A Brighter Future? Quantifying the Rebound Effect in Energy Efficient Lighting

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Abstract

This paper quantifies the direct rebound effects associated with the switch from incandescent lamps (ILs) or halogen bulbs to more energy efficient compact fluorescent lamps (CFLs) or light emitting diodes (LEDs) using a large nationally representative survey of German households. The direct rebound effect is measured as the elasticity of energy demand for lighting with respect to changes in energy efficient lamps. In particular, the rebound effect is decomposed into changes in lamp luminosity and burn time. For the average bulb, the associated total direct rebound effect is estimated at about 6%. The larger part (around 60%) of this rebound effect results from increases in bulb luminosity. For the most frequent (modal) bulb switch, i.e. the replacement of the main bulb in the living or dining room, the total direct rebound effect is just below 3%, with around 60% attributable to an increase in burn time. Average and modal bulb differences suggest that the magnitude of the rebound effect may decrease with intensity of initial bulb use. The magnitude of the direct rebound and the relative contributions of changes in luminosity and burn time also differ by initial bulb type and by replacement bulb type.

Key words

Rebound; lighting; energy efficiency;

Highlights

- A rebound effect of around 6% is estimated for the average transition to an energy efficient bulb.
- A rebound effect of just below 3% is estimated for the main bulb in the living or dining room.
- Higher luminosity accounts for 60% (40%) of the rebound effect for the average (modal) bulb.
- The magnitude of the rebound effect differs by initial bulb and replacement bulb type.
- A third of the bulb switches to energy efficient bulbs entail negative rebound effects with lower luminosity and/or burn time.

1 Introduction

Lighting accounts for around 10% of residential electricity consumption in the EU and has recently decreased by 5% from 84TWh in 2007 to 79.8 TWh in 2009 (Bertoldi et al., 2012). This development reflects a significant increase in the adoption of compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) in recent years at the expense of incandescent light bulbs (IL) (e.g. Bertoldi et al., 2012; IEA, 2012). ILs (and also halogens) are cheaper to purchase, but they are rather energy-inefficient. Typically, ILs transform less than 5% of the power input into visible light, while the remainder is converted into heat. Since CFLs and LEDs exhibit higher efficiency[1] than ILs, they require about 80% and 90% less electricity, respectively, but also have a higher initial purchase cost. Energy-efficient lamps are also more durable than ILs. CFLs and LEDs are supposed to last 6 and 25 times longer, respectively, than ILs (around 1000 hours) (e.g. CLASP, 2013; European Commission, 2011a,b).

The uptake of energy efficient bulbs has been held back by several barriers (e.g. Wall and Crosbie, 2009; Frondel and Lohmann, 2011; European Commission, 2011b; de Almeida et al., 2013). CFL, halogen and LED bulbs are all available for the typical E27 and E14 socket. But CFLs and LEDs differ in size and shape from ILs, and may not fit existing lamp fixtures or may face resistance for aesthetic reasons. Energy efficient bulbs are also often associated with lower lighting quality, with CFL bulbs in particular sometimes considered to be “cold” or too whitish compared to ILs or halogens. Most CFLs require a warm-up period before achieving full brightness and are also not dimmable. CFLs and LEDs have also been associated with negative health and environmental effects. Of particular note, CFLs contain toxic mercury and therefore require special disposal in accordance with the European Community Waste Electrical and Electronic Equipment Directive 2002/96/CE.[2] Finally, as pointed out by Mills and Schleich (2010) or Frondel and Lohmann (2011), among others, it may not be economically rational to replace IL bulbs with CFL bulbs for rooms with low usage (e.g. attic, storage room or bedroom), because the higher initial purchase costs of CFL bulbs may only pay-off after more than a decade.

1 Efficiency is measured as the ratio of the light output (luminous flux measured in lumens lm) to the electric power consumed (measured in wattage W).

2 See also Aman et al. (2013) for a thorough comparison of technological and environmental properties of different domestic lighting lamps.

To accelerate the diffusion of energy efficient light bulbs, many countries have recently implemented bans on imports and domestic sales of incandescent light bulbs (IEA, 2010).[3] According to EC 244/2009 sale and importation of non-clear incandescent bulbs was banned in the EU after September 2009 and non-directional incandescent bulbs were gradually phased out, starting in September 2009 for the highest wattage ILs (>= 100W), adding >=75W ILs in September 2010 and >=60 ILs in September 2011, and finishing by the end of September 2012 for the lowest wattage ILs (<60W). Since then, except for a few specialty bulbs, only energy efficient light lamps, such as CFLs and LEDs may be sold. Conventional low-voltage halogen bulbs can still be sold until September 2016. The ban is expected to affect the replacement of about 8 billion bulbs in EU households (European Commission, 2011b).

