Shedding light on the light bulb puzzle: attitudes and perception*

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Abstract

Despite the potential energy savings and economic benefits associated with compact fluorescent light bulbs (CFL's), their adoption by the residential sector has been limited to date. In this paper, we present a theoretical model that focuses on the agents' ability to perceive the correct cost of lighting and on the role of environmental attitudes as key determinants of the adoption decision. We use original data from Ireland to test our theoretical predictions. The results emphasize the importance of education, information and environmental awareness in the adoption decision. Based on our findings, we suggest policy measures to foster the adoption of CFL's.

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1 Introduction

Recent years have seen a flurry of proposals to reduce the use of incandescent light bulbs (IL's) in several jurisdictions. The European Union, California, Australia, Brazil, and the Philippines, among others, have either introduced or voiced their intention to adopt legislation banning the sale of IL's in an effort to induce consumers to adopt alternative technologies, and increase the energy efficiency of lighting in the residential sector.

Compact fluorescent light bulbs (CFL's), the natural alternative to traditional bulbs for domestic use, have indeed not fared well on the market. The slow rate of adoption of CFL's by households in most countries[1] presents economists with an interesting puzzle: consumers seem to ignore not only the significant potential energy savings (and the associated environmental benefits), but also the considerable financial benefits that could be realized in a short period of time. In this paper, we aim at contributing to this debate by investigating, both theoretically and empirically, the factors that determine (and deter) the CFL up-take decision by households. Understanding these factors is essential to evaluate the efficiency and distributional implications

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[1]The International Energy Agency estimates that CFL's represented a mere 4% of total worldwide electric light production in 2005 (IEA, 2006).

of any policy geared towards speeding up the adoption of CFL's. We focus on consumers' fuzzy perception of operating costs as one of the key barriers to adoption: the difficulty to estimate such costs by consumers without adequate technical background allows for *anchoring effects* and the associated well-known estimation biases. Environmental attitudes also play a relevant role in our explanation of consumers' choices. Our analysis leads us to emphasize the need to fill the information deficit prevalent among consumers, and suggests simple measures by which adoption can be fostered, as alternative to costly bans.

Using CFL's instead of conventional bulbs has significant implications. Lighting provision represented over 8.9% of total global energy consumption in 2003. The associated emissions of Carbon Dioxide (CO_2) totalled 1.9 billion tonnes worldwide, an amount equal to over 80% of the combined emissions of France, Germany, Italy and the United Kingdom.[2] Using current prices per tonne of CO_2 prevailing in the European Union Emissions Trading Scheme (€23.5-25) as a crude proxy of the scarcity value of the atmosphere to absorb additional greenhouse gasses, this implies that the gross externality imposed by lighting amounts to about €45-50 billion annually.

The residential sector is directly responsible for almost one third of this total, mainly due to its extremely low energy efficiency: compared to the average efficiency of lighting in the industrial (80 lm/W),[3] or the commercial sector (50 lm/W), the 16.8 lm/W estimated for residential use by IEA (2006) demonstrates the enormous potential for energy savings. In the context of devising the most appropriate policy mix to combat global climatic change, there is an opportunity to improve well being if a policy intervention can be made that reduces these externalities at costs below the cost of allowances. This opportunity is enhanced if the private benefits in the form of the value of energy savings of reducing emissions exceed the private costs - the environmental gain is in this circumstance a 'free' joint product. Such an intervention does exists. CFL's represent an efficient alternative to incandescent ones: the typical CFL consumes just a fraction (20 to 25%) of the energy used by an IL to provide the same level of light, and, in general, does not require changes to the light sockets. Moreover, CFL's have rated life spans between 5,000 and 25,000 hours, compared to only 1,000 hours for the average IL. The payback to switching from IL's to CFL's depends on the initial purchasing costs, the cost of electricity, and the rate of use. But there is unambiguous evidence that the payback is typically less than one year (see, for example Bertoldi and Atanasiu, 2006).

CFL's stand out among other energy saving technologies for a number of reasons. First, they are relatively inexpensive. Second, the turn-over time for light bulbs is much shorter than most other electrical appliances (white goods, for example), so that adoption may occur in a relatively short period of time. Third, the potential savings from adopting CFL's are very large, due to the extremely low efficiency of the alternative technologies.[4] Finally, irrespective of any environmental considerations, the financial case in favour of the adoption of CFL's is compelling. According to recent estimates by Bertoldi and Atanasiu (2006), substituting any IL (with a price of around €0.5, and a lifespan of 1,000 hours) burning at least 1 hour per day (365 hours per year) with a CFL (assuming a price of €10 for a 13 W CFL, with a life of 6,000 hours) would lead to cost savings for the household even with the lowest electricity price for residential customers

[2] IEA (2006) provides a thorough overview of the lighting sector.

