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Joachim Schleich, Bradford Mills, Elisabeth Dütschke

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Joachim Schleich
Bradford Mills
Elisabeth Dütschke

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

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 useful lighting demand with respect to changes in energy efficient lamps. In particular, the rebound effect is decomposed into changes in lamp luminosity and burn time. On average, more efficient replacement bulbs are 23% brighter and burn about 6.5 minutes per day longer than replaced bulbs. For the most frequent (modal) bulb switch, i.e. the replacement of the main bulb in the living or dining room, luminosity increases by 10% and burn time increases by 9 minutes per day. For the average bulb, the associated total direct rebound effect is estimated at 6.3%. The larger part (around 60%) of this rebound effect results from increases in bulb luminosity. For the modal bulb the total direct rebound effect is smaller at 2.6%, with around 60% attributable to an increase in burn time. Average and modal bulb differences suggest that the magnitude to 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 tend to differ by initial bulb type and by replacement bulb type. Finally, about a third of the bulb switches entail a negative rebound effect, i.e. energy savings are larger than expected if luminosity and burn time remained unchanged, highlighting significant heterogeneity in household responses to the adoption of energy efficient bulbs.

Key words: rebound effect, lighting, energy efficiency, energy demand

Highlights:

- A 6.3% rebound effect is estimated for the average transition to an energy efficient bulb.
- A rebound effect of 2.6% 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.

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1 Introduction

Residential 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, they transform less than 5% of the power input into visible light, while the remainder is converted into heat. Since CFLs and LEDs exhibit higher efficacy¹ 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, EC 2011a,b).

The up take of energy efficient bulbs had yet long been held back by several barriers (e.g. Wall and Crosbie 2009, Frondel and Lohmann 2011, European Commission 2011b, de Almeida et al. 2013). CFLs, halogens and LEDs 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. Of particular note, energy efficient bulbs are often associated with lower lighting quality. While incandescent and halogen bulbs generate a “warm” yellowish light, the light of CFLs is sometimes considered to be “cold” or too whitish. LEDs are in-between, exhibiting a more balanced spectral power distribution than CFLs. At least some CFLs may also require a warm-up period before achieving full brightness and most CFLs are not dimmable. CFLs, and to a lesser extent LEDs, have also been associated with negative environmental and health effects. CFLs contain toxic mercury and therefore require special disposal². Mercury vapor from broken CFLs may cause damage to or be hazardous to developing brains and nervous systems.

1 Efficacy (lm/W or LPW) is a measure for the energy efficiency of a light bulb: the ratio of the light output (luminous flux measured in lumens lm) to the electric power consumed (measured in wattage W).

2 According to the European Community Waste Electrical and Electronic Equipment Directive 2002/96/CE, in the EU CFLs must be collected and recycled by manufacturers and importers.

Also, CFLs and LEDs emit electromagnetic radiation, hence causing “electro smog”.³ Finally, as pointed out by Mills and Schleich (2010) or Frondel and Lohmann (2011), among others, it may not be economically rational to replace ILs with CFLs for rooms with low usage (e.g. attic, storage room or bedroom), because the higher purchasing costs of CFLs may only pay-off after more than a decade.

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).⁴ According to EC 244/2009 non-clear incandescent bulbs were banned from selling or importing in the EU after September 2009 and non-directional incandescent bulbs had to be gradually phased out, starting in September 2009 for the highest wattage ILs ($\geq 100\text{W}$) and finishing by the end of September 2012 for the lowest wattage ILs ($<60\text{W}$). Since then, only energy efficient light lamps, such as CFLs and LEDs may be sold, subject to a few exceptions (such as specialty lamps for sewing machines or ovens). Conventional low-voltage halogens can be sold until September 2016. This ban is expected to affect the replacement of about 8 billion bulbs in EU households (EC 2011b).

Replacing IL by energy efficient bulbs may result in lower electricity savings than expected from a strictly engineering-economic assessment due to the ‘rebound effect’ (e.g. Khazzoom 1980, 1987, 1989; Brookes 1990; Greening et al. 2000; Sorrell 2007). For example, according to 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 energy remains constant. Households, however, may change behavior e.g. in response to the lower effective costs of lighting services (or useful energy) of energy-efficient light bulbs. In particular, they may let bulbs burn longer, use more bulbs for additional lighting services, or increase the luminosity of bulbs. 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 attempt to quantify the magnitude of the rebound effect.

