Working Paper Sustainability and Innovation
No. S 1/2008

Bradford F. Mills
Joachim Schleich

Why Don't Households See the Light?

Explaining the Diffusion of Compact Fluorescent Lamps

Fraunhofer Institute
Systems and
Innovation Research

Abstract

Many countries are currently considering bans on incandescent light bulbs and other policies to enhance the residential diffusion of energy-saving compact fluorescent lamps (CFLs). However the reasons for currently limited diffusion of CFLs are largely unknown. This paper employs a Double Hurdle model to identify distinct barriers to household consideration of CFLs and the subsequent intensity of adoption using a large survey of German households. The results reveal that barriers to CFL consideration are low for all, except households with very low incomes. Further, barriers to CFL consideration are strongly linked to the characteristics of the residences of low-income households. Thus, the greatest potential for increasing the diffusion of CFLs lies not in addressing barriers to consideration, but in augmenting the intensity of household adoption particularly within high income groups.

Table of Contents

Page

List of Figures

List of Tables

1 Introduction

Improving energy efficiency is a core strategy for a sustainable energy system. In the residential sector, energy-saving technologies can spur cost savings for private households, while reducing greenhouse gas emissions and other pollutants and increasing the security of energy supplies. Two policy pathways exist to accelerate residential energy-efficiency gains. First, research investments and other policy interventions can be designed to accelerate the generation of new energy-saving innovations. Second, policies can be designed to promote the diffusion of existing residential energy-saving innovations. For example, residential energy efficiency in the European Union expanded group of 25 member states (EU 25) is estimated to have improved 10 percent since 1990 (ENERDATA 2007). However, the 2007 European Council Action Plan for Energy Efficiency (European Commission 2006) states that the residential buildings sector exhibits the potential for further cost-effective energy-savings of 27 percent by 2020 using existing technologies. Thus, enhanced diffusion of 'off-the-shelf'' technologies are expected to play a substantial role in medium-term residential energy savings and attendant greenhouse gas reductions.

Energy-efficient compact fluorescent lamps (CFLs) are an off-the-shelf technology with a particularly high potential to generate residential energy-savings. There are an estimated 33 billion light bulbs worldwide that consume 2,600 TWh per year or 19 percent of global electricity use, with 30 percent of this consumption by the residential sector (Zissis et al. 2007). However, energy efficient CFLs represent only 4 percent of the global market and 6 percent of the European market. Fluorescent lamp adoption is also considerably lower in the residential sector than in the service sector, despite significant publicly supported efforts to increase diffusion (Menanteau and Lefebvre 2000). Atanasiu et al. (2007) estimate that cost-effective savings of at least 11.7 TWh per year (1.5 percent) in residential electricity consumption still exist in the EU 25 from increased adoption of CFLs, with potential savings of up to 21.9 TWh per year with aggressive policies to increase diffusion.

A considerable body of research exists on the technical merits of CFLs. However, as with residential energy-saving technologies in general, empirical analysis of the relationship between socioeconomic factors and diffusion has been limited.[1] An early study of CFL adoption by Scott (1997) for Ireland finds very low levels of household use and few relationships with household socio-demography characteristics. Kumar et al. (2003) also find limited adoption in India, but increased probability of household adoption with higher education and income levels. We know of no recent studies that empirically examine the factors driving CFL diffusion, particularly for Northern European countries which have some of the highest rates of household adoption in the world (Menanteau and Lefebvre, 2000). However, understanding the relationship between socio-demographic characteristics and adoption is particularly timely in EU countries. At the Spring 2007 summit EU leaders urged the European Commission to rapidly submit proposals to increase the efficiency of residential lighting by 2009, including potentially banning the sale of incandescent bulbs (Council of the European Union 2007).[2] Such policies stand to differentially impact households based on current adoption levels. However, the distributional impacts of policies to aggressively promote residential use of CFLs are unclear without a solid understanding of the relationship between socio-demographic factors and household use of CFLs.

This paper empirically identifies the socio-demographic and other factors associated with the residential diffusion of energy-saving CFLs in Germany using a large household survey. As CFLs are a highly divisible innovation, a Double-Hurdle model is employed that specifies adoption as a two-part decision. In part one, the household decides whether to actively explore purchasing CFLs (enter the market). Then, in part two, the household determines the intensity of adoption. The statistical model and its empirical specification are presented in the next section. Data and descriptive statistics on residential CFL usage in Germany and on the variables employed to explain differential household market entry and adoption intensity are presented in Section 3. Model estimation results are presented in Section 4. The paper then concludes with an examination of the potential impact of policies to further increase diffusion.

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1 Previous studies of factors associated with other residential energy-saving innovations include attic and wall insulation and window glazing in the U.K (Brechling and Smith 1994) attic insulation and water heater insulation in Ireland (Scott, 1997), and energy efficient appliances and heating systems in Germany (Schlomann et al. 2004; Schlomann et al. 2005).

2 Australia and the United States have already passed similar legislation.

2 Conceptual Framework, Statistical Model, and Empirical Specification

CFL adoption is viewed as a utility maximizing decision by the household within the constraints of uncertain and costly information. The observed use of CFLs is assumed to stem from the following 'Double-Hurdle' decision-making process. In part one the household decides whether to enter the market for CFLs, which entails acquiring costly information on the technology. Rogers (2003) calls this stage-one decision the 'awareness stage' in the adoption process, while in the marketing literature this stage-one decision is referred to as the 'consideration set' (Manski 1977). The decision to enter the market is based on a comparison of the utility associated with CFL market entry based on expected electricity cost-savings and costs of obtaining information on the new alternative

$$\underset{b}{Max}\left[\int_0^\infty U(y+z(b)-c)dFz(b)\right]$$

and the utility associated with the current incandescent bulb technology $U(y)$; where *z(b)* is the expected net cost-savings from replacement of *b* incandescent lamps with CFLs, *b* is the choice of number of CFL bulbs, *y* is income, and *c* is the costs of acquiring information on CFL availability and performance. Denote *b** as the number of bulbs that maximizes household expected utility with market entry. Given that *z(b*)* is uncertain and the utility function is increasing and concave,

$$\int_0^\infty z(b^*)dFz(b^*)$$

must be greater than *c* for market entry to occur, with the magnitude of the difference representing the cost of uncertainty to the household.

