher price goods will reduce the rebound effect, the aggregate impact will also depend upon the relative emission intensity of high and low price goods. For example, Thiesen et al. [142] compare two Danish cheese products - one with ‘traditional’ packaging and the second with ‘convenience’ packaging. Since the latter is more expensive, purchasers of the traditional product save money that can be spent upon other goods and services. Using life-cycle analysis, Thiesen et al. [142] estimate that the traditional cheese is three times more emission-intensive, but this increases to seven times when the re-spending is allowed for.

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[13] Alfredsson also observes that: “….reductions in…CO_2 emissions achieved by adopting an overall ‘green’’ consumption pattern are outpaced, almost as soon as they are implemented, by increases in CO_2 emissions as a result of increasing consumption…”.

[14] Purchase of relatively expensive organic foods meant that households had less to spend on other goods and services, so the emissions associated with consuming those other goods and services were correspondingly reduced

Lenzen and Dey [143] also explore the impacts of a 'green diet', involving a 30% reduction in food expenditure. This achieves significant reductions in food-related energy consumption and GHG emissions, but once re-spending is allowed for, total energy consumption increases by 4-7%. Lenzen and Dey estimate a rebound effect of 112-123% for energy consumption, but only 45-50% for GHGs owing to the large reductions in methane emissions from livestock. These contrasting results highlight the importance of the choice of rebound metric.

The Lenzen and Day study has the drawback that the 'green' diet has a lower calorific content than a traditional diet. Grabs [144] overcomes this problem by modelling a switch to a vegetarian diet [145] while holding calorific content constant. This shift reduces food-related energy consumption by 16% and food-related GHG emissions by 20%, but the re-spending leads to rebound effect of 95-104% for energy and 49-56%% for GHGs. Grabs also finds that rebound effects are larger for low income groups.

Murray [40] models a mix of energy efficiency improvements and sufficiency actions by Australian households. For households with median income, reducing vehicle use leads to a rebound effect of 15-17%, while reducing electricity use leads to a rebound effect of 4.5-6.5%. One reason rebound effects are larger for reducing vehicle use is that additional savings are made on car maintenance and other costs. Murray also finds that rebound effects are larger for low income groups.

Druckman *et al* [9] model three sufficiency actions by UK households, namely: reducing internal temperatures by 1°C; eliminating food waste; and replacing car travel with walking or cycling for trips less than two miles. Re-spending the associated cost savings is estimated to lead to rebound effects of 7%, 51% and 25% respectively, or 34% for the three actions combined. In the case of the latter, spending all the cost savings on the least GHG intensive category leads to a rebound of 12% - which may be considered the minimum possible. However, Druckman *et al* use only 17 expenditure categories and most categories are likely to contain products with lower emission intensity. Nevertheless, re-spending *all* the cost savings on low-impact products seems unrealistic.

Chitnis *et al* [8] model the same actions to Druckman *et al* [9], and find that rebound effects are modest (12-17%) for reducing internal temperatures, larger (25-40%) for reducing vehicle use and very large (66-106%) for reducing food waste. These differences are explained by the GHG-intensity of expenditure (in £/tCO_2e) on each of these categories (which is high for heating fuels, lower for vehicle fuels and lower still for food products) relative to the average GHG-intensity of re-spending. Differences in the GHG-intensity of expenditure on each category are in turn influenced by the level of taxation on each category - which is low for heating fuels in the UK but very high for vehicle fuels. Chitnis *et al* also find that rebound effects are larger for low-income groups (Figure 9) because they spend a greater proportion of their cost savings on necessities such as food and heating that tend to be relatively GHG-intensive.

Finally, Bjelle *et al* [42] model a comprehensive set of 34 actions that Norwegian households could take to lower their GHG footprint - including both common energy sufficiency actions such as reducing car travel, and less common actions such as increasing the lifetime of household goods and reducing plastic use. They model average, marginal and 'green' re-spending patterns, where the latter involves avoiding re-spending on the most emission-intensive products. The study is notable both for the level of detail in the analysis, and the comparison of marginal and green re-spending. With the former, the average rebound effect across all the actions is 59%, while with the latter it reduces to 40%. The results in this study are influenced by the low GHG-intensity of electricity in Norway (owing to the large share of hydro), but this does not explain their comparatively low estimate for the rebound effect from food-related measures (16%).

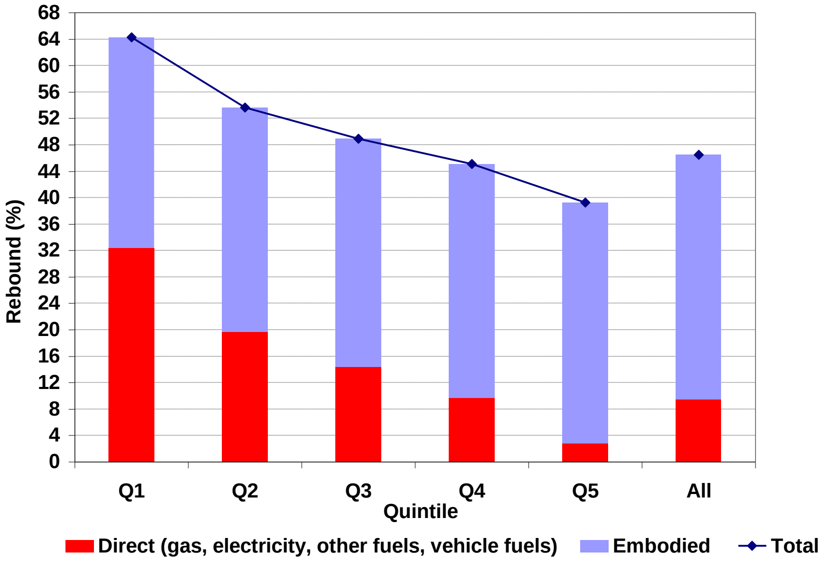

Figure 9. Estimates of the indirect rebound effect from reducing vehicle use for different income groups in the UK
Source: Chitnis et al [8].

Table 4 summarises and compares the results from these different studies. The key lesson is that indirect rebound effects appear larger for actions affecting transport fuels than for those affecting heating or electricity, and very large for actions affecting food consumption. These differences can be explained by the relative energy/emission intensity of these commodity groups (Figure 8), together with the extent to which the sufficiency actions affect other costs, such as car maintenance. The studies also suggest that indirect rebound effects are larger for low-income groups and vary with the metric used (i.e. energy, carbon or GHG's). Factors such as the emission intensity of electricity generation and the level of commodity taxation (especially for transport fuels) can have a significant influence on the magnitude of rebound effects, and these vary widely from one country to another.

