Working Paper Sustainability and Innovation
No. S 5/2013

Bradford Mills
Joachim Schleich

Household Transitions to Energy Efficient Lighting

A revised version of WP S3/2014 is published as:

Mills, B. and Schleich, J. (2014): Household Transitions to Energy Efficient Lighting. *Energy Economics* 46, 151-160. (http://dx.doi.org/10.1016/j.eneco.2014.08.022)

Abstract

New energy efficient lighting technologies have the potential to significantly reduce household electricity consumption. But adoption of many technologies has been slow. This paper employs a unique dataset of German households to examine the factors associated with the replacement of old incandescent lamps (ILs) with new energy efficient compact fluorescent lamps (CFLs) and light emitting diodes (LEDs). The 'rebound' effect of increased light luminosity during the transition to energy efficient bulbs is analyzed jointly with the replacement decision to control for household self-selection in bulb-type choice. The results indicate that the EU ban on ILs accelerated the pace of transition to CFLs and LEDs, while storage of bulbs significantly dampened the speed of the transition. Households also appear responsive to new bulb attributes, as those with stated preferences for energy efficient, environmentally friendly, and durable lighting are more likely to replace ILs with CFLs and LEDs. Higher lighting needs generally spur IL replacement with CFLs or LEDs. However, electricity gains from new energy efficient lighting are mitigated by increases in bulb luminosity; with average increases in luminosity of 23% and 47% upon transitioning to CFLs and LEDs, respectively.

Highlights:

- EU ban on ILs has fostered transitions to energy efficient lighting
- Stated preferences for energy efficient, environmentally friendly, and durable lighting make households more likely to transition to CFLs and LEDs
- Indicators of greater lighting needs are associated with higher propensities to replace ILs with CFLs and LEDs
- For residential lighting, the rebound effect prominently manifests itself through increases in luminosity

Table of Contents

Page

1 Introduction

Residential lighting technologies have shown dramatic increases in energy efficiency in recent years. Compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) last longer and are significantly more energy-efficient than ILs. Hence, widespread adoption of these technologies has the potential to significantly reduce household electricity consumption in the EU and elsewhere. Lighting accounts for around 10% of residential electricity consumption in the EU and total consumption figures have decreased recently by 5% from 84TWh in 2007 to 79.8 TWh in 2009 (Bertoldi et al. 2012). This trend is expected to continue with the recent market trend away from incandescent light bulbs (ILs) towards halogen bulbs and self-ballasted compact fluorescent lamps (CFLs). More recently, solid-state light emitting diodes (LEDs) have rapidly entered the residential light bulb market. LED market share is likely to continue to increase, as prices for LEDs are expected to decrease substantially.[1]

Several countries have recently implemented bans on imports and domestic sales of incandescent light bulbs in order to accelerate the transition of their lighting markets to more energy-efficient lighting. Cuba was the first country to ban ILs in 2006 (IEA 2010), followed by Australia and New Zealand in 2008. Canada, China and the US among others have started implement IL bans in 2012. Typically the phase-out of ILs has been implemented in stages, with higher wattage bulbs banned first, and lower wattage bulbs banned later (see IEA 2010 for an overview).

The EU, where ILs still accounted for more than 50% of the residential lighting stock in 2009 (Bertoldi, 2012), Commission Regulation (EC) No 244/2009 imposed an immediate ban of non-clear incandescent lamps along with a gradual phase-out of other incandescent household bulbs, starting in September of 2009 for the highest wattage ILs (>=100W), adding >=75W ILs in September 2010 and >=60 ILs in September 2011, and finishing in September of 2012 with the lowest wattage ILs (<60W). Since then, only relatively energy efficient light lamps, such as CFLs and LEDs can be sold in the EU, subject to a few exceptions (such as specialty lamps for sewing machines or ovens) (e.g. Bertoldi et al 2012). Conventional low-voltage halogens can currently still be sold, but will be

---

[1] McKinsey (2012, p. 24) estimates global LED (value based) market share at 7% in 2011, 50% in 2016 and 70% in 2020 for the residential sector.

banned after September 2016. The regulation applies to lamps manufactured in the EU and imported. Remaining warehouse stocks are still eligible for sale after the respective deadlines. The phase out regulation is expected to affect the replacement of about 8 billion bulbs in EU households (EC 2011).

Historically, within the EU various regional and country level policies have attempted to directly foster the diffusion of energy-efficient light bulbs. The EU has mainly relied on informatory measures to help households make well-informed bulb purchase decisions. Since 1999, packaging for household lamps is required to display compulsory energy labels (The Commission Directive 98/11/EC implemented the Council Directive 92/75/EEC “Labelling Directive”), ranging from category A (most efficient) to G (least efficient). National policies to support the deployment of energy-efficient bulbs in the residential sector include information campaigns in several EU countries, but also subsidy or rebate programs by utilities for the purchase of energy-efficient bulbs. These programs were either voluntary (e.g. in Germany by a few utilities), or part of so-called “white certificates” schemes in Italy and energy suppliers obligations in the United Kingdom (e.g. Waide and Buchner 2008) which require utilities to achieve mandatory energy savings targets among their residential customers. Denmark exempted energy-saving light bulbs from tax. Germany, Portugal, and the United Kingdom had limited programs to distribute free energy efficient bulbs.

Barriers to the diffusion of more energy-efficient bulbs include their size and shape (visual appearance), perceived lower lighting quality, environmental and health concerns associated with toxic mercury in CFLs, and higher initial purchase costs. Other factors, like education, may also influence household propensities to adopt energy efficient bulbs leaving sub-populations of non-adopters as possible targets for further diffusion efforts. Little is known about the role that the bulb ban has played in generating more rapid household transitions from ILs to energy efficient bulbs. Many households were already making this transition before the implementation of the ban. While other households with strong preferences for ILs may have stockpiled ILs prior to implementation of the ban on specific bulb types.

Slow diffusion may not be the only constraint inhibiting electricity savings from energy efficient bulbs. Electricity savings may be lower than expected from a strictly engineering-economic assessment due to the ‘rebound effect’ (e.g. Khazzoom 1980). Since purchasing energy-efficient light bulbs means lower costs of lighting services, households may respond by letting bulbs burn longer, using more bulbs for additional lighting services, or increasing the luminosity of bulbs purchased.[2] Previous research has studied changes in operating hours (e.g. Greening et al. 2000), but the magnitude of the rebound effect associated with increases in luminosity is not known.

In this paper, we explore three fundamental questions related to the efficacy of the EU ban on ILs. 1) Did the ban appreciably increase the rate of adoption of energy efficient CFL and LEDs? 2) What other factors are associated with the switch from ILs to energy efficient lamps? 3) To what extent do increases in lamp luminosity diminish the electricity savings associated with the changeover to energy efficient lamps?

These questions are addressed using a 2012 representative survey with more than 1,600 documented choices of how private households in Germany replaced ILs. The paper represents, to our knowledge, the first attempt to analyze household decisions with respect to the adoption of energy efficient bulbs after the implementation of the EU ban and document associated changes in bulb luminosity.

The remainder of the paper is organized as follows. Section 2 reviews the literature on IL, CFL, and LED performance and the factors that influence household transitions to energy efficient bulbs. Section 3 presents the theoretical framework and empirical model. Section 4 presents the data and descriptive statistics. Section 5 presents the results and Section 6 distills policy implications.

2 Literature Review

Analyses of the international market for residential lighting suggest that the transition from purchasing ILs to purchasing more energy-efficient CFL and LED bulbs has been going on for several years, and has recently accelerated (e.g. IEA 2010, McKinsey 2012). Only two decades ago the vast majority of residential light bulbs were ILs. For example, in 1995 the IL share of all bulbs in the average household in the EU27^{+} (i.e. EU 27 plus Norway and Switzerland) was about 85% (VITO 2009). By 2007 this share dropped to 54%, while the stock shares of halogens and CFLs were by then 23% and 15%, respectively (VITO 2009). Similarly the market share of ILs in the EU^{+} decreased from 61% in 2006

---

[2] Some increases in household welfare likely occur from the increased duration or intensity of lighting use.

to 41% in 2010, i.e. the number of ILs sold annually decreased from 1,747 million bulbs to 1,108 million bulbs. For the same period, the market share of CFLs increased from 15% to 23% (Bertoldi et al. 2012, IEA 2012). For Germany, the market share of CFLs in 2007 was about 12% (IL: 49%; halogen: 30%; fluorescent lamps: 8%) (de Almeida 2008), and 70% of the households had at least one CFL, significantly above the EU average of 52% (JRC 2007).