Household characteristics influence CFL market entry by determining costs of investment in information. Household characteristics may also be associated with non-monetary utility gains from CFLs use compared to the use of incandescent bulbs. Further, constraints on time, attention, or cognitive ability to process information may result in satisficing behaviour and the use of routines or rules of thumb in the market entry decision outside of the strict utility maximizing framework (Simon 1959). Such bounded rationality can generate barriers to market entry for energy efficient technologies – even with complete and certain information. Psychological considerations such as personal values, commitment and motivation, membership in social groups, and status considerations may also play key roles in consumer decisions about energy efficiency investments (Stern, 1986; Stern and Aronson 1984).

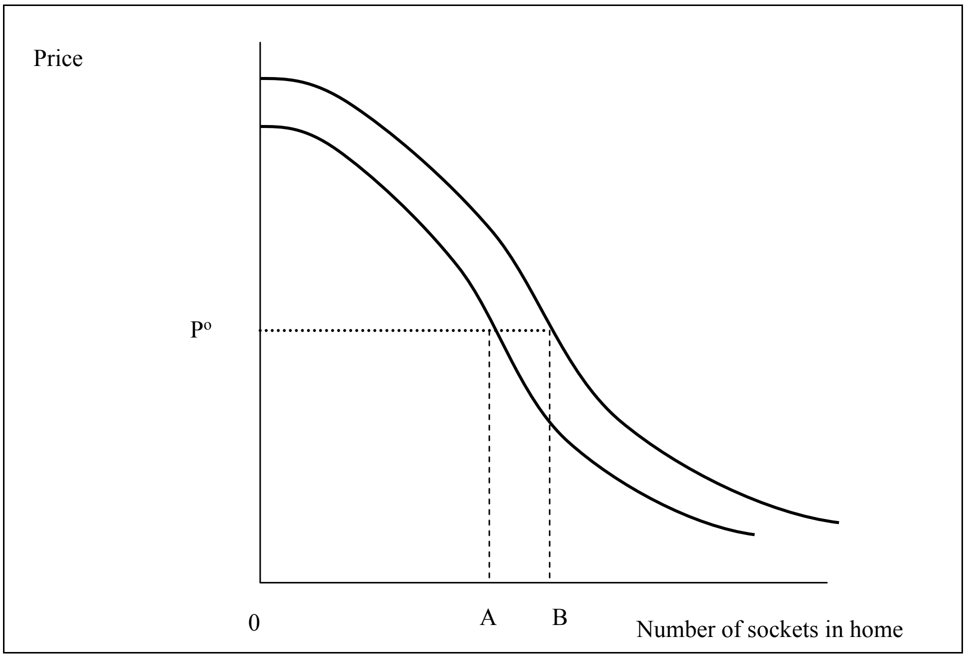
If the household overcomes these barriers and enters the market, the household's second decision is the intensity of purchase of CFLs for home use. In the simplest case the cost-savings with CFLs, *z(b),* are now fully known, so the household decision on the intensity of adoption is simply expressed as $\underset{b}{Max}\left[U(y+z(b)-U(y)\right]$

and the adoption intensity decision is based on the criteria of positive net cost-savings at the margin with censoring at zero (DeSarbo and Choi 1999).[3]

Assuming that cost-savings per-CFL decline across potential household applications, factors that increase cost-savings for all bulbs will also increase the intensity of CFL adoption. In figure 1 increased cost-savings are represented as an outward shift of the demand curve from I^0 to I^1 that increases the number of CFLs used by the household from A^0 to A'. Note, that such a shift, if incorporated into the market entry decision, also increases expected consumer surplus and, thus, raises the probability of market entry. Household characteristics as proxies for preferences will also influence adoption intensity if they shift the utility associated with non-monetary benefits and costs for the marginal CFL application.

3 Alternatively market entry information investments in the first stage could reduce but not eliminate uncertainty about cost savings, leaving the household to choose the optimal adoption intensity with some remaining uncertainty in a dynamic model of adoption (e.g. Tsur, Sternberg, and Hochman 1990).

Figure 1: CFL demand



Empirical model

The market entry decision is empirically specified in the discrete choice random utility framework as:

$$y^*_{1i} = X'_{1i} B_1 + u_{1i}$$

where y^*_{1i} is a latent variable for entry into the CFL market by household *i*, X_{1i} is a vector of proxies for cost-savings and preferences that determine market entry, B_1 is the associated vector of parameter estimates, and u_{1i} is an error term which in assumed *N.I.I.D.(0,1)*. The market entry decision is then represented as

$$y_{1i} = 1 \text{ if } y^*_{1i} > 0 \text{ and}$$
$$y_{1i} = 0 \text{ if } y^*_{1i} \leq 0$$

The adoption intensity decision is measured as the share of household bulbs which are CFLs and is also a latent variable since the distribution of adoption

intensity is censored at a lower bound of zero.[4]
Specifically,

$$y_{2i}^{*} = X_{2i}^{'}B_2 + u_{2i}$$

where y_{2i}^{*} is a latent variable for intensity of adoption, X_{2i} is a vector of determinants of adoption intensity, and u_{2i} is error terms which is assumed *N.I.I.D.(0,* σ). The observed adoption intensity, y_{2i}, has the following relationship with the latent variable

$$y_{2i} = y_{2i}^{*} \text{ if } y_{2i}^{*} > 0 \text{ and } y_{1i}^{*} > 0$$
$$y_{2i} = 0 \quad \text{otherwise.}$$

Observed positive adoption arises from both market entry and having a strictly positive latent adoption intensity.

The associated likelihood function for estimation, assuming independence of the two latent variable error terms, is:

$$L = \prod_{i=1}^{n}\left[1-\Phi\left(X_{1i}^{'}B_1\right)\Phi\left(\frac{X_{2i}^{'}B_2}{\sigma}\right)\right]^{1-I_i}\left[\Phi\left(X_{1i}^{'}B_1\right)\frac{1}{\sigma}\phi\left(\frac{y_{2i}-X_{2i}^{'}B_2}{\sigma}\right)\right]^{I_i}$$

where I_i is an indicator for observed adoption. The model can also allow for correlation between the error terms u_1 and u_2. However, this correlation is often difficult to estimate with precision (Smith, 2002).

Model specification

The expected impacts of explanatory variables on the market entry and the intensity of adoption decisions are outlined below.

