Report

The Rebound Effect: Implications of Consumer Behaviour for Robust Energy Policies

A review of the literature on the rebound effect in energy efficiency and report from expert workshops

international risk governance council

Abbreviations used in the text:

ACEEE	American Council for an Energy-Efficient Economy
AEO	Annual Energy Outlook
AES	actual energy savings
AIDS	almost ideal demand system
CEDM	Center for Climate and Energy Decision Making
CES	constant elasticity of substitution
CGE	computable general equilibrium
CMU	Carnegie Mellon University
GDP	gross domestic product
GHG	greenhouse gas
EIA	Energy Information Administration (USA)
EU	European Union
IEA	International Energy Agency
IO	input-output
IRGC	International Risk Governance Council
LCA	life cycle assessment
NAS	National Academy of Sciences (USA)
NRC	National Research Council (USA)
OECD	Organisation for Economic Co-operation and Development
PES	potential energy savings
SUV	sport utility vehicle
UBC	University of British Columbia

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Preface

The International Risk Governance Council (IRGC) is a non-profit and independent foundation whose purpose is to help improve the understanding and governance of systemic risks that have impacts on human health and safety, the environment, the economy and society at large.

In 2011 IRGC, the Center for Climate and Energy Decision Making (CEDM) at Carnegie Mellon University (USA) and the Interdisciplinary Research Unit on Risk Governance and Sustainable Technology Development (ZIRN) at the University of Stuttgart (Germany), in collaboration with the School of Public Policy and Management at Tsinghua University (China) and the University of British Columbia (UBC, Canada)[1], organised two workshops on the topic of "Energy Efficiency Policies and the Rebound Effect". Support for these efforts came from CEDM[2], IRGC, UBC and the University of Stuttgart.

The first workshop was held in Washington, DC, USA on 27–28 June 2011 and led by CEDM. The second was held in Stuttgart, Germany on 13–14 October 2011 and led by Dialogik gGmbH and the University of Stuttgart.

Participants were invited "to identify and develop research needs in respect to different approaches to measuring direct and indirect rebound effects that may arise from investments in, and policies regarding, energy efficiency". Prior to the workshops, investigators at the Center for Climate and Energy Decision Making and at the University of Stuttgart performed literature reviews that identified a very mixed and diverse set of findings in terms of the magnitude and importance of rebound effects across end-uses, time periods covered and regions or countries studied. The goal of the workshops was neither to provide a consensus on the magnitude of the rebound effect nor to perform new research. Rather it was to clarify confusion in the taxonomy, to identify the gaps in existing research and to identify future research needs.

We include on page 33 a list of the experts who participated in each workshop. In preparation for each of the workshops, all participants were asked to prepare a three-page "think piece" and a short presentation addressing a specific set of questions posed. The specific links to these "think pieces" can be found in Appendices 1 and 2, and the whole set can be found at: http://cedm.epp.cmu.edu/rebound.php. We cite several of these "think pieces" throughout this report.

Comments are especially welcome on how IRGC's focus on energy efficiency and the rebound effect could make a constructive contribution. More information on the project can be obtained from info@irgc.org.

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[2] CEDM support comes from a cooperative agreement (SES-0949710) between Carnegie Mellon University and the National Science Foundation of the USA.

Executive summary

In recent years, energy efficiency policies have been deployed or suggested across the world, as part of countries' energy policies and/or as a way to achieve climate change mitigation goals. Drivers for the promotion of energy efficiency policies include a desire to reduce energy consumption and in particular dependence on foreign fuel supply, to lower greenhouse gas (GHG) emissions in order to mitigate the impacts of climate change, to reduce criteria air pollutants, and to provide affordable energy services. While it is widely acknowledged that there is still a large potential for energy and greenhouse gas savings, the design of effective policies to realise that potential is challenging.

As consumers pursue cost-effective energy efficiency investments, they will have economic savings over the lifetime of their investment. Questions about how these economic savings are used by the consumers have led to a long debate in the energy economics and energy policy literature on whether some of the theoretically estimated gain in energy efficiency will be eroded as consumers consume additional goods and services. In this report, we summarise the findings from two workshops on the topic of "Energy Efficiency Policies and the Rebound Effect".

There has been considerable confusion about nomenclature with respect to the rebound effect. To clarify the discussion, we adopted a taxonomy for consumer responses to changes in end-use efficiency for an energy service. These include:

Direct rebound effect: Efficiency gains lead to a lower cost of energy services, leading to an expanded or intensified use of the energy consuming product/service. For example, when consumers switch from incandescent light bulbs to compact fluorescents, they may leave their lights on for more hours than they did previously because of lower lighting operation costs;

Indirect rebound effect: The additional income that is freed up by saving energy costs can be used for other energy- or carbon-intensive consumption. For example, the income gained by installing an efficient furnace and insulating one's house could be bundled into additional air travel, leading to an overall increase in GHG emissions.

The direct and indirect rebound effect can be related to two familiar economic effects:

Substitution effect: Efficiency gains in a particular energy service lead to a shift into more consumption of that service and out of other goods and services; and

Income effect: Efficiency gains in a particular energy service make available additional income from energy cost savings which can be used for greater consumption overall, in both energy and other goods and services.

Changes in consumption patterns: Substitution and income effects may lead to overall changes in consumption patterns. For example, energy efficiency gains lead to changes in behaviour (such as buying more frozen food when energy efficient freezers are available). Measurements of the direct and indirect rebound effect would also include these changes in consumption patterns.

Economy-wide rebound effect: Energy efficiency investments lead to changes in the prices of goods and services, which lead to structural changes in the economy, resulting in a new equilibrium in the consumption of energy and other goods and services.

Without first sorting and classifying studies in terms of these different mechanisms, it is not easy to compare study results or determine when and whether rebound effects are large or small.

Having clarified these differences, the report then reviews available literature. Direct rebound effects estimates for the residential sector are found to range from zero to 60 per cent depending on the end-use, the method used to estimate the rebound effect, the period of analysis and the geographical area under study. In the transport sector, studies on rebound effects report ranges from 4–87 per cent. Rebound effects in the commercial and industrial sectors, and indirect and economy-wide effects for all sectors, have been the focus of much less research, and there is a large uncertainty about the magnitude of these effects.

There is very little evidence of direct or indirect rebound effects exceeding 100 per cent (so called "backfire") for household energy efficiency investments in developed countries.

This report does not intend to present a full comprehensive analysis of the rebound effect. There are other drivers for consumer responses that might be important to understand consumer behaviour and that are included neither in the taxonomy above nor in this report, beyond emphasising their probable importance, and/or recommending that a research agenda on these topics is developed. These include, but are not limited to, perceptions of prices, prestige and status effects, attitudes and values, lack of knowledge in the application of energy efficient devices, lifestyles, moral licensing and personal norms, habits, time and needs satiation.

Rebound effects could be large in the developing world, among low-income groups, and in the production sector of the economy. There has been far too little study of these groups. Such research is needed to gain a better understanding of the magnitude of rebound and the extent to which such rebound effects lead to enhanced individual well-being and desirable socio-economic or macroeconomic co-benefits.

Many countries have ambitious energy policies goals and targets. Care should be taken to insure that energy efficiency policies are not called into question in general, as the existing studies suggest that energy savings are achieved. Energy efficiency policies could be improved by explicitly taking into account rebound effects, both in programme design and also in the energy scenarios and models that support policy decision-making. If policymakers are concerned with the environmental and health externalities associated with rebound effects, taxes or cap and trade policies would assure that the negative externalities from rebound effects – and energy demand in general – are accounted for.

Given the growing emphasis that decision-makers are placing on promoting energy efficiency as a strategy to deal with growing energy demand and costs, limited energy supplies and greenhouse gas emissions, it is critically important to develop a better understanding of the nature, determinants and magnitude of the drivers of energy demand.

1 Why do we care about characterising potentially unanticipated impacts from investments in energy efficiency?

Across the world countries have been adopting energy efficiency policies over recent years in efforts to lower reliance on foreign fuel supplies, reduce greenhouse gas emissions and air pollution, mitigate climate change and make energy supplies more affordable.

In the United States, energy efficiency standards for several end-uses and technologies have been fostered under revisions of the Energy Policy Act of 2005 and under the Energy Independence and Security Act of 2007. The American Recovery and Reinvestment Act of 2009 included a budget of roughly US$17 billion allocated to energy efficiency investments (ACEEE, 2011). In March 2011, the European Union pledged a reduction in primary energy consumption of 20 per cent by 2020, using 2006 as a baseline year (EU Commission, 2011). In China, the 12th five-year energy development plan for the period from 2011 to 2015, aims to achieve a 16 per cent reduction in energy consumption per unit of gross domestic product (GDP) and a 17 per cent reduction in carbon dioxide emissions per unit of GDP by 2015 compared with 2010 (Pew Center on Global Climate Change, 2011). A summary of the recent policies deployed by several countries, with the objective of improving efficiency by which energy is used, can be found in the International Energy Agency's (IEA) report for the Energy Efficiency Working Party (IEA, 2010; IEA, 2011).

Policy goals to foster energy efficiency generally assume that there is a subset of energy efficiency measures that would be cost-effective for consumers. For example, in the USA, the residential sector accounts for 37 per cent of national electricity consumption, 17 per cent of greenhouse gas emissions and 22 per of primary energy consumption[3,4]. Using a bottom-up model, Azevedo *et al.* (2009) estimated that nearly 30 per cent of USA residential carbon dioxide emissions could be avoided with energy efficiency strategies that provide the same level of energy services and are cost-effective for residential consumers. While it is widely acknowledged that the residential sector holds the potential for energy and greenhouse gas savings, the design of effective policies to realise that potential is challenging. Ehrhardt-Martinez and Laitner (2010a) suggest that "people-oriented" strategies (i.e., strategies that focus on behaviour related energy savings) could reduce energy consumption in the residential sector by up to 25 per cent.

Policymakers list a variety of objectives when implementing energy efficiency policies and measures in the buildings and transportation sectors. These include: reducing energy consumption; reducing greenhouse emissions; reducing consumers' energy bills; and moving toward a more sustainable energy system than that provided by "business as usual".

In order to know whether such goals will actually be met, and to pursue energy efficient strategies that are both smart and wise concerning the different policy goals mentioned above, a starting point is to understand the technological and economic potential for energy/carbon dioxide savings from energy efficiency measures. Several studies have addressed this issue (see for example, NRC, 2010; Azevedo, 2009; Azevedo *et al.*, 2013; Ürge-Vorsatz *et al.*, 2009; Brown, 1993; Rubin *et al.*, 1992; McKinsey, 2007; Brown *et al.*, 1998; Nadel *et al.*, 2004; Meier; 1982; Blumstein *et al.*, 1995; Rosenfeld *et al.*, 1991; Rosenfeld *et al.*, 1993; Koomey *et al.*, 1991; OTA, 1991).

However, grounding policies based solely on technological/economic potential may be a mistake: adoption of new energy efficiency technologies requires consumer acceptance, and thus the other aspect of relevance to policymakers, as they design energy efficiency policies, is to understand how consumer decision-making and behaviour affect efficiency investments, considering changes in economic incentives (Bohi and Zimmerman, 1984; Dahl and Sterner, 1991; Hanly *et al.*, 2002; Espey and Espey, 2004; Reiss and White, 2005; Frondel *et al.*, 2008, 2010; Madlener *et al.*, 2011; Greene, 2011), and social as well as psychological processes (Attari *et al.*, 2010; Ehrhardt-Martinez and Laitner, 2010a; Gardner and Stern, 1996; Stern, 1992; Wilhite and Lutzenhiser, 1999; Lutzenhiser *et al.*, 2001; Lutzenhiser, 1993). It could then be possible to predict how the net effect of these factors will influence the overall amount of energy used.

In this report, we focus on a subset of the above mentioned consumer behaviour related issues – if consumers pursue cost-

[3] Using 2008 AEO detailed tables, Table 10 – Energy Consumption by Sector and Source, US Energy Information Administration (EIA).

[4] Using EIA GHG flow from 2006. EIA reports that the residential sector is responsible for 1,234 million metric tons of carbon dioxide equivalent, and that total greenhouse gas emissions in the United States are 7,076 million metric tons of carbon dioxide equivalent.

effective energy efficiency investments, they will have economic savings over the lifetime of their investment. The issue of how these economic savings are used by consumers has led to a long debate in the energy economics and energy policy literature on whether some of the theoretically estimated gain in energy efficiency will be eroded as consumers consume additional goods and services. The purchase of a more fuel-efficient car may lead to a more frequent use of the car, as the driving cost per mile decreases. The result may be less energy saving than if the use patterns had remained unchanged. Similarly, more efficient appliances may provide greater capacity or be used more intensely. Consumers may re-spend the economic savings on other energy or non-energy services. Finally, if such changes in consumers' consumption patterns occur, producers are likely to adjust their production functions with the result that the overall structure of the economy may change. While we describe this effect using consumers as an example and focus mainly on household behaviour throughout the report, a similar logic applies to gains in energy efficiency experienced by producers.