Adopting energy-efficient technologies - such as replacing IL bulbs by energy efficient bulbs - may result in lower electricity savings than expected from strictly an engineering-economic assessment due to the ‘rebound effect’ (e.g. Khazzoom, 1980, 1987, 1989; Brookes, 1990; Greening et al., 2000; Sorrell, 2007). For example, in an engineering-economic assessment, an improvement in energy efficiency of 400% should lower energy use by 75%, i.e. to 25% of the initial level. This implicitly assumes that the demand for useful work remains constant. Households, however, may change behavior in response to the lower effective costs of lighting services of energy-efficient light bulbs by letting bulbs burn longer, using more bulbs for additional lighting services, or increasing the luminosity of bulbs. There may also be *indirect* and *macro-economic effects.*[4] The *indirect rebound* effect recognizes that lower costs for energy services may elicit higher expenditures and also higher energy use for other goods and services. *Macro-economic* effects involve supply- and demand side adjustments in factor and product markets, as well as *frontier* effects (Saunders and Tsao, 2012) or *technological innovation and diffusion effects* (van den Bergh, 2011), where energy efficiency improvements lead to new products, applications or even new industries. In the short to medium term, income effects and macroeconomic rebound effects associated with lighting in industrialized countries are small since lighting shares of total electricity consumption and of disposable income are rather low (e.g. Tsao and Waide, 2010; Fouquet and Pearson, 2012; Chitnis et al., 2013).

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3 Howarth and Rosenow (2014) discuss the ban on ILs in the context of German energy efficiency policy from an institutional perspective.

4 For overviews see Greening et al. (2000), Sorrell (2007), Madlener and Alcott (2009), van den Bergh (2011) or Turner (2013).

For residential lighting, the *direct rebound* effect has been explored empirically in several studies, but empirical evidence quantifying the size of the rebound is rather weak. Greening et al. (2000) find a 5% to 12% rebound in residential lighting based on four studies, but also raise doubts about the methodological soundness and strength of results of the studies. According to de Almeida (2008) 15% of German households surveyed stated that they let energy-efficient bulbs burn longer than the IL bulbs that they replaced. In a study that is not directly comparable to the current analysis, Chitnis et al. (2013), rely on a building stock model and estimate the sum of the direct and indirect rebound effect excluding luminosity changes to be 10% in terms of CO_2 emissions. Borenstein (2013) employs an illustrative example for LEDs and CFLs to show that rebound effects will largely depend on the size of the demand elasticity for lighting, but does not quantify the magnitude of the rebound effect. Fouquet and Pearson (2006, 2012) find that cheaper and better lighting services and higher incomes have led to substantial long-term historical growth in consumption of lighting services. Demand for lighting in the UK, for example, increased by a factor of 500 over the last three centuries. For the first decade of this century, Fouquet and Pearson (2012) estimate a -0.5 price elasticity of lighting demand in the UK. While this may only be a crude estimate for the size of the rebound effect in lighting demand and changes in electricity demand for lighting related to burn time or to luminosity are not disentangled in the analysis, the study offers some empirical evidence that the rebound effect is not negligible.

In this paper, we estimate the direct rebound effect of bulb replacements in the residential sector in Germany distinguishing explicitly between rebound effects associated with changes in luminosity and in burn time. Our analysis is based on a 2012 representative survey of more than 6,000 private households in Germany. Data availability further allows us to employ the most direct measure of the rebound, i.e. the efficiency elasticity of the demand for useful work. Thus, our methodology does not rely on the potentially restrictive assumptions that are invoked in econometric analyses estimating the rebound via the price elasticity of energy services or via the own price elasticity of energy demand (e.g. Frondel et al., 2008, 2012, 2013; Sorrell and Dimitropoulos 2008). Further, to the best of our knowledge, the paper represents the first attempt to quantify the effects of household adoption of energy efficient bulbs on luminosity.

The remainder of the paper is organized as follows. Section 2 describes the survey and develops the methods used to estimate the rebound effect in lighting. Results are presented in Section 3. Section 4 discusses the main findings and policy implications. Section 5 concludes.

2 Material and methods

The empirical analysis is based on data from a recent household survey in Germany. The total rebound effect and its luminosity and burn time components are calculated using the standard methods applied in the literature as outlined below.

2.1 Survey

In May and June of 2012 a computer-based survey of 6,409 German households was carried out within an existing panel. These households are initially recruited via randomly selected telephone numbers (random digit dialling). Participants could take part in the survey via computer or via a top box connected to their TV-set. Thus, unlike in pure online surveys, households without internet access are part of the sample. The panel is representative for the German Population aged 14 to 69 years. The questionnaire asked for information on the new and old bulb in the last bulb replacement. To contain recall bias, the survey asked very clear close-ended questions with an additional opt-out possibility ("I don't remember"). Participating households were equipped with a visual interface, where photographs of different bulb types could be shown to support recall. Households were also asked to check their three most important criteria for purchasing a light bulb from a list. For almost two-thirds of the respondents' electricity use / energy efficiency was included as one of the most important criterion (65%), followed by purchasing price (54%), durability (52%) and quality (spectral power, colour, etc.). Other criteria like environmental performance (26%), easiness of disposal (14%), form (8%), dimmability (5%), ratings in consumer reports (4%), or brands (2%) were substantially less important.