CFL bulbs can generate cost-savings for the household in two ways. First, CFL bulbs are more energy efficient than incandescent bulbs. For equivalent lighting, CFLs use between one-fifth and one-quarter of the power of equivalent incandescent lamps (General Electric, undated; Waide 2006). This results in considerable savings on electricity expenditures. The second avenue for expenditure reductions is through longer bulb-life. Currently, CFLs have a life span of between 6,000 and 15,000 hours and last six to twenty times longer than incan-

4 Censoring is also possible at the upper bound of 1 if CFL use in all household sockets is prevalent.

descent bulbs. These benefits come, however, at a much higher bulb price. Currently, the market price for CFLs is three to ten times higher than for equivalent incandescent bulbs.

Engineering data suggest that in most cases expenditure reductions significantly outweigh higher initial bulb prices, with total cost-savings estimated at Euro 80 over the CFL life for a 20 watt CFL compared to a lighting equivalent 100 watt incandescent bulb, assuming 3 hours continuous burning per day and an electrical price of 0.15 Euro/kWh (European Lighting Commission Federation 2007). However, household use patterns will influence the magnitude actual cost-savings. Given the relatively high initial cost, CFL bulbs are not profitable investments in very low use areas, e.g. cellars. Further, until recently CFL life decreased substantially with rapid on/off cycles. For example, in 2002 with an average 5 minute on/off cycle CFL life was equivalent to that of an incadescent bulb.[5] Thus, at the time of the 2002 survey data used in this paper cost-savings were considerably lower in areas requiring lighting for only brief periods, e.g. garages. These CFL bulb limitations support the assumption of decreasing marginal profitability of CFLs in household sockets indicated in figure 1 when total lighting needs are held constant. Consequently, 100 percent adoption of CFLs in all household sockets may be observed only rarely based strictly on the cost-savings criterion.

Declining marginal cost-savings of CFLs in residential applications and few households with 100 percent adoption, if empirically supported, have important implications for identification restrictions in the empirical model. Specifically, the number of sockets that support profitable CFL investments will be fixed per household after controlling for other factors that affect lighting usage like family and residence size. The intensity of adoption, as measured by the ratio of CFL bulbs to total bulbs is, therefore, expected to decline with the total number of bulbs in the household, *ceteris paribus*, if 100 per cent adoption is not profitable. In the empirical specification linear and quadratic terms for total number of bulbs are included to allow the impact to vary across total number of bulbs. The market entry decision should be, by contrast, unaffected by the total number of bulbs in the household. Expected aggregate cost-savings will differ little with additional sockets in the residence after controlling for lighting needs, because (if CFLs are not currently used in all sockets) the household would not expect to adopt CFLs in the additional sockets. By the same token, the size of the resi-

5 This deficiency has been addressed in more recent CFLs (ELC Federation 2007).

dence, as measured by meters squared of floor space, is positively associated with greater lighting needs. Floor space should, therefore, be positively associated with adoption intensity, given higher lighting needs per bulb after controlling for the total number of bulbs in the household. However, in this case greater total lighting needs will increase expected aggregate cost-savings and, thus, also increase incentives for market entry. In the empirical specification, linear and quadratic terms for floor space are included in both the market entry and adoption intensity equations.

Renting rather than owning the residence has been established as an important barrier to the adoption of residential energy-saving technologies, as it is often difficult to apportion energy-efficiency technology investments and savings between tenants and landlords (Jaffe and Stavins 1994; Sutherland 1996). The age of the residence may also influence adoption intensity, as it was initially more difficult to find CFLs that fit some older lighting fixtures (Menateau and Lefebrve 2000). If this constraint is found to be important, it would suggest that the diffusion of CFLs may be limited by the relatively slow renewal of housing stock. Therefore, an indicator for residences built prior to 1951 is included in both the market entry and adoption intensity specifications. Other attributes of the residence may also influence adoption decisions. For instance, living in a detached household may be associated with differential lighting needs, as well as lower costs of information on available residential energy-saving technologies due to greater involvement in home maintenance.

Household member characteristics may influence household lighting needs. For example, retirees are likely to spend more time at home, which will increase lighting needs. Retirees also spend more time shopping (Aguiar and Hurst 2007), which suggests that they are more willing to invest in information CFL bulbs. Households with more members will, *ceteris paribus*, have greater lighting needs. As mentioned, characteristics of household members may also influence the market entry decision through associations with the costs of acquiring information on CFLs. Elderly individuals may have higher costs to information acquisition particularly if the Internet is a major source, which will raise barriers to market entry. Linear and quadratic terms for age of the main income earner in the household are included in both the market entry and adoption intensity equations. In contrast, higher education should reduce the costs associated with information acquisition (Schultz 1979). Benefits of CFL use accrue over several years, but purchase costs occur up front. Education, as a long term investment, may be correlated with a low household discount rate and, thus, be positively associated with the intensity of adoption. Unfortunately, the survey provides limited information on the education of the highest income earner and only a discrete indicator of secondary school attainment is included in the specification. The presence of children in the household may also shift household preferences for CFLs, as may residence in a former East German Federal State.

An indicator for households headed by senior officials, senior managers, or highly skilled professionals is also included in both the market entry and adoption intensity equations. The potential influence of job type on the market entry decision is unclear a priori. On the one hand, senior managers and skilled professional may be more proficient at acquiring information and calculating the cost-savings associated with new technologies. On the other hand, the higher opportunity cost of time of this group of workers may reduce their willingness to invest in information on new technologies. Adoption intensity may also be influenced by job type if senior managers and skilled professional are better able to calculate the potential profitability of new innovations.

Household income often has a major influence on the market entry decision. Assuming the concavity of the utility function decreases with income, the differential between expected net cost-savings from CFL adoption,

$$\int_{-\infty}^{\infty} z(b^*)dFz(b^*),$$

and the costs of information acquisition, *c*, that is necessary for market entry also declines with income (Arrow 1974; Coady 1993). Thus market entry becomes more likely at higher income levels, *ceteris paribus*. Low income levels may also raise credit constraints to market entry. However, the initial cost of CFL bulbs is relatively low compared to other residential energy-saving innovations and such credit constraints may only be binding at very low income levels. Further, market entry may increase with income levels because the income elasticity of willingness to pay for environmental benefits is positive (Kristrom and Riera 1996). Higher opportunity costs of time for individuals in higher income groups are, however, likely to temper the positive impact of household income on market entry. Decreasing risk aversion and higher opportunities costs of time with higher income are likely to have a smaller impact on the intensity of adoption than on market entry, as information investments have already been made and the performance of the new technology is uncertain in the adoption intensity decision. In order to empirically capture non-linear income effects, indicators for the sixteen household monthly net income groups are included in the specifications of both the market entry and the adoption intensity equations.