One notable finding is that *taxing energy commodities leads to larger indirect rebound effects*, since it amplifies the cost savings from sufficiency actions [8]. But higher taxation also provides a financial incentive to reduce direct energy consumption and may also encourage some sufficiency actions. The net effect of taxation on energy use and emissions will depend upon the own-price elasticity of the relevant energy commodities and the energy/emission intensity of expenditure on energy commodities relative to that of other goods and services. But it will also depend upon various macroeconomic adjustments, as well as how the taxation revenues are spent. Neither of these are captured by the above studies, but both could be of considerable importance.

Table 4. Estimates of the indirect rebound effects from sufficiency actions

Author	Region	No. of categories	Measures	Metric	Rebound effect (%)
Alfreddson [38]	Sweden	300	Food, travel, utilities	CO_2	Food: 200% Travel: 35% Utilities: 20%
Lenzen and Day [37]	Australia	150	Food	Energy & GHGs	Energy: 112-123% GHGs: 45-50%
Grabs [144]	Sweden	117	Food	Energy & GHGs	Energy: 95-104% GHGs: 49-56%
Murray [40]	Australia	36	Transport, electricity	GHGs	Transport: 15-17% Electricity: 4.5-6.5%

Author	Region	No. of categories	Measures	Metric	Rebound effect (%)
Druckman *et al* [9]	UK	17	Heating, transport food	GHGs	Heating: 7% Transport: 25% Food: 51%
Chitnis *et al* [8]	UK	20	Heating, transport, food	GHGs	Heating: 12-17% Transport: 25-40% Food: 66-106%
Bjelle *et al* [42]	Norway	12	Transport, utilities, food, waste, other	GHGs	Transport: 83% Heating: 35% Clothing: 89% Food: 16% Furniture: -51% Paper: 190% Plastic: 95%

4.3 Rebound effects from downshifting

The studies reviewed above all assume that nominal income is unaffected by the sufficiency action. In other words, individuals are assumed to continue to work and earn as much as before. But as discussed in Section 3, an alternative approach to energy sufficiency is **downshifting -** defined here as a voluntary reduction in income. At the individual level, downshifting may occur through moving to a lower paid (but more satisfying) job, or through reducing working hours. It could also be achieved at the collective level through government regulation on working hours, but here the impacts on income are less straightforward. The primary attraction of downshifting is more leisure time and improved quality of life [86,146,147]. But as argued in Section 3, only a small number of households may have both the ability and inclination to make such a move.

Downshifting should have environmental benefits since the reduction in income will necessitate a reduction in consumption. As noted in Section 3, total (i.e. direct plus embodied) household energy use and emissions are strongly correlated with (equivalised) household income. For example, Nassen and Larsson [148] estimate the income elasticity of Swedish household GHG emissions to be 0.84, while Kerkhof *et al* [149] estimate a similar figure for Dutch households.

But while this correlation suggests that downshifting households will reduce their energy use and emissions, it does not mean that they will achieve a *proportional* reduction. Although downshifting does not lead to an indirect rebound effect (since the income effect is negative), there are other reasons why the environmental benefits of downshifting may be less than anticipated. These include: a) changes in the *pattern* of household expenditure; b) changes in *labour productivity* and employment; and c) *secondary effects*, including energy market effects. Each is briefly discussed below.

4.3.1 Changes in the pattern of household expenditure

If consumer preferences remain unchanged, the change in spending patterns from downshifting may be estimated from income elasticities (Annex 1). With lower income, consumption of normal goods should fall and consumption of inferior goods should increase. The impact on energy use and emissions will depend upon the distribution of foregone spending between different goods and services, together with the relative energy/emission intensity of those goods and services. The reduction in energy use will only be proportional to the reduction in income if the energy intensity of foregone consumption is equal to the energy intensity of 'pre-downshift' consumption - in other words, if the income elasticity of energy intensity is unity. In practice, this elasticity may be greater or less than unity, and if it is less than minus 1, reductions in expenditure will be associated with an *increase* in energy use.

In practice, low income households tend to spend a larger proportion of their budget on 'necessities' such as food and drink that are relatively energy intensive [8]. As a result, the

income elasticity of energy intensity is likely to be less than unity. Hence if downshifting households follow typical expenditure patterns, the reduction in energy use will be proportionately *less* than the reduction in income.[15] However, households could also choose to modify their expenditure patterns, and to prioritise additional sufficiency actions (e.g. giving up vacations abroad). In these circumstances, the energy savings from downshifting could be amplified by the additional energy savings from these additional sufficiency actions.

A key driver of changes in expenditure patterns could be changes in *time use*. If downshifting households reduce their working hours, they will have more leisure time and may become less concerned about saving time and more concerned about saving money and energy [140]. For example, they may choose to travel by public transport rather than by taxi, to cook at home rather than buy a ready-meal, or to spend time walking and gardening rather than commuting. If so, the reduction in energy use could be proportionately more than the reduction in income (i.e. the income elasticity of energy intensity could be greater than unity). But it is also possible that households will choose more energy-intensive leisure activities, such as long-distance driving and vacations abroad. The feasibility of these different choices will depend upon the new level of income. For example, if the household remains on a relatively high income even after downshifting, they may be able to take more vacations abroad. And since air travel is particularly energy-intensive, this could lead to an overall increase in energy use.

4.3.2 Changes in labour productivity and employment

A further complication is that reductions in working time may not necessarily be associated with reductions in income at either the individual or the aggregate level. To understand this, it is useful to decompose the per capita GDP of a country (€/person) as the product of the employment rate (%), average annual worktime per worker (hours) and average labour productivity (€/hour) [150]:

$$\frac{GDP}{Population} = \frac{Workers}{Population} * \frac{Work\_time}{Workers} * \frac{GDP}{Work\_time} \qquad 2$$

If employment and productivity are unaffected by changes in average worktime, widespread adoption of downshifting would reduce per capita GDP. However, the relationship should really be expressed as an equation since the variables are endogenous (i.e. they depend upon each other). Reductions in average worktime could be associated with, or enabled by, increases in labour productivity, which in turn could lead to an increase in hourly wages. Similarly, downshifting through job sharing could increase the employment rate, thereby offsetting the reduction in average working hours among the working population. Adjustments such as these would offset the reduction in per capita GDP and aggregate consumption, and thereby offset some of the environmental benefits of downshifting. As with the paradox of thrift, what works at the individual level may not necessarily work at the level of the economy as a whole.