[3] The symbol lm/W indicates lumens per watt. The lumen (symbol: lm) is the SI – International System of Units – unit of luminous flux, a measure of the perceived power of light. It differs from radiant flux, the measure of the total power of light emitted (measured in watts, symbol: W), in that the luminous flux is adjusted to reflect the sensitivity of the human eye to different wavelengths of light. The ratio of luminous to radiant flux thus measures luminous efficacy.

[4] For the EU-27 countries, Bertoldi and Atanasiu (2006) estimate potential savings to be between 12.5 and 18 TWh per year, based on 2005 data. This compares with a total electricity consumption for lighting of 91 TWh in 2005, thus potential savings equal almost 20% of the total.

in the EU (in 2005 this was 5.8 c€/kWh in Malta). Since cheaper CFL's have since become available (in the range of 3 to 5 euro), while the average electricity price for residential customers including taxes is close to c€18 for the EU27, switching to a CFL would reduce costs at almost every lighting point.[5]

Despite these many attractive features, the adoption of CFL's has been puzzlingly slow. According to IEA (2006), CFL's share in total lamps sales for the EU27 in 2003 was close to 10% of total sales, less that 4% for the US, and about 14% in Japan. Explaining this apparent irrational behaviour constitutes a key first step towards the design of policy aimed at improving the diffusion of CFL's.

The idea of implementing policies to encourage consumers to purchase more energy-efficient equipment is far from new. After Hausman (1979) measured the surprisingly high discount rates – over 25% – implicit in the adoption behaviour of consumers for energy-efficient domestic appliances, Gately (1980), found even higher implicit rates (45 to 300 %) and concluded that consumers were likely to make wrong decisions due to lack of information or irrationality. This suggests that policies leading to more informed choices on the part of consumers could help narrow down the gap between individual and the social discount rates, thus increasing the diffusion of energy-efficient equipment.

In what follows our aim is to shed some light on the reasons that have so far prevented more diffusion of CFL's in the residential market. We develop and test a simple theoretical model to understand consumers' choices among alternative sources of lighting. As in previous contributions (see Kooreman, 1996, for a discussion of the literature), the central element of the model is the trade-off of purchasing costs against operating costs. The novel feature of our analysis is that it transparently indicates the agents' inability to *correctly* gauge the overall cost of the alternatives as the key reason behind the hold-up in technology adoption. Our theoretical model thus captures the key issues reported in the literature (see Lefèvre, de T'Serclaes, and Waide, 2006) as barriers to the diffusion of the technology, namely the high initial cost, and the difficulty to assess the true cost per unit of lighting. As for the third issue mentioned by Lefèvre, de T'Serclaes, and Waide (2006), the fact that early generations of CFL's suffered from a number of quality and suitability issues, we note that most of these shortcomings have been resolved and the latest generations of CFL's are *de facto* perfect substitutes for IL's.[6] However, in our framework we allow for the possibility that these early shortcomings may have caused some distrust in the technology.

The second novel element in our investigation is the explicit modelling of preferences for the environment. While the importance of environmental attitudes and values has long been acknowledged by environmental psychologists, few economic studies on residential energy use have taken them into account. Van Raaij and Verhallen (1983) point to the influence of energy-related attitudes such as environmental and energy concerns in shaping individual behaviour regarding energy use. In their theoretical framework, attitudes are related to, but do not necessarily cause, behaviour. Recent studies, however, focusing on participation in green electricity programs (e.g. Clark, Kotchen, and Moore, 2003, Kotchen and Moore, 2007), find that environmental concern and altruistic attitudes are important determinants of the household up-take decision. Finally, Kahn (2007) finds a positive correlation between the number of registered Green Party voters in different communities in California and environmental behaviour. He

[5]It is worth noting here, however, that for low-usage lighting points a switch to CFL's is inefficient. A generalized ban on IL's that would force consumers to substitute IL's with CFL's at *all* lighting points would thus impose an unnecessary burden on them.