Prices are expected to influence both the aggregate and marginal cost-savings of CFLs relative the incandescent bulbs. Regional price data on CFLs is not available, but prices may not vary greatly across the Federal States of Germany. Federal State specific average household electricity prices are, however, generated from the dataset based on household reported kWh consumption and electricity expenditures and are included in both the market entry and adoption intensity specifications.[6]

Information constraints have often been cited as a significant barrier to adoption of CFLs (e.g. Sathaye and Murtishaw 2004). Several proxies for exposure to information on household energy use and CFL bulbs are included in the market entry equation specification as proxies for information constraints. Specifically, awareness of the potential of energy saving innovations is proxied for by an indicator for household knowledge of the energy-class of their refrigerator or freezer under the EU labeling scheme. Similarly, household awareness of their energy use is measured by an indicator of household ability to provide information on annual residential electricity use. A measure of the share of households in the Federal State using CFLs is also included in the market entry equation specification as a blunt measure of regional information networks.[7] Finally, potential geographic differences in accessibility to CFLs is proxied by two indicators for city size; residence in small towns with populations under 3,000 persons and residence in large cities with populations over one million. Large cities may have a greater array on retail outlets, making it easier for households to find and purchase CFLs (Sandahl et al. 2006). Large cities may also have been differentially targeted by electrical utilities with information campaigns on energy-saving bulbs, given decreased transaction costs of such campaigns in high density areas (Sandahl et al. 2006).

A key assumption underlying the double hurdle model is that some factors have different effects on household market entry and household adoption intensity decisions. Robust model identification also requires that some variables uniquely influence market entry and some variables uniquely influence adoption intensity (Maddala 1983). In the current application the four proxies for exposure to information on CFLs and accessibility to CFLs (knowledge of refrigerator – free-

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6 Calculations produced clearly infeasible prices for some households in the sample. Federal State average prices were, therefore, based on the average of households with calculated prices in the Euro 0.10 to Euro 0.20 per kWh range.

7 The rate is calculated for each household based on the observed adoption of all other households in the same Federal State.

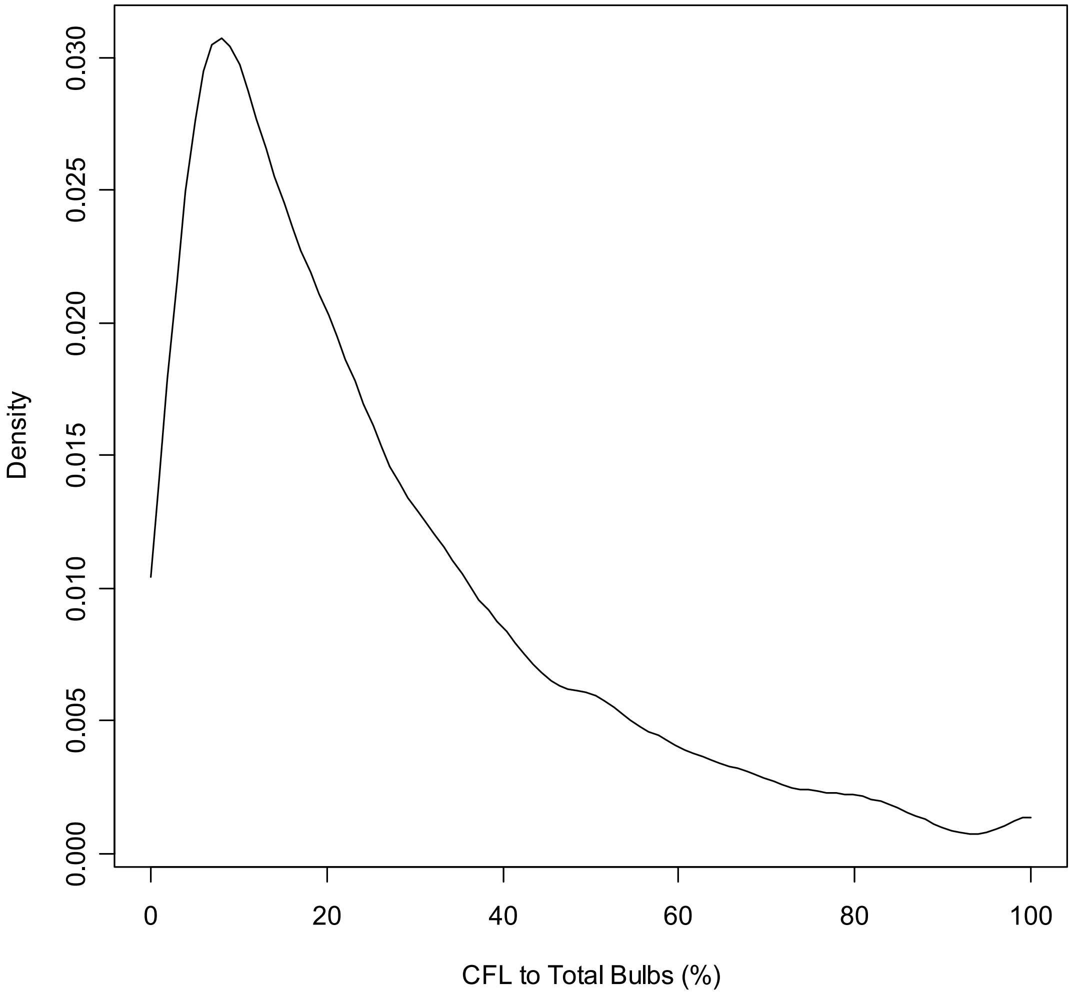
zer energy class, reported electric bill, regional CFL adoption rate, and city size) are included in the market entry equation, but excluded from the adoption intensity equation. Likewise, as discussed, the total number of light bulbs in the residence is specified to uniquely influence adoption intensity and is excluded from the market entry equation.