2 Defining the consumer responses to changes in efficiency

Research in energy efficiency suggests that there is an energy efficiency gap, i.e., a gap between current energy consumption levels and the potential optimal levels of consumption assuming the adoption of the cost effective and efficient end-use technologies that would provide the same level of energy services (Hirst and Brown, 1990; Jaffe and Stavins, 1994). Many scholars have described qualitatively the reasons why such a gap exists (Anderson and Claxton, 1982; Golove and Eto, 1996; Brown, 2001, Blumstein, Krieg *et al.*, 1980), categorising the reasons as market failures and barriers to the adoption of efficient technologies. Market failures are flaws in the market operation that make current consumption levels deviate from the social optimum. They include, for example, the fact that environmental and other externalities are not included in energy prices; the existence of distortional regulations such as subsidies for particular technologies or fuels; imperfect information; and split incentives. Barriers to energy efficient technology adoption are factors that lead to choices of energy inefficient technologies by consumers. These barriers include issues such as uncertainty regarding the future price of electricity or other fuels, lack of access to financing for energy efficiency measures and the fact that energy efficiency often is inseparable from other unwanted features in products (Golove and Eto, 1996). However, while all these issues are very relevant for consumer behaviour and energy consumption, our report does not attempt to address the issue of the energy efficiency gap. Instead, we start with the premise that an improvement in energy efficiency occurs and discuss the energy consequences associated with consumer behaviour. Recent and current literature on energy efficiency and energy efficiency "rebound" often lumps quite different consumer behaviours under the general term of "rebound".

Recent reviews (Sorrell, 2007; Turner, 2009; Jenkins *et al.*, 2011) of prior work have helped to untangle the definitions and estimates of each of these effects, but much confusion remains with respect to the taxonomy of mechanisms and the ranges of the estimates associated with these different "rebound effects". Here we use the following definitions:

1. Direct rebound effect: Efficiency gains lead to a lower price of energy services, leading to an expanded or intensified use of the energy consuming product/service. For example, when consumers switch from incandescent light bulbs to compact fluorescents, they may leave them on for more hours than they did previously because their operation costs less.

2. Indirect rebound effect: The additional income that is freed up by saving energy costs can be used for other energy- or carbon-intensive consumption. For example, the income gained by installing an efficient furnace and insulating one's house could be bundled into additional air travel, leading to an overall increase in GHG emissions.

The direct and indirect rebound effect can be related to two familiar economic effects:

Substitution effect: Efficiency gains in a particular energy service lead to a shift into more consumption of that service and out of other goods and services.

Income effect: Efficiency gains in a particular energy service make available additional income from energy cost savings which can be used for greater consumption overall, in both energy and other goods and services.

After accounting for substitution and income effects, the direct rebound effect focuses on net changes in energy service consumption, while the indirect rebound effect focuses on the net changes in other goods or service consumption.

3. Changes in consumption patterns: Substitution and income effects may lead to overall changes in consumption patterns. For example, energy efficiency gains lead to changes in behaviour (such as buying more frozen food when energy efficient freezers are available). Measurements of the direct and indirect rebound effect would also include these changes in consumption patterns.

4. Economy-wide rebound effect: Energy efficiency investments lead to changes in prices of goods and services, which lead to structural changes in the economy, resulting in a new equilibrium in the consumption of energy and other goods and services.

Without first sorting and classifying studies in terms of these different mechanisms, it is not easy to compare study results or determine when and whether rebound effects are large or small.

The classical economic explanation of the Jevons Paradox (Jevons, 1865) is that improvements in technology reduce the price of providing such services, therefore increasing demand for those or other energy-intensive services, and eroding the gains in energy and carbon dioxide reductions from efficiency. Jevons explored this issue in the context of the use of coal, looking at the increasing efficiency of conversion from coal to work in England in the 19th century. While there are many historical examples, it seems likely that this effect actually arises from a number of interactions between behavioural, economic and technical factors – and disagreements about the size of this effect are perhaps derived from the fact that researchers use different definitions and boundaries of analysis to estimate this effect.

The revival of attention to the issue of "rebound" emerged in the late 1970s with Brookes (1979), followed by Khazzoom (1980). However, instead of looking at the technological change in productive sectors, Khazzoom (1980) explored a very different issue: the impact of energy efficiency standards for household appliances. Khazzoom discussed the difference between the technical potential of energy efficiency and what in fact could be expected to happen given an elasticity of energy demand with respect to appliance efficiency, which under certain assumptions is equivalent to the elasticity of energy demand with respect to energy prices. In his seminal paper, Khazzoom also noticed that "conditions exist in which a program of accelerated improvement in efficiency can backfire", and that "there is no empirical evidence that would lead one to expect that [energy savings from efficiency standards] would apply similarly to all end uses". Basically, what Khazzoom claimed is that policymakers have not incorporated consumer price elasticity when estimating the energy savings that would result from implementing energy efficiency standards. While conditions exist in which backfire would occur, its likelihood is another matter.

Brookes (1990, 2000) continued Khazzoom's argument from a macroeconomic, production-side perspective, arguing that energy efficiency investments could lead to a net increase in energy demand, resulting in backfire, that is, a rebound greater than 100 per cent. Brookes argued that energy-price induced substitution of energy for capital or labour, which he calls energy productivity, and equates with energy efficiency investments in production, increases the productivity of capital and labour, leading to a greater growth in total factor productivity than in energy productivity, thus increasing overall energy consumption and greenhouse gas emissions. Saunders (1992, 2000, 2008, 2010) extended the "Khazzoom-Brookes" postulate, another name for the rebound effect, to the study of different production functions, (e.g. Leontief, Cobb-Douglas, Constant Elasticity of Substitution or Trans-log) and found that certain production functions are insufficiently flexible to measure the full extent of rebound effects (from negative to greater than 100 per cent) possible.

However, some authors have questioned the validity of Brookes' and Saunders' formulations, given that such models are highly stylised and entail limited or no empirical evidence. In addition, Brookes' price-induced energy substitution describes a broader situation than the increase in energy service demand described by Khazzoom. The distinction between consumers' behavioural responses to changes in energy prices versus changes in the energy efficiency of technologies was lost in Brookes' arguments. Howarth (1997) has shown that given the distinction between physical energy and energy services, and given an assumption that the production of energy services from physical energy occurs by means of the Leontief production function, Brookes' findings do not hold. Saunders (2000) shows that, using Cobb-Douglas production functions, fuel consumption increases with efficiency investments. However, Saunders (2008) shows that by their structure Cobb-Douglas functions always predict backfire. Accordingly, other authors (Sorrell, 2007; Sorrell *et al.*, 2008) have renewed the call for the study of rebound effects from an energy services perspective.

Binswanger (2001), starting with the same formulation as Khazoom (1980), provides the derivation for the rebound effect for a single service in a neoclassical framework. He then expands this single-service model, in which the "overall effect of an increase in energy efficiency on energy consumption depends on the substitutability between different services and on the direction of the income effect". In that same piece, Binswanger also highlights the importance of time-saving rebound effects associated with energy efficiency improvements.

Wirl (1995) discusses the economics of utility demand-side management programmes under different possible regulatory regimes, when the consequences from energy efficiency engineering improvements are considered (i.e., taking into account rebound effects). He argues that demand-side management strategies, used as a permanent policy option, will ultimately increase free-ridership as a result of strategic consumer reactions. Also, in Wirl (2000) the author highlights that free-ridership, rebound effects and strategic reactions from consumers will decrease the effectiveness of demand-side management programmes.

Many argue that consumers' behaviour towards energy end-use technologies is highly price inelastic (Bohi and Zimmerman, 1984; Henly *et al.*, 1988; Espey and Espey, 2004; Reiss and White, 2005; Schipper and Grubb, 2000; Small and van Dender, 2005, 2007; "think piece" presentation by Sweeney), even more inelastic than consumer behaviour towards changes in energy price (Hanly *et al.*, 2002). Therefore, the difference between the potential engineering derived gains and the actual gains should be negligible. Similar arguments have been advanced in connection with the behaviour of firms, claiming that because energy is generally only a small share of firms' resource allocation, and economic savings are allocated in firms' production functions, the overall impact of an increase or decrease in energy consumption and carbon emissions becomes unclear.

Using a different approach from price and income elasticity, Schipper and Grubb (2000) analysed historical data on energy use and prices in different sectors of the economy and showed that "key measures of activity (car use, manufacturing output and structure, housing floor space, etc.) have changed little in response to changes in energy prices or efficiency, instead continuing their long-term evolution relative to GDP or other driving factors".

Recent additions to the rebound literature have focused on analytical definitions of the rebound effect in terms of a variety of elasticities (Sorrell, 2007, Sorrell *et al.*, 2008; Turner, 2009; Guerra and Sancho, 2010). Khazzoom's formulation was in terms of efficiency elasticities of the demand for energy services from an appliance. However, this type of elasticity is rarely measured. In the absence of detailed energy service demand data for electricity, and limited variation in efficiency in transportation and natural gas demand, energy price elasticities have been used as a proxy for the energy service price elasticity in measuring the rebound effect. Hanly *et al.* (2002) have shown in the case of transport that price elasticities of petrol demand are an upper bound for price elasticities of vehicle miles travelled, because of the endogeneity between energy prices and efficiency choice. Thus, studies using energy price elasticities as a proxy for energy service price elasticities are likely to overestimate the rebound effect. The data requirement for properly estimating the rebound effect by end-use are great, requiring disaggregated energy service data over an appropriate timescale. However, not all researchers agree that energy services elasticities are a proper measure of the rebound effect and that price-induced efficiency should be excluded (Saunders, 2000; Jenkins *et al.*, 2011).

While in Section 3 of this report we highlight several behavioural factors that may explain the departures from neoclassical economics, the empirical literature on rebound effects is still dominated by approaches where price, income and substitution elasticities are estimated for a geographical region over a certain time period. Thus, in Sections 4 and 5, we provide a review of those empirical estimates.

As Brookes stated in his paper dated of 2000 revisiting his prior work of the 1990s, "the debate continues".

3 Drivers of consumer responses to changes in energy efficiency and energy prices

Here we outline a series of consumer related responses that are important to understand and address when pursuing policies to lower or stabilise energy demand and the rebound effect. The suggested drivers for consumption/reaction from consumers in this section are mainly the outcome of a group work session on "behavioural aspects of rebound effects" that occurred during our second workshop in Stuttgart. In addition to economic factors, a number of behavioural factors were identified and discussed.

Perception of prices: Price signals are the most obvious driver of rebound effects. They are the starting point for economic analysis on the micro level. However, consumers' perception of prices can be biased and, therefore, their rationality becomes "bounded" (Simon 1959; Kahneman and Tversky 1979). In particular, there may be thresholds that determine the boundary between negligible price effects that are ignored and noticeable price effects. Often customers of electricity are not aware of the electricity costs as they are not fully known, since they usually constitute only a small percentage of their expenditure (see also the "think piece" by Golde).

Prestige or status effects: Some scholars argue that conspicuous consumption is the main cause of most consumption activities that go beyond the pure satisfaction of biological and physical needs (Veblen 1899; Schor, 1999). Therefore, the dynamics of conspicuous consumption can be regarded as one driver of constantly increasing consumption levels (Alcott, 2004). However, neoclassical economics would simply explain this behaviour using a utility maximisation framework. New technologies and devices can always offer chances for conspicuous consumption. However, it is social processes and dynamics that determine which goods become "positional goods" (Hirsch, 1976). Changes in the social valuation of specific products can lower the psychological burdens and/or increase the social prestige of owning or using these products (de Haan *et al.*, 2006). For example, if SUVs become prestigious, more people will buy them for status reasons and because driving a big vehicle is perceived as socially accepted. However, this statement becomes more questionable when accounting for other services that are provided by SUVs (safety, comfort, etc.). Griskevicius *et al.* (2010) were able to show that consumers also use green products for conspicuous consumption. When status motives are activated in consumers, they are more likely to choose green products over non-green products, even if non-green products would be cheaper or more luxurious. Therefore, a mere "greening" of products might not be enough to lower negative side effects of individuals' consumption behaviour. The consumption of goods and services that are at least partly used for display of status and conspicuous consumption may likely be expanded when additional income is available, resulting in rebound effects.

Attitudes and values: Attitudes and values are an important driver of individual behaviour (Rokeach, 1973; Ajzen, 1991). Internalised values (e.g. frugality) and deduced attitudes (e.g. environmental consciousness) may both positively and negatively influence energy consumption. Whereas environmental consciousness may prevent people from overconsumption and steer their investments towards low emission goods and services (thereby avoiding indirect rebound effects), a strong hedonistic or egoistic value orientation may prevent people from taking into account the environmental impacts of their behaviour.

As Kaiser argued in a "think piece" prepared for the Stuttgart workshop, frugality could be one starting point for lowering rebound effects. People differ regarding the significance they place on frugality. Since "a heterogeneous and presumably infinite number of personal goals are constantly ready to take advantage of a technology's efficiency gains in terms of freed time and/or money" ("think piece" by Kaiser), efficient technologies are expected to work only with frugal people where frugality has become an important personal goal. Therefore, it can be assumed that only people with a comparatively pronounced frugality will use efficient technology in a way to avoid rebound effects. However, Azevedo and other participants raised the issue that if a household has a certain level of income, it might be the case that individuals pursue

a frugal daily life, but use the savings that arise from such patterns of frugality to pursue other (potential energy and carbon intensive) activities, such as to travel more. Without a proper boundary of analysis, claims for frugality are unsubstantiated. For further information on the interaction between frugality and energy consumption, please refer to the "think piece" by Kaiser.

