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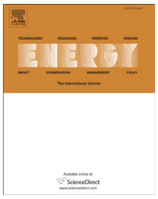

Quantification of (p)rebound effects in retrofit policies – Why does it matter?

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ABSTRACT

The 'prebound effect' characterises how average heating energy consumption in older homes is consistently lower than these buildings' calculated energy ratings, and helps explain why energy savings from thermal upgrades are often lower than anticipated. This paper explores the conceptual links between prebound and rebound effects and aims to quantify these behavioural effects. It applies the resulting mathematical model to empirical examples of actual and calculated energy consumption at scales of individual dwelling and national housing stock. These show that the rebound effect, as defined in econometrics literature, can only indicate proportionate reductions in energy consumption and can mask high levels of absolute consumption. The prebound effect, however, can identify under- and over-consumption regardless of rebound effects. A combination of high prebound effect and low income suggests fuel poverty, and the rebound effect here is less relevant regarding total energy consumption. Policymakers should identify housing with high prebound effects in order to eliminate fuel poverty, and be aware of inaccuracies in calculating payback time where economic viability of retrofits is mandated. Further research is needed to understand motivations and practices in households that have high prebound effects and to identify specific priority groups for thermal retrofit policy.

1. Introduction

Nearly a quarter of low-income households in the EU cannot afford to have a comfortable indoor environment in their homes due to energy prices [1]. Retrofit programmes, driven by policy instruments such as the EU Energy Efficiency Directive 2012/7 [2]), can generate economic and societal benefits. However, the level of direct energy subsidies allocated to fuel poor households in some EU countries is much higher than budgets allocated to energy retrofit programmes, which could offer more sustainable support to fuel poor households and thereby address the cause of the problem. This calls for improvement of statistical data collection by providing more precise evidence of fuel poverty in the EU, and more linkage between the data in order to better identify the relationship between housing conditions and fuel poverty [3].

This paper aims to contribute to this discussion on housing conditions and fuel poverty in a policy context, by showing how the notion of the 'prebound effect', a term coined by Sunikka-Blank and Galvin [4], can be used as an indicator of fuel poor households, and setting this alongside established formulations of the 'rebound effect' (see list of special terms, symbols and abbreviations used in this paper, in Table 1).

It is first necessary to clarify the definitions and mathematics behind the prebound effect and the established rebound effect, which, we argue, is a key concept in setting accurate and equitable energy saving policy targets. The concept of the 'rebound effect' has a long history and is now deeply embedded in policy and academic discussion. This was initiated by Khazzoom's [5] empirical finding that energy savings were smaller than expected when new regulations demanded increases in the energy efficiency of electrical appliances. These regulations were enacted to reduce energy consumption in the wake of the oil crises of the early and mid-1970s, but Khazzoom found they were failing to do so proportionately, and might instead be having the opposite effect. He called this 'backfire', and in a later publication Khazzoom [6] linked this to a similar phenomenon observed by the 19th century economist William Stanley Jevons [7].

In the numerous empirical studies that followed, it was generally found that 'backfire' seldom occurred, but still the energy savings were seldom proportionate to the energy efficiency increase. It

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Table 1
Symbols, acronyms and specialist nomenclature used in this paper.

Symbol, acronym or term	Meaning
A	Coefficient of C in best-fit power curve for actual against calculated consumption
B_E	Proportionate change in energy consumption
B_ε	Proportionate change in energy efficiency
C	Calculated (theoretical) energy consumption
D	Exponenet of the best-fit power curve for actual against calculated consumption
E	Actual energy consumption
EC	European Commission
EPC	Energy Performance Certificate
kWh	Kilowatt-hours
kWh/m^{2}a	Kilowatt-hours of energy consumed per square meter of floor area per year
ln	The natural logarithm (of the quantity in the brackets)
P	Prebound effect
R	Rebound effect
S	Energy services
U-value	Coefficient of thermal transmittance, e.g. of walls and windows
ε	Energy efficiency
DENA	German Energy Agency (Deutsche Energie-Agentur)
DIN	German Institute of Standards (Deutsches Institut für Normung)
EU	European Union
Backfire	The situation where the rebound effect is greater than 1 (=100%).
Elasticity	(in economics) a measure of the proportionate change in one variable as a ratio of the proportionate change in another variable
Prebound effect	A measure of the shortfall in actual energy consumption as a proportion of theoretical, calculated consumption
Rebound effect	A measure of the proportion of an energy efficiency increase that is used to increase the level of energy services, rather than decrease the level of energy consumption.