3 Data

The dataset comes from a written survey of private sector household energy consumption conducted in December of 2002 as part of a multi-topic survey of an existing representative panel of German households (Schlomann 2004). O-verall, 20,235 households (75 percent) responded to the mailed questionnaire. Survey responses were generally of high quality and 17,828 respondents provided information on all the variables used in this study and were retained in the current sample.

Approximately two-thirds of the households in the sample reported some use of CFLs, suggesting widespread exposure to CFL technologies and a high level of market entry (table 1). However, the overall intensity of adoption is rather low, with the average household reporting 16.9 percent all household bulbs being CFLs. Even among households reporting some use of CFLs the overall intensity of adoption is limited, with CFLs representing 25.5 percent of all bulbs. Given the longer life for CFLs compared to incandescent bulbs, these estimates are consistent with a slightly more recent estimate of a 6 percent share for CFLs in the European market (Sathaye and Murtishaw 2004). A kernel estimate of the probability density function for adoption intensity of households with some CFL use is presented in figure 2. The estimated distribution clearly suggests censoring at the lower limit of adoption intensity, supporting use of a Tobit estimator. On the other hand, there is little evidence of censoring at upper 100 percent limit of adoption intensity, with only 0.8 percent of sample households reporting 100 percent CFL adoption. Thus, the descriptive data supports an important necessary condition for the total number of light sockets to have no impact on the market entry decision - that few households expect to have 100 percent a-doption intensity. In fact, the highest concentration of probability in the adoption intensity density is in the 0 to 20 percent range, with the median household a-doption intensity being 9.1 percent. Descriptive statistics for model covariates are also provided in table 1.

Figure 2: Kernel density estimate for households with positive adoption intensity



Note: Bandwidth = 0.035

Table 1: Descriptive statistics (n=17,828)

Variable	Description	Mean	St. Dev.	Min.	Max.
Use of any energy-saving bulbs	some use = 1	0.6626		0	1
Ratio energy-saving to all bulbs		0.1688	0.213	0	1
Total number of bulbs		26.5343	19.150	2	705
Residence size	meters2	99.3236	43.226	11	490
Detached home	yes = 1	0.3609		0	1
Rent residence	yes = 1	0.4579		0	1
Residence older than 1951	yes = 1	0.2619		0	1
Retiree	yes = 1	0.3192		0	1
Number of persons	truncated at 5 persons	2.3110	1.097	1	5
Age of main income earner		51.6523	15.065	16	95
Children in household	under 6 years = 1	0.0932		0	1
East Germany	yes = 1	0.2064		0	1
Higher education	secondary school main inc. earner, yes=1	0.7192		0	1
Management position	sen. official, exec. or skilled profess. =1	0.1042		0	1
Income class	monthly net income (Euro)				
Class 1	0 - 499	0.0094		0	1
Class 2	500 - 749	0.0247		0	1
Class 3	750 - 999	0.0402		0	1
Class 4	1,000 - 1,249	0.0717		0	1
Class 5	1,250 - 1,499	0.0967		0	1
Class 6	1,500 - 1,749	0.0960		0	1
Class 7	1,750 - 1,999	0.0882		0	1
Class 8	2,000 - 2,249	0.1070		0	1
Class 9	2,250 - 2,499	0.0923		0	1
Class 10	2,500 - 2,749	0.0797		0	1
Class 11	2,750 - 2,999	0.0581		0	1
Class 12	3,000 - 3,249	0.0638		0	1
Class 13	3,250 - 3,499	0.0412		0	1
Class 14	3,500 - 3,749	0.0269		0	1
Class 15	3,750 - 4,000	0.0235		0	1
Class 16	4,000+	0.0805		0	1
Regional power price	Ave. elect. price in Federal State (kWh)	0.1564	0.005	0.151	0.171
Regional rate of adoption	Federal region, excluding own household	0.5955	0.031	0.556	0.668
Village	local population <3,000 = 1	0.0849		0	1
City	local population > 1,000,000 = 1	0.0892		0	1
Report annual electric bill	yes = 1	0.7015		0	1
Know fridge-freezer energy class	yes = 1	0.2197		0	1

4 Results and Discussion

The Double Hurdle model is initially estimated allowing for correlation between the market entry and the adoption intensity error terms. However, a χ^2 test (0.164 with d.f.=1) fails to support rejection of independence of error terms.[8] Further, the parameter estimates in the Double Hurdle model with dependent error terms (available from the authors upon request) are virtually identical to those in the independent error term model. Thus, the independent error term estimation results are presented in table 2 and are the focus of the ensuing discussion.

Focusing first on the market entry equation results, the parameter estimate for the linear floor size term is negative but not statistically significant.[9] However, the parameter estimate for the quadratic term for floor size is positive and significant at the *p*=0.05 level. Combined, the parameter estimates imply that the probability of CFL market entry increases with residence floor size across the relevant range of floor space sizes found in the dataset. Further, the effect appears to be stronger at higher levels of floor space. Thus, greater lighting needs that are entailed in larger households appear to generate strong incentives to overcome information and accessibility barriers to CFL market entry. The indicator for detached housing has a significant positive parameter estimate, which implies that market entry is more likely for residents in detached housing than for residents in other housing types. However renting rather than owning and pre-1951 age of residence do not significantly influence market entry.

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8 Note the point estimate for the error correlation coefficient ρ is close to zero (0.033), but the standard error on the estimate is quite large. Problems with the precision of error correlation coefficient estimates in the Double-Hurdle model have been previously noted by Smith (2002).

9 Floor size and residence size are divided by 100 to allow reporting of the parameter estimates with four decimal places.