3 Life Cycle Assessment studies by OSRAM (2009) and the US Department of Energy (US DOE 2012) conclude that LEDs are less environmentally harmful than CFLs and ILs. See also Aman et al. (2013) for a thorough comparison of technological and environmental properties of different domestic lighting lamps.

4 Howarth and Rosenow (2014) discuss the ban on ILs from an institutional perspective within German energy efficiency policy.

This *direct rebound* effect has been explored empirically by a few studies, but the empirical evidence for quantifying the size of the rebound is rather weak. According to the survey by Greening et al. (2000) the rebound in residential lighting amounts to 5% to 12%, based on four studies. Greening et al. (2000) explicitly raise doubts about the methodological soundness of these studies, and find the results inconclusive. According to de Almeida (2008) 15% of the German households surveyed stated that they let energy-efficient bulbs burn longer than ILs they had replaced. Chitnis et al. (2013) rely on a building stock model and estimate the rebound effect (in terms of CO₂ emissions) at 10%. While they also recognize possible effects on illumination levels, Chitnis et al. (2013) do not include luminosity change in their quantitative estimate. Fouquet and Pearson (2006, 2012) find that cheaper and better lighting services and higher incomes have led to a substantial growth in consumption of lighting services over the last few hundred years. 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 the price elasticity of lighting demand in the UK at -0.6, implying (rather large) rebound effects.

Apart from direct rebound effects, there may also be *indirect* and *macro-economic effects*.⁵ The indirect rebound effect captures that energy efficiency improvements in one area may lead to an increase in consumption in another area, e.g. the 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. In a wider perspective, macro-economic effects also encompass *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. At least in the short to medium term, income effects and macroeconomic rebound effects associated with lighting in industrialized countries are small since the share of lighting of total electricity consumption and of disposable income in these countries is rather low (e.g. Fouquet and Pearson 2012, Chitnis et al. 2013)⁶.

⁵ For overviews and taxonomies of rebound effects see Greening et al. (2000), Sorrell (2007), Madlener and Alcott (2009), van den Bergh (2011) or Turner (2013).

⁶ See also Tsao and Waide (2010). For a case study on the diffusion of energy efficient light bulbs in India see Kumar et al. (2003).

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 analyses are 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 the demand for useful work. Thus, our methodology does not rely on the potentially restrictive assumptions that need to be invoked in econometric analyses estimating the rebound via the price elasticity of useful energy or via the own price elasticity of energy demand (e.g. Frondel et al. 2008, 2012, 2013). To the best of our knowledge, this paper also 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 methodology for estimating the rebound 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 representative computer-based survey of 6,409 German households was carried out within an existing panel. Among others, the questionnaire asked for information on the new and old bulb in the last bulb replacement. To contain recall bias, the survey aimed at asking very clear close-ended questions and opt-out possibilities (“I don’t remember”). Since participating households were equipped with a visual interface, photographs of different bulb types could be shown. 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 the most important criterion (65%), followed by purchasing price (54%), durability (52%) and quality (spectral power, colour, etc.). Other criteria like environmental perform-

ance (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 installing a new lighting fixture. To limit recall bias in self-reported data we limit further analyses to observations where the replacement occurred in 2012 (72%) or in 2011/2010 (25%). The vast majority 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 also excluded from further analyses. This leaves us with 4,061 bulb replacements. Of those, 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 and end up with 3,871 observations.

Changes in luminosity are captured in the survey by asking households about the wattage of the initial and the new bulb.⁷ 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 assess the impact of bulb switches on increases or decreases in burn time, the respondents indicate 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. 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

⁷ 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).

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).

Naturally though, data quality depends on respondents' subjective assessment and for the wattage (or luminosity) data also on their memory and 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, but also 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 make better "educated guesses" 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 to provide 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). 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 (i.e. efficacy measured in lm/W).⁸ Substituting (1) in (2) and taking partial derivatives, yields

⁸ For discrete changes, the efficiency elasticity as given in equation (2) may be transformed into an – arguably more intuitive – definition of the rebound effect: $1 - \frac{\text{observed electricity savings}}{\text{theoretical electricity savings}} = 1 - \frac{\varepsilon_i^{-1} \phi_i t_i - \varepsilon_r^{-1} \phi_r t_r}{\varepsilon_i^{-1} \phi_i t_i - \varepsilon_r^{-1} \phi_i t_i}$. 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 efficacy as the replacement bulb, but the luminosity and burn time of the initial bulb.