ILs (and also halogens) are rather cheap to purchase but quite energy-inefficient, since they typically transform less than 5% of the input power into visible light (IEA 2010). The remainder of the input energy is converted into heat. Thus, ILs are rather expensive to operate as luminosity generators. In contrast, CFLs, and LEDs exhibit higher efficacy[3] than ILs, but also have a higher initial purchase cost. Compared to an incandescent light bulb, CFLs and LEDs require about 80% and 85% less electricity, respectively (CLASP 2013; IEA 2012; VITO, 2009).[4] For example, the most popular IL in Germany (a 60W bulb) produces a light output of 720 lumens, the wattage equivalence is about 11W for a CFL and 8W for a LED. Energy-efficient lamps are also more durable than ILs. The rated service lives for CFLs and LEDs are at least 6 and 25 times longer, respectively, than for ILs (around 1000 hours) (e.g. CLASP 2013, EC 2011b).

Despite these clear advantages, the diffusion of energy-efficient light bulbs has been hampered by several factors (e.g. Frondel and Lehmann 2011, European Commission 2011, de Almeida et al. 2013). CFLs, halogens and LEDs all come in the E27 and E14 socket sizes typically used for general lighting services lamps. But the bulbs differ in size and shape from ILs, and may not be supported by existing lamp fixtures or may face resistance for aesthetic reasons. When asked why they never or rarely use CFLs, 26% of the German households surveyed in de Almeida (2008) refer to size, and 22% refer to appearance. The purchasing price is mentioned as a main barrier by 20% of German respondents in the same survey, reflecting high up-front costs of CFLs. Initial purchase cost constraints are even more severe for LEDs. For example, a 60W IL costs less than 1 Euro at the retail store, while its CFL equivalent cost around 5 Euro

---

[3] 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).

[4] Since efficacy varies with technology, manufacturer, voltage and wattage, figures on electricity savings can only be approximate.

and its LED equivalent costs more than 30 Euro (e.g. European Commission 2011, p. 7).

Around 15% of the German respondents in the de Almeida (2008) survey referred to lighting quality as a main barrier, arguably reflecting discontent with the fact that CFLs and also LEDs radiate different spectral distributions than ILs. Incandescent and halogen bulbs generate a “warm” yellowish light, while the light of CFLs is sometimes considered to be “cold” or whitish. LEDs are in-between, exhibiting a more balanced spectral power distribution than CFLs. Further, most (but no longer all) CFLs require a warm-up period and may take several seconds before achieving full brightness. Most CFLs are not dimmable, either. CFLs, and to a lesser extent LEDs, are also associated with negative environmental and health effects. CFLs contain toxic mercury and, thus, need special disposal. In the EU CFLs must be collected and recycled by manufacturers and importers in accordance with the European Community Waste Electrical and Electronic Equipment Directive. Mercury vapor from broken CFLs may cause damage to or be hazardous to developing brains and nervous systems. Also, CFLs and LEDs emit electromagnetic radiation, hence causing “electro smog”.[5] Moreover, concerns have been raised that the blue spectral component of LED light damages the retina, although these fears do not appear to be substantiated (European Commission 2011, p.8).

As pointed out by Mills and Schleich (2010) and Frondel and Lehmann (2011), among others, it may not be economically rational to replace all ILs in a household (~ 25 on average in Germany) with CFLs. Frondel and Lehmann (2011) illustrate that for the main bulb in the German living/dining area, which is typically used for around 3 hours a day, the higher purchasing costs of a CFL are amortized in less than one year. For a bulb in the attic, storage room or bedroom where the daily usage time is less than 15 minutes, higher purchasing costs of CFL may only pay-off after more than a decade. Thus, a ban on ILs may be costly to consumers with a substantial share of low-use lighting applications. However, no empirical analysis has been undertaken on the actual impact of the EU ban, particularly when accounting for the existing market shift away from ILs.

---

[5] 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.

Even though the “Labelling Directive” 92/75/EEC requires the label on the packaging of bulbs to also include the luminous flux of the lamp in lumens, the input power (wattage) and the average rated life of the lamp, households may still suffer from lack of information or bounded rationality when making purchase decisions. As argued by the European Commission (2011a, 2001b), the information provided on the package is often poorly explained or even misleading (e.g. equivalence claims about the light output). Likewise, consumers may not understand the various technical properties, or lack the capabilities to evaluate financial costs and benefits. Hence, even under perfect information, households may exhibit satisficing behavior, using routines, or rules of thumb (Simon, 1959) and neglect opportunities for improving energy efficiency. In particular, households may habitually replace a broken bulb by an identical bulb. Similarly, household willingness to change bulb types may depend on search costs of information on the performance of alternatives. Search costs are likely to be higher with greater opportunity costs for household time, implying search costs are greater for high income households. Conversely, search costs may be lower for more educated households, as education lowers the costs associated with the acquisition of information (Schultz 1975).

Finally, household storage of ILs slows down the transition towards more energy-efficient bulbs. Households may stockpile bulbs to prevent extended loss of lighting services should a bulb suddenly break or in order to lower transaction costs related to purchasing bulbs. Households may also decide to hoard ILs in response to a phase-out, as was observed in several European countries. For example, the sales of ILs in Germany increased by 34% in the first half of 2009, while the sales of CFLs increased by only 2%.[6]

While there is substantial literature on the technical merits and engineering-economic costs and benefits of energy efficient lighting, few studies have explored the relation between socioeconomic factors and adoption. Scott (1997) finds little association between CFL adoption and socio-demographic characteristics of households in Ireland. But Kumar et al. (2003) find that households with higher income and education levels in India are more likely to purchase CFLs. For German households, Mills and Schleich (2010) find adoption of CFLs is positively linked to some residential characteristics like low-income and to

---

[6] New York Times Online: Europe’s Ban on Old-Style Bulbs Begins (http://www.nytimes.com/2009/09/01/business/energy-environment/01iht-bulb.html, accessed 13 March 2013)

knowledge of household energy consumption. They conclude that high income households with greater number of lighting applications and greater lighting needs appear to be particularly willing to pay higher electricity costs rather than give up preferred lighting attributes of ILs. Finally, di Maria et al. (2010) highlight the important role of environmental awareness, along with education, income, and information in the diffusion of CFLs in Ireland. Existing studies though are based on data collected either in the 1990s or early 2000s. Since then, the quality of CFLs has improved in terms of color, flickering, and start-up delays, and the availability of shapes has expanded. CFLs are now almost perfect substitutes for ILs. In addition, LEDs have entered the market, broadening the technology choice set for household purchase decisions.

Lighting rebound effects stem from higher demand for lighting services with increases in energy efficiency. Direct rebound effects stem from lower effective prices for luminosity (e.g. van den Bergh 2011; Brookes 1990; Frondel 2008; Greening et al. 2000; Khazzoom 1980, 1987, 1989; Madlener and Alcott 2009; Sorrell 2007). Indirect and economy-wide rebound effects may also exist. Indirect rebound effects reflect additional energy use associated with higher expenditures for other goods and services based on cost savings. Macro-economic (or economy-wide) rebound effects are typically the result of productivity improvements and radical innovations resulting in additional applications of energy-using technologies and economic growth (i.e. a macroeconomic growth effect). Income effects and economy-wide rebound effects associated with lighting are typically, in the short to medium term, small since the share of lighting of total electricity consumption and of disposable income is rather small (e.g. Fouquet and Pearson 2012, Chitnis et al. 2013)[7].

A few empirical studies explore direct rebound effects associated with energy efficient lighting. Greening et al. (2000) report 5% to 12% longer burning times in four empirical studies for residential lighting. Similarly, according to Almeida (2008) 15% of German households stated that they let energy-efficient bulbs burn longer than ILs they had replaced. Relying on a dwelling stock model for the UK, Chitnis et al. (2013) calculate the rebound effect (in terms of CO_2 emissions) for energy efficiency gains in lighting at 10%. Chitnis et al. (2013) also acknowledge possible effects on illumination levels, but – like all other studies

---

[7] Relying on data for several hundred years, Fouquet and Pearson (2006, 2012) find that total consumption of lighting services increased substantially over time in response to cheaper and better lighting services and to growing incomes. For example, lighting demand increased by a factor of 500 over the last three centuries in the UK.

we are aware of – they do not include luminosity change in their quantitative estimate of rebound effects. Borenstein (2013) uses an illustrative example for LEDs and CFLs to demonstrate that rebound effects will largely depend on the size of the demand elasticity for lighting – leaving the magnitude of the rebound effect as, essentially, an empirical question.