Table 2: Double hurdle model estimates (n=17,828)

	Market Entry			Adoption intensity		
	Coefficient	Std. Err.		Coefficient	Std. Err.	
Total number of bulbs/100				-0.6451	0.0328	**
Total number of bulbs/100 sq.				0.3335	0.0271	**
Residence size/100	-0.3950	0.6021		-0.0154	0.0253	
Residence size/100 sq.	1.0368	0.4072	**	0.0141	0.0072	**
Detached home	0.2404	0.1101	**	0.0181	0.0067	**
Rent residence	-0.1081	0.0793		0.0091	0.0073	
Residence older than 1951	-0.0324	0.0631		0.0110	0.0059	*
Retiree	0.1634	0.0869	*	0.0221	0.0086	**
Number of persons	0.1765	0.0539	**	0.0117	0.0033	**
Age of main income earner	0.0039	0.0129		0.0112	0.0014	**
Age of main income earner sq.	0.00001	0.00012		-0.00009	0.00001	**
Children in household	0.1068	0.0637	*	-0.0058	0.0062	
East Germany	-0.1107	0.1753		-0.0172	0.0101	*
Higher education	0.1918	0.1600		0.0070	0.0113	
Management position	-0.2404	0.1284	*	0.0056	0.0090	
Income class						
Class 1 (€0 - €499)	-0.5846	0.1889	**	0.1388	0.0374	**
Class 2 (€500 - €749)	-0.2405	0.1608		0.0402	0.0219	*
Class 3 (€750 - €999)	0.0747	0.1611		0.0240	0.0172	
Class 4 (€1,000 - €1,249)	-0.1915	0.1297		0.0342	0.0134	**
Class 5 (€1,250 - €1,499)	-0.2203	0.1254	*	0.0136	0.0123	
Class 6 (€1,500 - €1,749)	-0.2118	0.1279	*	0.0163	0.0119	
Class 7 (€1,750 - €1,999)	0.0553	0.1493		-0.0128	0.0117	
Class 8 (€2,000 - €2,249)	-0.0075	0.1545		-0.0021	0.0115	
Class 9 (€2,250 - €2,499)	-0.0132	0.1634		-0.0003	0.0118	
Class 10 (€2,500 - €2,749)	0.2252	0.2234		-0.0303	0.0128	**
Class 11 (€2,750 - €2,999)	0.2301	0.2232		-0.0085	0.0123	
Class 12 (€3,000 - €3,249)	0.3943	0.3168		-0.0089	0.0141	
Class 13 (€3,250 - €3,499)	0.3322	0.3455		0.0005	0.0160	
Class 14 (€3,500 - €3,749)	0.1057	0.4247		-0.0386	0.0180	**
Class 15 (€3,750 - €4,000)	0.1225	0.2402		-0.0195	0.0122	
Class 16 (€4,000+)	21.2650	12.2432	*	0.7134	0.8745	
Regional rate of adoption	0.2293	1.3386				
Village	-0.0890	0.1159				
City	0.0120	0.1239				
Report annual electric bill	0.1529	0.0535	**			
Know fridge - freezer energy class	0.6654	0.1112	**			
Constant	-3.5358	1.9666	*	-0.1896	0.1455	
Sigma	0.2598	0.0040	**			
Log-likelihood	-6563.85					

Note: * indicates significance in two-tailed t-test at p =0.10 level,
** indicates significance in two-tailed t-test at p =0.05 level.

Several household member characteristics that influence household lighting needs also appear to generate incentives for market entry. Specifically, the probability of market entry increases with the number of persons in the residence and, weakly, with the presence of children under 6 years of age (p=0.10). The parameter estimate for households headed by retirees is also positive and weakly significant (p=0.10).

The probability of market entry appears to be lower for households where the head has a senior management position or is a skilled professional (p=0.10). Thus, the socio-economic elite do not appear to have greater propensities to overcome information barriers to CFL adoption. This finding is also supported by the income group parameter estimates. With the median income group (class 8) as the default for comparison, only the lowest income group (class 1) shows a significantly lower propensities to enter the CFL market at the p=0.05 level. Two other lower income groups (class 5 and class 6) show weaker negative associations with market entrance (p=0.10). On the other hand, none of the higher income groups are estimated to have a significantly different propensity from the median income group to enter the CFL bulb market. The result suggests that income constraints to market entry are strong only at very low income levels. Cost factors also appear to influence market entry, as the probability of market entry increases with regional energy prices.

Proxies for regional information networks in the form of Federal State adoption rates and regional accessibility in the form of town size indicators are not significant. However, parameter estimates for indicators for household awareness of their residential energy situation (in the form of knowledge of the energy rating of the refrigerator or freezer and knowledge of household annual electrical consumption) are positive. Thus, awareness of energy use appears to be an important factor in the market entry decision.

Estimated relationships in the adoption intensity equation are in many cases very different from those found in the market entry equation. The parameter estimate on the linear term for total number of bulbs in the household is negative, while the estimate on the quadratic term is positive in the adoption intensity equation. The combined effect of the parameters on the intensity of CFL adoption is negative for the range of the number of bulbs found in the vast majority of households (up to 194 total bulbs in the residence). Further, the absolute value of the negative effect of total number of bulbs on adoption intensity increases up to 97 bulbs, which includes over 99 percent of households in the sample. Thus, as expected, adoption intensity is lower in households with a relatively high number of sockets after controlling for floor area and lighting needs. Residence size also influences adoption intensity by raising lighting needs, particularly after controlling for the total number of bulbs in the household. The linear term for residence size is not significant, while the quadratic term is positive and significant. Combined, the effect of residence size on adoption intensity is positive and increasing for residences with floor areas greater than 54m^2 (89.6 percent of the sample).

Adoption intensity is found to be significantly higher in detached homes and, somewhat surprisingly, in homes built prior to 1951. The latter effect is, however, only significant at the p=0.10 level. When combined with the insignificant effect of pre-1951 housing on market entry, the result suggests that the fixed housing stock is not a major constraint to the diffusion of CFLs. The finding is also consistent with the fact that modern CFLs were available for virtually every type of socket and size of lighting fixture (Sandahl et al., 2006). The fact that, in contrast to the findings for other residential energy-saving innovations, tenancy does not influence either market entry or the intensity of adoption may be in part due to the possibility for renters to take CFLs with them when moving.

For household characteristics, adoption intensity is higher among retirees and increases with the number of members of the household. As with residence size, these estimates are consistent with a positive association between adoption intensity and lighting needs. In the quadratic specification for the age of the main income earner, the parameter estimate for the linear term is positive and the estimate for the quadratic term is negative. Combined, the parameter estimates suggest that age has a positive, but declining, impact on adoption intensity up to 62 years, and then a negative impact. Unlike for market entry, the presence of children in the household has no impact on adoption intensity. However, residence in a former East German Federal State is weakly associated with lower adoption intensity. The impact of income on adoption intensity is also notably different than the impact on market entry. Compared to the median income group (class 8), adoption intensity is higher for some of the lower income groups; class 1 and class 4 at the p=0.05 level and class 2 at the p=0.10 level. By contrast, the parameter estimates for all income groups above class 8 are negative, with the estimates for class 11 and class 15 being statistically significant. The results imply that lower income groups tend to adopt more intensively than higher income groups. This effect may stem from greater utility gains from the monetary value of cost-savings associated with CFL investments due to higher marginal utilities of income in low income households. Finally, regional power prices do not significantly influence adoption intensity. Thus, while high regional power prices spur CFL market entry, they do not generate significant incentives to increase adoption intensity.