[6]First generation CFL's were only available in cooler light colours, and had a tendency to flicker. Their magnetic ballasts were prone to delays when starting up, and their shapes were generally inadequate for traditional house fittings.

shows that individuals living in communities with a higher share of 'Greens' are more likely to commute by public transit, purchase hybrid vehicles, and consume less gasoline than people in other communities. We take these findings into account in our analysis and use survey data from Ireland to test our theoretical insights into the factors slowing down the adoption of CFL's by including environmental attitudes among our regressors.

Our results highlight the importance of education, information and environmental awareness in the household's adoption decision. First, we look at the reasons that the respondents state as key barriers to the adoption of energy-saving devices. Over 50 percent of the households surveyed point out at the lack of awareness of the benefits or even the existence of such technologies. Second, we estimate a probit model in which the probability of adopting CFL's is a function of environmental attitudes and awareness, education, income and other controls. We find that in addition to income, environmental attitudes, and, above all, education play key roles in explaining the adoption decision.

Ireland represents an interesting case to study as it is the country with the highest share of lighting consumption in total electricity use in the residential sector among the EU15 with 18 percent. This compares to 6 percent in France, and 8 percent in Denmark. Moreover, Irish households consume twice as much energy as the EU25 average for lighting (1,000 kWh compared to 507 kWh in 2005), and they have one of the lowest CFLs adoption rates in Europe; only 38% of Irish households used at least one CFL in 2005 (30 percent at the time of the survey, in 2001), compared with 70% in Germany and an average of 54% in the EU25. Indeed, given the high price of electricity for residential consumers (over 14c€/kWh), a CFL operating for 2,000 hours per annum would pay back its upfront cost in about two months.[7]

O'Doherty, Lyons, and Tol (2007) also used Irish data to investigate issues of energy-efficiency, albeit without a specific focus on residential lighting. Their data set, the Irish National Survey of Housing Quality, contains information on a large number of households, but only includes a limited list of socio-demographic controls, and lacks information on both education, and environmental attitudes. In an earlier study, Scott (1997) models the adoption of attic and water cylinder insulation and low energy light bulbs by Irish households. While her data set does not contain information on the environmental attitudes of respondents, it does include variables capturing the familiarity of the respondent with the items, which turn out to be significantly related to the probability of adoption.

The rest of the paper proceeds as follows: the theoretical model is presented in section 2, while the description of the dataset and of the empirical analysis is contained in sections 3 and 4, respectively. Section 5 discusses policy options and concludes.

2 Behavioural model

When it comes to understanding electricity consumption by households, the literature has focused on the purchase of durable goods, notably household appliances and equipment for heating and cooling. As energy efficient equipment tends to be relatively expensive, the question is whether consumers are rational in the sense of trading-off the observed capital costs against the fuzzier operating costs. One common way to model such behaviour is via intertemporal models that focus on the time preferences of consumers and allow the estimation of the implicit discount rates (Hausman, 1979, Gately, 1980, Kooreman, 1996, for example). While this

[7]This example assumes replacing a 100W bulb operating for 2000 hours per annum, hence consuming 200kWh/Year, with a 20W CFL, and an electricity charge of 14c/kWh plus 13.5% VAT. The annual operating cost would be close to €32 per annum, the CFL bulb could avoid 80% of this cost, or €25.6 per annum. This would pay back the extra upfront cost (about 4-5€) in just about two months.

approach is justified to study appliances that require investments whose pay-back times may be counted in years, we argue that for CFL's – whose pay-back horizon can be counted in weeks – the additional complexity of a dynamic model is not warranted. We thus opt for a simpler model than the ones usually found in the literature on durable goods, and concentrate on a static framework.

The model we present here describes an agent's choice between purchasing a CFL and a conventional light bulb. This choice is determined by her preferences and by her *perception* of the relative cost of the two alternatives. This cost comprises the up-front purchasing cost of the bulb, and the operating cost. Given that correctly estimating the actual operating cost is not an easy task without appropriate technical training and measuring instruments, we allow for the estimated cost to differ from the true one. Thus, it is the *perceived* relative cost, rather than the actual one, that determines purchasing behaviour. In modelling agents' perceptions of operating costs, we build on the literature which emphasizes the existence of *anchoring effects* in decision making under imperfect information (see, for example, Gilovich, Griffin, and Kahneman, 2002). This literature suggests that people make estimates by starting from an initial, familiar value, that is adjusted to yield the final answer. Here, we assume that agents erroneously guess that CFL's consume as much energy per lumen as IL's, *unless they put some effort in understanding the new technology* and adjust their estimate. Investing effort in this pursuit comes at a cost and generates rewards – i.e. a better understanding of the true operating cost – depending on the agent's individual ability. We thus propose that the existence of an upward bias in the *perceived cost* of energy-efficient residential lighting offers an alternative explanation for the unrealistically high discount rates found in the literature.