Almost all participating households had at least one energy efficient light bulb installed in their home (90%). Around three-fourths of the respondents remembered when they last replaced a single bulb or possibly multiple bulbs due to installation of a new lighting fixture. To limit recall bias in the self-reported data we restrict further analyses to observations where the replacement occurred in 2012 (72%) or in 2011/2010 (25%). The vast majority of new bulbs replaced a broken or burned out bulb (86%); 7% of new bulbs replaced a bulb that was not broken. The remainder were mostly part of a fixture replacement and are excluded from further analyses. This leaves us with 4,061 bulb replacements. Of these, most bulbs were replaced in the living or dining room (30%), followed by the hallway (19%), bathroom (15%), the kitchen (14%) and the bedroom (7%). The remainder were for child rooms, outdoors, and other rooms. In 74% of the cases, the initial bulb was the main bulb, i.e. the primary source of light in the room, as compared to background or side lighting. For the empirical analyses we further exclude replacements involving tubes, leaving 3,871 observations.

Changes in luminosity are captured in the survey by asking households about the wattage of the initial and the new bulb. Bulb wattage rather than luminosity was asked, because households are more familiar with wattage and, unlike luminosity, wattage appears on the bulb (as well as on the package). Five different wattage categories were given per bulb type, with the categories being specific to the wattages commonly associated with each bulb type (e.g. de Almeida et al. 2008). Standard figures from the literature were then used to transform the wattage figures into luminosity per bulb. Since efficiency per bulb type also varies with technology, manufacturer, and voltage, this typically involved taking the means of the ranges of lumens given. There are 3,627 observations for which luminosity data for both the initial and replacement bulb could be inferred from the data provided by respondents.

Second, to asses the impact of bulb switches on increases or decreases in burn time, respondent indications of positive or negative changes in bulb burn time with the replacement bulb from among the following categories (in minutes): 0, <15, 15 to 30, 30 to 60, >60 are analyzed. In total, there are 3,366 responses on change in burn time available. Where information on percentage change in burn time is required, we relate these responses to standard benchmark figures on burn time by room type and by purpose from de Almeida et al. (2008) and from VITO (2009). For example, the data by VITO (2009) for daily burn time of the main lamp in a German household correspond to 3 hours in the dining/living room, 2.6 hours in the kitchen, 1.6 hours in the bedroom, and 1.4 hours in the bathroom. The burn time for secondary lamps is typically about 50 to 60% lower than for the main lamp.

Several caveats with respect to the data are worth noting explicitly. Data quality depends on respondents' subjective assessment. Particularly, wattage (or luminosity) data relies on the accuracy of respondent recall and/or willingness to check the required information for the replacement bulb. For these reasons findings are reported both for the replacement of the average bulb in the sample and for the most frequently documented bulb switch, i.e. for the replacement of the main bulb in the living or dining room (modal bulb). Respondents are expected to be more accurate in their recall for main bulb replacements in these rooms than for the other bulbs. Just as importantly, the burn time of these modal bulbs is expected to be greater than for other bulbs, so changes in luminosity and burn time are expected to weigh more heavily in the calculation of total household energy savings.

2.2 Total direct rebound and decomposition into luminosity and burn time effects

For the purpose of our analysis, the demand for useful work from lighting services may be expressed as

$$(1) \quad S = \Phi t$$

where Φ stands for luminosity (in lm), and t reflects burn time (in h). Thus useful work refers to luminous energy and is measured in lumen hours. Useful work of lighting differs from the vaguer concept of energy services. The latter depends on the actual purpose of the lighting device and may also include quality characteristics, among others. Following Khazzoom (1980), Berkhout et al. (2000) or Sorrell and Dimitropoulos (2008), we take the *efficiency elasticity of useful work* as a direct measure of the rebound effect

$$(2) \quad \eta_{S,\varepsilon} = \frac{\partial S}{\partial \varepsilon}\frac{\varepsilon}{S}$$

where ε reflects efficiency (measured in lm/W).[5] Substituting (1) in (2) and taking partial derivatives, yields

$$(3) \quad \eta_{S,\varepsilon} = \frac{\partial \Phi}{\partial \varepsilon}\frac{\varepsilon}{\Phi} + \frac{\partial t}{\partial \varepsilon}\frac{\varepsilon}{t} = \eta_{\Phi,\varepsilon} + \eta_{t,\varepsilon}$$

Hence, the efficiency elasticity of useful work may be decomposed into the elasticity of luminosity (*luminosity rebound*) and the elasticity of burn time (*burn time rebound*). Since energy demand is $E = \Phi t \varepsilon^{-1}$, the *efficiency elasticity of energy demand* can be written as

$$(4) \quad \eta_{E,\varepsilon} = \eta_{\Phi,\varepsilon} + \eta_{t,\varepsilon} - 1$$

Hence, the observed savings from adopting more energy efficient light bulbs will correspond to the engineering-economic savings (i.e. $\eta_{E,\varepsilon} = -1$) if $\eta_{S,\varepsilon} = 0$. If

5 For discrete changes, the efficiency elasticity as given in equation (2) may be transformed into an – arguably more intuitive – definition of the rebound effect: $1 - \frac{observed\ electricity\ savings}{theoretical\ electricity\ savings} = 1 - \frac{\varepsilon_i^{-1}\Phi_i t_i - \varepsilon_r^{-1}\Phi_r t_r}{\varepsilon_i^{-1}\Phi_i t_i - \varepsilon_r^{-1}\Phi_i t_i}$. Thus, the theoretical electricity savings are calculated as the difference between electricity use of the initial bulb *i* and of a replacement bulb *r* exhibiting the same efficiency as the replacement bulb, but the luminosity and burn time of the initial bulb.