Two alternative specifications of the model are also estimated in order to explore the robustness of the results to exclusion restrictions. In the first alternative addresses the concern that the number of bulbs in the residence may influence market entry. Specifically, the market entry exclusion restriction is dropped and the total number of bulbs variable is included in the market entry equation. Thus, identification of the market entry equation is, in this case, based on the non-linearity of the estimator. The results do not support concerns about the validity of the exclusion restriction, as the total number of bulbs is not significant in the market entry equation and other parameter estimates are similar in magnitude and significance.[10] The second alternative specification drops the regional share of other households adopting CFL bulbs from the market entry equation. Again, the results are virtually unchanged from the initial estimate. Of particular note, the regional power price parameter point estimates are almost identical, alleviating concerns that limited, and possibly highly correlated, variation in regional power price and regional adoption rate variables might mask the impact of power prices on CFL uptake.

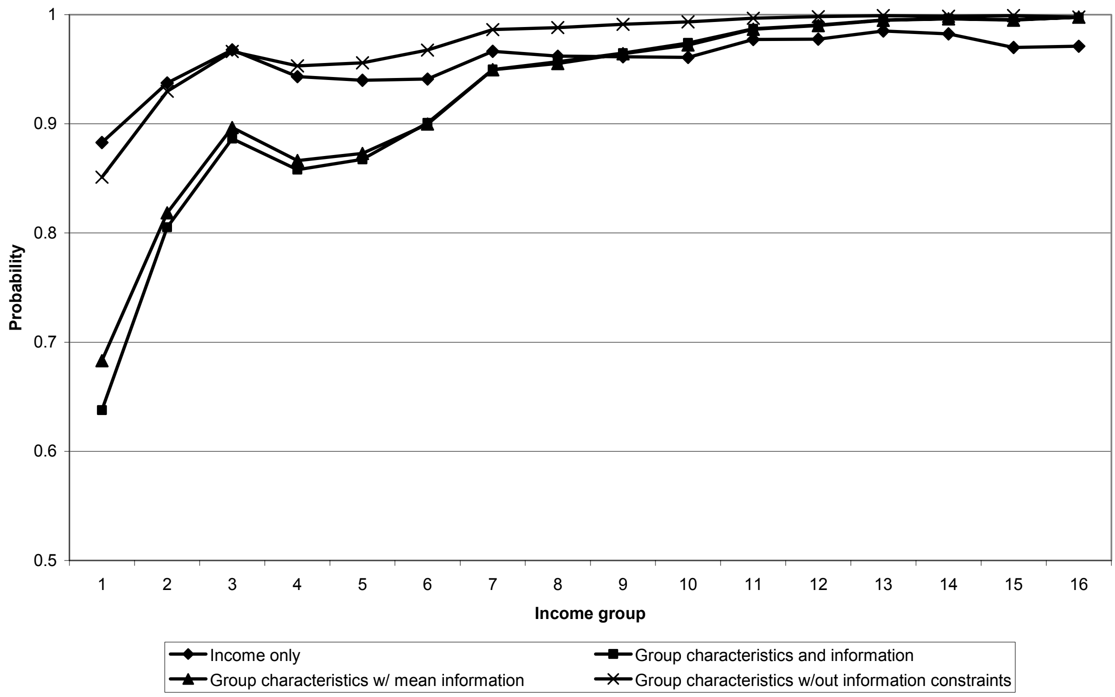
Income group simulations

Figure 3 presents the estimated probability of CFL market entry for each sample income group after controlling for other characteristics of the household. Specifically, the following variables are set to their average for the whole sample: number of bulbs in the household, detached household, renting, pre-1951 age of residence, floor area, number of persons in the household, age of main income earner, regional power prices, adoption rate in region, knowledge of annual electricity bill, and knowledge of refrigerator – freezer energy rating. At the same time, the following indicators are set to zero in light of their relatively low frequency across all income groups: retiree, presence of children under 6 in household, residence in East Germany, senior manager or highly skilled professional head, residence in village under 3,000 persons, and residence in city with more than one million persons. Similarly, the indicator for secondary school education of the head is set to one, since most household heads have at least this level of education in all income groups. The simulation results, depicted by the diamond-ticked line, indicate that the probability of market entry generally

10 A table of results is available from the authors upon request.

increases across income groups. However, the probability is quite high for all groups; ranging from 88 percent for the lowest income group (one) to 97 percent for the highest income group (sixteen).