3 Framework and Model Specification

The framework starts with a utility maximizing household that needs to replace a IL. The household makes two choices: 1) what bulb type to replace the initial IL with and 2) the wattage of the replacement bulb relative to the initial IL bulb. Assume that household utility associated with bulb replacement can be captured from net income after replacement, y, and lighting luminosity - that has a bulb-type *i* specific relationship with wattage $L^i(w)$.[8]

$$U(y, L^i(w)) \quad \text{where } i = \text{IL, CFL, LED.}$$

Net income after replacement depends on base income, y^0, bulb-type and wattage specific costs of purchase, $B^i(w)$, and bulb-type specific variable costs of bulb use, $C^i(w)$.

$$y = y^0 - B^i(w) - C^i(w).$$

Given a bulb type, maximization of utility subject to the income constraint yields the optimal choice of bulb wattage *w** where

$$\frac{\partial U}{\partial L^i(w^*)}\frac{\partial L^i(w^*)}{\partial w^*} = \frac{\partial U}{\partial y}\left[\frac{\partial B^i(w^*)}{\partial w^*} + \frac{\partial C^i(w^*)}{\partial w^*}\right] \qquad (1)$$

The marginal utility of the luminosity associated with increased wattage equals the marginal utility of income associated with the variable and fixed costs of the increased bulb wattage.

In choosing bulb type, the household chooses the highest ratio of marginal utility of luminosity-wattage to marginal costs:

---

[8] Utility from all other goods not influenced by the bulb decision is assumed constant, as is bulb burn time.

$$\frac{\frac{\partial U}{\partial L^i(w^*)}\frac{\partial L^i(w^*)}{\partial w^*}}{\frac{\partial B^i(w^*)}{\partial w^*}+\frac{\partial C^i(w^*)}{\partial w^*}} > \frac{\frac{\partial U}{\partial L^k(w^*)}\frac{\partial L^k(w^*)}{\partial w^*}}{\frac{\partial B^k(w^*)}{\partial w^*}+\frac{\partial C^k(w^*)}{\partial w^*}} \quad \forall \quad k \qquad (2)$$

The marginal costs in the denominator highlight the tradeoffs households face in IL replacement choice, as upfront costs increase from ILs to LEDs while variable costs decrease:

$$\frac{\partial B^{IL}(w)}{\partial w} < \frac{\partial B^{CFL}(w)}{\partial w} < \frac{\partial B^{LED}(w)}{\partial w} \quad and \quad \frac{\partial C^{IL}(w)}{\partial w} > \frac{\partial C^{CFL}(w)}{\partial w} > \frac{\partial C^{LED}(w)}{\partial w}.$$

Clearly, an increase in bulb efficiency $\frac{\partial L^i(w^*)}{\partial w^*}$ or a decrease in marginal fixed costs $\frac{\partial B^i}{\partial w^*}$ or variable costs $\frac{\partial C^i}{\partial w^*}$ at the optimal wattage will make a household more likely to adopt a bulb type. Similarly the natural tendency for increased bulb efficiency to lead to increased luminosity is apparent in equation (1), as households will indulge in greater luminosity with part of their cost-savings.[9]

Three other aspects of bulb choice are worth noting in the model. First, some households (particularly with early generations of CFLs) prefer the light quality of ILs. In this case $\frac{\partial U}{\partial L^{IL}(w^*)} > \frac{\partial U}{\partial L^{CFL}(w^*)}$ and CFLs will need differential cost-savings to overcome light quality preferences. Second, households may have incomplete information, particularly with respect to the efficiency of bulb types, $\frac{\partial L^i(w)}{\partial w}$, and the variable costs, $\frac{\partial C^i(w)}{\partial w}$. Generally, household information on new bulb types is expected to be less complete than information on the initial IL bulb. Adoption of the energy-efficient bulb types will be deterred if efficiency gains are underestimated or if the probability of high levels of gains is discounted due to uncertainty.[10] Households can reduce information uncertainties through research on bulb performance, however such research is costly to the household and will further raise the upfront costs of CFLs and LEDs over that of

---

[9] Assuming no satiation in lighting needs.

[10] Although Allcott, Mullainathan, and Taubinsky (2012) find that providing households with economic information on CFL bulb efficiency relative to ILs does not change bulb purchase probability.

ILs. Third, bulb purchase and use costs occur over different timeframes. Thus, individual time preferences are likely to also influence bulb choice. Specifically, individuals with high discount rates will be more attracted to continue to use ILs, while those with low discount rates will be more attracted to the lower long-run costs of CFLs and LEDs.

Model Specification

The statistical model is specified in light of the above framework. Two choice equations are specified; the first governing bulb-type choice and the second governing luminosity choice. Location and intensity of use of bulbs will have a large impact on both bulb-type choice and luminosity-wattage choice. Bulbs that are designated for main lighting needs are likely to be used more intensively and generate greater variable cost savings for CFLs and LEDs relative to ILs. ‘Main’ bulbs are, thus, more likely to be replaced with CFLs and LEDs than are bulbs used for secondary lighting. Similarly, the marginal utility of luminosity may be greater for ‘main’ bulbs, which will make households more likely to increase bulb luminosity in response to variable cost savings for main lighting than secondary lighting when replacing a IL with a CFL or a LED. In particular, the fact that marginal variable costs increase less with luminosity equivalent wattage for CFLs and LEDs will also tend to increase the relative magnitude of the rebound effect for main lighting.

The room in which the bulb is placed is also likely to impact bulb usage. As with ‘main’ lighting, households may be more likely to replace ILs with CFLs and LEDs in high lighting-use rooms like living rooms and kitchens and may be more likely to upgrade wattage in these rooms due to greater utility from increased lighting and larger marginal variable cost savings.

The literature frequently identifies rental units as less likely to adopt energy efficient technologies. For capital intensive systems like space and water heating, insulation, and appliances landlords often make investment in energy efficient technologies, while tenants capture the benefits (e.g. Mills and Schleich, 2009; Gillingham, Harding, and Rapson, 2012; Davis, 2012). Deterrents to energy efficient adoption associated with lack of benefit appropriability may be less of an issue for bulbs, as they are less capital intensive and may – unlike most thermal insulation measures - be easily transferred to a new apartment. In fact, Mills and Schleich (2010) find renting does not significantly influence CFL adoption in German households. But LEDs have a much longer life and this may deter renter investments if renters are more mobile than homeowners and expect to move within several years. Renting is, however, unlikely to have a large impact on luminosity choice and is excluded from that equation.

Preferences for bulb attributes may also influence bulb type choice and luminosity decisions. In the survey respondents were allowed to choose up to three criteria (of ten listed) that they felt were most important in the choice of a bulb. Six criteria - price, quality, electricity use, durability, environmental friendliness, and dimmable - are included in the bulb choice equation specification. The same criteria, except for dimmable, are also included in the wattage choice equation. Those who list price as an important criteria may be less likely to replace ILs with initially more expensive CFLs or LEDs. An emphasis on price as a bulb criteria may also deter luminosity increases if it is indicative of cost consciousness.

Stating bulb ‘quality’ as an important attribute may deter replacement with CFLs, as ILs are felt by some to produce higher quality lighting. If quality is an important attribute to bulbs, households may also be less likely to invest in increased wattage for CFLs, as they will derive less utility from increased CFL luminosity. On the other hand if ‘electricity use’ is stated as an important bulb attribute, households may be more likely to place an emphasis on variable cost savings and switch to energy efficient bulbs - particularly very energy efficient LEDs. How stated importance of energy efficiency in bulbs may influence luminosity changes is left as an empirical question. Emphasis on electricity conservation may deter luminosity increases with more efficient bulbs. On the other hand, respondents may have been deterred from increasing luminosity previously with less efficient ILs and respond more vigorously. Similarly, listing durability as an important attribute implies an emphasis on long-term costs of the bulb, rather than just up front purchase price. Thus, durability is expected to be associated with an increased propensity to replace ILs with CFLs, and a very high propensity to replace ILs with LEDs.

The impact on IL replacement of stating ‘environmental friendliness’ as an important bulb attribute is less clear. The mercury found in CFLs is an environmental concern, which may deter adoption in favor of ILs. However, CLFs and LEDs have significant environmental benefits related to electricity savings. The net outcome of these different environmental attributes is an empirical question. In terms of changes in wattage, environmental concerns may temper household willingness turn part of their electricity savings into increases in luminosity. Dimmable CFL and LED bulbs are much more expensive, and reviews on performance are mixed (CLASP, 2012), thus emphasis on dimmability as a bulb criteria is expected to deter the replacement of ILs with CFLs and LEDs.