$\eta_{S,\varepsilon} > 0$, actual energy savings will be smaller (positive rebound). If $\eta_{S,\varepsilon} > 1$ overall energy use increases in response to improved energy efficiency. In this case, adoption of more energy efficient bulbs is said to "backfire" (Saunders 1992). Finally, if $\eta_{S,\varepsilon} < 0$, adopting a more energy-efficient bulb results in larger energy savings than expected, i.e. a lower demand of service than before. In this case the direct rebound effect is negative.

Data availability allows us to calculate the rebound effects directly from equations (2) and (3). Hence, our estimate of the rebound does not suffer from the potential shortcomings of econometric analyses estimating the rebound via the price elasticity of energy services (e.g. vehicle km) or via the own price elasticity of energy demand (e.g. for household mobility see Frondel at al., 2008; Frondel et al., 2012; Frondel and Vance, 2013). Due to data limitations, these studies need to assume that increasing (decreasing) energy efficiency has the same effect on the costs of useful work as decreasing (increasing) energy prices. Relying on the own price elasticity of energy demand as a measure of the rebound requires in addition, that energy efficiency does not vary with the level of energy use (e.g. Sorrell and Dimitropoulos, 2008; Frondel et al., 2008; Sorrell et al., 2009).

3 Results

In this section we present the main findings from the survey, quantify the rebound effect for lighting and calculate the individual contribution of changes in luminosity and burn time.

3.1 Bulb choices

Table 1 shows the types of the initial and replacement bulbs in our final sample. Accordingly, about 42% of the initial bulbs are ILs, reflecting the prevalence of use and shorter life-spans of IL bulbs. CFLs represent 30% of initial bulbs, while halogens and LEDs represent 25% and 3% percent of initial bulbs, respectively. Most consumers (72%) kept the same type of bulb technology when replacing a bulb (e.g. an IL is replaced with an IL). Of the 28% who did change bulb types, over two-thirds switched from an IL bulb to another type of bulb. In the subsequent analyses efficiency improvements associated with bulb switches mean a switch to a more efficient bulb technology, i.e. a switch from an IL to a halogen bulb, a CFL or an LED bulb, a switch from a halogen to a CFL or an LED bulb, and a switch from a CFL to an LED bulb. For technical reasons moving from a lower wattage bulb to a higher wattage bulb of the same type also involves an efficiency improvement. For example, a 100W IL bulb is automatically more efficient than a 60W IL bulb. However, households are unlikely to be aware of this kind of efficiency improvement. Since rebound effects are thought to be caused by behavioral change, our analysis considers efficiency to remain unchanged if the initial bulb and the replacement bulb are of the same type. A switch to a less efficient bulb is defined analogously. Accordingly, about 23% (923 observations) of the switches involved a transition to a more efficient bulb technology and are used for the rebound effect calculations. About 5% of bulb replacements entailed a switch to a less efficient bulb.

Table 1: Initial and replacement bulb choice by types

	Replacement bulb type				
Initial bulb type	IL	Halogen	CFL	LED	*Sum*
IL	984	56	544	94	*1,678*
Halogen	94	728	41	113	*976*
CFL	68	18	1,026	75	*1,187*
LED	0	8	6	98	*112*
Sum	*1,146*	*810*	*1,617*	*380*	*3,953*

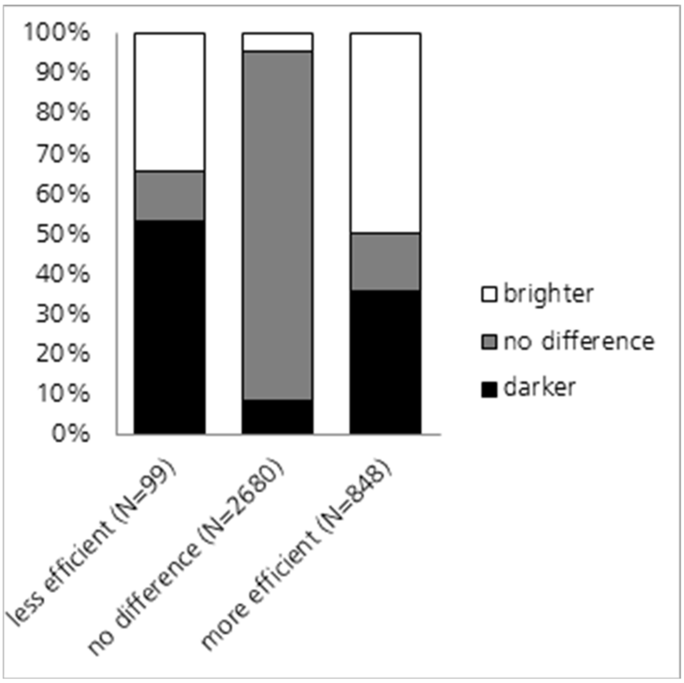
Note that for initial ILs, 80% (544 of 638) of the efficiency-improving switches were towards CFLs. In contrast, for initial halogen bulbs most efficiency-improving switches were towards LEDs (73%). As mentioned above, this may be due to characteristics of the respective fixtures that limit choice of bulb technology.