Figure 3: Probability of market entry

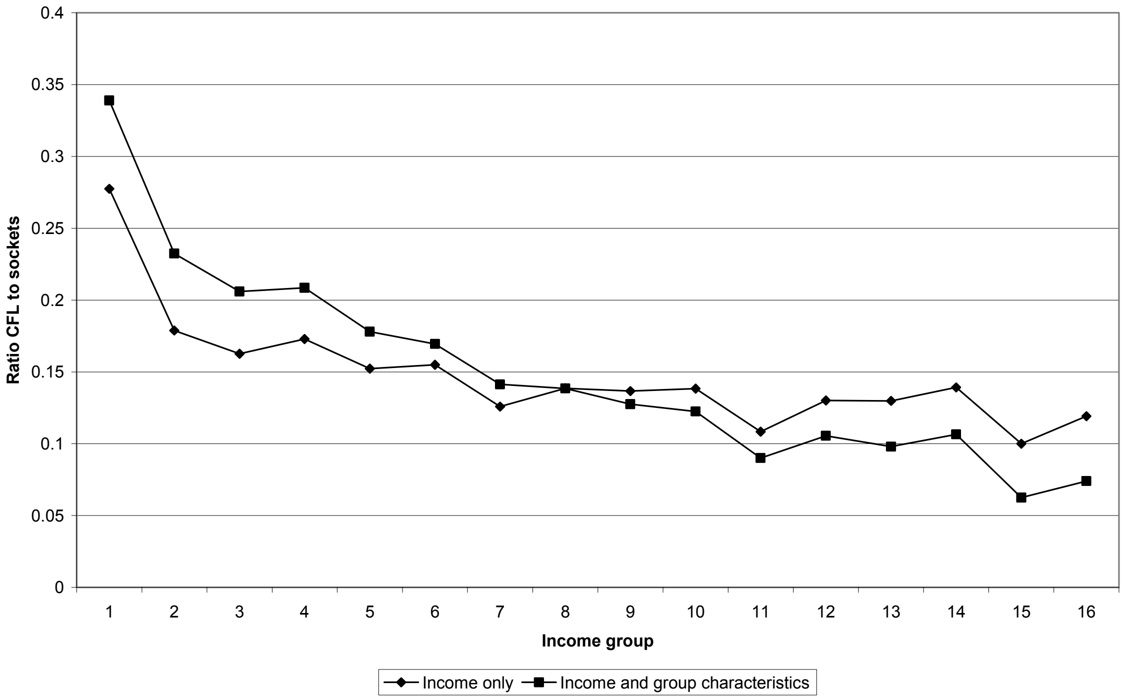


As household income is highly correlated with characteristics of the residence, a second simulation is conducted where the number of bulbs and the floor space of the residence are set as income-group-specific averages, as are the frequencies associated with indicators for detached, pre-1951, and rented residences. The results, depicted by the triangle-ticked line, indicate that these bundles of residence characteristics within income groups have a much stronger impact on market entry than income alone; as the probability of market entry now ranges from 68 percent for the lowest income group to virtual certainty in the highest income groups. Thus barriers to CFL market entry among low income groups appear to stem more from residence characteristics associated with income levels than from income levels themselves.

Low income households also have less knowledge about their level of electricity consumption (as measure by ability to provide information of annual electricity consumption and energy class of refrigerator or freezer). Two simulations are conducted to assess the potential impact of these energy consumption information constraints on CFL market entry. First, information constraints are set to income group specific averages in the square-ticked line. The results show that relatively low levels of information on electricity consumption prevalent in lower income households only slightly decrease the probability of market entry (e.g. the probability of entry drops from 68 percent to 63 percent for the lowest income group). The second simulation examines the, somewhat unrealistic, implications of providing all households with complete information on household energy consumption by setting indicators of knowledge of household annual energy consumption and knowledge of refrigerator-freezer energy class to one for all income groups in the x-ticked line. As the lowest income groups start with the lowest level of knowledge, the simulation has the greatest impact on the group's probability of market entry and essentially offsets the negative influence of the residence characteristics of low income households on market entry. By contrast, the impact of knowledge constraints on market entry for households with income above the median is rather small due to very high initial probabilities of market entry.

Figure 4 depicts the impacts of income and associated residence characteristics on adoption intensity. The diamond-ticked line estimates adoption intensity by income group with other characteristics again held constant. Adoption intensity declines rapidly across income groups from 28 percent for group one to 12 percent for group sixteen. Further, allowing the characteristics of the residence to take income-group-specific averages (square-ticked line) intensifies this decline. It is important to note, however, that the average total number of bulbs in the household increases almost four-fold from the lowest to the highest income group. As a result, the share decline in adoption intensity associated with income and income related residence characteristics translates into a relatively constant expected number of CFLs per household of between three and four in every income group.

Figure 4: Adoption intensity



5 Conclusions and Policy Implications

As might be expected, given that CFLs have been widely available for some time, barriers to market entry are low for all households except those with net incomes below 750 Euros per month. Further, barriers to market entry appear to arise as much from the characteristics of the residences of low income households, like small residence size and infrequent detached housing, as from income levels themselves. Untargeted campaigns to address market barriers to entry will, therefore, have little widespread impact on CFL diffusion. There is, however, some room to specifically address knowledge barriers to market entry among low income households. Such targeting might best be done in conjunction with means-tested housing programs (e.g. rent subsidies and provision of low-income housing).

Given low barriers to market entry, efforts to substantially increase CFL diffusion will need to focus on increasing the intensity of household adoption. Surprisingly, adoption intensity varies inversely with household income. But given that the number household sockets increases rapidly with income, the average number of CFLs per household remains relatively constant in the range of three to four for all household income groups. This implies that the number of lighting sockets for which households perceive CFL investments to be warranted is relatively fixed in absolute value across socio-economic groups. At the same time, CFL adoption intensity does appear to be responsive to a number of indicators of lighting needs. However raising lighting needs in order to promote diffusion is clearly counter-productive to the objective of lowering residential energy consumption and reducing greenhouse gas emissions.

The responsiveness of adoption intensity to energy prices also appears to be low, suggesting that increasing taxes on electricity use will have little impact on the overall diffusion of CFLs. Although it is worth reiterating that price response is based on calculated average regional power prices that do not completely reflect prices paid by individual households. Bans on incandescent bulb sales are the most direct policy to increase diffusion. But bans would be costly for households, as even with relatively widespread exposure to CFLs most households choose to invest in only a limited number of applications. Such bans would not, however, have a strong disproportionate impact on low income households, as lower income households are already proportionately intense CFL adopters especially in light of their relatively low lighting needs.

Continuing technological innovation to further increase performance and lower initial costs, some of which has occurred since the 2002 survey, can extend the number of lighting applications for which CFLs are perceived as profitable household investments and promote further diffusion. Despite impressive technical specifications, for some CFLs a substantial gap may exist between engineering data and residential performance. Subsidies may be needed to focus research innovation on closing this gap in order to speed diffusion and lower the costs to households of any imposed restrictions of the sale of incandescent bulbs.

Areas for further research are strongly linked to the need for improved household data. Specifically, panel data on household uptake of CFLs and changes in CFL prices and power prices would significantly improve estimates of responses to economic incentives. Household panel data would also provide the opportunity to better control for time-invariant unobserved household heterogeneity, particularly with respect to attitudes towards the environment that may be associated with current measures of knowledge of household electricity bills and refrigerator energy class.

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Contact:

Brigitte Kallfass
Fraunhofer Institute for Systems
and Innovation Research (Fraunhofer ISI)
Breslauer Strasse 48
D-76139 Karlsruhe
Telephone: +49 / 721 / 6809-150
Telefax: +49 / 721 / 6809-272
e-mail: brigitte.kallfass@isi.fraunhofer.de
URL: www.isi.fraunhofer.de

Karlsruhe 2008