In Sorrell's "think piece", some additional thoughts on sufficiency are provided. Focusing on the notion of consuming less, the concept of sufficiency is similar to frugality. Referring to Princen (2005), Sorrell defines sufficiency "[…] as a social organising principle that builds upon established notions such as restraint and moderation to provide rules for guiding collective behaviour" ("think piece" by Sorrell). According to Sorrell, sufficiency is a concept complementary to efficiency that could improve the quality of life and help to adapt to tightening ecological constraints.

Lack of knowledge in the application of energy efficient devices: Lack of knowledge in the application of energy efficient devices can also lead to a reduction in realised energy savings. A study on condensing boilers conducted by the German "Verbraucherzentrale" found that out of 1,000 condensing boilers two thirds were incorrectly calibrated and not well optimised which leads to a loss of up to 10 per cent of potential energy savings (Verbraucherzentrale, 2011). Consequently, the "Verbraucherzentrale" advises the appliance industry to focus on facilitating the calibration of condensing boilers for lay people as well as heating installers. Furthermore, there should be incentives for consumers to change the default settings and adapt the condensing boilers to their needs and the conditions of their buildings. Similar problems can also be imagined in the use of other appliances.

Lifestyles: Lifestyle research is based on the assumption that social differences in modern societies are no longer singularly due to the unequal distribution of material resources. To an increasing degree, such social differences can be explained by the different use of these resources. Many of these differences are dependent on individual values, attitudes and aesthetic preferences (Otte, 2005). In the social sciences, lifestyle approaches have become a popular tool for analysing private consumption in several domains of everyday life (e.g. mobility, nutrition and clothing). Since changes in individual behavioural patterns have been identified as the crucial starting point for a reduction of rebound effects (Druckman *et al.*, 2010), lifestyle concepts may offer a promising approach for analysing the social dimension of rebound effects (Peters *et al.*, 2012). Here, practice theory offers another perspective regarding lifestyles as consisting of different social practices and for analysing relations between ordinary technologies and consumption practices (Reckwitz, 2002; Brand, 2009). Results from empirical studies suggest that many lifestyle patterns favour the use of electricity over other forms of energy. For example, the substitution of electric ovens and stoves in place of gas appliances has been common in many urban and suburban households. Moreover, the replacement of old energy consuming appliances has often resulted in using the old appliances as a backup or as additional service for cooling or cooking (Gram-Hanssen, 2006). Time constraints and dual career strategies reinforce the use of frozen food and functional food, which in turn leads to higher overall energy consumption (Hand and Shove 2007). For these and many other reasons, the electricity demand of German households increased from 1997 to 2005 by 13 per cent (Kaschenz *et al.*, 2007) in spite of a decreasing energy use per unit energy service of electricity consuming appliances and equipment.

Moral licensing, social and personal norms: The term "moral licensing" refers to the fact that virtuous deeds boost individuals' moral self-image and thus can liberate them to engage in immoral, unethical or problematic behaviours. Otherwise these negative behaviours would have been avoided due to the individual's feelings of guilt and fear of appearing immoral (Merritt *et al.*, 2010; with regard to rebound effects: Santarius, 2012). Regarding environmentally friendly consumption, Mazar and Zhong found that "… people act less altruistically and are more likely to cheat and steal after purchasing green products than after purchasing conventional products" (Mazar and Zhong, 2010). Closely related to the issue of moral licensing is the possibility that energy efficiency investments might change personal norms and, thus, lower the psychological costs of ownership of specific goods (de Haan *et al.*, 2006; de Haan, 2008). The purchase of a hybrid car can weaken the personal norm of energy saving so that the individual feels free to consume more energy in other fields of everyday life (e.g. heating). Another example is the purchase of high-efficiency washers. Applying an experimental approach, Davis (2008) was able to show that households increased clothes washing on average by 5.6 per cent after receiving a high-efficiency washer.

Habits: Many kinds of energy consuming behaviour are governed by habits and routines that are extremely resistant to change (Hobson, 2003). Where habits are strong, behavioural changes and, thus, direct rebound effects (i.e., an increase in the time or frequency of usage of an energy technology/service) may be unlikely. However, persistent habits could be a driver of increased energy usage because they prevent behaviour changes that could reduce energy consumption (Maréchal, 2009). There is also evidence that energy-efficiency investments may lead to spillover effects by motivating people to save even more energy (Thøgersen and Ölander, 2003). However, other streams of empirical research have shown that habits seem to prevent the occurrence of spill-over effects (Ronis *et al.*, 1989; Verplanken and Aarts, 1999). On the other hand, sometimes the purchase of a new product could result in sufficient change to cause the user to abandon old habits. In short, the question whether habits and routines prevent or enforce the occurrence of rebound effects, and whether they increase or decrease energy consumption, cannot be clearly answered.

Time: Technological progress allows us to perform specific activities in a decreasing amount of time. For example, ever faster transport systems (e.g., German InterCity Express – ICE) allow us to travel further distances or to engage in more consumption activities, sometimes resulting in additional energy use. Some authors have defined this as a "time rebound effect" (Binswanger, 2001; Jalas, 2002; Jalas, 2005). Jalas (2002) concludes in his study on time rebound effects: "…there is a time use rebound effect in any efficiency measures that transfer household activities to markets and thereby contribute to a market bias in delivering welfare. Due to this temporal rebound effect and the consequent new consumption activities, some of the efficiency gains will be lost".

Satiation: A basic economic assumption is the insatiability of wants, needs and preferences. Each time one want or need is satisfied, others may arise. Wants and needs are regarded as main drivers of individuals' consumption behaviour, since material goods are typically used to satisfy them. According to Wörsdorfer (2010), rebound effects are most likely to occur where wants or needs are unsatisfied. This is consistent with the empirical findings of higher rebound effects in low income groups and developing countries (Sorrell, 2007; van den Bergh, 2011). However, Witt (2001) assumes that to a certain extent, desired levels of satiation regarding specific goods, as well as the perception of a product's usefulness for satisfying a specific need, can change over time and are subject to learning processes. This raises questions about how learning processes can be initiated to steer individuals' consumption behaviour to other sources of needs satisfaction than material goods and services that give rise to intense greenhouse gas emissions (Jackson *et al.*, 2004). It is also important to understand to what extent wants and needs related to a certain technology are satisfied and whether further increase in usage of the technology is likely or not.

Time horizon: Studies focusing on consumer direct and indirect rebound effects have a time span of years or at most decades. Recent work from Tsao *et al.*, (2010) focused on historical consumption patterns for artificial lighting, and found that per-capita consumption of light (in terms of energy service, i.e., lumen hours) and GDP per capita have been proportional and following a constant ratio of 0.0072 for centuries. Fouquet and Pearson (2012) also look at rebound effects from lighting. The authors show that lighting consumption was 40,000 times greater by 2000 when compared with 1800. Fouquet and Pearson (2012) estimate income and price elasticities of demand for lighting services from 1700 until 2000, showing that income and price elasticities first increased between 1840s and 1890s and then decreased in the 20th century. In another recent piece, Fouquet (2012) estimates income and price elasticities for passenger transport demand in the United Kingdom over a long time period, finding that income and price elasticities were very large (3.1 and 1.5, respectively) in the mid-19th century, and have declined since then.

4 Previous studies of "direct rebound effects"

Several studies attempt to estimate direct rebound effects in different sectors of the economy (e.g. Frondel *et al.*, 2008, 2010; Greene, 2012; Madlener and Hauertmann, 2011; Brännlund *et al.*, 2007; Mizobuchi, 2008; Small and van Dender, 2005, 2007). In this section, we describe the studies that self-reported to be assessing "direct rebound effects" – despite the fact that the terminology and methods might not be consistent across studies. These studies report a large range in the estimates of direct rebound effects, largely due to differences in the populations studied, the time horizon considered in the study, and the methodological approaches. Generally, in the studies referenced below, direct rebound effects mean an increased level of energy or energy service demand due to the lower price of energy services with an efficiency investment, measured by the price elasticity of energy or energy services (Sorrell and Dimitropolous, 2008).
Many studies only focused on the United States, which raises the question of the extent to which these results can be applied to other countries. The following sections provide a brief overview of estimates of direct rebound effects in the residential, mobility and industrial sectors, illustrating their heterogeneity. We note that empirical research using energy expenditure data would require knowing the marginal prices faced by consumers. However, such detailed price data are generally unavailable to modellers (see the "think piece" presentation by Cullenward).

4.1 Residential sector

Most recent studies on the direct rebound effect focus on the residential sector. Here, rebound effects can occur in various areas and energy services such as residential lighting, space heating, space cooling, water heating, dish and clothes washing machines and refrigerators. Therefore, it is difficult – and likely wrong – to estimate overall direct rebound effects in the residential sector. A study carried out by Barker and Foxon (2008) estimated an overall direct rebound effect of 23 per cent for UK households in 2010, showing a comparatively low level of rebound effects compared with estimates for the industrial or mobility sectors. There are also studies available that disaggregate households' energy consumption by different energy services, giving a more comprehensive picture of direct rebound effects in households. Table 1 shows the range of rebound estimates for different consumer energy services in developed nations drawing on reviews from Jenkins *et al.* (2011), Greening *et al.* (2000) and Sorrell (2007).

Table 1. Ranges of estimates for direct rebound effects from previous studies

Energy service	Range of estimates (%)	Number of studies
Residential lighting	5–12	4
Space heating	2–60	9
Space cooling	0–50	9
Water heating	< 10–40	5
Other consumer energy services	0–49	3

Sources: "Water heating" from Jenkins *et al.* (2011). "Space heating" and "other consumer energy services" from Sorrell (2007). "Residential lighting" and "space cooling" from Greening *et al.* (2000).

The overview shows varying uncertainties in the rebound estimates for different energy services. While rebound estimates for residential lighting seem to be low with a modest range of uncertainty, rebound estimates for space heating and cooling, water heating and other consumer energy services are large and show a much higher range of uncertainty. Consequently, Sorrell assigns a low level of confidence to the estimates of direct rebound effects in "space heating" and "other consumer energy services" (Sorrell, 2007). Currently, the Sussex Energy Group, SPRU, University of Sussex and the Centre for Environmental Strategy at the University of Surrey are conducting a joint research project to estimate the direct and indirect rebound effects associated with both energy efficiency improvements (e.g. buying a more fuel-efficient car) and behavioural changes (e.g. reducing car use) by UK households (for further information, please see the "think piece" by Sorrell).

Reiss and White (2005) have also found that consumer behaviour in residential energy demand varies by income. They found that the price elasticity of residential electricity demand, an upper bound estimate of the rebound effect (Henly *et al.*, 1988, Hanly *et al.*, 2002), varies with income from as high as 49 per cent for households with incomes under US$18,000 to 37 per cent for middle income and 29 per cent for high income households.

4.2 Mobility sector

Considering 16 studies on direct rebound effects for personal automotive transport[5], Sorrell and Dimitropoulos (2007) find short-run rebound effects ranging from 5–87 per cent and long-run rebound effects between 5–66 per cent (Sorrell and Dimitropoulos, 2007). However, the studies are of only limited comparability because they use different kinds of data. Some studies have used aggregate time series or cross-sectional data, others disaggregate data or aggregate panel data to estimate rebound effects. Moreover, out of the 16 studies, 12 are based on data from the United States, one from the OECD-25, one from the OECD-17, one from the United Kingdom, France and Italy and one from Germany. Despite wide range of estimates, Sorrell and Dimitropoulos conclude that "nevertheless, personal automotive transportation provides one of the few areas where the evidence base for the direct rebound effect is strong and where the size of the effect can be estimated with some confidence" (Sorrell and Dimitropoulos, 2007). Using household panel data collected in Germany between 1997 and 2005, Frondel *et al.* (2008) found direct rebound effects ranging between 57–67 per cent (for further information, please refer to the "think piece" by Frondel and Vance). Small and van Dender (2005) found that the rebound effect in personal vehicle travel in the United States has been declining over time as incomes rise, from 5 per cent (in the short-run) and 22 per cent (in the long-run) for US states panel data between 1966–2001 to 2.6 per cent (in the short-run) and 12 per cent (in the long-run) for the 1997–2001 data. Greene (2012) found similar results for the 1966–2007 US national travel time series data. More information on rebound effects in the mobility sector can also found in the "think piece" by Greene. Fouquet (2012) found that in 2010, long-run income and price elasticity of aggregate land transport demand are 0.8 and 0.6.

Compared with the findings on direct rebound effects in the residential sector, estimated rebound effects in the mobility sector seem to be higher and their size appears to be estimated with greater confidence.