If the technology switch results in higher efficiency, the replacement bulb is estimated to be about four times more efficient than the initial bulb. This holds for average and for modal bulb switches.

3.1.1 Effects on luminosity

Figure 1 shows the relation between the change in luminosity and the change in efficiency of the replacement and the initial bulb. Switches to a more efficient bulb tend to be associated with an increase in luminosity in about 50% of the cases, indicating a luminosity rebound. By the same token, switches to less efficient bulbs tend to be primarily associated with a loss in luminosity. Thus, the data suggest symmetry in the luminosity rebound effect with respect to upward and downward changes in bulb efficiency. Figure 1 also suggests a negative rebound effect in a substantial portion of households, i.e. in about a third of the cases switches to more (less) efficient bulbs are associated with a decrease (increase) in luminosity.

Figure 1: Change in luminosity and efficiency (replacement bulb compared to initial bulb) in % of bulb replacements

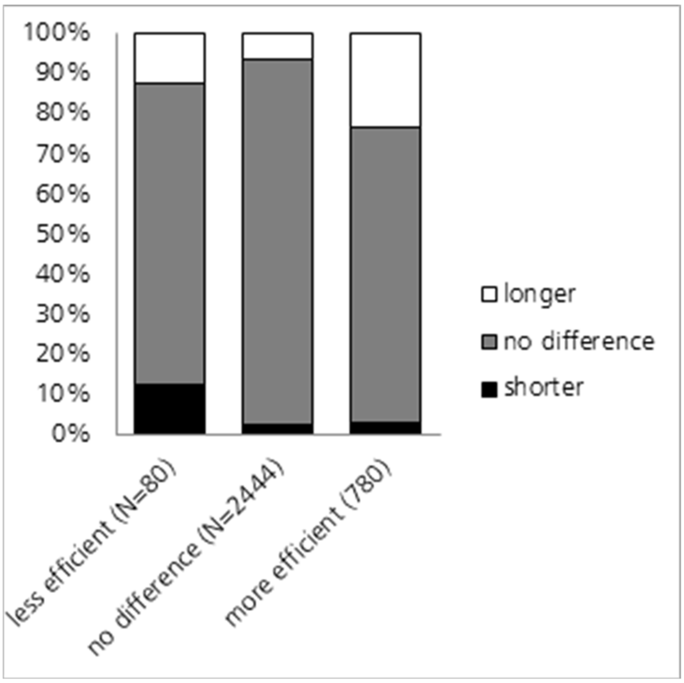


When examining the percentage change in luminosity, the replacement bulb is on average 7% brighter than the initial bulb. However, when the replacement bulb is more efficient than the initial bulb, it is about 24% brighter. To calculate the *net* effect, we also need to account for changes in luminosity when the replacement bulb is equally or less efficient than the initial bulb. Since in this case luminosity increases by about 1%, the *net* effect in terms of higher luminosity with more efficient bulbs is 23%. Based on average lumen for the initial bulbs in our sample, this 23% in luminosity corresponds to 130lm, i.e. the equivalent of a 20W IL. For the modal bulb switch, a more efficient replacement bulb is about 13% brighter than the initial bulb, and the associated net effect is approximately 10%.

3.1.2 Effects on burn time

Figure 2 shows the relation between the change in burn time and the change in efficiency of the replacement and the initial bulb. Switches to a more efficient bulb tend to be associated with an increase in burn time in about 23% of the cases, indicating a burn time rebound. Switches to less efficient bulbs, however, are not systematically associated with shorter average burn time. Figure 2 further implies that - unlike for luminosity - there appears to be no negative rebound effect for burn time.

Figure 2: Change in burn time and efficiency (replacement bulb compared to initial bulb) in % of bulb replacements



Quantifying the magnitude of changes in burn time with efficiency increases, the average replacement bulb burns about 3 minutes per day longer than the initial bulb. If the replacement bulb is more efficient than the initial bulb, daily burning time is about 8 minutes longer. Since burn time increases by around 1.5 minutes if the replacement bulb is not more efficient than the initial bulb, the *net* effect of increased burn time with more efficient bulbs is estimated to be about 6.5 minutes per day. For the modal bulb, the net effect is about 9 minutes per day, and hence appears to be slightly larger than for the non-modal bulbs. Assuming that the modal bulb, i.e. the average bulb in the dining or living room area burns for 3 hours a day (e.g. de Almeida, 2008; VITO, 2009) the net effect of 9 minutes corresponds to a 5% increase in daily burn time.

In total almost 90% of the efficiency-improving bulb switches are associated with changes in either luminosity or burn time, or both. Thus, total rebound effects arising from luminosity and burn time changes are quantified next.