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

Hence, the efficiency elasticity of useful energy 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* may 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 $\eta_{S,\varepsilon} > 0$, 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 useful energy (e.g. vehicle km) or via the own price elasticity of energy demand (e.g. for household mobility see Frondel et al. 2008, Frondel et al. 2012, Frondel and Vance 2013). For 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 for our final sample. Accordingly, about 42% of the initial bulbs are ILs, reflecting the prevalence of use and shorter life-spans of ILs. 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 to another type of bulb. About 23% (923 observations) of the switches involved a transition towards a more efficient bulb technology and may thus be used for analysis on rebound (i.e. switches from IL to halogen, CFL or LED; from halogen to CFL or LED, and from CFL to LED).⁹ About 5% switched to a less efficient bulb.

Table 1: Initial and replacement bulb choice by types

Initial bulb type	Replacement bulb type				Sum
	IL	Halogen	CFL	LED	
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
<i>Sum</i>	<i>1,146</i>	<i>810</i>	<i>1,617</i>	<i>380</i>	<i>3,953</i>

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.

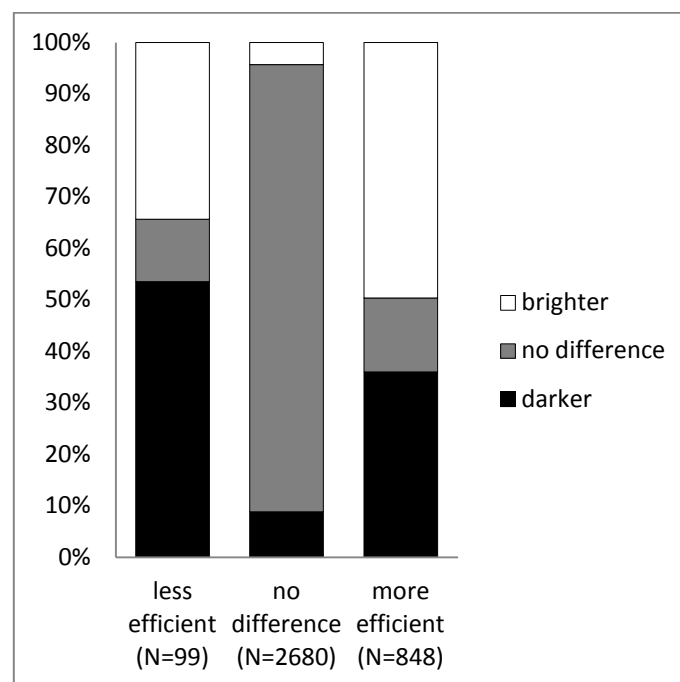
If the technology switch results in higher efficiency, the replacement bulb is estimated to be – on average – 4.4 times more efficient than the initial bulb. For the replacement of the modal bulb, 4.3 is the associated estimate of the increase in efficiency.

⁹ For technological 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 is automatically more efficient than a 60W IL. However, households are unlikely to be aware of this kind of efficiency improvement. Since rebound effects are caused by behavioral change, our analysis considers efficiency to remain unchanged if the initial and the replacement bulbs were of the same type.

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



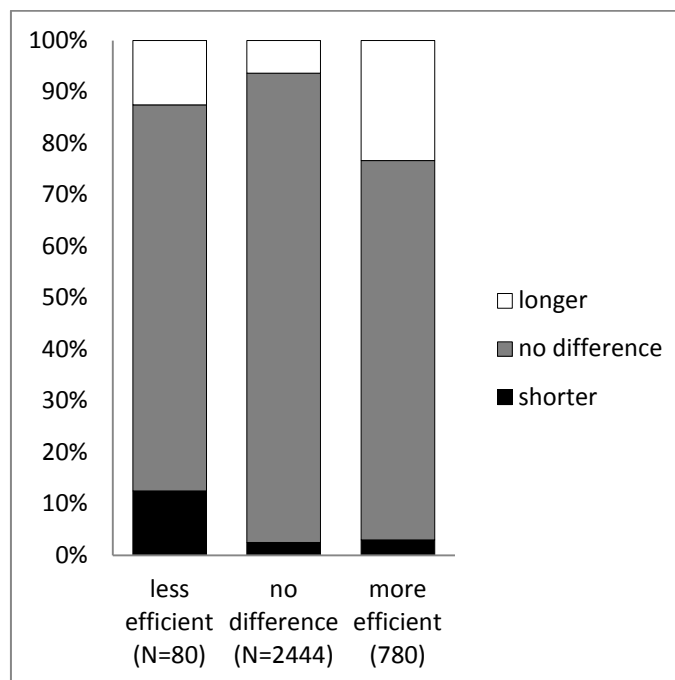
When examining the percentage change in luminosity, the replacement bulb is on average 6.7% brighter than the initial bulb. However, when the replacement bulb is more efficient than the initial bulb, it is about 24.2% brighter. Since luminosity increases by 1.4% if the initial bulb is more or equally efficient as the replacement bulb (i.e. the “control” group) the *net* effect in terms of higher luminosity with more efficient bulbs is 22.8%. Based on average lumen for the initial bulbs in our sample, this corresponds to 130lm, i.e. the equivalent of an IL with