4.3.3 Secondary effects

Downshifting will also lead to other secondary effects at the level of the macro-economy. In particular, lower energy use by downshifting consumers will reduce energy prices and thereby encourage increased energy use by other consumers, both in the same country and abroad [138]. As noted in Section 2, this energy market rebound can be significant and will offset the energy and emission savings from downshifting.

In addition, large-scale downshifting may have detrimental effects on aggregate social welfare. Although downshifting households may benefit from increased leisure time, their reduced spending will mean less income for producers, less economic activity and slower economic growth. This in turn could mean reduced profits, more bankruptcies, higher

[15] Similar conclusions follow from cross-sectional comparisons of the energy and emission intensity of different countries.

unemployment, more foreclosures, lower tax revenues, cuts in public services and increased poverty. Hence, any benefits from increased leisure time and reduced energy use and emissions need to be balanced against these potential reductions in economic activity and consequent impacts on welfare. Options are available to mitigate these negative impacts, but they require collective rather than individual action.

4.3.4 Estimates of rebound effects from downshifting

The potential impact of reduced income on energy use and emissions can be estimated in a similar manner to indirect rebound effects: namely, by combining estimates of the income elasticity and energy/emission intensity of different categories of goods and services. But these studies do not capture the additional effect of changes in time use. For the latter, is necessary to include measures of time use within the econometric model. Building upon the pioneering work of Schor [145], there is a small but growing literature in this area that uses either macro-data on average working times in different countries, or micro-data on time use patterns for individual households. Four examples are summarised below.

Rosnick and Weisbrot [9] estimate primary energy consumption as a function of per capita GDP, employment rate (%), average work hours and other variables for 48 countries in 2003. They estimate an elasticity of energy consumption with respect to work hours of 1.33 - suggesting that reductions in working time are associated with a *more* than proportionate decrease in energy consumption (holding other variables constant). But a relationship estimated from cross-sectional data in a single year cannot necessarily be applied to worktime reductions in particular countries.

Knight *et al* [146] estimate similar models for carbon emissions for 29 high-income countries over the period 1970 to 2007. They estimate a similar elasticity to Rosnick and Weisbrot, but when they control for per capita GDP they find the coefficient on work hours to be insignificant - thereby suggesting that the reduction in carbon emissions derives primarily from the reduction in income rather than changes in time use. However, if changes in income are the primary driver, Knight *et al*'s estimate of income elasticity appears unusually high [81,149,151]. Also, incomes were growing during most of this time period, and the estimated elasticities may not hold for reductions in income.

Nassen and Larsen [148] take a micro approach, combining expenditure and time use data for Swedish households. Their results suggest that a decrease in working time by 1% is associated with a 0.7% reduction in energy use and a 0.8% reduction in GHG emissions. They further find that reductions in income are the primary cause, with shifts in time use accounting for only one tenth of the total. Nassen and Larsen's income elasticity estimates are closer to the consensus in the literature.

Shao and Shen [150] extend the above studies by investigating the potential for non-linear relationships between working time and environmental impacts [150]. Using data from EU 15 countries over the period 1970-2010, they employ a 'threshold auto regression' technique to test for turning points in this relationship. Their results suggest reduced working hours may be associated with *increased* environmental impact in some high-income countries, such as Germany and Denmark – contradicting the conclusions of the other studies. One possible explanation for this result is that, beyond a certain level of income, additional leisure time is used for relatively energy and carbon intensive activities - such as more travel.

In sum, the literature has yet to reach a consensus on the relationship between working time and energy use/emissions. While most studies suggest that reduced working time is associated with reductions in energy use and emissions, they disagree on whether these benefits are proportionately larger or smaller than the reduction in income. In addition, it seems likely that the relationship depends upon both the initial level of income and the initial number of working hours.

Table 5. Estimates of elasticities of energy use or emissions with respect to changes in working time

Study	Metric	Elasticity	Method and data
Rosnick and Weisbrot [9]	Energy	1.33	Panel data, 48 countries, 2003-2005
Knight *et al* [146]	Carbon	1.30	Panel data, 29 OECD countries, 1970 2007
Fitzgerald *et al* [61]	Energy	0.32	Panel data, 52 countries, 1990-2008
Nassen *et al* [64]	Energy GHG	0.83 0.85	Household expenditure and time-used data, Sweden 2006
Nassen and Larsen [148]	Energy GHGs	0.70 0.80	Household expenditure and time-use data, Sweden 2006

4.4 Psychological drivers of sufficiency rebounds

Deeper insight into the potential for sufficiency rebounds may be obtained by moving beyond these economic models and considering some of the broader psychological factors that influence sufficiency-related decisions. The key issue here is how sufficiency actions in one area (e.g. cycling to work) influence decisions in other areas (e.g. electricity use, vacations abroad).

The social psychology literature has long recognised that the adoption of a pro-environmental behaviour in one area can make the adoption of a pro-environmental behaviour in another area *more* likely. However, in some circumstances it can make the adoption of that behaviour *less* likely. These contrasting outcomes are termed *positive spill-over* and *negative spill-over* respectively - although other terms are also used [3,101]. Negative spill-over may be considered a form of rebound effect that offsets the original energy and emission savings, while positive spill-over acts to increase those savings. Or in other words, negative spill-over is a positive rebound effect while positive spill-over is a negative rebound effect.

Positive and negative spill-overs may be associated with both energy efficiency improvements and sufficiency actions (Table 1). But the econometric techniques used to estimate indirect rebound effects operate at too aggregate a level to capture such effects - which are likely to vary widely from one household to another. Instead, spill-overs can be better explored through experimental and survey methods. Clearly, much depends upon: first, whether a particular efficiency improvement or sufficiency action leads to positive or negative spill-over; and second, whether the induced behaviour is more or less energy/emission-intensive than the original behaviour. For example, recycling achieves only limited GHG emission reductions, whereas giving up car use achieves 5 to 25 times greater emission reductions [8]. Hence, if engaging in recycling encourages less car use (positive spill-over) the GHG benefits of recycling will be greatly enhanced (a negative sufficiency rebound). Conversely, if engaging in recycling encourages more car use (negative spill-over) the outcome will be higher GHG emissions (a positive sufficiency rebound exceeding 100%).