4.3 Industrial and commercial sectors

The direct rebound effects in the industrial and commercial sectors have been investigated far less than rebound effects in the residential and mobility sectors (Jenkins *et al.*, 2011). According to Greening *et al.* (2000), most of the evidence for direct rebound effects in these sectors stems from energy audits and energy efficiency programme evaluations. Greening *et al.* (2000) give an overview of direct rebound effects estimates in firms reporting rebound effects for "process uses" (short-run) ranging from 0–20 per cent and for "lighting" (short-run) ranging from 0–2 per cent (Greening *et al.*, 2000: 398). However, regarding "process uses" they only refer to one study and regarding "lighting" to four. Furthermore, they critically point out that the studies were only done with one or two methods and were inconclusive in their results.

In the industrial and commercial sectors, the estimated rebound effects seem to be low. However, because of the limited number of studies, the evidence on direct rebound effects in this sector is weak. Without further investigation and empirical studies, there is high uncertainty about the magnitude and range of rebound in these sectors. A recent study from Saunders (forthcoming) shows that backfire occurred in these sectors as a result of technological change in all factors of production. Saunders finds that for energy technology gains alone, the long-term rebound is around 50 per cent (higher or lower depending on the productive sector).

For further information on rebound effects in the industrial sectors, please also refer to the "think piece" by Turner.

[5] We only include estimates of direct rebound effects for personal automotive transport, therefore direct rebound effects from freight transport are excluded.

5 Uncertainties in the estimates of indirect and economy-wide rebound effects

There is a small but growing literature that displays significant uncertainties about the magnitude of indirect and economy-wide rebound effects and thus the impacts for social welfare and policymaking.

Schipper and Grubb (2000) defined the re-spending effect, or what is now called the "indirect" rebound, as the effect of household re-spending of energy cost savings on other goods that require energy for production. They argued that "almost all other ways of consumer spending typically lead to only 5–15 per cent of the expenditure going indirectly to pay energy use…In other words, the energy intensity of re-spending is diluted by an order of magnitude or more." In contrast, Berkhout *et al.* (2000) argued that "the rebound effect is difficult to assess in a world in which the consumer has to make choices from a very long list of substitutable and complementary commodities, all having an own intrinsic energy intensity and price elasticity." The rebound effect he describes, which includes the indirect effect, could range from positive, in the case of goods complementary to an energy service, to negative, in the case of substitution into one energy service leading to a net reduction of other, more energy-intensive, energy services consumption.

Brännlund *et al.* (2007) tackled the issue of jointly estimating direct and indirect rebound effects for a broad set of consumer goods using Swedish household surveys between 1980–1997 and estimating own-price and cross-price elasticities for energy and other goods using an almost ideal demand system (AIDS) econometric model. In a simulation of a 20 per cent efficiency improvement in the heating and transport sectors, they find a rebound, or backfire, of 107–115 per cent is possible in carbon dioxide emissions. However, Mizobuchi (2008) argued that in neglecting capital costs, Brännlund *et al.'s* (2007) estimates of rebound were biased. Using a similar methodology as Brännlund *et al.* for the case of Japanese household expenditures during 1990–1998, Mizobuchi (2008) finds that the direct and indirect rebound effect in carbon dioxide emissions is reduced from 115 per cent without consideration of capital costs to 27 per cent when considering capital costs. These studies did not explicitly separate direct rebound effects from indirect rebound effects. If one assumes that direct rebound effects are equal to their own-price elasticity estimates for energy fuels, Brännlund *et al.* (2007) find long-run direct rebound effects of 24 per cent for electricity and 15 per cent for car transport, leading to indirect rebound effects of 92 per cent for transport and 83 per cent for heating.

Thomas and Azevedo (2013a, 2013b) provide an alternative method to jointly simulate direct andindirect rebound effects by integrating input-output (IO) life cycle assessments of the energy and emissions embedded in various goods and services and econometric estimates of the direct rebound effect. They find that for the average US household, rebound effects from energy efficiency investments measured in terms of primary energy or carbon dioxide emissions are 5–15 per cent, assuming a 10 per cent direct rebound, or a combined rebound effect of 15–25 per cent. They also find significant sources of variation in the rebound effect from electricity efficiency, due to the US household's income-elastic demand for driving, electricity prices and electricity grid emissions factors.

Druckman *et al.* (2010) have shown that indirect rebound effects apply even for conservation measures, where there are no price or direct rebound effects. They find wide ranges of possible rebound effects from re-spending conservation savings on high-energy intensity goods. These typically range from 7–51 per cent, but in one case reach 515 per cent. They conclude that policymakers should play a role in shifting consumer spending towards less energy-intensive areas to reduce the indirect rebound effect.

Lecca *et al.* (2011) have also studied indirect rebound effects in the consumption sector in the UK. They find that the key determinants of the indirect rebound effect include the shift in consumer demand into non-energy goods and services and out of energy, triggered by the efficiency investment, which can crowd out export demand, leading to a decline in the country's competitiveness unless the increase in real income with the efficiency investment leads to a decline in household wage demand. In addition, they find that the decline in energy demand following an efficiency investment could trigger a negative multiplier effect throughout the economy, due to the decline in revenue and disinvestment in the energy supply sector.

The literature has identified both large positive (greater than 100 per cent) as well as negative drivers of the indirect rebound effect. However, the indirect rebound effect is likely to depend on the economy under study and most of these drivers have not been thoroughly investigated across a broad number of economies. In addition, prior work has been largely parametric; empirical research on the magnitude of elasticities relevant to indirect rebound effects is needed.

Despite these uncertainties, when all relevant factors, such as capital costs, are considered, there is limited evidence of backfire (rebound greater than 100 per cent) from energy efficiency investments in households.

The economy-wide rebound effect describes a wide range of effects at the macroeconomic level. Greening *et al.* (2000) defined “secondary effects,” or what is now called the “economy-wide rebound effect” as “the interrelationship of prices and outputs of goods and resources in different markets […]. Any shift in the determinants affecting one good [such as efficiency] may have widespread repercussions on the equilibrium prices and outputs of other goods.”

Turner (2009) provides an updated classification of economy-wide rebound effects in terms of the familiar substitution and income effects, as well as mechanisms which would lead to a positive economy-wide rebound such as the “composition effect,” which describes a change in aggregate output “as relatively energy-intensive products benefit more from the fall in effective and/or actual energy prices,” and the output/competitiveness effect, which describes an industry’s increase in international competitiveness as a result of the fall in energy prices that might occur with an investment in energy efficiency. In addition, Turner identifies a mechanism for a negative economy-wide rebound called the “disinvestment effect” which, in the decline in energy prices following an investment in efficiency leads to a reduction in resource production capacity, thereby exerting upward pressure on energy prices.

The economy-wide rebound effect is generally studied using computational general equilibrium (CGE) models. These models usually focus on the production side of an economy, and how input and output demand relationships between sectors of the economy change as a result of price changes and economic growth. They often assume non-linear production functions (e.g. constant elasticity of substitution or trans-log) and require tuning of elasticities of substitution for all covered sectors (Sorrell, 2007).

A key parameter of interest in these CGE studies is the elasticity of substitution between energy and other factors of production (capital, labour, etc.). Saunders (2000) argues that as the elasticity of substitution for energy increases, rebound and backfire are more likely. However, Allan *et al.* (2006) note that the elasticity of substitution for energy is not the only determining factor for the rebound effect, defined as the efficiency elasticity of the demand for energy services (Khazzoom, 1980), and argue that demand sector responses, openness of the economy under study, time frame of analysis, and elasticity of other production inputs will also be important. Allan *et al.’s* (2006) analysis assumes that energy efficiency will lead to measurable and significant changes in energy prices, and hence the focus on price elasticities of energy. However, it is an empirical question as to whether energy efficiency has led to changes in energy prices in an economy, and requires further investigation.

Saunders (2008) demonstrates the relationship between the rebound effect, as defined by Khazzoom (1980), and elasticity of substitution for energy for a variety of non-linear production functions, and finds that the shares of energy and labour in the production function are also key factors in the short-run and long-run rebound effects. Saunders (2010, see Saunders’ “think piece”) has measured “rebound effects” that vary widely by productive sector, based on the historical rate of technological progress in factors of production such as energy, labour and capital. However, Saunders measures energy efficiency as a “technology gain” parameter in factors of production such as capital, labour, energy and materials from an econometric model of production factoring in prices and production costs. This measure of “technological gain” differs substantially from the representation of exogenous, costless, energy efficiency in other CGE models of rebound effects. Consensus on the relationship between Saunders’ measure of technological gain and measures of energy efficiency in factors of production are yet to be established and are likely to be the focus of future research. The few GCE studies of the economy-wide rebound effects vary widely in their region of study, economic assumptions and how efficiency improvements are modelled, as seen in Figure 2.

Some economy-wide rebound studies also use input-output models, which assume linear production functions and fixed prices to model marginal changes in demand, coupled with optimisation models (Howells *et al.*, 2007) or CGE models (Guerra and Sancho, 2010). Howells *et al.* (2007) focused on the carbon dioxide emissions rebound from nuclear power plant investments using a hybrid input-output and optimisation approach. They used the goals for future emissions intensity from five-year plans for the Republic of Korea’s electricity sector for the potential energy savings baseline, and emissions data obtained from the input-output multipliers from different benchmark years of input-output data tables for the Republic of Korea coupled with an energy sector optimisation model which modelled future investments in power plants to project annual energy savings in each year. They found that a measurable emissions rebound of 12 per cent was possible over the model time frame. However, the authors’ approach is limited to long-run energy supply rebound effects, and cannot be applied to investigating efficiency improvements in energy consumption, as they acknowledge.

Guerra and Sancho (2010) argue that engineering-economic estimates of potential energy savings are biased because they occur within a partial equilibrium framework that does not take into account the energy embodied in intermediate goods. Thus, they estimate actual energy savings with a CGE model, which takes into account any changes in energy prices that might occur due to economy-wide efficiency investments, and adjusts potential energy savings with an input-output model, which represents the general equilibrium with the limitation that prices are held constant, by representing a parametric efficiency improvement (perhaps obtained from an engineering-economic estimate) as a reduction in the intermediate use of energy in both the CGE and IO models. They find that using an engineering-economic estimate of PES underestimates the rebound effect in cases when rebound is under 100 per cent and overestimates the rebound effect in the case of backfire (rebound greater than 100 per cent). Guerra and Sancho's approach is also limited to modelling efficiency in the production sector and is unable to account for rebound effects due to consumer investments affected by energy efficiency standards or electric utility-run demand-side management programmes.

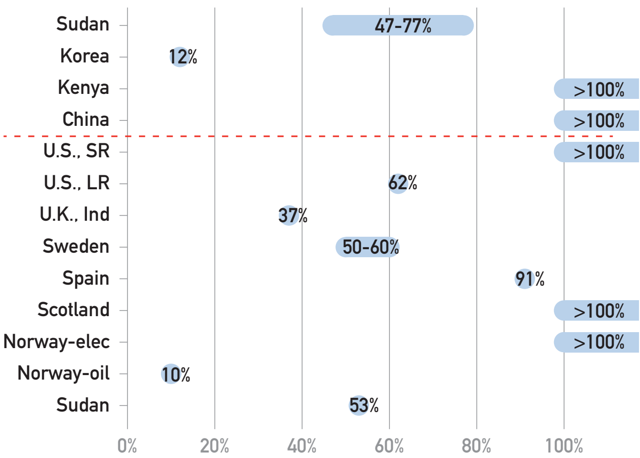


Figure 1. Economy-wide rebound estimates vary by country

Sources: Various studies reviewed in Sorrell (2007), Republic of Korea estimated from Howells et al. (2007), Spain estimated from Guerra and Sancho (2010), US estimated from Saunders (2010).

From the range of methods and simulations, we find that the economy-wide rebound effect will vary considerably by country and region depending on the production function specifications of the CGE model, types of industries in the economy under study and the elasticity of substitution between energy and other productive factors for these industries. Allan *et al.* (2007) note "there is no consensus in the CGE literature on where the appropriate place for energy is in the production structure." In addition, "Devarajan and Robinson (2002) argue that there is a natural tension between a desire for transparency on the one hand, and perhaps use of stylized models, and the policy requirement for sectoral and institutional detail provided by a large and more complex model" (in Allan *et al.*, 2007). There is an urgent need for more communication from CGE modellers to non-CGE users on key assumptions for elasticities and overall structure of these models so that an open and transparent discussion can take place.

It is also the case that some of the rebound effect described above induces additional utility or welfare. Estimates of the impacts of energy efficiency rebound effects on welfare have not been adequately studied and are a critical area of research needed for this discussion.

6 Rebound effects in developing countries and economies in transition

Energy consumption in developing countries and economies in transition is likely to increase as income increases, energy prices decrease and technologies with improved performance and efficiency become available and affordable. The drivers and impacts of energy demand in developing countries are largely understudied. Some authors will attribute much of the growth in energy demand in developing countries and economies in transition to the "rebound effect", but that is a very loose definition of rebound (i.e., whatever driver that leads to an increase in energy consumption). A strict definition of the rebound effect, as described by Khazzoom (1980) and Henly *et al.* (1988), would hold constant income, energy prices and technology performance attributes, and would examine the increase in energy consumption caused solely by the use of technologies with improved energy efficiency. The focus on "improved energy efficiency" implies that a product with similar performance attributes but lower efficiency was already available in the marketplace. Even with no improvement in energy efficiency, energy use will increase as incomes rise and new products become available in the market, so it is important to control for these factors in studies of the rebound effect in developing countries.