Lighting fixtures and accessories are rapidly evolving to accommodate the small size and low heat output of LEDs. Thus replacement of the whole lamp-set, instead of just the bulb, may foster transitions to energy saving LEDs. The impact of lamp-set replacement on CLF uptake is less clear a priori. But households may be more likely to increase wattage as part of their investments in lighting needs that require lamp replacement, particularly in the transition to LEDs.

One would expect that households would be more likely to replace bulbs in 2012 with CFLs and LEDs than in 2010 or 2011, as the market share has trended towards CFLs and LEDs. Time trends in bulb uptake are also likely to be affected by the implementation on the IL ban. The impact of the IL ban is inferred through an interaction term between 2012 replacement and initial ILs greater that 60W. This interaction term is employed because this group of bulbs is certain to be subject to the IL ban at the time of the replacement in 2012. If the ban is effective the change in the propensity to replace these banned bulb types with CFLs and LEDs should be greater than the change in propensity in 2012 for other bulb types not subject to the ban. It is also possible that some 60W+ ILs replaced in 2010 and 2011 were also subject to the ban, as were some 60W bulbs in 2012. Thus, the ‘bantime’ variable should be seen as a lower bound measure of the impact of the IL ban on bulb replacement choice. Similarly, as discussed, many households may have stored IL bulbs for use after the ban. Therefore, taking a replacement bulb from storage should strongly decrease the probability of bulb replacement with an energy-efficient CFL or LED. Similarly, bulbs from storage are more likely to be of similar luminosity if both the initial bulb and the replacement are ILs.

Household characteristics may also influence both bulb type and luminosity choice. Higher levels of education are usually associated with more rapid levels of adoption of energy efficient technologies, as more educated individuals can more quickly and easily gain and process information on the costs and benefits of new technologies. Further, more educated individuals are likely to have higher incomes and be less financially constrained by the high up-front costs of energy efficient bulbs. The potential impact of education on luminosity choice is unclear. Highly educated individuals should be better able to determine the correct luminosity equivalent wattage of CFL and LED bulbs. However, the more educated individuals with associate higher incomes may also be more willing to indulge in higher luminosity after bulb replacement. Household member age may also impact bulb replacement decisions; younger households (with heads between 16 and 26) may be more financially constrained and less willing or able to pay high upfront costs for CFL and LED bulbs. On the other hand, elderly household members are generally more reluctant to change technologies and, thus, may also be more reluctant to replace ILs with CFLs or LEDs. The elderly may be more set in their lighting habits, and less likely to increase bulb luminosity upon bulb replacement, particularly for IL to IL replacement. The impact of gender on bulb type and wattage decisions is left as an empirical question. However, larger households may be expected to use bulbs more intensively, thus households of more than two persons 'twoplus' might be more likely to adopt energy efficient bulbs as the payback time will be shorter with higher usage.

Statistical Model

As mentioned, the household chooses the bulb type with the highest marginal utility of luminosity to bulb marginal cost ratio. Denoting this ratio in the statistical model y^{B*}, $y_i^{B*} > \max(y_j^{B*}) \quad for \quad j \neq i.$ The observed choice of bulb-type *i* can be modeled a linear function of observable covariates and a random error component by multinomial logit.

$$y^B = z\gamma + \eta \qquad (3)$$

Change in bulb luminosity, y^L, can also be modeled as a linear function of model covariates and an error component.

$$y^L = x\beta + u \qquad (4)$$

However, change in luminosity is only observed for the bulb-type with the highest marginal utility of luminosity to marginal bulb costs ratio, leading to highly selected samples of observed household change in bulb luminosity choices. As Heckman (1979) shows, the error term in equation (4) can be conditioned on the probabilities of selection of the alternative bulb types in order to correct for this sample selection bias. Two correction methods are employed that use the multinomial logit in equation (3) to generate Heckman-type selectivity correction terms. The first is the Dubin and McFadden (1984) selectivity correction estimation method. The method places no restrictions on the covariances of the bulb choice equation and the bulb-type specific luminosity choice equations by including selectivity correction terms for all three bulb type choices in each luminosity choice equation. The second is the well-established Lee method (1983) that includes only one selectivity correction term based on the choice probabilities of the observed outcome. The Lee method is parsimonious and, thus, well-suited for relatively small samples of observed choice outcomes like those in the current study. However, parsimony comes at the cost of strong implied restrictions on the correlations between alternative bulb choices and luminosity choice. Following Bourguignon, Fournier, and Gurgand (2007), the restriction that the covariances sum to one in the Dubin and McFadden estimator is also dropped, as this variation of the sample selection correction method performs best in Monte Carlo simulations with moderate sample sizes similar to those in the current study. Standard errors are generated based on bootstrapping with replacement with N=500. The three changes in luminosity equations are also estimated by OLS without any correction for selectivity for comparison.

4 Data

A representative survey of 6,409 households in Germany was carried out in May and June of 2012. The survey was implemented as a computer based questionnaire within an existing panel, where participating households were equipped with a visual interface (e.g. photographs of different bulb types were shown). Around 90% of households stated that they had at least one energy efficient light bulb installed in their home. About three-fourths of the households remembered when they last replaced a light bulb. Further, to limit recall bias in self-reported data only observations where the replacement occured in 2012 (75%) or in 2011/2010 (25%) are retained. This leaves 4,061 events involving replacement decisions, either for a single bulb or for replaced lighting fixture. The vast majority of the new bulbs replaced a broken or burned out bulb (86%), however 7% of new bulbs replaced a bulb that was not broken, and 5% were part of a replacement fixture.

Table 1 presents these transitions by initial and replacement bulb type. Almost half of the initial bulbs are ILs (44%), this stems both from ILs prevalence of use and from the fact that ILs have shorter life-spans. CFLs represent 30% of initial bulbs, while Halogens and LEDs represent 23% and 3% percent of initial bulbs, respectively.

Most consumers (71%) maintained the same type of bulb when replacing a bulb (e.g. a IL is replaced with a IL). Of the 29% who did change bulb types, over two-thirds switched from an IL to another type of bulb. On the other hand, consistent with the general movement towards more energy efficient bulbs, less than 10 percent of these reported transitions were from an IL to a halogen lamp.[11] The remainder of the empirical analysis in the paper focuses on the replacement decisions of 1,714 households who initially had ILs and either maintained a IL (58%) or replaced a IL with a CFL (35%) or a LED (7%).

The second dependant variable of interest in the analysis is the change in bulb luminosity associated with bulb replacement. In the survey households were asked about the wattage of both the replaced bulb and the new bulb.[12] Five different wattage categories were given, with the categories being specific to the wattages commonly associated with each bulb type. Luminosity was then calculated on a per bulb per wattage basis with standard figures from the literature.

There are 1,660 observations with luminosity data for both the initial and replacement bulb. These observations are used to calculate the ratio of the luminosity of the new bulb to the old bulb (fluxratio). The sample average is 1.10, indicating a 10% increase in luminosity on average with bulb replacement. However, the change in luminosity differs by new bulb type. Those who replace the IL with another IL have virtually no change in calculated luminosity (-2%), while households who replace the IL with a CFL and a LED have calculated increases in luminosity of 25% and 47%, respectively. This suggests that there may be a very significant rebound in terms of lighting intensity with the transition from ILs to energy efficient lamps. The factors associated with the magnitude of this rebound effect are identified in the multivariate analysis.

Table 2 provides descriptive statistics on the dependent and independent variables used in the analysis of bulb transition choices and change in luminosity choices. Sample sizes for the replacement bulb choice and luminosity choice equations differ slightly due to missing data on the wattage of the initial or replacement bulb, so descriptive statistics are presented for both samples.

Of note, a ‘bantime’ variable identifies 12% of the initial ILs that were replaced in 2012 and were certain to have been subject to the ban (given the classification this entails IL over 60 watts). On the other hand, over 60% of bulbs came from storage rather than direct purchase, which would mitigate the impact of the ban.

---

[11] For this reason, halogen bulbs are not included in the empirical analysis.

[12] 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).

Two-thirds of initial bulbs were used for main lighting of rooms, as opposed to background or side lighting. Around 28% percent of initial ILs were located in the living or dining room, while 19% were in hallways, 16% were in bathrooms, 12% were in the kitchen, 9% were in the bedroom, and 16% were for child rooms, outdoors, and other rooms.

In terms of bulb purchasing criteria, energy efficiency, price, durability, and quality were most important criteria for bulb choice listed by respondents, while environmental friendliness and dimmability were far less frequently listed as important criteria.

Turning to the personal characteristics of respondents, approximately 28% of the respondents are in the baseline low education group with a high-school or lower level of education, 48% are in the middle group technical school group, and 30% have a University degree. Females represent 40% of the respondents in the sample and most respondents are middle-age (around 5% are between 16 and 26 years of age and around 18% are over 65 years of age). Single individuals represent 28% of respondents, while 42% of respondents live in two-person households, and 30% live in households containing more than two persons. Around 45% of households in the sample rented their house.