There are a number of psychological models that explain why and how the adoption of a particular behaviour may influence subsequent behaviours. These typically emphasise the *motivations* for undertaking the initial behaviour, together with the type of social *feedback* people receive about that behaviour (e.g., being praised for being environmentally friendly or for being frugal). Evidence suggests that positive spill-over is more likely when people have strong *pro-environmental values* and when feedback on the original behaviour reinforces those environmental values, for instance by receiving praise for being environmentally friendly. However, if the original behaviour is motivated more by economic incentives, negative spill-over is more likely to occur. Evidence also suggests that the *financial or other costs* (e.g. time, inconvenience) of the original behaviour play an important role. Specifically, costly pro-environmental behaviour is associated with a strengthening of one's moral self-identity and thereby positive spill-over, while low cost

behaviour is associated with 'moral licensing' of subsequent behaviour and thereby negative spill-over [136].

Both energy efficiency improvements and sufficiency actions may lead to cost savings and hence financial gains. However, there is evidence that financial incentives are not only less effective in encouraging pro-environmental behaviour, but can even discourage that behaviour [134-137]. One explanation of this observation is that people are balancing competing goals. Steg and colleagues suggest that people are guided by three overarching goals: hedonic goals (short term pleasure), moral goals (doing the right thing) and gain goals (control, power, wealth, fame) [152-154]. They also suggest that the salience of these goals depends upon the context. For instance, hedonic goals may be more salient on a night out whereas gain goals may be more salient when applying for a job. The theory suggests that moral goals tend to be the weakest and need support to become salient [152-154]. Moreover, when hedonic and gain goals are strengthened, moral goals are weakened further. This means that promoting pro-environmental behaviour by focusing on hedonic goals (e.g. this action will bring you pleasure) or gain goals (e.g. this action will make you look successful) could weaken or undermine moral goals (e.g. this action will reduce your carbon footprint). Since financial incentives strengthen hedonic and gain goals, they could potentially undermine moral goals. For example, Bolderdijk *et al* [134] show that behaviour with both economic and environmental benefits can be encouraged by interventions that highlight the environmental benefits, but not by interventions that highlight the financial benefits. Similarly, Schwarz *et al* [100] find that highlighting the financial benefits of an energy-saving program reduces people's willingness to enrol in that program and results in less consideration of the environmental benefits of the program.

Jacobsen*, et al.* [155] find evidence of negative spill-over in a US green power program. Participation in the program was voluntary, and the households who 'bought into' the program at the minimum level were found to subsequently increase their electricity consumption. However, households who bought in at a higher level did not significantly change their electricity consumption. One explanation for this could be that households who have a higher level of environmental commitment are less likely to exhibit negative spill-over. A large investment indicates that people care about the environmental impact of electricity use, which then (positively) spills over into other behaviour.

As noted in Section 3, most research in this area assumes that pro-environmental behaviour is motivated by environmental values. Such behaviour may be costly to the individual (e.g. in time, money or inconvenience) but is nevertheless perceived as the 'right' thing to do. The behaviour could therefore be primarily driven by *guilt* [90,126] and it is guilt that underlies the concept of *moral licencing*. The idea here is that doing something 'good' makes people feel less guilty about subsequently doing something 'bad' [156]. Hence, adopting a particular moral behaviour makes people less likely to adopt subsequent moral behaviours.

Moral licencing has been demonstrated in consumer, social, health and other domains where people have been shown to be more likely to adopt a selfish or self-indulgent behaviour after having adopted a moral or good behaviour. For example, Tiefenbeck *et al* [157] find that feedback on water consumption lowered water consumption but increased energy consumption (although Truelove *et al* [3] question the statistical significance of this result). Mazar and Zhong [158] find that mere exposure to green products activates social responsibility but actually purchasing those products results in moral licensing.[16] Miller *et al* [159] find that focus group participants do not feel a need to be environmentally friendly on vacation if they engage in pro-environmental behaviours at home [159]. Similarly Klöckner *et al* [160] find that Norwegian electric car owners both drive more than conventional car owners and report less obligation to reduce car use.

Overall, there is strong evidence that moral licensing is prevalent in a variety of domains, including many that are relevant to energy and climate change [136,161-165]. However, there is also evidence that moral licensing is not inevitable and is less likely when initial

[16] Their study involved students playing an on-line shopping game in either a green store or a conventional store and subsequently playing a game in which they could win money. They found that students buying in green store were more likely to cheat and steal in the subsequent game.

behaviours are costly and when they reinforce moral and environmental values and identities [101,126,166]. A relevant factor here is the perceived need for *consistency* in moral behaviour [125]. Many studies have demonstrated how reminders of morality can strengthen a person's moral identity and encourage future moral behaviour. For example, Van der Werff *et al* [166] show how reminders of past 'good' behaviour can increase adoption of subsequent good behaviour, especially when the past behaviour was costly and/or provided a strong signal that the person was pro-environmental. Similarly, Gneezy *et al* [136] find that costly behaviours are more likely to lead to positive spill-overs. Moreover, adopting a pro-environmental behaviour to avoid paying a fine can also strengthen a moral or environmental self-identity as was shown in a study evaluating the introduction of the plastic bag charge in Wales [167]. In addition there is evidence that making someone adopt a pro-environmental behaviour reinforces their pro-environmental identity – effectively a 'foot in the door' technique [131].

In sum, the social psychology literature provides a wealth of insights and evidence that can help explain when sufficiency rebounds are likely to be larger or smaller, and help identify ways in which they may be minimised. Key insights include: a) sufficiency actions may encourage 'spill-over' behaviour in other areas that may either increase or offset the original energy and emission savings; b) positive spill-over is more likely to occur when people have strong pro-environmental values and when the sufficiency action entails significant financial or other costs (e.g. inconvenience); and c) negative spill-over is more likely to occur when people have weaker environmental values and feel less need for consistency in their behaviours, and/or when the initial action involves little cost and is partly motivated by financial gain. The last observation is particularly important for policy, as many attempts to encourage sufficiency actions focus upon cost savings from those actions. But *not only does re-spending the cost savings create an indirect rebound effect, emphasising those cost savings could encourage moral licensing and thereby amplify that rebound effect*.