We now turn to presenting our formal behavioural model. Let ℓ_1 be lumens produced from conventional lamps, and ℓ_2 lumens from CFL's.[8] As discussed in the introduction, bulb users might perceive CFL's and IL's as imperfect substitutes due to objective characteristics or because of negative experiences with earlier vintages of CFL's. To take this into account, we introduce a parameter (δ) to represent the "quality" deficit of CFL's, assuming that $\delta \in (0,1]$.

CFL's require only a fraction of the energy used by IL's to produce the same lighting services. Thus, the environmental impact associated with lighting services is $I = \varepsilon_1\ell_1 + \varepsilon_2\ell_2$, where ε_i stands for the environmental impact of technology $i \in \{1,2\}$. Upon normalizing ε_1 to 1, and letting $\varepsilon_2 = \varepsilon < 1$, we get $I = \ell_1 + \varepsilon\ell_2$.

We assume that preferences can be represented by a Cobb-Douglas utility function defined over lumens and (the reciprocal of) environmental impact, $1/I$, with elasticities α, and $(1-\alpha)$ respectively. By applying a logarithmic transformation, we get an expression for the agents' utility, $\log(\ell_1 + \delta\ell_2) - \phi\log(\ell_1 + \varepsilon\ell_2)$, where $\phi = (1-\alpha)/\alpha$ represents the relative weight of environmental preferences.[9]

Agents only differ in their ability to understand the operating costs associated with CFL's. Letting the operating cost of the technology be $p^* < 1$, we ranked agents in terms of increasing ability by index $j \in (0, 1-p^*]$. By investing an amount of effort equal to $\eta \in [0,1]$, any agent can improve her guess of the operating costs. The estimated cost per lumen generated by a CFL for agent j is given by $p = 1 - j\eta$, such that the "best" agent correctly estimates the operating cost, p^*, when exerting one unit of effort. The (constant) marginal cost of effort is κ.

Each agent maximizes her utility from lighting and environmental quality by choosing how much lighting of each type to purchase and how much effort to exert, subject to her budget constraint $M \geq f_1 e_1 + f_2 e_2 + \ell_1 + p\ell_2 + \kappa\eta$. Here f_i is the fixed cost associated with the use of

[8] In what follows subscript 1 indicates variables that refer to IL's, while 2 identifies CFL-related ones.

[9] To guarantee the positivity of marginal utilities, we assume that $\phi < \bar{\phi} \equiv \varepsilon/\delta \leq 1$.

lighting technology $i \in \{1,2\}$, with the assumption that $f_1 < f_2$, i.e., that the fixed costs for CFL's are higher,[10] while e_i is an indicator function such that:

$$e_i = \begin{cases} 0 & \text{if} \quad \ell_i = 0, \\ 1 & \text{if} \quad \ell_i > 0; \end{cases}$$

and p is the relative operating cost of a lumen provided by CFL's as perceived *ex-ante* by an agent, having normalized the cost of a lumen of the conventional technology to 1.

In short, an agent solves:

$$\begin{aligned} \max_{\ell_1,\ell_2,\eta} \; & \log(\ell_1 + \delta\ell_2) - \phi\log(\ell_1 + \varepsilon\ell_2) \\ s.t. \; & M \geq f_1 e_1 + f_2 e_2 + \ell_1 + p\ell_2 + \kappa\eta; \\ & \ell_i \geq 0, \text{ for } i \in \{1,2\}; \\ & p = 1 - j\eta \text{ with } j \in [0, 1-p^*]; \\ & 0 \leq \eta \leq 1. \end{aligned} \tag{1}$$