3.2 Quantifying the rebound and its components

The total rebound is calculated and partitioned into contributions from changes in luminosity and changes in burn time based on a discrete version of equation (3). Strictly speaking though, equations (2) to (4) hold for marginal changes only. For discrete changes the observed efficiency elasticity of useful work in equation (2) differs from the calculated sum of the luminosity elasticity and the burn time elasticity in equation (3). In calculating the rebound shares we distributed this residual in proportion to the calculated relative shares of the luminosity elasticity and the burn time elasticity. The residual is, however, rather small and accounts for only 3.6% of the total rebound effect. Hence, our method chosen to allocate the residual to the individual components has little influence on the results.

Table 2 provides a comprehensive overview of the estimates of the total rebound, luminosity rebound, and burn time rebound for transitions involving initial ILs and halogen bulbs. Notably, estimates of rebound components vary by type of bulb switch, but the differences may not be statistically significant. Therefore, two-sided t-tests are also conducted to assess differences in the means for (i) modal and non-modal bulb switches, (ii) switches of initial ILs versus initial halogen bulbs, and (iii) switches to replacement CFL and LED bulbs. Statistically significant differences are briefly highlighted together with the associated p-values.

When an average IL or a halogen bulb is replaced by a CFL or an LED the total direct rebound effect is slightly above 6%. The larger part of this rebound (ca. 60%) results from higher luminosity of the replacement bulb. For the modal bulb, the total rebound effect is just below 3% and the larger part (ca. 60%) is due to a longer burn time.[6] The difference in total rebound between non-modal and modal bulbs is statistically significant (7% versus 3%, $p<0.1$).

There appears to be no difference in the magnitudes of the total rebound or its luminosity and duration components for bulb switches involving initial ILs versus initial halogen bulbs when looking at the combined transitions to CFL and LEDs. However, when an average halogen bulb is replaced by an LED rather than by a CFL, the total rebound is much smaller (0% versus 23%, $p<0.1$), in particular because the luminosity rebound is smaller when the replacement bulb is an LED rather than a CFL (-2% versus 20%, $p<0.05$).

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6 Since data may suffer from recall bias, we also calculated the rebound effect only for bulb replacements in 2012. Our calculations using only the 2012 data suggest that the rebound is about 0.3 (0.2) percentage points higher for all bulbs (modal bulbs). Thus, distortions associated with duration of recall appear to be rather small.

Table 2: Quantification of total rebound, luminosity rebound and burn time rebound by type of bulb switch

	Type of bulb switch	Total rebound	Luminosity rebound	Burn time rebound	Share of luminosity rebound	N
All bulbs	IL & Halogen to CFL & LED	6%	4%	2%	59%	603
Modal bulb	IL & Halogen to CFL & LED	3%	1%	2%	38%	131
All bulbs	IL to CFL & LED	7%	4%	3%	62%	487
	IL to CFL	6%	4%	2%	62%	416
	IL to LED	10%	6%	4%	59%	71
Modal bulb	IL to CFL & LED	4%	2%	2%	55%	99
	IL to CFL	4%	2%	2%	61%	81
	IL to LED	4%	1%	3%	29%	18
All bulbs	Halogen to CFL & LED	5%	2%	3%	47%	116
	Halogen to CFL	23%	20%	3%	85%	25
	Halogen to LED	0%	-2%	2%	-	91
Modal bulb	Halogen to CFL & LED	-1%	-2%	2%	-	32
	Halogen to CFL	13%	10%	3%	77%	4
	Halogen to LED	-3%	-4%	2%	-	28
All bulbs	IL & Halogen to CFL	7%	5%	2%	66%	441
	IL & Halogen to LED	4%	1%	3%	29%	162
Modal bulb	IL & Halogen to CFL	4%	3%	2%	63%	85
	IL & Halogen to LED	-2%	-4%	2%	-	46

Similarly, there appears to be no difference in rebound effects by replacement bulb types, when considering the combined transitions from IL and halogen bulbs. But when the replacement bulb is an LED, the total rebound is larger, when the initial bulb is an IL bulb rather than a halogen bulb (10% versus 0%, $p < 0.1$). Again, this difference is mainly due to the luminosity rebound, which in this case is larger for initial ILs than for halogens (6% versus -2%, $p < 0.1$).

Finally, the aggregate data presented in Table 2, mask that about one third of the bulb switches are associated with a negative total rebound, i.e. energy savings are larger than expected. As can be seen from Figures 1 and 2, the underlying reason of this negative rebound is a loss in luminosity rather than shorter burn times.

4 Discussion

Our estimates of the size of the direct rebound for lighting are at the lower range of the few previous estimates of rebound effects in the literature. At first glance, this may be surprising since those studies only consider changes in burn time. Conversely, our findings suggest that higher luminosity accounts for a substantial part of the total rebound. However, with the large recent efficiency gains of more than 400% in lighting, small direct rebound effects are to be expected. Mathematically, to observe direct rebound effects of more than 20%, luminosity and burn time would both have to increase by at least one third, for example. This would imply fairly large unsatiated lighting needs, ceteris paribus. As the relative efficiency improvements in lighting (for switches from ILs or halogen bulbs to CFLs or LEDs) are much larger than those typically observed for heating or transport, associated rebound effects are bound to be lower for lighting.[7]

While the long term studies by Fouquet and Pearson (2006, 2012) or Tsao et al. (2010) find very substantial rebound effects for lighting, our analyses only captures short-term effects and cannot account for frontier or innovation and diffusion effects. For example, our analysis neglects additional energy demand related to, among others, the installation of additional light fittings - such as multiple embedded light fittings in new ceilings - which are generally also associated with higher levels of illumination.