4.5 Summary

This section has examined the rebound effects from sufficiency actions. Although these have received comparatively little attention in the literature, they may in some cases be large. There are five main conclusions:

First, re-spending the cost savings from sufficiency actions leads to indirect rebound effects. The size of these will depend upon the energy/emission intensity of the re-spending relative to that of the original energy service. Sufficiency actions that save on other types of cost (e.g. car maintenance) will have larger rebound effects. Sufficiency actions may also lower energy prices, thereby encouraging other people to increase their energy consumption.

Second, evidence suggests that indirect rebound effects are modest (e.g. <10%) for sufficiency actions affecting electricity use and heating, larger (e.g. 20-40%) for those affecting transport fuels and very large (e.g. 60-100%) for those affecting food products. Shifting to a vegetarian diet, for example, could potentially increase global GHG emissions. Rebound effects tend to be larger for low-income groups than for high income groups within a country and for energy carriers that are subject to energy/carbon taxation. However, the precise figures are sensitive to the context and metric used and may vary widely from one country to another. Also, none of the estimates to date incorporate secondary effects.

Third, downshifting reduces aggregate consumption and hence the environmental impact of that consumption. But downshifting may also encourage changes in expenditure and time-use patterns that offset at least some of the energy and emission savings. Downshifting will also lower energy prices and have complex impacts on the broader macro-economy. Hence, the reduction in energy use and emissions from downshifting may not be proportional to the reduction in income.

Fourth, if people engage in sufficiency actions in one area they may consider they have 'moral licence' to be less environmentally responsible in other areas (negative spill-over). Such outcomes are more likely to occur when people have weak environmental values and when the initial action involves little cost and is partly motivated by financial gain. Moral

licensing is therefore an additional, non-economic source of rebound – and one that could be amplified by policies that emphasise the cost savings from sufficiency actions. However, engaging in sufficiency actions may also encourage people to be *more* environmentally responsible in other areas (positive spill-over). This appears likely to occur when people have strong pro-environmental values and when the sufficiency action entails significant financial or other costs. The balance between positive and negative spill-over may therefore be critical to the effectiveness of any sufficiency actions.

5 Summary and implications

This report has examined the relationship between energy sufficiency and rebound effects - focusing solely upon actions by consumers. The key insight is that while energy sufficiency actions may mitigate rebound effects, rebound effects may undermine energy sufficiency actions.

Below we summarise the main conclusions from the analysis and highlight some relevant policy implications.

5.1 Rebound effects from energy efficiency

- It is misleading to talk about a single rebound effect. Instead, rebound effects are the net result of multiple mechanisms that sometimes reinforce and sometimes offset each other, and their magnitude varies widely between different situations and over time. While attention frequently focuses solely upon direct rebound effects, the indirect and secondary effects may be equally if not more important in many cases.
- The drivers of rebound effects are the same as the drivers of improved welfare. Rebound effects are associated with increased consumption of both energy and energy services. They should only be considered undesirable if the external costs of the former exceed the welfare benefits of the latter.
- The evidence suggests that rebound effects are frequently large and therefore should not be ignored. It is common to find estimates of direct or combined direct and indirect rebound effects that exceed 30%, especially for energy efficiency improvements by low-income groups - and the limited evidence from macroeconomic models suggest that economy-wide effects could be larger still. However, since it is rare to find rebound effects exceeding 100%, the majority of energy efficiency improvements should still lead to energy and emission savings.

5.2 Drivers of energy sufficiency

- There is no single definition of energy sufficiency, but it is useful to distinguish between energy sufficiency as an action relevant to a single energy service, and energy sufficiency as a goal relevant to all energy services. While the latter would have more far-reaching impacts, it is much harder to operationalise and achieve.
- For energy sufficiency as an action, it is useful to distinguish between actions involving restraint (e.g. lowering thermostats) and those involving substitution (e.g. cycling rather than driving). While most actions focus upon highly visible energy services, such as car travel, the embodied energy/emissions associated with other goods and services form a large proportion of the total environmental impact of household consumption.
- For energy sufficiency as a goal, both the total amount of household expenditure and the targeting of that expenditure become important. Since total environmental impacts are strongly correlated with household income, downshifting to a lower level of income can potentially reduce a household's total environmental impact. But since various physical, economic and social factors obstruct downshifting, the number of people with the ability and/or inclination to downshift may be relatively small.
- To reduce the rebound effects from energy efficiency improvements, households must limit consumption of the relevant energy service(s) and re-spend the cost savings on non-energy-intensive goods and services. In other words, they must complement the energy efficiency improvement with informed sufficiency actions across multiple areas of consumption. This requires motivation and a good understanding of the environmental impacts of different actions.
- The psychological literature suggests that energy sufficiency actions are primarily motivated by environmental values, but also by self-interest. Awareness of the environmental impact of different actions tends to be limited, with the result that people may not prioritise the most effective actions. Relevant enablers of sufficiency actions

include tailored information and frequent and comparative feedback, but financial incentives may in some circumstances be counter-productive.

- While environmental values are correlated with specific pro-environmental behaviours, there is little evidence that they are correlated with total environmental impact, once socioeconomic variables such as household income have been controlled for. However, this lack of evidence is partly due to the challenge of simultaneously measuring the environmental values and total environmental impacts of individual households.

5.3 Rebound effects from energy sufficiency

- Re-spending the cost savings from sufficiency actions leads to indirect rebound effects. The size of these will depend upon the energy/emission intensity of the re-spending relative to that of the original energy service. Sufficiency actions that save on other types of cost (e.g. car maintenance) will have larger rebound effects. Sufficiency actions will also lower energy prices, thereby encouraging other people to increase their energy consumption.
- Evidence suggests that indirect rebound effects are modest (e.g. <10%) for sufficiency actions affecting electricity use and heating, larger (e.g. 20-40%) for those affecting transport fuels and very large (e.g. 60-100%) for those affecting food products. Shifting to a vegetarian diet, for example, could potentially increase global GHG emissions due to rebound effects. Rebound effects are larger for low-income groups and for energy carriers that are subject to energy/carbon taxation. However, the precise figures are sensitive to the context and metric used.
- Downshifting encourages shifts in expenditure and time-use patterns that offset at least some of the energy and emission savings from lower overall expenditure. Downshifting may also lower energy prices and have complex impacts on the broader macro-economy. Hence, downshifting may not achieve a proportionate reduction in energy use and emissions.
- If people engage in sufficiency actions in one area they may consider they have ‘moral licence’ to be less environmentally responsible in other areas. Such outcomes are more likely to occur when people have weak environmental values and when the initial action involves little cost and is partly motivated by financial gain. Moral licensing may be considered an additional, non-economic source of rebound.
- Emphasising the cost savings from sufficiency actions may potentially amplify the rebound effect by encouraging moral licensing.