Given the high degree of substitutability between lumens produced by the two technologies, it should not come as a surprise that the problem admits corner solutions for most combinations of the parameters' values. The key dimensions determining the behaviour of the agents are the degree of 'greenness' of their preferences, ϕ, and their ability to understand technical information j. It is possible to identify three thresholds that partition the parameter space (ϕ, j) in as many areas where different equilibria obtain. First, notice that no agent will find it optimal to invest effort and choose IL's. For low levels of j, η is always zero as the returns to effort are minimal. Since CLF's are then believed to have no advantage over IL's in terms of cost, the choice of IL vs. CFL only depends on how "green" the agent's preferences are. Thus, the first threshold identifies the condition separating situations where in equilibrium only IL's are chosen (and no effort is exerted) from ones where only CFL's are chosen. In short, strategy {CFL, $\eta = 0$} dominates {IL, $\eta = 0$} if and only if ϕ is large enough to solve

$$\left(\frac{\delta}{\varepsilon^{\phi}}\right)^{\frac{1}{1-\phi}} > \frac{M - f_1}{M - f_2}, \tag{2}$$

we identify this threshold level of ϕ by $\widetilde{\phi}$ in Figure 1.

For relatively "brown" preferences, i.e. low levels of ϕ, using CFL's becomes attractive only when exerting effort is effective enough to provide a quite low educated guess of the operating cost of CFL's, that is when j exceeds a certain threshold (recall that $p = 1 - j\eta$). Formally, this {CFL, $\eta = 1$} dominates {IL, $\eta = 0$} if and only if

$$j > \widetilde{j}(\phi) \equiv 1 - \left(\frac{\delta}{\varepsilon^{\phi}}\right)^{\frac{1}{1-\phi}} \frac{M - f_2 - \kappa}{M - f_1}. \tag{3}$$

Intuitively, $\widetilde{j}$ decreases with ϕ: as environmental motivations increase, the fall in the perceived price needed to make CFL's attractive gets smaller.

Finally, {CFL, $\eta = 1$} dominates {CFL, $\eta = 0$}, if and only if

$$j > \overline{j} \equiv 1 - \frac{M - f_2 - \kappa}{M - f_2}. \tag{4}$$

[10] One can think of such fixed costs as the price per light bulb, plus any other cost involved in the purchasing decision, e.g. search costs.

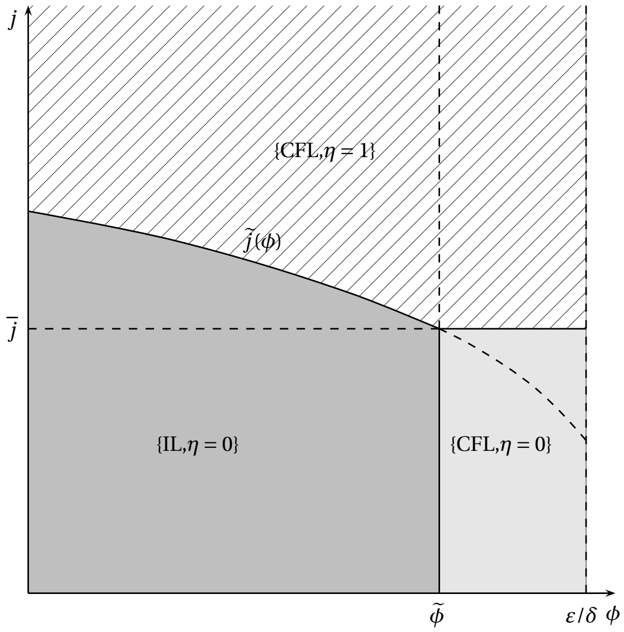

Figure 1: *Equilibria in the parameter space* (ϕ, j).

This analysis leads to the equilibria described in Figure 1. IL's will be the bulbs of choice for agents with a low – smaller than $\tilde{\phi}$ – weight for environmental quality in the utility function, and for all those for whom the returns to spending time and effort on getting to know the new technology are low, i. e. those with $j < \tilde{j}$.

It is a straightforward exercise in comparative statics to show that the vertical $\tilde{\phi}$ threshold shifts to the right with an increase in f_2, while it moves to the left whenever the available budget (M) increases, or if IL's become more expensive to purchase, i.e. if $\mathrm{d}f_1 > 0$. A similar exercise reveals that increases in δ, M, and f_1 all lead to downwards shifts in the $\tilde{j}(\phi)$ threshold, while the opposite occurs for increases in ε, κ, and f_2. Thus, our stylized model predicts that more agents would prefer CFL's if they were cheaper to purchase, more comparable to IL's in terms of lighting performance, more environmentally friendly, and if it were less costly to understand the potential savings accruing to adopters. All this conforms with economic intuition.