about 20W. For the modal bulb switch, a more efficient replacement bulb is about 13% brighter than the initial bulb, and the 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. However, switches to less efficient bulbs 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. However, 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 initial bulb is at least as efficient as the replacement 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. Assuming that 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 corresponds to 5% of 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 from changes in burn time based on a discrete version of equation (3).¹⁰ We first analyze the effects for all types of initial bulbs. However, as most transition occurs from ILs and Halogens (table 1), the analysis is also conducted separately for initial ILs and halogen bulbs. We also differentiate by the types of replacement bulb, e.g. between CFLs and ILs.

When an average IL or a halogen bulb is replaced by a CFL or an LED the total direct rebound effect is 6.3%. 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 2.6% and the larger part (ca. 60%) is due to a longer burn time. The difference in total rebound between modal and non-modal bulbs is statistically significant ($p < 0.05$).

Figure 3 and Figure 4 display the total rebound effect and its components when the initial bulb is an IL and a halogen bulb, respectively. If the average initial bulb is an IL rather than a halogen bulb, the total rebound is larger (6.7% versus 4.8%), and the luminosity rebound is larger (3.9% versus 2.3%). The burn time rebound is almost identical for ILs and halogen bulbs. Similarly, for the total rebound is also larger (4.8% versus -0.8%), and the burn time rebound is similar for ILs and halogen bulbs. None of these differences between IL and halogen initial bulbs, however, are statistically significant. If the initial bulb is an IL or a halogen bulb, and if the average replacement bulb is a CFL rather than an LED, the total rebound is larger (7.1% versus 4.3%), and the luminosity rebound is

¹⁰ Strictly speaking, equations (2) to (4) hold for marginal changes. For discrete changes the observed efficiency elasticity of useful energy 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, the method chosen to allocate the residual to the individual components hardly influences the results.

larger (4.7% versus 1.2%), but the burn time rebound is somewhat smaller (2.4% versus 3.0%). Similarly, if the modal replacement bulb is a CFL rather than an LED, the total rebound is larger (4.4% versus -1.7%) and the luminosity rebound is larger (2.8% versus -4.2%), but the burn time rebound is smaller (1.6% versus 2.4%). Yet, none of these differences between CFL and halogen replacement bulbs are statistically significant.

Figure 3: Total rebound and decomposition by bulb type in % of bulb replacements (initial bulb = IL)