5.4 Policy implications

Our results demonstrate the importance of accounting for rebound effects within appraisals of both energy efficiency and energy sufficiency policies. At present, this tends to be the exception rather than the rule. While some policy appraisals allow for direct rebound effects (e.g. for insulation measures), indirect and secondary effects are almost invariably overlooked. This may be partly because a significant proportion of the relevant effects occur outside the host country, and partly because the size of these effects remains uncertain. But failure to take account of these effects will lead to an overestimate of global emission savings, in some cases by a significant amount.

The most effective way to mitigate rebound effects is likely to be through some form of carbon pricing. In the EU, this is provided by the EU ETS and a variety of other national initiatives (e.g. the UK carbon price floor), but prices are low and there is inconsistency of coverage between sectors and countries. Ideally, a carbon pricing scheme should incentivise efficiency improvements and sufficiency actions, while at the same time mitigating any associated rebound effects and protecting low-income groups. This may be best achieved by economy-wide schemes with revenue recycling that incorporate border carbon adjustments to capture the emissions embodied in traded goods. However, while financial incentives encourage energy efficiency improvements they may not be the best way to encourage energy sufficiency actions. Also, since expenditure by low-income households is

comparatively energy and emission-intensive, carbon pricing of household energy use would be regressive without carefully targeted compensation. Such a scheme would also fail to capture the bulk of emissions from high-income households, the majority of which are embodied in the goods and services they consume.

The case for economy-wide carbon pricing is reinforced by our observation that taxing energy commodities leads to larger rebound effects. High taxation means that a unit reduction in consumption leads to greater cost savings and the re-spending of those cost savings leads to a larger rebound effect. The paradox is that higher taxation also provides a stronger incentive to reduce consumption of energy commodities and hence to reduce the associated direct emissions. However, this problem would be mitigated if the carbon pricing were economy-wide, since this would raise the price of all goods and services in proportion to their carbon intensity, and thereby lower the carbon intensity of expenditure (in tCO_2e/£) of those goods and services – and hence of re-spending. It would also provide incentives to reduce both household emissions and the GHG emissions associated with manufactured goods. The net result should be to reduce the size of the indirect rebound effect. But to be fully effective such a scheme would also need to capture the emissions embodied in internationally traded goods. While mechanisms such as border carbon adjustments are feasible, they present considerable legal and practical challenges and may capture only small proportion of the relevant emissions. Ultimately, this form of 'carbon leakage' can only be adequately addressed through the development of international climate agreements that cover a significant proportion of global emissions.

Cap and trade schemes such as the EU ETS have the advantage of focusing upon the desired ends (limiting carbon emissions) rather than problematic means to achieve those ends. But the partial coverage of existing schemes is problematic. For example, as electricity systems decarbonise, those efficiency improvements and sufficiency actions that affect electricity use will save fewer and fewer emissions. But they will continue to save money. And if that money is re-spent on goods and services that are not covered by a cap and trade scheme, overall emissions can increase [7].

Although carbon pricing incentivises both improved energy efficiency and energy sufficiency, various other barriers tend to obstruct such actions [168]. Political economy factors have also made it difficult to either expand the scope or increase the stringency of carbon pricing schemes [169]. Hence, carbon pricing can only form part of the policy mix and must be complemented by energy efficiency regulations, information programmes and other measures. For *regulations* to be effective, they need to anticipate the possibility of rebound effects. For example, if standards on the energy efficiency of refrigerators are specified on a kWh/m^3 basis, it is possible for a large, energy efficient refrigerator to use more energy than a small, inefficient refrigerator. But if the standards for large fridges are tighter than those for small fridges, this problem can be avoided. Similarly, for *information programmes* to be effective, they need to be informed by research in environmental psychology. For example, emphasising the monetary benefits from sufficiency actions may be counter-productive, since this may encourage moral licensing. These broader considerations on policy design are covered in detail in the other reports in this series.

6 Annex 1 – Formulae for estimating rebound effects

This Annex develops some mathematical expressions for estimating direct and indirect rebound effects in a partial equilibrium framework (secondary effects are ignored). The resulting formulae allow rebound effects to be estimated from the results of econometric studies.

Let q_S represent the quantity demanded of a particular energy service *s* by a household (e.g. lumens of lighting), q_e the quantity of energy (*e*) required to provide that energy service (e.g. kWh of electricity), $\varepsilon = q_S / q_e$ the energy efficiency of the relevant equipment (e.g. lumens/kWh) and p_e the unit price of the relevant energy carrier (e.g. £/kWh). Then $p_S = p_e / \varepsilon$ is the 'energy cost' of the energy service (e.g. £/lumen). In addition, let x represent total household expenditure (e.g. in £), q_i the quantity of good or service i purchased by the household ($i = 1,\ldots N$) and p_i the unit price of good i. Other goods are assumed to include other energy services (e.g. heating). Total household expenditure is then:

$$x = p_s q_s + \sum_{i=1,2\ldots N} p_i q_i \qquad 3$$

Let R_D represent the direct rebound effect following a marginal improvement in energy efficiency and R_I the indirect rebound effect. The 'total' rebound effect (R_T) is given by the sum of the two: $R_T = R_D + R_I$. With these definitions, Chitnis and Sorrell [46] derive the following expression for the total rebound effect:

$$R_T = -\eta_{q_s, p_s} - \sum_{i(i \neq s)} \psi_i \eta_{q_i, p_s} \qquad 4$$

Where η_{q_s, p_s} is the own-price elasticity of demand for the energy service ($\partial \ln q_S / \partial \ln p_S$), η_{q_i, p_s} is the elasticity of demand for good *i* with respect to the price of the energy service ($\partial \ln q_i / \partial \ln p_s$) and ψ_i is the ratio of energy or emissions associated with expenditure on good *i* to those associated with expenditure on the energy service:

$$\psi_i = \frac{u_i w_i}{u_s w_s} \qquad 5$$

Where w_i is the share of commodity *i* in total household expenditure ($w_i = (p_i q_i) / x$), u_i is the energy or emission intensity of that expenditure (in kWh/£ or tCO_2/£) and w_S and u_S are the corresponding values of these variables for the energy service. The energy and emission intensities include both direct and embodied emissions.