By either rebound definition, there has been limited serious analysis for the rebound effect in economies in transition countries. However, it is precisely in these economies, in which the desire for basic goods and services is not adequately met, that the potential for energy demand growth and "rebound" is probably the greatest. If more affordable technology for services such as lighting or transport is introduced in a developing economy, use will almost certainly increase. So will the utility and welfare enjoyed by the consumers of that economy. Such utility increases presumably also occur in many of the examples of rebound discussed in the sections above, and are all too often ignored in the literature on rebound.

Below, we highlight three studies that evaluate energy efficiency programmes in developing countries that attempt to estimate the direct rebound effect.

One study focused on India (Roy, 2000) found mixed evidence of the rebound effect. For example, when the Ministry of Rural Energy Sources (MRES) gave rural households free solar PV (SPV) lanterns as a means to reduce kerosene lamp consumption, scholars found that lighting demand increased from 2 hours per day to 4–6 hours per day, and kerosene lamps were still used at times when the SPV lanterns were not operational. Scholars measured a 50–80 per cent rebound effect in kerosene consumption as a result of this programme. However, Roy (2000) notes that the presence of kerosene supply constraints, unmet demand for lighting, free provision of the efficient lantern and large subsidies for kerosene as other possible reasons for the large rebound effect in the lighting case study.

Davis *et al.* (2012) conduct an econometric study of the "Cash for Coolers" incentive programme for efficient refrigerators and air conditioners in Mexico. Their evaluation of the incentive programme finds that refrigerator replacement results in a 7 per cent decrease in monthly electricity consumption but that air conditioner replacement leads to a net increase in electricity consumption. This would imply a 93 per cent shortfall in expected energy savings for refrigerator investments and a greater than 100 per cent shortfall (backfire) from air conditioner investments. However, these measured shortfalls in energy savings include both rebound effects (i.e. changes in consumer demand for energy services) and miscalibrated engineering models of energy savings. In particular, since a refrigerator has a set number of operating hours (24 hours/day), miscalibrated engineering savings estimates seems to have played a large role in the outcomes of this programme. The authors also note that by design, the "Cash for Coolers" programme did not have stringent eligibility standards for qualifying efficient appliances and non-functioning baseline appliances may have also contributed to net increases in air conditioning usage.

Wang *et al.* (2012) study the direct rebound effect for passenger transport in urban China through an "almost ideal demand system" econometric framework, similar to Brännlund *et al.* (2007) and Mizobuchi (2008). Wang *et al.* (2012) estimate a national average rebound effect for transport of 96 per cent, with significant regional variation ranging from 2 per cent direct rebound in Shanghai to 246 per cent in Jilin province. However, the translation from price and income elasticities to direct rebound effect estimate was not made transparent.

In addition, there are a few studies, which estimate price and income elasticities for specific energy services. These price elasticities can provide at least a first proxy for direct rebound effects, and using price and income elasticities one could develop a first order estimate of indirect rebound effects. However, the limitation is that once again most of these studies focus on developed economies. For example, Baltagi *et al.* (1997) analysed the price elasticity of petrol consumption in OECD countries using several models and estimators. Lee and Lee (2010) estimated the income and price elasticity of total demand for energy and total demand for electricity in 25 OECD countries, using panel co-integration techniques, unit root techniques and panel causality techniques. Yet a different class of studies uses bottom-up approaches, using generally household data on energy consumption by different appliances and end-uses. Fouquet (2012) suggests that future elasticities in developed economies may gradually decline. Fouquet also argues that transportation demand elasticities are likely to decline more rapidly in developing economies as the economies develop.

While the goal of this report is not to provide an extensive review of the price and income elasticity estimates for developing countries, in Table 2 we show a few examples reported in Lee and Lee (2010) regarding studies focusing on economies in transition or developed countries (for countries that were under that category at the time the referenced study was performed) from the literature of energy demand.

Table 2. Estimates of price and income elasticity for energy in developing countries and economies in transition from previous studies (adapted from Lee and Lee, 2010)

Authors	Country	Period	Price elasticity	Income elasticity
Dhungel (2003)	Nepal	1980–1999	-3.45–1.65	3.04
Galindo (2005)	Mexico	1965–2001	-0.43–0.07	0.45–0.64
Holtedahl and Joutz (2004)	Taiwan, China	1957–1995	-0.15	1.57
Kulshreshtha and Parikh (2000)	India	1970–1995	-0.66–0.12	0.67–1.57

From the point of view of global strategy to limit the emissions of carbon dioxide and other greenhouse gases, there is a clear and urgent need for studies of rebound in developing economies. The magnitude of rebound that is likely to be observed in these studies will probably be much larger in some cases than the analogous values observed in the industrialised world. The policy implication of such results should not be to limit the introduction of energy efficient technologies across the developing world. Rather such results should be seen as reinforcing the need to search for strategies in both the industrialised and the developing world that support the provision and growth of social well-being, without doing major harm to the environment.

We also note that while some policies are designed in terms of energy intensity and decoupling energy consumption from economic growth. However, in this report, when referring to energy efficiency, we are focusing in improving the conversion process from primary energy to useful energy services.

7 The integration of rebound effects in energy scenarios and models

Energy scenarios and energy models are widely used as tools to support analysis and decision-making in the context of energy and climate policy. However, the sophistication with which rebound is included in such work is at best modest.

While scenarios can be helpful, Morgan and Keith (2008) have argued that as a result of psychological phenomena such as "availability", scenarios can often also be misleading. Many past scenarios have not incorporated a consideration of rebound; while those that have typically have done so through the incorporation of assumptions about price-demand elasticities.

To the extent that rebound is fully captured through estimates of elasticities, partial and general equilibrium models include rebound by definition. The same is true in a number of other integrated assessment models. For example, rebound effects can be explored by modifying a parameter in the MARKAL/TIMES family of models.

For further information on the integration of rebound effects in energy scenarios and models, please also refer to the "think pieces" by Naegler and Vögele.

8 Do drivers for energy efficiency affect rebound effects?

One research gap in the existing research literature is whether direct, indirect and economy-wide rebound effects depend on the nature of the specific policy mechanism or process that leads to an energy efficiency improvement.

In this section, we highlight how different processes and policies resulting in an increase in energy efficiency have not been carefully tackled in the empirical literature and should be incorporated in the rebound discussion and analysis.

For example, most of the empirical literature estimating direct rebound effects uses price elasticities as a proxy for direct rebound. However, doing so ignores the fact that in many cases there is the initial cost associated with the purchase of an energy efficient technology. Thus, the empirical estimation of the neoclassical model for consumer behaviour needs to account for the total costs of ownership. This aspect is generally ignored in most econometric analysis that estimates the direct rebound effects. Similarly, if an energy efficiency measure is implemented through energy efficiency or demand side management programmes that provide incentives or subsidies for a particular technology, it must be included in the total ownership costs and accounted for as rebound effects are estimated.

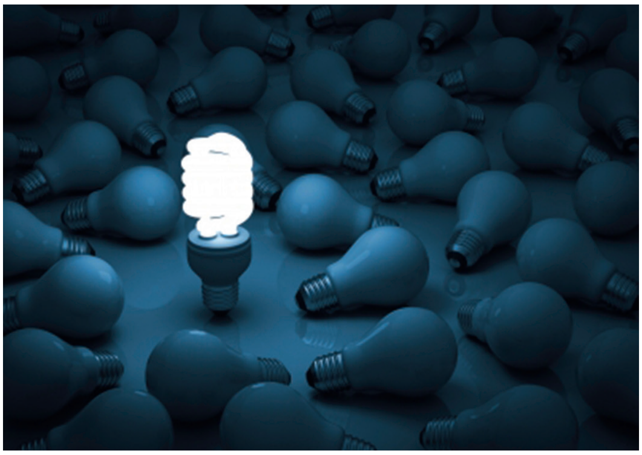
In studies of direct, indirect and economy-wide rebound effects the following issue arises: the studies have as a starting point that an energy efficiency measure is implemented, or, in the case of CGE models, there is an improvement in total factor productivity. However, this stands in contrast to the energy efficiency literature that describes the energy efficiency gap, i.e., as we described in Section 3, the fact that consumers very often do not choose the technologies that are the most energy efficient and cost-effective.

Methodological approaches that include behaviourally realistic consumer decision-making models, considering issues such as the influence of incentives or subsidies, market failures and barriers to energy efficient technology adoption, coupled with assessment of rebound effects, are lacking in the literature and need to be developed.

9 Policy implications

The evidence to date from econometric studies that generally use price elasticity, income elasticity and elasticity of substitution suggests that direct and indirect rebound effects in developed economies are moderate and that investments in energy efficiency can save between 70 and 85 per cent of the anticipated energy reduction, while allowing households to enjoy the benefits of higher consumption.. Such moderate rebound effects would imply that energy efficiency policies such as utility energy efficiency programmes, appliance and vehicle efficiency standards, energy efficiency resource standards, and rebates and tax credits for energy efficiency all will produce energy savings, although not as much as an engineering analysis would suggest. However, rebound assessments should be incorporated in the development of these energy efficiency policy instruments, so that realistic forecasts of their cost and effectiveness can be made.

However, as we highlight in Section 8, there is a large gap in the literature on how different drivers for energy efficiency may lead to different important outcomes related to rebound effects. For example, when minimum energy standards are implemented, the consumer cannot choose between a "baseline" (a more inefficient) technology and the efficient substitute: the inefficient version simply stops being available. This is the case with the minimum efficiency standards for lighting currently in place in several countries. Other policy mechanisms, such as energy efficiency subsidies and rebates will encompass welfare transfers. The consequences of energy efficiency policy designs (standards, substitutes and rebates, other market based mechanisms) on consumer behaviour and choice need to be further studied both using economic and other social sciences approaches.



On the basis of the outcomes of the two workshops and the several "think pieces" prepared by participants, this section summarises policy implications for coping with rebound effects:

1. Economists often propose reducing the externality of energy use by increasing energy prices (by introducing energy taxes, carbon prices, etc.). Other strategies include "energy budgets" or "caps" placed on energy consumption ("think pieces" by Golde, Frondel and Vance, and Sorrell). If all negative externalities could be incorporated in the energy price, the only rebound effects would be those that improve welfare.

2. Rebound effects are neglected or insufficiently included in many energy scenarios and models. This omission raises the risk of underestimating future energy demand. Including rebound effects is difficult because knowledge in specific contexts is still uncertain. Some scenarios and models take into account rebound effects implicitly, but use a different wording. Here, clear definitions and a common wording are needed (Naegler and Vögele "think pieces").

3. Among middle- and upper income consumers in the US who display lower price elasticities, direct rebound effects appear to be modest, falling in the range of 3 per cent (in the short-run) to 22 per cent (in the long-run) for transportation (Small and van Dender, 2005), and 29–37 per cent for residential electricity demand in the US (Reiss and White, 2005) (see Section 5).

4. There is very little evidence of rebound effects exceeding 100 per cent (backfire) for household energy efficiency investments in developed countries (see Section 6).

5. Rebound effects can be large in the developing world, among low income groups, and could be large in the production sector of the economy; there has been too little study of these groups ("think pieces" by Chi, Polimeni and Thomas). Especially in developing countries and low income groups, it is crucial to gain a better understanding of the extent to which rebound effects lead to enhanced individual well-being and desirable socio-economic or macroeconomic co-benefits ("think piece" by Golde).

6. It is important that policymakers understand that their policy strategies to increase the energy efficiency of goods and services may not be as effective as simple direct analysis suggests. At the same time, care should be taken that energy efficiency policies are not called into question in general. Energy efficiency policies could be improved by explicitly taking into account rebound effects.

7. In situations in which empirical analysis suggests that rebound effects are greater than a few per cent, these effects should be considered in the design of policy programmes (see for example the Fong and Golde "think pieces").

8. The UK systematically takes into account direct rebound effects (i.e. people increase the temperature of their homes due to financial savings from installed energy efficiency measures in building designs). The US Environmental Protection Agency (EPA) also assumes a 10 per cent rebound effect in vehicle miles travelled in assessing the regulatory impacts of fuel economy standards (2009). Elsewhere, rebound effects are generally neglected in policymaking. As more countries begin to pursue serious energy efficiency policies, the consideration of rebound effects will become increasingly important.

9. For local or regional energy efficiency policies such as utility efficiency programmes and state-level energy efficiency resource standards, energy savings estimates from engineering estimates should be reduced by the estimate of the direct rebound effect. Energy demand changes from indirect and economy-wide rebound effects are not yet attributable at less than national scales.

10. For national energy efficiency policies such as appliance and vehicle standards and rebates and tax credits for energy efficiency, engineering estimates of energy savings should be reduced by estimates of the direct and indirect rebound effect. However, it is also important to account for the improvement in household well-being or increase in firms' profits that is possible from re-spending energy cost savings for greater consumption or production.