Our findings on the magnitude of the rebound effect suggest that the benefits of regulations to improve the energy performance of lighting such as the EU ban on incandescent light bulbs (and of halogen bulbs in the near future) are not dissipated by substantial rebound effects. Likewise, the ongoing transition towards more efficient and cheaper LED lighting will likely be associated with rather small direct rebound effects. According to McKinsey (2012, p. 24) the global LED (value based) market share for the residential sector will be 50% in 2016 and 70% in 2020 compared to 7% in 2011. Likewise, the global lighting market is expected to grow by 3 to 5 % per year until 2020, with LED sales accounting for more than 80% of a then 100 billion Euros market (McKinsey 2012). The corresponding price decrease in lighting is expected to foster additional lighting applications and the emergence of new types of demand for lighting services, reflect rebound due

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7 To illustrate, replacing a car which uses 10 liters of gasoline per 100 km by a new car which uses 6 liters per 100 km corresponds to an improvement in fuel efficiency of 40%. If usage of the new car was 20% higher than of the old car, the rebound effect would be 30%. In comparison, if instead the new car used 2 liters of gasoline per 100 km (i.e. efficiency improvement of 400%), a 20% increase in usage would lead to a rebound of 5% only.

to frontier effects (Saunders and Tsao, 2012) or technological innovation and diffusion effects (van den Bergh, 2011).

If projected increases in the demand for energy services are a sign of unsatiated needs and result from individuals' well-informed purchasing decisions, then the related moderate rebound effects are welfare improving and would hardly justify policy intervention. For example, fixture maximum wattage ratings, which for most existing fittings are determined based on heat dissipated by ILs, may constrain luminosity needs in ILs but not in CFLs or LEDs. Higher observed luminosity or burn time may also be a rational response by consumers to – perceived or actual – inferior performance of energy efficient bulbs, e.g. to CFLs which produce a different light than ILs and typically require a warm-up period.

Since consumer choices depend on the options offered, technology availability may also affect the size of the rebound. In particular, some portion of the luminosity rebound may arise from differences in luminosity associated with popular wattage categories for initial ILs and halogens and replacement CFLs and LEDs. If the luminosity of more energy-efficient bulbs on the market does not correspond to the luminosity of initial ILs, consumers are possibly more likely to purchase energy efficient bulbs in a category with higher luminosity than to move down to a category with lower luminosity. This would increase the calculated rebound.[8] But limited technology availability may also lower rebound figures. The observed small luminosity rebound associated with a switch of the modal bulb to an LED – for initial halogen bulbs it is even negative – may be explained by the fact that LEDs with high lumens, which are typically required for the main bulb in the living or dining room, have just started to enter the market and may not have been available at the time of purchase. Thus, technological advances in LED technologies may lead to greater future luminosity rebounds than suggested by our estimates.

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8 By far the most frequent bulb transitions in our sample (ca. 60%) involve initial ILs of 40W and 60W to CFLs (see VITO, 2009, for similar findings for other EU countries). For a 40W IL the equivalent CFL would be of 7W or 8W, depending on technology, manufacturer, etc. Since in our study CFLs of 7W and 8W are in the same category, and since we used the same luminosity (350W) for this category as for the category comprising the 40W IL, our estimates on the luminosity rebound are unlikely to be upward (or downward) biased for these switches. In fact ¾ of the switches from the 40W IL category towards CFLs involve no change in luminosity, but 25% involve switches towards CFL categories with higher luminosity. For a 60W IL, the equivalent CFL could be in either of two categories: the one containing the 11W CFL or the one containing the 12W CFL. The shares of switches from 60W ILs into these two CFL categories is almost the same (about 40%), so the bias in our rebound calculations is likely to be small. The remaining 20% of the switches involve transitions to CFL categories with clearly higher luminosity levels than the initial 60W IL.

The EU “Labelling Directive” 92/75/EEC together with Commission Directive 98/11/EC and European Commission (2012) mandates information on the input power (wattage), the luminous flux of the lamp in lumens, and the average rated life of the lamp to appear on the packaging of bulbs. In addition, for energy efficient bulbs manufacturer packaging or retail stores often provide information on the IL equivalent wattage (based on luminosity equivalence). Yet, consumers may suffer from lack of information or bounded rationality when making purchase decisions. The reports by the European Commission (2011a, b) suggest that the information provided on bulb packages is often poorly explained or even misleading (e.g. equivalence claims about the light output). Similarly, consumers may not comprehend the technical information, or lack the capabilities to evaluate financial costs and benefits. Kumar et al. (2003) for example, find that for India a lower education (and income) level is associated with a lower propensity to adopt energy efficient bulbs, but for EU countries socio-economic factors (including education) have not been found to be good predictors of bulb choice (e.g. Scott 1997, Mills and Schleich 2010). Even under perfect information, households may exhibit satisficing behavior, using routines, or rules of thumb (Simon, 1959) and neglect opportunities for improving energy efficiency. For example, households may habitually replace a broken bulb by an identical bulb. Likewise, households may act on a ‘rather be safe than sorry’ basis when exchanging an IL for an energy efficient bulb. The difference of choosing an LED of 11W rather than of 9W may seem fairly minor, but the change in lumen is much larger than choosing an IL of 60W rather than of 50W.