5 Result

Replacement Bulb Type Choice

Multinomial model estimation results for the choice of bulb type equation are presented in table 3. The model is estimated with two samples; all households with the observed replacement of a bulb or fixture (N=1,714) and the slightly smaller sample of households who report the wattage of both the initial and the replacement bulb (N=1,660). This slightly smaller sample is employed in the subsequent analysis of changes in bulb-wattage luminosity. Parameter estimates are reported as relative risk ratios, with IL to IL replacements as the base category.[13] Focusing first on the sample of all households, the relative risk ratio in column 1 for the variable ‘lamps’ indicates that for households which replace a lamp fixture along with the bulb the relative ‘risk’ or relative likelihood of

---

[13] In the presentation of the results, parameter estimates are significant at the conventional p=0.05 level unless the significance level is noted.

choosing a CFL compared to an IL increases by a factor of 2.8.[14] Similarly, the relative risk of choosing a LED increases by a factor of 4.0 with lamp fixture replacement. Thus, lamp fixture replacement is strongly associated with the choice of energy efficient bulbs.

Surprisingly, model results indicate that there is actually a decrease in the relative risk of IL replacement with CFLs and with LEDs when the bulb is replaced in 2012 compared to when the bulb is replaced in prior years. The result seems to be at odds with market trends which clearly indicate a movement over time toward CFL and LED bulbs. However, care should be taken in the interpretation of this trend parameter. ILs burn out far more quickly than CFLs or LEDs, thus households with a high share of ILs are more likely to have replaced a bulb in 2012. This sampling issue may partially explain the decrease in the relative risks of CFL and LED replacement in 2012. On the other hand, the 'bantime' estimates - indicating bulbs replaced in 2012 that were definitely subject to the EU ban at the time of replacement - have the expected sign. The relative risk of IL replacement with a CFL increases by a factor of 1.8, while the relative risk of replacement with a LED increases by a factor of 3.2 when the wattage of the initial IL made it subject to the ban in 2012. It is also worth noting that the sign and magnitude of the 'bantime' parameter estimates remain largely unchanged if IL bulbs in the next wattage category with initial wattages between 41W and 60W are included in the banned bulb group. A significant share of bulbs in this group are, presumably, 60W bulbs and would have also been included under the ban in 2012. As expected, retrieval of the replacement bulb from storage shows a strong negative association with the movement towards energy efficient bulbs. The relative risk of IL replacement with a CFL decreases by a factor of 0.2, while replacement with a LED decreases by a factor of 0.03.

Turning to variables on bulb use, as expected the relative risks of IL replacement with a CFL and with a LED (p=0.10) both increase when the bulb is used for 'main' lighting; the increases are by factors of 1.4 and 1.7, respectively. However, the room in the households where the bulb is used has little impact on the relative risk of replacement with energy saving bulbs. In fact the only significant estimate is a decline in the risk of IL replacement with an LED in 'other rooms' relative to the base living room category by a factor of 0.4. Renting also has no significant impact on bulb choice.

---

[14] A relative risk ratio of 1.0 would indicate that there is no change in the risk of one bulb type choice compared to another type the change in the variable.

Stated importance of several bulb attributes show a significant association with bulb choice. Surprisingly, price does not matter. But listing lighting ‘quality’ as an important bulb attribute increases the relative risk of IL replacement with a LED by a factor of 1.7. As expected, listing electricity use as an important bulb attribute strongly increases the relative risk of CFL adoption by a factor of 2.5 and has an even stronger impact on LEDs adoption, increasing the relative risk by a factor of 7.8. Thus, consumers with strong preferences for electricity saving lighting appear to recognize the superior performance of LEDs. Relative risks of CFL (p=0.10) and LED adoption also increase marginally when durability is listed as an important bulb attribute, while listing dimmability as an important bulb attribute increases the relative risk of IL replacement with a LED (p=0.10). Listing environmental friendliness increases the relative risks of IL replacement with a CFL and with a LED by factors of 2.4 and 3.0, respectively. Thus, disposal concerns associated with CFLs do not appear to deter adoption among households with preferences for environmentally friendly bulbs.

In terms of household characteristics, education has no significant impact on IL bulb replacement choices. However, female survey respondents are less likely to replace ILs with LEDs, with the relative risk decreasing by a factor of 0.6. Similarly, young respondents between 16 and 26 years of age are less likely to replace ILs with CFLs (p=0.10) or LEDs (p=0.10) compared to respondents between 27 and 65 years of age, with relative risks decreasing by factors of 0.6 and 0.4, respectively, for the two bulb types. Older respondents (over 65 years of age) show a decreased relative risk of CFL adoption (p=0.10), but no change in the propensity to replace ILs with LEDs. Finally larger (more than two person) households show an increased relative risk (by a factor of 1.9) of replacing ILs with LEDs, this may stem from higher lighting demands in larger households.

Multinomial model relative risk ratio parameter estimates for the smaller sample of households that have complete information on initial and replacement bulb wattage are provided in column five for CFL replacements and column seven for LED replacements in table 3. Overall, despite the slightly smaller sample size the results look very similar. The two notable exceptions are that bulb replacement in 2012 no longer decreases the relative risk of IL replacement with a LED and older respondent no long show a significant decrease in the relative risk of replacing a IL with a CFL.

Change in Luminosity

Results for the sample-selectivity corrected IL to IL, IL to CFL, and IL to LED change in luminosity equations using the Dubin-McFadden selectivity correction method are presented in table 4. Overall, the statistical models associated with the luminosity changes for all three bulb transitions have very low predictive power. F-tests indicate that overall variables in the IL to IL change in luminosity model and the IL to CFL change in luminosity model have significant explanatory power, however variables in the IL to LED model do not. Reported adjusted R-squared statistics for the three models are also low.

Descriptive statistics indicate no overall change in the bulb luminosity ratio for IL to IL bulb transitions. However, a number of individual covariates are significantly associated with the luminosity ratio. Taking a bulb from storage is associated with a decrease in the tendency to increase bulb luminosity, with an estimated 18 percent lower luminosity ratio than when a new IL bulb is bought from a store. As expected, when a bulb is used for main lighting, the luminosity of the new IL is, on average, 6 percent brighter. Bulb location in the household, however, is not associated with changes in luminosity.

Surprisingly, two stated important attributes of bulbs, energy efficiency and environmental friendliness, show a positive association with the bulb luminosity ratio in the IL to IL model. One might speculate that stated energy efficiency and environmental preferences are weak if one decides to replace an IL bulb with another IL. The bulb luminosity ratio is found to be lower among younger (16 to 26 years of age) respondents (*p*=0.10). Finally, the IL to CFL selectivity correct coefficient (m12) is significant, implying that there is significant correlation between the unobserved heterogeneity in the IL to CFL bulb choice equation and the unobserved heterogeneity in the IL luminosity choice equation.

As noted, the descriptive statistics indicate that the average increase in bulb luminosity when moving from an IL to a CFL is 23 percent. The IL to CFL luminosity choice equation estimates indicate that there is a very strong decrease in bulb luminosity when the initial bulb is an IL and the replacement is a CFL taken from storage instead of bought at a store. Individuals who plan ahead and store new CFL bulbs for replacement may take more time to establish the equivalent luminosity. There is, on the other hand, an increase in luminosity when the respondent indicates that energy efficiency is an important bulb attribute. In this case the result is understandable and consistent with the rebound effect, as respondents who place an emphasis on energy savings may be willing to indulge more in luminosity when they use an energy efficient CFL replacement bulb. Education also appears to influence CFL luminosity choice (*p*=0.10), as luminosity of the CFL relative to the initial IL decreases 23 percent when the respondent has a university education as opposed to high school or less – essentially offsetting the observed average luminosity increase in IL to CFL transitions. The result is consistent with the hypothesis that education assists individuals in effectively deciding equivalent luminosity when moving from ILs to CFLs. Luminosity increases in transitions from IL to CFL bulbs are also found to be greater in larger (more than 2 person) households which presumably have greater lighting needs. The IL to CFL selectivity correct coefficient (m12) is again significant (*p*=0.10), implying in this case that there is correlation in the unobserved heterogeneity in the IL to CFL bulb choice and the CFL luminosity choice equations.

Even though descriptive statistics indicate that luminosity increases by 47 percent on average when ILs are replaced by LEDs, the IL to LED luminosity equation has little explanatory power and the F-test for overall significance of the model is rejected at conventional significance levels. In fact, the only variable showing statistical significance at conventional levels is the indicator for LEDs in bathrooms (*p*=0.10). The small number of IL to LED transitions is one factor in the weak statistical performance of the model.