11. Intervention strategies, such as the introduction of feedback mechanisms on energy consumption (smart metering) or contracting models for heating etc., promise to foster energy conservation behaviour. However, in order for them to lead to significant changes in consumer changes, multiple intervention strategies must be applied (Ehrhardt-Martinez *et al.*, 2010b).

Please note that the "think pieces" by Fong, Gloger, Golde and von Rheinbaben explicitly refer to policy implications arising from the issue of rebound effects.

10 Research roadmap

Given the growing emphasis that decision-makers are placing on promoting energy efficiency as a strategy to deal with growing energy costs, limited supplies and greenhouse gas emissions, it is critically important to develop a better understanding of the nature, determinants and magnitude of rebound. Based on our review of the literature and the deliberations in the two workshops, we identify the following research needs:

To better understand energy demand and its drivers

- **Improved understanding of the drivers of demand.** We do not yet adequately understand the factors that shape the demand of individuals, firms and others for energy services. We need empirical research that better articulates those factors, on a cross-national basis, especially integrating behavioural and cultural factors. Without this, programmes to promote greater energy efficiency will not be able to anticipate likely consequences.

- **Develop an improved taxonomy of factors shaping energy demand.** As this report has made clear, too many different processes have been lumped under the general heading of "rebound". Research is needed that provides a clear classification of the many factors that shape energy use, a subset of which may be rebound, so that comparison of study designs and results becomes easier.

- **Better and more sophisticated treatment of rebound in energy use scenarios and in energy models.** Some energy models include parametric treatment of rebound. CGE models incorporate rebound to the extent that this is the result of decisions made by rational utility-maximising actors. Our observations are that neither of these approaches is sufficient. Once a better understanding of rebound has been developed, it needs to be incorporated into improved energy use scenarios and in energy models.

To collect data and estimate direct and indirect rebound effects

- **Collection of data that allow studies of neglected sectors and developing economies.** The majority of studies on energy demand and rebound have focused on individual consumers in industrialised economies. Efforts are needed to assemble data sets that will allow similar studies in commercial and industrial sectors and in developing economies.

- **Econometric and other studies of rebound in commercial and industrial sectors.** As better data on these sectors become available, especially at the firm level, research is needed on how they respond to new technologies and prices. Even without improved data sets some research with aggregate data should be possible today.

- **Econometric and other studies of rebound in developing economies.** There is reason to believe that growth in energy demand, and perhaps rebound, may be largest in developing economies in which there is enormous unmet demand for energy services. Research is needed on rebound in developing economies. Even without improved data sets, some research should be possible today.

- **Improved empirical measures of technological change and energy efficiency.** Recent literature differs in measurements and in assumptions about the triggers of rebound effects, with some analysts focusing on technological gains in factors of production while others focus on engineering efficiency gains. Empirical research distinguishing energy efficiency improvements from other technological improvements at the production sector- or energy service-level is needed.

To understand better the rebound effect in developing countries

- While better data are needed, even without improved data sets some additional research should be possible today.

To understand better economic and social consequences

- **Econometric and other studies of relationship between energy efficiency and energy prices.** Much of the CGE literature assumes that energy efficiency leads to a measurable decrease in overall energy prices or other prices of the economy, despite the fact that energy is a small portion of household consumption and a small portion of the production function for many sectors. Empirical research is needed to understand if there is any causal relationship between investments in energy efficiency and market prices for energy, distinguishing between efficiency versus supply and demand drivers of energy prices.

- **Clearer articulation of the role of welfare benefits.** Too much past research on energy efficiency has treated rebound as a negative externality of energy efficiency investments without considering the fact that, in many cases, the resulting increased use of energy is simultaneously the source of considerable improvements in social welfare (see for example Saunders, 1992). More research is needed that adopts a multi-objective perspective.

To identify efficient policy and intervention strategies

- **Improved study of the design of rebound-robust efficiency policies and intervention strategies.** In industrialised economies efforts should be made to identify energy intensive end-uses where usage is not likely to change much before and after the energy efficiency intervention. Intervention strategies such as economic incentives, consumer feedback mechanisms and behavioural programmes to shift attitudes and habits should be studied for effectiveness in counteracting changes in energy usage and consumption patterns that occur with rebound effects.

Appendix 1

"Think pieces"/presentations for the first Energy Efficiency and the Rebound Effect Workshop, AAAS Building, Washington, DC, 27–28 June 2011

Note to reader: The agenda and think pieces are available at http://cedm.epp.cmu.edu/reboundpresentations.php.
If the hyperlinks below are not active, please contact the IRGC Secretariat at info@irgc.org for a pdf copy.

Ines Azevedo: "Energy Efficiency and the Rebound Effect"
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Ines%20Azevedo.pdf

Michael Blackhurst: "The direct rebound effect"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Michael%20Blackhurst.pdf

Cheryl Chi: "The Rebound effect in the Chinese context"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Cheryl%20Chi.pdf

Danny Cullenward: "Lessons from the U.S. Industrial Sector: Limitations of Existing Data and Methods"
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Danny%20Cullenward.pdf

Hadi Dowlatabadi: "Aligning consumer decisions and sustainability objectives: energy efficiency in the residential retrofit market"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Hadi%20Dowlatabadi.pdf

Michael Dworkin: "Energy efficiency rebound: A little bit of data makes the hypothesis go down"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Michael%20Dworkin.pdf

Paul Fischbeck: "Rebound and Transportation: In search of the ultimate dataset"
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Paul%20Fischbeck.pdf

John Graham: "Does the Rebound Effect Matter? It Depends…"
http://cedm.epp.cmu.edu/ReboundMeeting2011/John%20Graham.pdf

David Greene: "Rebound Effects in Transportation"
http://cedm.epp.cmu.edu/ReboundMeeting2011/David%20Greene.pdf

Mike Griffin: "Rebound effect, alternative fuels and LCA"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Griffin.pdf

Kevin Hassett: "Rebound Effects and Attic Insulation"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Kevin%20Hassett.pdf

Chris Hendrickson: "A Perspective on 'Rebound' Effects and Demand/Supply Equilibrium"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Chris%20Hendrickson.pdf

Jesse Jenkins: "Hot topic: Does energy efficiency lead to increased energy consumption?"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Jesse%20Jenkins.pdf

Bob Kopp: "Macro economic rebound, Jevons Paradox and economic development"
http://cedm.epp.cmu.edu/ReboundMeeting2011/Bob%20Kopp.pdf

Skip Laitner: “Energy efficiency policies and the rebound effect”
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Skip%20Laitner.pdf

Christa McDermott: “It’s ok, honey, we’re an 8! The potential for rebound in a residential energy efficiency program”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Christa%20McDermott.pdf

Bob Nordhaus: “Conservation, energy efficiency, and GHGs: some questions”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Robert%20Nordhaus.pdf

John Polimeni: “The Jevons Paradox in Transitional and Developing Countries: Questions to be Addressed”
http://cedm.epp.cmu.edu/ReboundMeeting2011/John%20Polimeni.pdf

Ortwin Renn and Marco Sonnberger: “Can behavioral and social aspects of rebound effects be a starting point for policy interventions?”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Ortwin%20Renn%20Marco%20Sonnberger.pdf

Costa Samaras: “The Rebound Effect in Transportation: Understanding the Important Implications for Climate Change”
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Costa%20Samaras.pdf

Alan Sanstad: “Frontiers of research in energy efficiency”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Alan%20Sanstad.pdf

Harry Saunders: “U.S. Economy-wide rebound”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Harry%20Saunders.pdf

Jon Strand: “”Virtual rebound effects_” with emphasis on long term infrastructure investments, and their interaction with absolute (ordinary) rebound effects”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Jon%20Strand.pdf

Jim Sweeney: “Bounding the Rebound Effect: Key Conceptual Issues and a Framework for Estimation”
http://cedm.epp.cmu.edu/ReboundMeetingFinals/Jim%20Sweeney.pdf

Brinda Thomas: “Economic input-output life-cycle assessment methods for estimation of indirect rebound effects”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Brinda%20Thomas.pdf

Jeff Tsao: “Lighting, Energy Consumption, and Human Productivity”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Jeff%20Tsao.pdf

Karen Turner: “An Overview of Rebound Research and Policy Focus in the EU”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Karen%20Turner%201.pdf

Karen Turner: “Determinants and potential magnitude of economy-wide rebound effects: overview of key findings from a research project funded by the UK Economic and Social Research Council”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Karen%20Turner%202.pdf

Elena Verdolini: “A tassel in the study of technological change dynamics”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Elena%20Verdolini.pdf

Ed Vine: “The rebound effect and energy efficiency programs: an evaluator’s perspective”
http://cedm.epp.cmu.edu/ReboundMeeting2011/Ed%20Vine.pdf

Appendix 2

“Think pieces”/presentations for the second “Energy Efficiency Policies and the Rebound Effect Workshop”, Kongresshotel Europe, Stuttgart, 13–14 October 2011

Note to reader: The agenda and think pieces are available at: http://cedm.epp.cmu.edu/Stuttreboundpresentations.php.
If the hyperlinks below are not active, please contact the IRGC Secretariat at info@irgc.org for a pdf copy.

Patty Fong: “Policies to Overcome the Rebound Effect”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Fong.pdf

Manuel Frondel and Colin Vance: (after Steve Sorrel)
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Frondel,%20Vance.pdf

Stefan Gloger: “Policies to overcome the rebound effect - a new challenge for environmental policy”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Gloger.pdf

Michael Golde: “Policies to Overcome the Rebound Effect”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Golde.pdf

Florian Kaiser: “Frugality: Psychology’s ultimate challenge to prevent rebound effects”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Kaiser.pdf

Reinhard Madlener: “Steigerung der Energieeffizienz: Problem oder Lösung?”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Madlener,%20Alcott.pdf

Tobias Naegler: “Possibilities to include rebound effects in energy scenarios”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Naegler.pdf

Constanze von Rheinbaben: (after Stefan Gloger)
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20von%20Rheinbaben.pdf

Steve Sorrell: “Some thoughts on rebound effects”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Sorrell.pdf

Brinda Thomas: “Estimating direct and indirect rebound effects for U.S. households”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Thomas.pdf

Karen Turner: “Supply-side Determinants and Potential Magnitude of Economy-wide Rebound Effects:
Overview of Key Findings from a Research Project Funded by the UK Economic and Social Research Council”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Turner.pdf

Stefan Vögele: “Integration of Rebound Effects in Scenario Analysis”
http://cedm.epp.cmu.edu/StuttReboundMeeting2011/Rebound%20Think%20Piece%20-%20Vigele.pdf

References

[ACEEE, 2011] American Council for an Energy Efficient Economy, Recovery and Reinvestment Act of 2009, http://www.aceee.org/topics/arra

[Ajzen, 1991] Ajzen, I., "The theory of planned behaviour", *Organizational Behaviour and Human Decision Processes*, vol. 50, no. 2, 179–211.

[Alcott, 2004] Alcott, B., "John Rae and Thorstein Veblen", *Journal of Economic Issues*, vol. 38, no. 3, 765–786.

[Allan *et al*., 2006] Allan, G., Hanley, N., McGregor, P., Swales, K. and Turner, K., *The macroeconomic rebound effect and the UK economy*, Report to Department of Environment, Food and Rural Affairs (DEFRA).

[Allan *et al.,* 2007] Allan, G., Gilmartin, M. and Turner, K., *UKERC Review of Evidence for the Rebound Effect. Technical Report 4: Computable general equilibrium modelling studies,* Working Paper, UK Energy Research Centre.

[Anderson and Claxton, 1982] Anderson, C. and Claxton, J., "Barriers to consumer choice of energy efficient products", *Journal of Consumer Research*, vol. 9, no. 2, 163–170.

[Attari *et al.,* 2010] Attari, S.Z., DeKay, M.L., Davidson, C.I. and Bruine de Bruin, W., *Public perceptions of energy consumption and savings,* Proceedings of the National Academy of Sciences, vol. 107, no. 37, 16054–16059.

[Azevedo, 2009] Azevedo, I.L., *Energy Efficiency in the U.S. Residential Sector: An Engineering and Economic Assessment of Opportunities for Large Energy Savings and Greenhouse Gas Emissions Reductions*, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, (PhD thesis).

[Azevedo *et al.,* 2011] Azevedo, I.L., Morgan, M.G. and Lave, L., "Residential and regional electricity consumption in the US and EU: How much will higher prices reduce CO_2 emissions?", *The Electricity Journal*, vol. 24, no. 1, 21–29.

[Azevedo *et al.,* 2013] Azevedo, I.L., Morgan, M.G, Palmer, K., and Lave, L., "Reducing U.S. residential energy use and CO_2 emissions: how much, how soon, and at what cost?", in press at *Environmental Science & Technology*.

[Baltagi and Griffin, 1997] Baltagi, B.H. and Griffin, J.M., "Pooled estimators vs their heterogenous counterparts in the context of dynamic demand for gasoline", *Journal of Econometrics*, 77, 303–327.

[Barker and Foxon, 2008] Barker, T. and Foxon, T., *The Macroeconomic Rebound Effect and the UK Economy*, Research Report, UK Energy Research Centre.

[Berkhout *et al.,* 2000] Berkhout, P.H.G., Muskens, J.C. and Velthuijsen, J.W., "Defining the rebound effect", *Energy Policy*, vol. 28, 425–432.