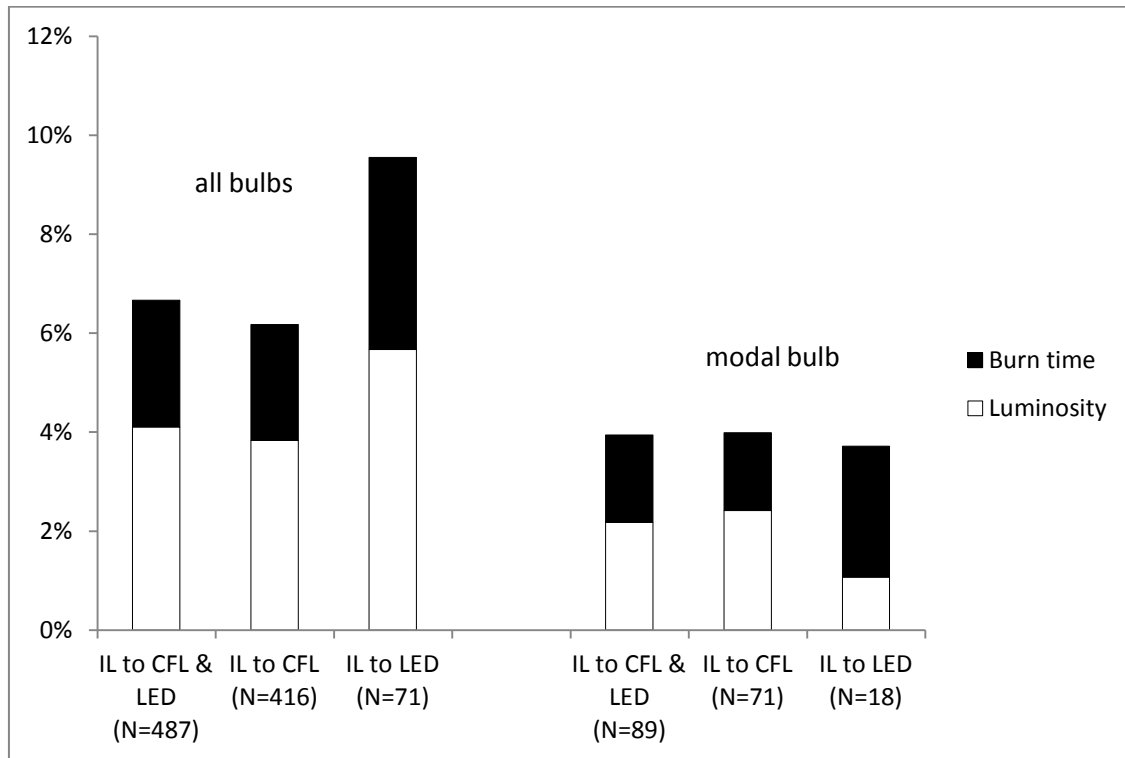
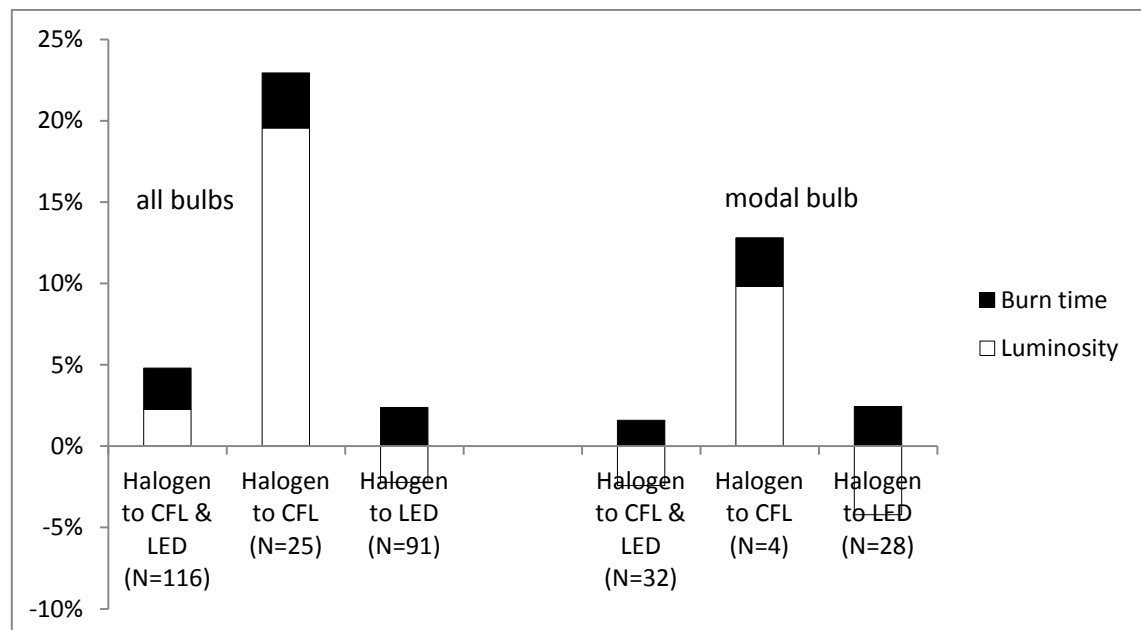


Figure 4: Total rebound and decomposition by bulb type in % of bulb replacements (initial bulb = halogen)



If the initial bulb is an IL the luminosity rebound accounts for about 60% for a CFL or an LED replacement bulb. The average rebound is higher when the replacement bulb is an LED rather than a CFL (9.5% versus 6.2%). For the modal bulb, the increase in luminosity accounts for 55% of the total rebound. Compared to non-modal bulbs the modal bulb exhibits a smaller rebound (3.9% versus 7.3%), a smaller luminosity rebound (2.2% versus 4.4%), and a smaller burn time rebound (1.7% versus 2.6%). For the modal bulb the luminosity rebound associated with a switch from an IL to an LED is particularly low (1% versus 2.4% for a switch to a CFL). However, none of the differences discussed in this paragraph is statistically significant.