Change in bulb luminosity parameter estimates using the more parsimonious Lee selectivity correction model are presented in table A.1. For IL to IL bulb replacements the results look fairly similar overall. The two exceptions being that female respondents tend to increase bulb luminosity relative to males (*p*=0.10) and older respondents tend to decrease bulb luminosity relative to those 27 to 65 years of age (*p*=0.10). There is less similarity in the Lee results and the Dubin-McFadden results for changes in luminosity with IL to CFL bulb replacements. While the parameter estimate for taking the new bulb from storage is still large and negative, it is no longer statistically significant when the Lee selectivity correction method is employed. Similarly, stating energy efficiency as an important bulb attribute is no longer associated with increased luminosity in IL to CFL transitions. On the other hand, luminosity changes with IL to CFL transitions are now significantly lower when light quality is stated as an important bulb attribute. More associations are also found with respondent characteristics. Specifically, female respondents tend to increase bulb luminosity more than males, while the elderly show a lower increase than those 27 to 65 years of age. Large (more than 2 person) households no longer show significant increases in luminosity compared to single person households when IL bulbs are replaced with CFLs.

The more parsimonious Lee selectivity correction model appears to perform slightly better than the Dubin-McFadden model in terms of significant parameter estimates with the small sample of IL to LED transitions. The large positive coefficient associated with lamp replacement is now statistically significant. Further, the selectivity correction coefficient is now negative and significant.

OLS parameter estimates are presented in table A.2. Again, the model F-tests and adjusted R-squared results suggest the three equations explain little of the observed variance in changes in bulb luminosity. Parameter estimates are different than those presented in the Dubin-McFadden and Lee results, particularly for the IL to IL luminosity change equation. Since selectivity correction coefficients are significant in both the Dubin-McFadden and Lee models, the OLS results serve to highlight how incorrect inferences may arise when sample selection issues are not controlled for in estimation. For instance, we would conclude that taking IL bulbs from storage tends to lead to the use of higher luminosity IL bulbs.

6 Conclusions and policy implications

Observed household behavior with respect to bulb type and luminosity choices generally conform with the responses expected from the economic incentives generated by energy efficient bulbs. Several factors significantly impact household transitions from ILs to CFLs and to LEDs. Of particular note is the EU ban on IL bulbs. Households show a significant differential increase in the propensity to replace ILs with banned wattage levels in 2012 relative to non-banned bulbs. On the other hand, storage of bulbs significantly slows transitions from ILs to more energy efficient lighting. Storage does not imply households are hoarding bulbs to avoid having to transition to less preferred CFLs or LEDs. Households may have stored IL bulbs in order to take advantage of bulk purchase discounts or sales, or to avoid fixed costs of purchase every time a bulb needs replacement. Regardless of motivation, bulb storage appears to substantially lengthen the timeframe for transitions to new energy efficient technologies. Engineering estimates, projected future costs, and market trends all suggest that CFLs are only transitionary technology and should lose significant future market share to more efficient LEDs. However, the impact of bulb storage on future CFL to LED transitions is likely to be even greater than that observed for IL to CLF transitions, as bulb life of CFLs is much greater than ILs.

Policy options to mitigate the negative impacts of storage on transitions to more energy efficient lighting include bulb buy-back programs or bulb credits towards new technology bulbs. In the case of future CFL to LED transitions, buy-back programs will also provide a mechanism to address disposal issues associated with mercury in CFLs. Households are found to be much more likely to adopt LEDs when fixtures are replaced than when bulbs are replaced, in part because new fixtures take full advantage of the small sizes and lower heat levels of LEDs. Programs to foster transitions to more energy efficient lighting may also focus on providing incentives for lighting fixture replacement rather than bulb replacement. However, as noted, the most common incentives to date have been to either provide new energy efficient bulbs for free or at a highly subsidized price.

Bulb attributes also matter in generating transitions to energy efficient lighting. Stated importance of energy efficiency motivates consumer transitions, as does environmental friendliness and durability. Interestingly, stated importance of light quality does not deter transitions from ILs to CFLs. However, preferences for light 'quality' do foster transitions from ILs to LEDs. Thus, it appears that consumers will be responsive to further effects to convey the beneficial attributes of energy efficient bulbs. As regulations already require a significant amount of information on the label, focus, emphasis, and placement of information may be key for label effectiveness and should be explored further through focus groups. It is also worth noting that education is not a major factor in determining bulb choice. This result suggests differential access to information that is commonly associated with education level may not be a major constraint in the transition to energy efficient bulbs. Price, as an important stated attribute, also does not influence IL to CFL and IL to LED transitions. Thus, higher up front CFL and LED costs may not be a significant barrier to adoption.

A major empirical finding of the paper is that there is a large, and previously undocumented, rebound effect stemming from luminosity increases in transitions from IL to CFL and LED bulbs. When an IL bulb is replaced with another IL, luminosity is virtually unchanged. However, luminosity increases by 23 percent on average when ILs are replaced by CFLs and by 47 percent on average when ILs are replaced by LEDs. The fact that the rebound effect increases with bulb efficiency suggests that consumers rationally invest part of their energy cost savings from energy efficient bulbs in increased lumens to meet unsatiated lighting needs. If individuals are making informed decisions to purchase more lumens with per-lumen costs decreases associated with the new technology, then policies to curtail the rebound effect are unlikely to increase household welfare.

Bulb storage, while deterring transitions from ILs to more energy efficient lighting, mitigates luminosity increases associated with bulb transitions. Luminosity increases could also possibly be deterred through buy-back programs to match the bulb luminosity of old and new bulbs. Such programs would increase household welfare if information on equivalent bulb wattage is lacking or if individuals use bounded rationality in making bulb luminosity decisions. For example, the change in Wattage of an IL from 50W to 60W seems a lot larger than a change in a LED from 9W to 11W and households may act on a “rather be safe than sorry” basis in thinking the move from 9W to only 11W is inconsequential. However, the change in lumen is much larger for the latter. The results do provide some evidence of information constraints with respect to equivalent bulb luminosity. Specifically, luminosity increases associated with IL to CFL transitions are lower at higher levels of education. This may be because more educated individuals are better able to calculate equivalent wattage. As noted for other bulb attributes, information constraints and bounded rationality in decision making could be addressed through new packaging guidelines that require the equivalent wattage of the three major bulb types to be prominently displayed. Difficulties comparing luminosity base on wattage may also be a transitional problem, as younger generations become used to multiple bulb technologies and view luminosity, not wattage, as the appropriate benchmark.

Finally, a notable feature of the results is that most of the variation in the large average increases in luminosity changes with bulb transitions, particularly LEDs, remains unexplained. Further research is needed to unlock key factors associated with the magnitude of bulb rebound effects. This research should focus on understand and fostering transitions to LEDs and other future generates of energy efficient bulbs, as they become the dominant technologies.

Acknowledgements

We are thankful to Elisabeth Dütschke for her insightful comments on an earlier version of the paper. 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”.

Literature

Allcott, H., S. Mullainathan, and Taubinsky, D. (2012). Externalities, Internalities, and the Targeting of Energy Polic. National Bureau of Economic Research Working Paper Number 17977. Cambridge, MA.

Bertoldi, P; Hirl, B. and Labanca, N. (2012): Energy Efficiency Status Report 2012 – electricity Consumption and Efficiency Trends in the EU-27. European Commission Joint Research Centre Institute for Energy and Transport, Ispra, Italy.

Berkhout, P. H. G., Muskens, J. C., and Velthuijsen, J. W., (2000). Defining the rebound effect. Energy Policy, 28, 425–432.

Borenstein, S. (2013). A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications. National Bureau of Economic Research Working Paper Number 19044. Cambridge, MA.

Brookes, L. (1990): The greenhouse effect: the fallacies in the energy efficiency solution. Energy Policy 18(2),199–201.

CLASP (2013) Estimating potential additional energy savings from upcoming revisions to existing regulations under the ecodesign and energy labelling directives: a contribution to the evidence base. Report published 18. February 2013.

Davis L.W. , "Evaluating the Slow Adoption of Energy Efficient Investments: Are Renters Less Likely to Have Energy Efficient Appliances?", in: The Design and Implementation of U.S. Climate Policy. Don Fullerton and Catherine Wolfram, eds. University of Chicago Press: Chicago. 2012.

de Almeida, A. (2008): Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE). Deliverable D9: Report with the results of the surveys based on questionnaires for all countries. Downloaded from:www.isr.uc.pt/~remodece.

de Almeida, A.,, Zissis, G, Quicheron, M., Bertldi, P. (2013): Accelerating the deployment of solit state lighting (SSL) in Europe, Joint Research Center, European Union 2013.

di Maria, C., Ferreira, S. and Lazarova, E. (2010): Shedding Light on the Light Bulb Puzzle: the Role of Attitudes and Perceptions in the Adoption of Energy Efficient Light Bulbs, Scottish Journal of Political Economy, 57(1): 48-67, 2010.