Thus, based on the information at hand, it cannot be definitively stated that changes in luminosity (or burn time) may be considered welfare-improving behavioral responses to lower costs of energy services. Observed changes, particularly in luminosity, may also result from lack of knowledge or bounded rationality. The latter effect would not classify as rebound effect in the purest behavioral sense because the observed (or rather stated) changes in luminosity are not induced by changes in costs.

Our findings suggest that there is substantial heterogeneity in both the magnitude and composition of the rebound effect. Some of this heterogeneity stems from difference in initial and replacement bulb types. Analysis of differences in average and modal bulb rebound effects suggest that the location of the bulb in the home also accounts for part of rebound effect heterogeneity. Future research is needed to relate rebound effects to socio-economic characteristics, attitudes or social and personal norms (e.g. di Maria et al., 2010 or Mills and Schleich, 2013) and to explain households’ heterogeneous responses to the adoption of energy efficient bulbs, such as the negative rebound we find in about a third of the bulb switches in our sample. Future rebound research needs to also take into account the needs and motives of households' technology choice. If households simultaneously chose the level of energy service (here luminosity or burn time) and the bulb type, econometric analyses must account for this endogeneity or risk generating biased rebound estimates.

Finally, while our findings are based on a rather large sample, they should be interpreted with some caution. As pointed out in Section 2, our estimates of the change in luminosity and burn time rely on respondents' recall of past decisions and may be subject to measurement error. There is no evidence that these errors systematically bias rebound estimates, but the possibility cannot be ruled out. As in other survey-based analyses with similar questions (e.g. de Almeida et al., 2008) responses are best interpreted as educated guesses. The costs of actually measuring changes in burn time would be prohibitive. Further, our percentage quantification of the magnitude of the burn time rebound is based on standard values of burn time taken from the literature and may not perfectly correspond with usage of the survey participants.

5 Conclusions and policy implications

This paper estimates the direct rebound of lighting based on a large representative survey of more than 6,000 private households in Germany. Our data allows the direct rebound to be estimated by the efficiency elasticity of demand for useful work, which is – from a methodological perspective – the preferred measure. The available data on the initial and the replacement bulb further allow us to decompose the total rebound into effects related to changes in luminosity and in burn time.

Our empirical findings suggest that the switch from an IL or a halogen bulb to a more energy-efficient CFL or LED leads to an average rebound of around 6% across all bulb switches, with a lower rebound effect of just below 3% for the main bulb in the living or dining room (modal bulb). Changes in luminosity, which previously have not been quantified, explain a substantial share of the rebound: 60% for the average bulb and 40% for the modal bulb. The total rebound effect and its decomposition in luminosity and burn time effects also differ by the types of the initial bulb (IL or halogen) and by the types of the replacement bulb (CFL or LED).

A major finding of this study is that the magnitude of the rebound effect is overall rather low, and may be particularly low (in percentage terms) in high use bulbs.

Thus, energy savings from the recent EU ban on incandescent (and halogen) bulbs or other types of energy efficiency standards for lighting are unlikely to be dissipated by substantial increases in lighting use (in terms of either burn time or luminosity). Similarly, the predicted strong future diffusion of LEDs is not expected to spur substantial direct rebound effects that would mitigate attendant energy savings. We also find some evidence that in a number of transitions to CFLs and LEDs electricity savings are larger than expected. Together with the positive rebound effects, these “negative” rebound effects would also need to be taken into account in ex-ante or ex-post policy evaluations.

On the one hand, the stated increase in energy services may satisfy additional household needs for luminosity or burn time, and hence increase household welfare. Higher luminosity and longer burn time may also reflect a rational response to inferior performance of energy efficient bulbs stemming from lower (perceived) lighting quality or warm-up periods. The analysis provides some evidence that changes to CFLs, which are often perceived to have lower light quality, are associated with greater increases in luminosity and with lower increases in burn time than changes to LEDs. The size of the rebound may also depend on the technologies available on the market. In particular, to avoid a loss in luminosity, consumers are expected to rather purchase energy efficient bulbs with higher luminosity than with lower luminosity compared to the initial bulb. Higher luminosity of energy efficient replacement bulbs may also stem from a lack of information or bounded rationality due to poor information display on bulb packages or from consumer inability to process the technical information. In these cases, policy intervention to overcome informational barriers may be justified and ultimately welfare enhancing.

Acknowledgements

We thank two anonymous reviewers for their comments, and suggestions and Patrick Plötz for his insights on the physical definition of rebound effects. The usual disclaimer applies. This work has been supported by the German Federal Ministry of Education and Research (BMBF) within the framework of the project “Social Dimensions of the Rebound Effect”.

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