6.1 Direct rebound

The first term in Equation 4 is the direct rebound effect (R_D):

$$R_D = -\eta_{q_s,p_s} \qquad 6$$

Hence, the actual saving in energy consumption will only be equal to the anticipated saving when this elasticity is zero. If the demand for the energy service is inelastic ($0 < \eta_{q_s,p_s} < 1$), improvements in energy efficiency should reduce energy consumption. But if the demand for the energy service is elastic ($\eta_{q_s,p_s} > 1$), improvements in energy efficiency will increase energy consumption (backfire).

The direct rebound effect may be decomposed into a *substitution* effect and an *income* effect using the Slutsky equation:

$$\eta_{q_s,p_s} = \tilde{\eta}_{q_s,p_s} - w_s \eta_{q_s,x} \qquad 7$$

Where: $\eta_{q_s,x}$ is the expenditure (or income) elasticity of the energy service ($\partial \ln q_s / \partial \ln x)$); and $\tilde{\eta}_{q_s,p_s}$ is the *compensated* own-price elasticity of demand for the energy service, holding utility constant ($\partial \ln q_s / \partial \ln p_s)|_{U=-constant}$). The second term in Equation 7 is the income effect ($-w_s \eta_{q_s,x}$) and the first term is the substitution effect ($\tilde{\eta}_{q_s,p_s}$). These may either offset or reinforce one another (**Error! Reference source not found.**). If estimates of η_{q_s,p_s} are also available the direct rebound effect can be derived, and if estimates of $\eta_{q_s,x}$ are also available it can be decomposed. In contrast, if only estimates of $\eta_{q_s,x}$ are available, then only the income effect can be obtained. This will provide a biased estimate of the direct rebound effect since substitution effects will be overlooked.

Table 6. Determinants of the sign of the direct rebound effect

Nature of energy service	Sign of expenditure elasticity	Sign of compensated own-price elasticity	Relative size of income and substitution effects	Sign of uncompensated own-price elasticity	Sign of direct rebound effect
Normal good	$\eta_{q_s,x} > 0$	$\tilde{\eta}_{q_s,p_s} < 0$	Not relevant	$\eta_{q_s,p_s} < 0$	$R_D > 0$
Inferior good	$\eta_{q_s,x} < 0$	$\tilde{\eta}_{q_s,p_s} < 0$	$\lvert\tilde{\eta}_{q_s,p_s}\rvert > \lvert w_s \eta_{q_s,x}\rvert$	$\eta_{q_s,p_s} < 0$	$R_D > 0$
Giffen good	$\eta_{q_s,x} < 0$	$\tilde{\eta}_{q_s,p_s} < 0$	$\lvert\tilde{\eta}_{q_s,p_s}\rvert < \lvert w_s \eta_{q_s,x}\rvert$	$\eta_{q_s,p_s} > 0$	$R_D < 0$

6.2 Indirect rebound

The second term in Equation 4 is the indirect rebound effect (R_I):

$$R_I = -\sum_{i(i \neq s)} \psi_i \eta_{q_i,p_s} \qquad 8$$

Hence, the indirect rebound effect associated with commodity *i* depends upon the elasticity of demand for commodity *i* with respect to the energy cost of the energy service (η_{q_i,p_s}) and the energy (or emissions) associated with expenditure on that commodity ($u_i\, w_i$) relative to that associated with the energy service ($u_S\, w_S$). Consumption of commodities that are complements (substitutes) to the energy service will increase (reduce) following the energy efficiency improvement. The impact of this on emissions will depend upon the emissions associated with expenditure on the commodity relative to that associated with expenditure on the energy service (ψ_i).

The overall indirect rebound effect is given by the sum of the individual effects for each commodity. Equation 8 demonstrates that commodities with a small cross-price elasticity may nevertheless contribute a large indirect rebound effect if they are relatively energy/emission-intensive and/or have a large expenditure share (and vice versa).

The indirect rebound effect may also be decomposed into the sum of income and substitution effects:

$$R_I = \sum_{i(i \neq s)} \left\lfloor \psi_i w_s \eta_{q_i,x} - \psi_i \tilde{\eta}_{q_i,p_s} \right\rfloor \qquad 9$$

The first term in in Equation 9 is the income effect ($\psi_i w_S \eta_{q_i,x}$) and the second term is the substitution effect ($-\psi_i \tilde{\eta}_{q_i,p_s}$). The substitution effect for commodity *i* may offset or reinforce the income effect for that commodity (**Error! Reference source not found.**). Consumption of commodities that are complements (substitutes) to the energy service will increase (reduce) following the energy efficiency improvement.

If estimates of both η_{q_i,p_s} and $\eta_{q_i,x}$ are available the indirect rebound effects for each commodity can be derived and decomposed, but if only estimates of $\eta_{q_i,x}$ are available, only the income effect can be obtained. To estimate the overall indirect rebound effect we need to sum the corresponding change in emissions over all commodities.