European Commission (2012): Commission Delegated Regulation of 12.7.2012 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of electrical lamps and luminaires.

European Commission (2011): European Commission, Joint Research Centre, European LED Quality Charter, February 2011

European Commission (2011): Green Paper: Lighting the Future, Accelerating the deployment of innovative lighting technologies. The European Commission, Brussels, 15.12.2011, COM(2011) 889 final.

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

Fouquet R, Pearson PJG. (2006): Seven Centuries of Energy Services: the Price and Use of Light in the United Kingdom (1300–2000). The Energy Journal, 27(1):139–177.

Frondel, M., Peters, J. and Vance C. (2008): Identifying the Rebound: Evidence from a German Household Panel. The Energy Journal, 29 (4), 154-163.

Frondel, M.and Lohmann, S. (2011): The European Commission's light bulb decree: Another costly regulation? Energy Policy 39, 3177-3181.

Gillingham, K., Harding, M., and D. Rapson (2012). Split Incentives in Residential Energy Consumption. The Energy Journal, 33(2).

Greening, L.A., Greene, D. L., Difiglio, C. (2000): Energy efficiency and consumption - the rebound effect - a survey. Energy Policy 28 (6), 389-401.

Herring, H. and Sorrell, S. (2009). Energy efficiency and sustainable consumption - the rebound effect. Energy, Climate and the Environment Series. New York: Palgrave, MacMillan.

IEA (2010): Phase out of ILs. Implications for international supply and demand for regulatory compliant lamps. Information Paper. OECD/IEA, Paris.

IEA (2012): http://mappingandbenchmarking.iea-4e.org/ (IEA 18 February 2013)

Khazzoom, J.D. (1980): Economic implications of mandated efficiency in standards for household appliances. The Energy Journal 1(4), 21-40.

Khazzoom J.D. (1987): Energy savings resulting from the adoption of more efficient appliances. Energy Journal 8(4), 85–89.

Khazzoom J.D. (1989) Energy savings from more efficient appliances: a rejoinder. The Energy Journal 10(1), 157–166.

Kumar, A., S.K. Jain, and N.K. Bansal (2003): Disseminating Energy-Efficient Technologies: A Case Study of Compact Fluorescent Lamps in India. Energy Policy 31 59-272.

McKinsey (2012): Lighting the way: Perspectives on the global lighting market. 2nd Edition, August 2012. McKinsey&Company.

Madlener, R., and Alcott, B. (2009). Energy rebound and economic growth: A review of the main issues and research needs. Energy, 34, 370–376.

Menanteau, P. and H. Lefebvre (2000). Competing Technologies and the Diffusion of Innovations: The Emergence of Energy-Efficient Lamps in the Residential Sector. Research Policy 29, 375-389.

Mills, B. and J. Schleich (2009). Profits or Preferences? Assessing the Adoption of Residential Solar Thermal Technologies. Energy Policy. 37(10), 4145-4154.

Mills, B. and Schleich, J. (2010): Why Don't Households See the Light? Explaining the Diffusion of Compact Fluorescent Lamps. *Resource and Energy Economics* 32 (3), 363-378.

OSRAM (2009): Opto Semiconductors, Life Cycle Assessment of Illuminants, A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps. Executive Summary, November 2009. OSRAM Opto Semiconductors GmbH, Innovations Management, Regensburg, Germany. http://www.osram.at/_global/pdf/Consumer/General_Lighting/LED_Lamps/Life_Cycle_Assessment_of_Illuminants.pdf

Scott. S. (1997): Household Energy Efficiency in Ireland: A Replication Study of Ownershipof Energy Saving Items. Energy Economics 19, 187-208.

Schultz, T.W. (1975). The Value of the Ability to Deal with Disequilibrium. Journal of Economic Literature. 13 (3), 827-46.

Simon, H.A. (1959). Theories of decision-making in economics and behavioural science. The American Economic Review, 49:253-283.

Sorrell, S. (2007). The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency. A report produced by the Sussex Energy Group for the technology and policy assessment function of the UK Energy Research Centre. Sussex: UK Energy Research Centre.

United States Department of Energy (US DOE) (2012): Solid-State Lighting Research and Development: Manufacturing Roadmap, August 2012. US Department of Energy, Office of Building Technology, Washington DC. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_august2012.pdf.

van den Bergh, J. C. J. M. (2011). Energy conservation more effective with rebound policy. Environmental & Resource Economics, 48, 43–58.

VITO, 2009. Preparatory Studies for Eco-design Requirements of EuPs. Final report Lot 19: Domestic lighting, October 2009.

Waide, P. and B. Buchner (2008): Utility energy efficiency schemes: savings obligations and trading. Energy Efficiency (Special issue on Tradable White Certificate Schemes)

Wall, R. and T. Crosbie (2009): Potential for Reducing Electricity Demand for Lighting in Households: An Exploratory Socio-Technical Study. Energy Policy 37, 1020-1031.

Tsao, J.A.Y., Saunders, H.D., Creighton, J.R., Coltrin, M.E. and Simmons, J.A. (2010). Solid-state lighting: an energy-economics perspective. Journal of Physics D: Applied Physics 43 (35) 354001, doi:10.1088/0022-3727/43/35/354001

Tsao, J.Y. and Waide, P. (2010). The world's appetite for light: Empirical data and trends spanning three centuries and six continents. Leukos 6, 259–81.

Table 1. Replacement Bulb Choice by Type

	Replacement Type		
Initial Bulb	IL	CFL	LED
IL	996	601	117
CFL	73	1053	82
LED	0	6	100

Table 2. Descriptive Statistics

		Bulb Type Data (N=1,714)	Luminosity Data (N=1,660)
Variable	Description	Mean	Mean
IL to IL	IL to IL transition (share)	0.581	
IL to CFL	IL to CFL transition (share)	0.351	
IL to LED	IL to LED transition (share)	0.068	
fluxratio	Ratio luminosity new to initial bulb		1.101
lamp	Replacement lamp=1	0.054	0.051
time12	Bulb replaced in 2012=1	0.735	0.739
bantime	Bulb replaced 2012 & banned=1	0.124	0.119
storage	Replacement bulb from storage=1	0.613	0.623
main	Bulb used for main lighting=1	0.668	0.669
living	Bulb in living/dining room (base)	0.279	0.274
bedrm	Bulb in bedroom=1	0.086	0.085
kitcrm	Bulb in kitchen=1	0.121	0.123
hallrm	Bulb in hallway=1	0.190	0.192
childrm	Bulb in child's room=1	0.023	0.022
bathrm	Bulb in bathroom=1	0.162	0.160
otherrm	Bulb in other room=1	0.107	0.110
outdoor	Bulb outdoors=1	0.033	0.034
rent	Rent home=1	0.450	0.448
price	Price a listed criteria=1	0.547	0.544
quality	Quality a listed criteria=1	0.517	0.517
electuse	Energy efficiency a listed criteria=1	0.598	0.599
durable	Durability a listed criteria=1	0.522	0.523
environ	Environmental friendly listed criteria=1	0.228	0.228
dimmable	Dimmabilty a listed criteria=1	0.061	0.063
low	High school or less (base)	0.215	0.219
middle	Technical school=1	0.485	0.481
high	University=1	0.299	0.299
female	Female respondent=1	0.402	0.395
young	16 to 26 years of age=1	0.058	0.054
old	65 years of age or older=1	0.183	0.187
single	Single person household (base)	0.274	0.275
twopers	Two person household=1	0.423	0.425
twoplus	Two plus person household=1	0.303	0.299