The sample is much smaller for the switch from an initial halogen bulb to a CFL or an LED (N=116) than when the initial bulb is an IL. The total rebound effect when the initial bulb is a halogen is calculated at 4.8% and the increase in luminosity accounts for almost half of the total rebound (47%). However, when the replacement bulb is an LED, the total rebound and the luminosity rebound are negative. Further, the total rebound and the luminosity rebound (but not the burn time rebound) are lower than when the replacement bulb is a CFL. Both differences are statistically significant at $p < 0.1$. For the modal bulb, the total rebound is also negative (-0.8%), but not statistically different from the rebound of non-modal bulbs (7.2%). Only 4 initial halogen bulbs were replaced by a CFL, so it is not meaningful to analyze these observations separately.

Differences in rebound effects across initial bulb types and replacement bulb types are now compared. When the (modal or non-modal) replacement bulb is a CFL, total rebound, luminosity rebound and burn time rebound are higher if the initial bulb is an IL rather than a halogen bulb. But none of these differences turns out to be statistically significant. In contrast, if the replacement bulb is an LED, the total rebound is larger (at $p < 0.05$) when the initial bulb is an IL rather than a halogen bulb (9.56% versus -0.1), mainly because the difference in the luminosity rebound is larger (5.2% versus -2.2%) ($p < 0.1$). A similar result also holds for the modal bulb, but in this case, the burn time rebound is also larger when the initial bulb is an IL rather than a halogen (3.6% versus 1.4%) ($p < 0.1$).

Finally, the aggregate data presented in Figure 3 and Figure 4, 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 in the literature. At first sight, this may be surprising since those studies only considered changes in burn time. Conversely, our findings suggest that higher luminosity accounts for a substantial part of the total rebound. However, in light of the large efficiency gains of more than 400% associated with the more efficient 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*.

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. Arguably then, technological advances in LED technologies may lead to greater future rebound than suggested by our estimates. Alternatively, consumers may be willing to invest more heavily in the lighting needs for main bulbs in living and dining rooms even with traditional bulbs, leaving lighting needs relatively satiated even before bulb replacement.

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 halogens in the near future) are not dissipated by substantial rebound effects. Likewise, the ongoing transition towards more efficient and cheaper LED lighting will be associated with rather small direct rebound effects.¹¹ Instead, the effective price decrease in lighting is likely to foster additional lighting applications and the emergence of new types of demand for lighting services, thereby reflecting frontier effects (Saunders and Tsao 2012) or technological innovation and diffusion effects (van den Bergh 2011).

If the stated increase in the demand for energy services is a sign of unsatiated needs and results from individuals' well-informed purchasing decisions, the related moderate rebound effects are welfare improving, and would hardly justify policy intervention. 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.

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. Yet, consumers may suffer from lack of information or bounded rationality when making purchase decisions. As voiced by the European Commission (2011a, b), the information provided on the package 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. 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 by 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.

¹¹ 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.

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 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 may better 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 estimates of the rebound effect.

Finally, while our findings are based on a rather large sample, they should be interpreted with some caution. As already pointed out in Section 2, our estimates of the change in luminosity and burn time relies on respondents' own assessment and may be subject to measurement error. As in other survey-based analyses with similar questions (e.g. de Almeida et al., 2008) these responses can only be 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 6000 private households in Germany. Our data allows the direct rebound to be estimated by the efficiency elasticity of useful energy demand, 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 6.3% across all bulb switches, with a lower rebound effect of 4.4% 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. About a third of the bulb switches involve energy savings which are larger than expected, thus suggesting a “negative rebound. 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 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 unlikely to spur substantial direct rebound effects that would mitigate attendant energy savings.

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 CFL which are often perceived to have lower light quality are associated with greater increases in luminosity and lower increases in burn time than changes to LEDs. Higher luminosity of an energy efficient replacement bulb may also emerge 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.

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Authors' affiliations

Joachim Schleich

Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany

Grenoble Ecole de Management, Grenoble, France

Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA

Bradford Mills

Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA

Elisabeth Dütschke

Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany

Contact: Brigitte Kallfaß

Fraunhofer Institute for Systems
and Innovation Research (Fraunhofer ISI)

Breslauer Strasse 48

76139 Karlsruhe

Germany

Phone: +49 / 721 / 6809-150

Fax: +49 / 721 / 6809-272

E-Mail: brigitte.kallfass@isi.fraunhofer.de

www.isi.fraunhofer.de

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