Table 7. Determinants of the sign of the indirect rebound effect for commodity j

Nature of commodity *i*	Sign of expenditure elasticity for commodity *i*	Sign of compensated cross-price elasticity	Relative size of income and substitution effects	Sign of uncompensated cross-price elasticity	Sign of indirect rebound effect for commodity *i*
Normal good	$\eta_{q_i,x} > 0$	$\tilde{\eta}_{q_i,p_s} < 0$ Net complements	Not relevant	$\eta_{q_i,p_s} < 0$ Gross complements	$R_{I_i} > 0$
Normal good	$\eta_{q_i,x} > 0$	$\tilde{\eta}_{q_i,p_s} > 0$ Net substitutes	$\lvert\tilde{\eta}_{q_i,p_s}\rvert < \lvert w_s \eta_{q_i,x}\rvert$	$\eta_{q_i,p_s} < 0$ Gross complements	$R_{I_i} > 0$
Normal good	$\eta_{q_i,x} > 0$	$\tilde{\eta}_{q_i,p_s} > 0$ Net substitutes	$\lvert\tilde{\eta}_{q_i,p_s}\rvert > \lvert w_s \eta_{q_i,x}\rvert$	$\eta_{q_i,p_s} > 0$ Gross substitutes	$R_{I_i} < 0$
Inferior good	$\eta_{q_i,x} < 0$	$\tilde{\eta}_{q_i,p_s} < 0$ Net complements	$\lvert\tilde{\eta}_{q_i,p_s}\rvert > \lvert w_s \eta_{q_i,x}\rvert$	$\eta_{q_i,p_s} < 0$ Gross complements	$R_{I_i} > 0$
Inferior good	$\eta_{q_i,x} < 0$	$\tilde{\eta}_{q_i,p_s} < 0$ Net complements	$\lvert\tilde{\eta}_{q_i,p_s}\rvert < \lvert w_s \eta_{q_i,x}\rvert$	$\eta_{q_i,p_s} > 0$ Gross substitutes	$R_{I_i} < 0$
Inferior good	$\eta_{q_i,x} \leq 0$	$\tilde{\eta}_{q_i,p_s} > 0$ Net substitutes	Not relevant	$\eta_{q_i,p_s} > 0$ Gross substitutes	$R_{I_i} < 0$

The different components of the total rebound effect are summarised in **Error! Reference source not found.**.

Table 8. Analytical expressions for the components of the total rebound effect

	Direct rebound effect	Indirect rebound effect for commodity *i*
Income effect	$\hat{R}_D = w_s \eta_{q_s,x}$	$\hat{R}_{I_i} = \psi_i w_s \eta_{q_i,x}$
Substitution effect	$\tilde{R}_D = -\tilde{\eta}_{q_s,p_s}$	$\tilde{R}_{I_i} = -\psi_i \tilde{\eta}_{q_i,p_s}$

7 Annex 2 – Methods for estimating rebound effects

Empirical estimates of rebound effects may be obtained through a variety of techniques that are frequently used in combination. The main approaches are summarised below.

First, estimates may be required of the energy, emission and cost savings from the relevant measure in the absence of any rebound effects (*PES*). These can be produced from engineering models of household energy use, combined with data on the cost and energy/emission intensity of the relevant energy carriers. In many cases, simple 'back of the envelope' calculations may suffice.

Second, estimates may be required of the own-price elasticity of the relevant energy service, since this provides a measure of the direct rebound effect (see Annex 1) [18]. This may be achieved through econometric analysis of secondary data on the price and consumption of the relevant energy service (e.g. heating). However, such data is frequently not available. A common alternative is to estimate the own-price elasticity of the relevant energy carrier (e.g. natural gas), since data on this is more readily available. If the energy carrier is used for a single energy service, then this should provide an upper bound for the rebound effect [18]. However, since most energy carriers are used for several energy services (e.g. electricity), and/or several energy carriers are used for the same energy service (e.g. heating), it is difficult to isolate the direct rebound effects for individual energy services [170,171].

Third, estimates may be required of the cost savings from the measure and how they will be re-spent on different categories of goods and services. The most common approach is to assume that the re-spending will resemble the spending patterns observed in the past, either for households as a whole or for relevant socio-economic group. These patterns can be estimated from the econometric analysis of survey data on household expenditures [7-9,39,46,172,173]. To estimate the full response it is necessary to estimate the own-price elasticity of demand for the relevant energy service (direct rebound) and the elasticity of demand for other goods and services with respect to the price of the energy service (indirect rebound) - see Annex 1. However, the required data is frequently not available. A common alternative is to estimate own and cross price elasticities for the relevant energy carrier, but this creates similar problems to those indicated above. Moreover, the data requirements are onerous and the limited degrees of freedom means that only a limited number of categories of goods and services can be employed [46]. A much simpler alternative is to estimate the income elasticities of different categories of goods and services (i.e. the percentage increase in demand following a percentage increase in income) and to use these to estimate the income effects. This provides a biased estimate of the rebound effect since substitution effects are ignored, but the data requirements are less onerous and the greater degrees of freedom allow household expenditure to be broken down into a large number of categories.

Fourth, estimates may be required of the energy consumption, carbon emissions or GHG emissions that are 'embodied' in different categories of household goods and services. These arise from the production and distribution of the product, including supply chains of component parts and materials. To be accurate, such estimates should reflect the specific origins of different goods and services (e.g. UK, China, US), together with the corresponding differences in the energy/carbon/GHG-intensity of production and distribution. Such estimates can be produced, to an increasing degree of accuracy, from multiregional, environmentally-extended input-output (I-O) models [174-176], but if these are not available the energy/emission intensity of domestic production can be used instead. I-O models are calibrated to national data on the economic relationships between different sectors, but have the drawback that economic structure and relative prices are assumed to be fixed.

Fifth, estimates may be required of the own-price elasticities of supply and demand for the relevant energy commodity. These may be obtained from the econometric analysis of energy market data. Since price and quantity are simultaneously determined and hence endogenous, there is the risk of biased estimates. Sometimes it is possible to accurately

estimate the supply (demand) elasticity with the help of an 'instrumental variable' that is correlated with price but does not influence supply (demand) [177]. Alternatively, a simultaneous equation model may be used to estimate both elasticities simultaneously. However, the required data may not be available.

Sixth, estimates may be required of the broader macroeconomic adjustments to improved energy efficiency (secondary effects). Since these are difficult to measure, the most common approach is to stimulate efficiency improvements with computable general equilibrium (CGE) models of the macro-economy [178]. These are based upon I-O models, but (unlike the latter) are able to simulate adjustments to prices and other variables. Most models simulate national economies, but these can be extended to reflect the energy or emissions embodied in imported goods. The typical approach is to compare the economy-wide energy consumption in a baseline scenario to that in a scenario that includes an energy efficiency improvement in one or more sectors. However, the results of such simulations are highly sensitive to both the structure of the model and the parameter values assumed, so relatively little confidence can be placed in the quantitative results [14]. Instead, such models are more useful for qualitatively illustrating the nature of the economic response under different conditions and assumptions.

Finally, estimates may be required of the energy consumption, carbon emissions or GHG emissions that are 'embodied' in the energy efficiency measures themselves (e.g. LED light bulbs), together with those embodied in the relevant alternative (e.g. conventional incandescent bulbs). These may be obtained, to varying degrees of accuracy, from life-cycle analyses of the relevant technologies.

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