[Binswanger, 2001] Binswanger, M., "Technological progress and sustainable development: what about the rebound effect?", *Ecological Economics*, vol. 36, no. 1, 119–132.

[Blumstein *et al*., 1980] Blumstein, C., Krieg, B. *et al*., "Overcoming social and institutional barriers to energy conservation", *Energy*, vol. 5, no. 4, 355–371.

[Blumstein and Stoft, 1995] Blumstein, C. and Stoft, S.E., "Technical efficiency, production functions and conservation supply curves", *Energy Policy*, 23, 9, 765–768.

[Bohi and Zimmerman, 1984] Bohi, D. and Zimmerman, M., "An Update on Econometric Studies of Energy Demand Behavior", *Annual Review of Energy*, vol. 9, 105–154.

[Brand, 2009] Brand, K.W., "Social Practices and Sustainable Consumption: Benefits and Limitations of a New Theoretical Approach", in *Environmental Sociology: European Perspectives and Interdisciplinary Challenges*, Gross, M. and Heinrichs, H. (eds), Dordrecht, Heidelberg, London, New York, Springer, 217–235.

[Brännlund *et al*., 2007] Brännlund, R., Ghalwash, T. and Nordström, J., "Increased energy efficiency and the rebound effect: Effects on consumption and emissions", *Energy Economics*, vol. 29, no.1, 1–17.

[Brookes, 1979] Brookes, L., "*A low energy strategy for the UK* by G. Leach *et al*., a review and reply", *Atom*, no. 269.

[Brookes, 1990] Brookes, L., "The greenhouse effect: the fallacies in the energy efficiency solution", *Energy Policy*, vol. 18, 199–201.

[Brookes, 2000] Brookes, L., "Energy efficiency fallacies revisited", *Energy Policy*, vol. 28, 355–366.

[Brown, 2001] Brown, M., "Market failures and barriers as a basis for clean energy policies", *Energy Policy*, vol. 29, no. 14, 1197–1207.

[Brown, 1993] Brown R.E., "Estimates of the Achievable Potential for Electricity Efficiency in U.S. Residences", University of California, Berkeley, (MA thesis), LBNL-44869.

[Brown *et al.,* 1998] Brown, M.A., Levine, M.D., Romm, J.P., Rosenfeld, A.H. and Koomey, J., "Engineering-economic studies of energy technologies to reduce greenhouse gas emissions: Opportunities and challenges", *Annual Review of Energy and the Environment*, 23, 287–385.

[Dahl and Sterner, 1991] Dahl, C.A. and Sterner, T., "Analysing Gasoline Demand Elasticities: A Survey", *Energy Economics*, vol. 13(3), 203–210.

[Davis, 2008] Davis, L.W., "Durable Goods and Residential Demand for Energy and Water: Evidence from a Field Trial", *RAND Journal of Economics*, vol. 39, no. 2, 530–546.

[Davis *et al.,* 2012] Davis, L., Fuchs, A. and Gertler, P., *Cash for Coolers*, National Bureau of Economic Research Working Paper no. 18044.

[de Haan, 2008] de Haan, P., *Identification, quantification, and containment of energy-efficiency induced rebound effects: A research agenda,* Rebound Research Report 1, ETH Zürich.

[de Hann *et al*., 2006] de Haan, P., Mueller, M.G. and Peters, A., "Does the hybrid Toyota Prius lead to rebound effects? Analysis of size and number of cars previously owned by Swiss Prius buyers", *Ecological Economics,* vol. 58, no. 3, 592–605.

[Devarajan and Robinson, 2002] Deverajan, S. and Robinson, S., *The influence of computable general equilibrium models on policy*, TMD Discussion Paper no. 98.

[Dhungel, 2003] Dhungel, K.R., "Income and price elasticity of the demand for energy: A macro-level empirical analysis", *Pacific and Asian Journal of Energy*, 13(2): 73–84.

[Druckman *et al.,* 2010] Druckman, A., Chitnis, M., Sorrell, S. and Jackson, T., *An investigation into the rebound and backfire effects from abatement actions by UK households,* RESOLVE Working Paper 05-10, Guildford, University of Surrey.

[Ehrhardt-Martinez and Laitner, 2010a] Ehrhardt-Martinez, K. and Laitner, J.A. "Skip", "Rebound, Technology, and People: Mitigating the Rebound Effect with Energy-Resource Management and People-Centered Initiatives", in *People-Centered Initiatives for Increasing Energy Savings*, Ehrhardt-Martinez, K. and Laitner, J.A. "Skip" (eds), Washington, DC, American Council for an Energy-Efficient Economy, 80–89.

[Ehrhardt-Martinez *et al*., 2010b] Ehrhardt-Martinez, K., Donnelly, K. and Laitner, J.A. "Skip", *Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities*, Washington, DC, American Council for an Energy-Efficient Economy.

[EPA, 2009] Environmental Protection Agency, United States, *Proposed Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards*, EPA-420-D-09-003.

[Espey and Espey, 2004] Espey, J. and Espey, M., “Turning on the Lights: A Meta-Analysis of Residential Electricity Demand Elasticities”, *Journal of Agricultural and Applied Economics*, vol. 36, 65–81.

[EU Commission, 2011] EU Commission, COM (2011) 109 final, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Energy Efficiency Plan 2011.

[Fouquet, 2012] Fouquet, R., “Trends in income and price elasticities of transport demand (1850–2010)”, *Energy Policy Special Issue on Past and Prospective Energy Transitions*, 50, 62–71.

[Fouquet and Pearson, 2012] Fouquet, R. and Pearson, P.J.G., “The long run demand for lighting: elasticities and rebound effects in different phases of economic development”, *Economics of Energy and Environmental Policy* 1(1) 83–100.

[Frondel *et al.,* 2008] Frondel, M., Peters, J. and Vance, C., “Identifying the Rebound. Evidence from a German Household Panel”, *Ruhr Economic Papers*, no. 32.

[Frondel *et al.,* 2010] Frondel, M., Ritter, N. and Vance, C., “Heterogeneity in the Rebound Effect. Further Evidence for Germany”, *Ruhr Economic Papers*, no. 227.

[Galindo, 2005] Galindo, L.M., “Short- and long-run demand for energy in Mexico: A cointegration approach”, *Energy Policy*, 33(9): 1179–1185.

[Gardner and Stern, 1996] Gardner, G.T. and Stern, P.C., Environmental Problems and Human Behavior, Boston, Allyn & Bacon.

[Gillingham *et al.,* 2013] Gillingham, K., Kotchen, M., Rapson, D. and Wagner, G., “Energy policy: The rebound effect is overplayed”, *Nature*, vol. 493, 475–476.

[Golove and Eto. 1996] Golove, W. and Eto J., *Market Barriers to Energy Efficency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency*, University of California, Lawrence Berkeley National Laboratory, Energy Environment Division.

[Gram-Hanssen, 2006] Gram-Hanssen, K., “Consuming Technologies – Developing Routines”, in *Perspectives on Radical Changes to Sustainable Consumption and Production*, Andersen, M.M. and Tukker, A. (eds), Workshop of the Sustainable Consumption Research Exchange (SCORE!) Network, 20–21 April 2006, Copenhagen, Denmark, 79–90.

[Greene, 2011] Greene, D.L., “Uncertainty, loss aversion and markets for energy efficiency”, *Energy Economics*, vol. 33, 608–616.

[Greene, 2012] Greene, D.L., “Rebound 2007: Analysis of U.S. Light-Duty Vehicle Travel Statistics”, *Energy Policy*, vol. 41, 14–28.

[Greening *et al.,* 2000] Greening, L.A., Greene, D.L. and Difiglio, C., “Energy efficiency and consumption – the rebound effect – a survey”, *Energy Policy*, vol. 28, no. 6–7, 389–401.

[Griskevicius *et al*., 2010] Griskevicius, V., Tybur, J.M. and van den Bergh, B., “Going Green to Be Seen: Status, Reputation, and Conspicuous Conservation”, *Journal of Personality and Social Psychology*, vol. 98, no. 3, 392–404.

[Guerra and Sancho, 2010] Guerra, A. and Sancho, F., “Rethinking economy-wide rebound measures: An unbiased proposal”, *Energy Policy*, vol. 38, 6684–6694.

[Hand and Shove, 2007] Hand, M. and Shove, E., “Condensing Practices. Ways of Living with a Freezer”, *Journal of Consumer Culture*, vol. 7, no. 1, 79–103.

[Hanly *et al.,* 2002] Hanly, M., Dargay, J.M. and Goodwin, P.B., *Review of income and price elasticities in the demand for road traffic.* Final report to the DTLR under contract number PPAD 9/65/93, ESRC Transport Studies Unit, University College London, London.

[Henly *et al*., 1988] Henly, J., Ruderman, H. and Levine, M., “Energy Saving Resulting from Adoption of More Efficient Appliances: A Follow-up”, *The Energy Journal*, vol. 9, 163–170.

[Hirsch, 1976] Hirsch, F., *Social Limits to Growth*, Cambridge, Harvard University Press.

[Hirst and Brown, 1990] Hirst, E. and Brown, M., “Closing the efficiency gap: barriers to the efficient use of energy”, *Resources, Conservation and Recycling,* vol. 3, no. 4, 267–281.

[Hobson, 2003] Hobson, K., “Thinking Habits into Action: The Role of Knowledge and Process in Questioning Household Consumption Practices”, *Local Environment*, vol. 8, no. 1, 95–112.

[Holtedahl and Joutz, 2004] Holtedahl, P. and Joutz, F.L., “Residential electricity demand in Taiwan.” *Energy Economics*, 26(2): 201–224.

[Howarth, 1997] Howarth, R., “Energy Efficiency and Economic Growth”, *Contemporary Economic Policy*, vol. XV, no. 4, 1–9.

[Howells *et al*., 2007] Howells, M., Jeong, K., Langlois, L., Ki Lee, M., Nam, K. and Rogner, H.H., “Incorporating macroeconomic feedback into an energy systems model using an IO approach: Evaluating the rebound effect in the Korean electricity system”, *Energy Policy*, vol. 38, 2700–2728.

[IEA, 2010] International Energy Agency, *Summary of Country Reports Submitted to the Energy Efficiency Working Party*.

[IEA, 2011] International Energy Agency, *Implementation of the 25 energy efficiency policy recommendations in IEA member countries: recent developments.*

[Jackson *et al.,* 2004] Jackson, T., Jager, W. and Stagl, S., “Beyond Insatiability – Needs Theory, Consumption and Sustainability”, in *The Ecological Economics of Consumption*, Reisch, L.A. and Røpke, I. (eds), Cheltenham, Edward Elgar, 79–110.

[Jaffe and Stavin, 1994] Jaffe, A.B. and Stavins, R.N., “The energy-efficiency gap What does it mean?”, *Energy Policy*, vol. 22, no.10, 804–810.

[Jalas, 2002] Jalas, M., “A time use perspective on the materials intensity of consumption”, *Ecological Economics*, vol. 41, no. 1, 109–123.

[Jalas, 2005] Jalas, M., “The Everyday Life Context of Increasing Energy Demands. Time Use Survey Data in a Decomposition Analysis”, *Journal of Industrial Ecology*, vol. 9, nos 1–2, 129–145.

[Jenkins *et al*., 2011] Jenkins, J., Nordhaus, T. and Shellenberger, M., *Energy Emergence. Rebound & Backfire as Emergent Phenomena,* Oakland,The Breakthrough Institute.

[Jevons, 1865] Jevons, W.S., *The Coal Question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-Mines*, London, Macmillan and Co.

[Kahneman and Tversky, 1979] Kahneman, D. and Tversky, A., “Prospect theory: An analysis of decision under risk”, *Econometrica* 47, no. 2, 313–327.

[Kaschenz *et al.,* 2007] Kaschenz, H., Albert, R., Mordziol, C., Schubert, J., Wachsmann, U., Schwermer, S. and Berg, H., *Stromsparen: weniger Kosten, weniger Kraftwerke, weniger* CO_2 *Fakten und Argumente für das Handeln auf der Verbraucherseite*, Positionspapier, Dessau-Roßlau, Federal Environment Agency.

[Khazzoom, 1980] Khazzoom, J.D.,“The economic implications of mandated efficiency in standards for household appliances”, *The Energy Journal,* vol. 1, no. 4, 21–40.

[Koomey *et al.,* 1991] Koomey, J.G, Atkinson, C., Meier, A., McMahon, J.E., Boghosian, S., Atkinson, B., Turiel, I., Levine, M.D., Nordman, B. and Chan, P., *The potential for electricity efficiency improvements in the U.S. residential sector*, Lawrence Berkeley National Laboratory, LBL-30477.

[Kulshreshtha and Parikh, 2000] Kulshreshtha, M. and Parikh, J.K., "Modeling demand for coal in India: vector autoregressive models with cointegrated variables", *Energy*, 25(2), 149–168.