Table 3: Multinomial Logit Relative Risk Ratio Estimates

	Full-Sample						Change in Luminosity Sample					
	IL to CFL			IL to LED			IL to CFL			IL to LED		
	RRR	Std. Err.		RRR	Std. Err.		RRR	Std. Err.		RRR	Std. Err.	
lamp	2.792	1.040	***	4.035	2.029	***	3.102	1.184	***	3.638	1.906	**
time12	0.585	0.082	***	0.591	0.162	*	0.625	0.090	***	0.639	0.182	
bantime	1.821	0.373	***	3.226	1.092	***	1.591	0.344	**	3.742	1.312	***
storage	0.183	0.023	***	0.033	0.011	***	0.184	0.024	***	0.028	0.010	***
main	1.415	0.202	***	1.736	0.512	*	1.411	0.207	**	1.860	0.572	***
bedrm	0.809	0.194		1.803	0.739		0.844	0.211		1.874	0.805	
kitcrm	0.910	0.186		1.492	0.539		1.012	0.212		1.652	0.612	
hallrm	0.808	0.147		1.117	0.376		0.862	0.161		1.083	0.381	
childrm	1.049	0.425		1.004	0.753		1.119	0.469		1.385	1.057	
bathrm	0.748	0.142		0.537	0.208		0.729	0.143		0.545	0.217	
otherrm	0.964	0.205		0.381	0.204	*	1.064	0.231		0.393	0.213	*
outdoor	1.150	0.417		1.625	0.981		1.317	0.480		1.803	1.112	
rent	1.045	0.141		0.748	0.192		1.067	0.148		0.772	0.205	
price	1.159	0.164		1.396	0.411		1.147	0.168		1.373	0.424	
quality	1.195	0.165		1.722	0.504	***	1.230	0.176		1.812	0.561	**
electuse	2.504	0.328	***	7.834	2.497	***	2.697	0.367	***	8.917	3.032	***
durable	1.275	0.166	*	1.825	0.514	**	1.255	0.169	*	1.980	0.582	**
environ	2.391	0.385	***	2.969	0.971	***	2.531	0.420	***	3.198	1.094	***
dimable	0.768	0.212		2.303	1.151	*	0.872	0.242		2.553	1.306	*
middle	1.080	0.170		0.963	0.279		1.052	0.169		0.894	0.264	
high	1.088	0.186		0.756	0.245		1.035	0.180		0.668	0.222	
female	0.909	0.113		0.556	0.139	**	0.810	0.105		0.553	0.143	**
young	0.598	0.160	*	0.380	0.212	*	0.419	0.125	***	0.366	0.208	*
old	0.749	0.126	*	1.124	0.355		0.795	0.135		1.061	0.350	
twopers	1.033	0.159		1.008	0.308		0.988	0.156		1.016	0.322	
twoplus	1.124	0.195		1.868	0.620	*	1.079	0.192		1.863	0.641	*
Log-likelihood	-1165.846						-1102.132					
N	1,714						1,660					

Table 4: Bulb Luminosity Change Estimates, Dubin-McFadden Method with Bootstrap (N=500)

	IL to IL			IL to CFL			IL to LED		
	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
lamp	0.164	0.131		0.289	0.258		1.169	0.875	
storage	-0.176	0.063	***	-0.936	0.303	***	-1.110	1.050	
main	0.060	0.024	**	0.141	0.111		0.253	0.556	
bedrm	0.010	0.041		0.055	0.193		-0.004	0.513	
kitcrm	0.020	0.026		0.026	0.137		0.018	0.433	
hallrm	0.006	0.026		0.109	0.133		0.495	0.462	
childrm	0.068	0.057		-0.078	0.250		0.865	1.034	
bathrm	0.011	0.030		0.005	0.151		-0.837	0.499	*
otherrm	0.002	0.037		-0.199	0.149		-0.604	0.777	
outdoor	0.005	0.071		-0.102	0.190		0.048	0.672	
price	0.011	0.021		0.012	0.096		-0.115	0.271	
quality	0.002	0.019		-0.103	0.093		-0.275	0.329	
electuse	0.091	0.037	**	0.334	0.167	**	0.461	0.585	
environ	0.076	0.037	**	0.196	0.139		-0.068	0.435	
middle	0.006	0.024		-0.132	0.118		0.323	0.325	
high	-0.014	0.024		-0.228	0.117	*	0.137	0.413	
female	0.025	0.020		0.061	0.091		-0.132	0.369	
young	-0.067	0.039	*	0.128	0.254		-0.962	0.634	
old	-0.042	0.028		-0.169	0.105		0.299	0.419	
twopers	-0.002	0.020		0.115	0.098		0.080	0.339	
twoplus	-0.002	0.025		0.254	0.117	**	0.626	0.434	
M*11*	-0.074	0.085		-0.932	0.835		-0.758	2.032	
M*12*	0.329	0.181	**	0.310	0.172	*	-1.474	2.103	
M*13*	0.338	0.269		1.105	0.763		0.589	0.452	
constant	1.217	0.106	***	0.664	0.633		-1.837	1.990	
Sigma2	0.167	0.134		2.064	1.953		3.385	10.183	
F-Test	2.090	**		2.020	**		1.170		
Adj. R^2	0.026			0.043			0.036		
N	996			553			111		

Table A.1: Bulb Luminosity Change Estimates, Lee Method with Bootstrap (N=500)

	IL to IL			IL to CFL			IL to LED		
	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
lamp	0.183	0.129		-0.151	0.186		1.121	0.669	*
storage	-0.147	0.054	***	-0.232	0.164		-1.094	0.852	
main	0.055	0.022	**	0.026	0.087		0.243	0.520	
bedrm	0.006	0.038		0.011	0.162		-0.052	0.465	
kitcrm	0.015	0.026		-0.019	0.114		-0.018	0.403	
hallrm	0.004	0.024		0.115	0.128		0.456	0.412	
childrm	0.067	0.049		-0.054	0.201		0.875	0.926	
bathrm	0.017	0.028		0.134	0.123		-0.810	0.451	*
otherrm	0.010	0.033		-0.107	0.112		-0.574	0.717	
outdoor	0.001	0.074		-0.221	0.143		0.022	0.684	
price	0.010	0.019		-0.013	0.081		-0.106	0.271	
quality	-0.001	0.018		-0.166	0.078	**	-0.273	0.325	
electuse	0.072	0.029	**	-0.034	0.105		0.435	0.471	
environ	0.071	0.031	**	-0.019	0.102		-0.044	0.311	
middle	0.005	0.023		-0.111	0.109		0.338	0.285	
high	-0.012	0.024		-0.196	0.100	**	0.159	0.388	
female	0.030	0.018	*	0.168	0.076	**	-0.113	0.340	
young	-0.059	0.033	*	0.328	0.222		-0.954	0.617	
old	-0.045	0.024	*	-0.172	0.080	**	0.269	0.354	
twopers	-0.004	0.020		0.093	0.085		0.064	0.305	
twoplus	-0.009	0.022		0.135	0.105		0.587	0.411	
m*i*	0.300	0.084	***	-0.270	0.254		-1.298	0.650	**
constant	1.152	0.077	***	1.183	0.311	***	-1.251	1.558	
Sigma2	0.071	0.013	***	0.769	0.217	***	7.331	7.511	
N	996			553			111		

Table A.2: Bulb Luminosity Change Estimates, OLS

	IL to IL			IL to CFL			IL to LED		
	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
lamp	0.001	0.069		-0.206	0.146		0.505	0.378	
storage	0.036	0.019	**	-0.084	0.078		0.207	0.376	
main	0.024	0.017		0.001	0.090		-0.087	0.323	
bedrm	0.017	0.028		0.034	0.148		-0.483	0.395	
kitcrm	0.024	0.025		-0.011	0.122		-0.231	0.329	
hallrm	0.023	0.022		0.133	0.113		0.320	0.314	
childrm	0.073	0.053		-0.075	0.244		0.764	0.735	
bathrm	0.044	0.023	*	0.145	0.116		-0.537	0.381	
otherrm	0.015	0.026		-0.130	0.127		-0.130	0.545	
outdoor	-0.025	0.043		-0.229	0.209		-0.365	0.538	
price	0.006	0.016		-0.022	0.082		-0.062	0.233	
quality	-0.009	0.016		-0.177	0.080	**	-0.257	0.272	
electuse	-0.011	0.015		-0.104	0.085		-0.189	0.339	
environ	-0.003	0.021		-0.090	0.088		-0.075	0.273	
middle	-0.003	0.019		-0.119	0.095		0.480	0.270	*
high	-0.014	0.020		-0.206	0.104	**	0.412	0.295	
female	0.045	0.015	***	0.171	0.076	**	0.143	0.250	
young	-0.022	0.030		0.352	0.193	*	-0.780	0.532	
old	-0.031	0.019	*	-0.144	0.103		0.171	0.318	
twopers	-0.001	0.018		0.100	0.088		-0.095	0.306	
twoplus	-0.015	0.020		0.145	0.098		0.179	0.303	
constant	0.921	0.035	***	1.464	0.168	***	1.440	0.625	**
F-Test	1.380			1.640			1.050		
Adj. R^2	0.008			0.024			0.009		
N	996			553			111		

Authors' affiliations

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

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

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

Karlsruhe 2013