seemed the energy efficiency increase was being divided into two parts: one portion went to reduce energy consumption, and the remaining portion was ‘taken back’ to increase the consumption of ‘energy services’ [8]. Energy services are the benefits people get from consuming energy, such as warmer homes, greater distances travelled, more goods produced, and brighter lighting. This two-part phenomenon came to have the label ‘rebound effect’, a term which first appears in academic literature in 1983 [9].

Due to the strong involvement of economists in rebound effect discussion, the concept of the rebound effect has been rigorously mathematically defined in econometric terms, and the mathematics of how it links the parameters of energy consumption, energy efficiency, energy services consumption and the price of energy have been developed in detail (see, e.g., [11,13]). In such literature the rebound effect is defined as the ‘energy efficiency elasticity of energy services’ (see definition in Section 2.2). There are other, alternative definitions of the rebound effect (see discussion in Refs. [12,13]), but the ‘elasticity’ definition found in economics literature tends to hold sway in most policy and planning discussion.

It is generally argued that there are four different forms of rebound effect: direct, indirect, economy-wide, and transformational [14]. The direct rebound effect is where consumers increase their energy service consumption in the same area that has the energy efficiency increase. With the indirect rebound effect, consumers use money saved as a consequence of an energy efficiency increase in one area, such as home heating, to increase their energy services in another area, such as holiday travel. The economy-wide rebound effect is a measure of the total rebound throughout a country's whole economy, as a consequence of all the energy efficiency increases in that country. The transformational rebound effect occurs when an energy efficiency increase results in social and organisational change, which increases the need or desire for the more energy efficient product. Direct rebound effects only are considered in this paper.

The difficulties of quantifying rebound effects are widely recognised, but estimates of the rebound effect and ‘comfort taking’ related to space heating generally lie within the range of 10–35% [13]. Sorrell [15] suggests direct rebound effects are likely to decline in the future, if the demand for energy services saturates, and calls for 70% reductions in energy use in housing based on the engineering estimates.

Bodies such as the European Council for an Energy Efficient Economy emphasise the societal benefits of energy efficiency [16]. However, failure to take into account the rebound effect has been recognised as leading to shortfalls in achieving energy policy goals and as the reason actual energy savings fall short of estimates [15]. A useful feature of rebound effect mathematics is that this can be used in reverse, to estimate the actual level of energy efficiency that would be required, to achieve the reductions in energy consumption that policymakers are aiming for [67] (see calculation methodology in Ref. [17]). Taking this several steps further, Cellura et al. [18] use an input–output model in a specific country's building and policy framework, to evaluate the energy and environmental effects of energy efficiency measures. These approaches to modelling makes the rebound effect a very useful concept for aiding policy on energy and environmental planning.

The rebound effect has been seen as a phenomenon that needs to be prevented, reduced and counteracted [19]. On the other hand, parties such as the International Energy Agency (IEA) have started to recognise the rebound effect as a co-benefit of energy efficiency policy that has wider social benefits, such as reduction of fuel poverty [20]. This is because the rebound effect implies an increase in the level of energy services, which is what is needed in fuel poor homes.

The term ‘prebound effect’ gave a name to a phenomenon that was appearing persistently in a number of European housing stocks [4]. While the rebound effect focused on *over*-consumption *after* an energy efficiency upgrade, consistent evidence of *under*-consumption *prior to* or in the absence of energy efficiency upgrades was observed in Germany [21,22], France [23]; the Netherlands [24], Belgium [25] and the UK [26]. Four key observations made in relation to the prebound effect are: (a) for any specific value of calculated consumption there is a diverse range of actual consumption values; (b) on average in German datasets, actual consumption is about 35% below calculated consumption; (c) this gap increases as calculated consumption increases; and (d) for low energy houses (those with very low calculated consumption) the gap goes into reverse [4]. Consequently, the estimates of the economic viability of thermal retrofits are likely to be extremely over-