[Lecca *et al*., 2011] Lecca, P., Swales, J.K. and Tuner, K., "Rebound effects from increased efficiency in the use of energy by UK household", *Strathclyde Discussion Papers in Economics,* no. 11–23. Available from: http://www.strath.ac.uk/media/departments/economics/researchdiscussionpapers/2011/11-23_Final.pdf

[Lee and Lee, 2010] Lee, C.-C. and Lee, J.-D., "A panel data analysis of the demand for total energy and electricity in OECD countries", *The Energy Journal*, 31, 1, 1–24.

[Lutzenhiser, 1993] Lutzenhiser, L., "Social and Behavioral Aspects of Energy Use", *Annual Review of Energy and the Environment*, vol. 18, 247–289.

[Lutzenhiser *et al.,* 2001] Lutzenhiser, L., Harris, C.K. and Olsen, M.E., "Energy, Society, and Environment", in *Handbook of Environmental Sociology*, Dunlap, R.E. and Michelson, W. (eds), Westport, Greenwood Press, 222–271.

[McKinsey, 2007] McKinsey & Company, *Reducing the U.S. greenhouse gas emissions: how much at what cost?*, U.S. greenhouse gas abatement mapping initiative.

[Madlener and Hauertmann, 2011] Madlener, R. and Hauertmann, M., *Rebound Effects in German Residential Heating: Do Ownership and Income Matter?* FCN Working Paper no. 2/2011.

[Maréchal, 2009] Maréchal, K., *The crucial role of habits in energy consumption: an evolutionary approach on changing current patterns,* ECEEE 2009 Summer Study – Act! Innovate! Deliver! Reducing Energy Demand Sustainably, 1693–1703.

[Mazar and Zhong, 2010] Mazar, N. and Zhong, C.-B., "Do Green Products Make Us Better People?", *Psychological Science*, vol. 21, no. 4, 494–498.

[Meier, 1982] Meier, A., *Supply curves of conserved energy*; Lawrence Berkeley National Laboratory, LBL-14686.

[Merritt *et al*., 2010] Merritt, A.C., Effron, D.A. and Monin, B., "Moral Self-Licensing: When Being Good Frees Us to Be Bad", *Social and Personality Psychology Compass*, vol. 4, no. 5, 344–357.

[Mizobuchi, 2008] Mizobuchi, K., "An empirical study on the rebound effect considering capital costs", *Energy Economics*, vol. 30, no. 5, 2486–2516.

[Morgan and Keith, 2008] Morgan, M.G. and Keith, D., "Improving the Way We Think About Projecting Future Energy Use and Emissions of Carbon Dioxide", *Climatic Change*, 90(3), 189–215.

[Nadel *et al.,* 2004] Nadel, S., Shipley, A. and Elliott, R.N., *The Technical, Economic and Achievable Potential for Energy-Efficiency in the U.S. – A Meta-Analysis of Recent Studies*, American Council for an Energy Efficient Economy.

[NRC, 2010] National Research Council, *Realistic prospects for energy efficiency in the United States,* National Academies Press.

[OTA, 1991] OTA, *Changing by Degrees: Steps to Reduce Greenhouse Gases*, Office of Technology Assessment, OTA-0-489.

[Otte, 2005] Otte, G., "Hat die Lebensstilforschung eine Zukunft? Eine Auseinandersetzung mit aktuellen Bilanzierungsversuchen"*, Kölner Zeitschrift für Soziologie und Sozialpsychologie*, vol. 57, no. 1, 1–31.

[Peters *et al*., 2012] Peters, A., Sonnberger, M., Dütschke, E. and Deuschle, J., *Theoretical perspective on rebound effects from a social science point of view* – Working Paper to prepare empirical psychological and sociological studies in the REBOUND project, Fraunhofer ISI, Working Paper Sustainability and Innovation, no. S 2/2012. Available at: http://www.isi.fraunhofer.de/isi-media/docs/e-x/working-papers-sustainability-and-innovation/WP02-2012_Rebound_psychological_sociological_background.pdf?WSESSIONID=raibdmyryz

[Pew Center, 2011] Pew Center on Global Climate Change, *Energy and Climate Goals of China's 12th Five-Year Plan*. Available at: http://www.pewclimate.org/international/factsheet/energy-climate-goals-china-twelfth-five-year-plan

[Princen, 2005] Princen, T., *The Logic of Sufficiency*, Boston, MIT Press.

[Reckwitz, 2002] Reckwitz, A., "Toward a Theory of Social Practices. A Development in Culturalist Theorizing", *European Journal of Social Theory*, vol. 5, no. 2, 243–263.

[Reiss and White, 2005] Reiss, P. and White, W., "Household Electricity Demand, Revisited", *Review of Economic Studies*, vol. 72, 853–883.

[Rokeach, 1973] Rokeach, M., *The Nature of Human Values*, New York, The Free Press.

[Ronis *et al*., 1989] Ronis, D.L., Yates, J.F. and Kirscht, J.P., "Attitudes, decisions, and habits as determinants of repeated behaviour", in *Attitude structure and function*, Pratkanis, A.R., Breckler, S.J., Greenwald, A.G. (eds), Hillsdale, Lawrence Erlbaum, 213–239.

[Rosenfeld *et al*., 1991] Rosenfeld, A., Atkinson, C., Koomey, J., Meier, A., Mowris, R. and Price, L., *A Compilation of Supply Curves of Conserved Energy*, Berkeley, California, Center for Building Science, Lawrence Berkeley National Laboratory, LBL-31700.

[Rosenfeld *et al*., 1993] Rosenfeld, A., Atkinson, C., Koomey, J., Meier, A., Mowris, R. And Price, L., "Conserved energy supply curves for U.S. buildings", *Contemporary Policy Issues*, vol. 11, 45–68.

[Roy, 2000] Roy, J., "The rebound effect: some empirical evidence from India", *Energy Policy*, vol. 28, 433–438.

[Rubin *et al.,* 1992] Rubin, E.S., Cooper, R.N., Frosch, R.A., Lee, T.H., Marland, G., Rosenfeld, A.H. and Stine, D.D., "Realistic mitigation options for global warming", *Science*, vol. 257, 148–149, 261–266.

[Santarius, 2102] Santarius, T., *Green Growth Unravelled. How rebound effects baffle sustainability targets when economy keeps growing*, Berlin, Heinrich Böll Foundation and the Wuppertal Institute for Climate, Environment and Energy. Available at: http://www.boell.de/downloads/WEB_121022_The_Rebound_Effect-_Green_Growth_Unraveled_TSantarius_V101.pdf

[Saunders, 1992] Saunders, H.D., "The Khazzoom-Brookes postulate and neoclassical growth", *The Energy Journal*, vol 13 (4), 131–148.

[Saunders, 2000] Saunders, H.D., "A view from the macro side: rebound, backfire, and Khazzoom-Brookes", *Energy Policy*, vol. 28, 439–449.

[Saunders, 2008] Saunders, H.D., "Fuel conserving (and using) production functions", *Energy Economics*, vol. 30, 2184–2235.

[Saunders, 2010,] Saunders, H.D., *Historical Evidence for Energy Consumption Rebound in 30 US Sectors and a Toolkit for Rebound Analysts. In review*. Working version available from author at: http://thebreakthrough.org/blog/Historical Evidence Article 11-11-10.pdf

[Saunders, forthcoming] Saunders, H.D., "Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts", *Technological Forecasting and Social Change*.

[Schipper and Grubb, 2000] Schipper, L. and Grubb, M., "On the rebound? Feedback between energy intensities and energy uses in IEA countries", *Energy Policy*, vol. 28, 367–388.

[Schor, 1999] Schor, J.B., *The Overspent American. Why we want what we don't need,* New York, HarperCollins.

[Simon, 1959] Simon, H., "Theories of decision making in economics and behavioral science", *American Economic Review*, vol. 49, no. 3, 253–283.

[Small and van Dender, 2005] Small, K. and van Dender, K., *The Effect of Improved Fuel Economy on Vehicle Miles Traveled: Estimating the Rebound Effect Using U.S. State Data, 1966-2001*, University of California Energy Institut, Energy Policy and Economics 014.

[Small and van Dender, 2007] Small, K. and van Dender, K, "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect", *The Energy Journal*, vol. 28, 25–51.

[Sorrell, 2007] Sorrell, S., *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*, A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, UK Energy Research Centre.

[Sorrell and Dimitropoulos, 2007] Sorrell, S. and Dimitropoulos, J., *UKERC Review of Evidence for the Rebound Effect Technical Report 2: Econometric Studies*, Working Paper, UK Energy Research Centre.

[Sorrell and Dimitropoulos, 2008] Sorrell, S. and Dimitropoulos, J., "The rebound effect: Microeconomic definitions, limitations and extensions", *Ecological Economics*, vol. 65, 636–649.

[Stern, 1992] Stern, P.C., "Psychological Dimensions of Global Environmental Change", *Annual Review of Psychology*, vol. 43, 269–302.

[Thøgersen and Ölander, 2003] Thøgersen, J. and Ölander, F., "Spillover of environment-friendly consumer behaviour", *Journal of Environmental Psychology*, vol. 23, no. 3, 225–236.

[Thomas and Azevedo, 2013a] Thomas, B. and Azevedo, I.L., "Estimating Direct and Indirect Rebound Effects for U.S. Households with Input-Output Analysis Part 1: Theoretical Framework", *Ecological Economics*, 86, pp 199–210.

[Thomas and Azevedo, 2013b] Thomas, B. and Azevedo, I.L., "Estimating Direct and Indirect Rebound Effects for U.S. Households with Input-Output Analysis Part 2: Simulation", *Ecological Economics*, 86, pp, 188–198.

[Tsao *et al.,* 2010] Tsao, J., Saunders, H.D., Creighton, J., Coltrin, M. and Simmons, J., "Solid-state lighting: an energy economics perspective", *Journal of Physics D, Applied Physics*, vol. 43, no. 35, 1–17.

[Turner, 2009] Turner, K., "Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the U.K. economy", vol. 31, 648–666.

[van den Bergh, 2011] van den Bergh, J., "Energy Conservation More Effective With Rebound Policy", *Environmental and Resource Economics*, vol. 48, no. 1, 43–58.

[Veblen, 2007 (1899)] Veblen T., *The Theory of the Leisure Class*, Oxford, Oxford University Press.

[Verbraucherzentrale, 2011] Verbraucherzentrale, Die "Aktion Brennwertcheck" der Verbraucherzentralen, Berlin, Verbraucherzentrale Bundesverband e.V. (vzbv).

[Verplanken and Aarts, 1999] Verplanken, B. and Aarts, H., "Habit, attitude, and planned behaviour: Is habit an empty construct or an interesting case of automaticity?", *European Review of Social Psychology*, vol. 10, 101–134.

[Wang *et al.,* 2012] Wang, H., Zhou, P. and Zhou, D.Q., "An empirical study of the direct rebound effect for passenger transport in urban China", *Energy Economics*, vol. 34, 452–460.

[Wilhite and Lutzenhiser, 1999] Wilhite, H. and Lutzenhiser, L., "Social Loading and Sustainable Consumption", Advances in Consumer Research, vol. 26, 281–287.

[Wirl, 1995] Wirl, F., "Impact of Regulation on Demand Side Conservation Programs", *Journal of Regulatory Economics*, vol. 7, 43–62.

[Wirl, 1999] Wirl, F., "Conservation Incentives for Consumers", *Journal of Regulatory Economics*, vol. 15, 23–40.

[Wirl, 2000] Wirl, F., "Lessons from Utility Conservation Programs", *The Energy Journal*, vol. 21, 1, 87–108.

[Witt, 2001] Witt, U., "Learning to consume – A theory of wants and the growth of demand", *Journal of Evolutionary Economics,* vol. 11, 23–36.

[Wörsdorfer, 2010] Wörsdorfer, J.S., *Consumer needs and their satiation properties as drivers of the rebound effect: The case of energy-efficient washing machines*, Papers on Economics and Evolution no. 1016. Jena, Max Planck Institute of Economics, Evolutionary Economics Group.

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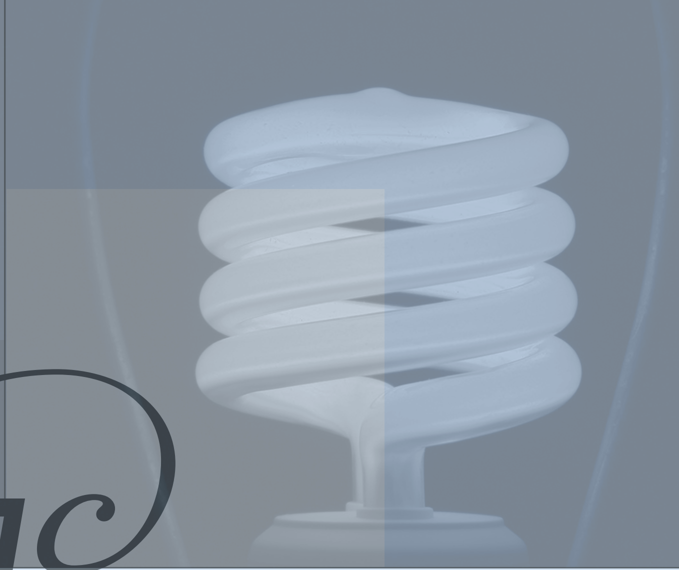

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