We derive the following testable implications from our discussion so far: The probability of adopting CFL's (i) increases with the individual's degree of preference for the environment ϕ; (ii) increases with the ability of the individual to estimate correctly the relative cost of lighting provided by CFL's (for example with the level of education); (iii) increases with the level of income; (iv) decreases with the fixed costs associated with purchasing of CFL's, including search costs, e.g., the likelihood of adoption is lower, the more difficult it is to find CFL's in local stores.

In the rest of the paper, we test the empirical significance of these implications of our theoretical model using the dataset described in the following section.

3 Description of variables and data sources

The source of data for the empirical analysis is the Urban Institute Ireland National Survey on Quality of Life (UII, 2001) where a representative sample of 1,500 men and women, aged 18 and over and living in Ireland, was interviewed in 2001.[11] In addition to income and the standard socio-demographic and socio-economic controls, the survey gathered information on several aspects of the respondents' quality of life and contained questions on general attitudes towards some topical issues (including the environment) and on the adoption of energy-saving measures by the household.

Our dependent variable is a binary variable that takes the value of one if the respondent reported to have energy efficient light bulbs installed in his dwelling. As shown in Table 1, 30 percent of the respondents have installed at least one CFL. The survey, however, did not collect information on the number of points in which efficient light bulbs are used, or on the energy consumption devoted to lighting in the household.

In the dataset, there are three variables that can be used to assess the environmental attitudes of respondents and their familiarity with environmental issues. The first one is constructed from the responses to a question assessing the respondent's support to the Kyoto Protocol (with 4 categories ranging from 'not at all supportive' to 'very supportive' and a specific category for 'don't know'). The variable used in the analysis has 3 categories: not supportive (including 'not at all supportive,' 'not supportive' and 'don't know') coded as 1, supportive and very supportive, coded as 2 and 3, respectively. A second question asked how important was the "protection of the environment" to the respondent, and responses were recorded into 4 categories: 'not important', 'neither important nor unimportant', 'important, and 'very important.' Due to the small number of observations in the first two categories, they are combined in the empirical analysis. The third variable, relates to knowledge of specific environmental issues and is built as a dummy with a value of one if the respondent has heard of global warming and the greenhouse effect. We will use these three variables as proxies for preferences for the environment of each individual in the regression analysis.[12] Notably, the respondents have stated high preferences for the environment: the mean values for 'Support Kyoto' and 'Importance of Environment' are above 2, and 85 percent of the respondents are aware of global warming and greenhouse effect as shown in Table 1.

Among the socio-economic characteristics, the dataset contains information on educational attainment (primary, lower secondary/junior high school, upper secondary/senior high school and university degree). Education is regarded as a proxy for the respondent's ability to predict correctly the operational cost of energy-saving devices. Thus, we expect to see that agents with higher educational attainment are more likely to adopt CFL's.

The income variable in the dataset is gross household income. Missing values, 23.7 percent of those interviewed, were imputed based on the respondent's socio-demographic characteristics including age, gender, marital status, education level, area inhabited and employment status.[13]

To control for relative fixed costs in terms of accessibility to CFL's depending on the type of the locality where the respondent lives, we include a dummy variable for those respondents living in a rural area. As shown in Table 1, 38 percent of the respondents live in rural areas. We expect these agents to have a lower probability of installing CFL's.

Other individual socio-economic and socio-demographic characteristics included in the sur-

[11] Due to missing observations the final sample in the probit regressions consists of 1,339 observations. The effective response rate is 66.6 percent. The margin of error using the entire sample is ± 2.5 percent at a 95 percent confidence level (see UII, 2001).

[12] The correlation between these three variables is relatively low: 0.18, 0.29, and 0.14 for Corr(Support Kyoto, Importance of Environment), Corr(Support Kyoto, Knowledge of Environment), and Corr(Importance of Environment, Knowledge of Environment), respectively; which allows us to include them as regressors without incurring in imperfect multicollinearity.

[13] The original income variable was divided into 10 categories, so mid-points were used. The survey was carried out when Ireland was still using the Irish Pound, so we converted to euros using the fixed rate of IR£1= €1.26974.

vey are: age, sex, marital status, and number of dependent children. Previous studies (for example Van Raaij and Verhallen, 1983) point at the importance of 'life cycle' considerations when deciding the purchase of energy-using devices, and although they are less likely to be important in the adoption of CFL's, we include them in the regressions as controls.

'Appropriability' also seems to be an important factor when considering energy saving investments. Renters are less likely to recoup the benefits of their energy-saving investment, and thus will invest less. Landlords, on the other hand, may consider that they will not recover expenditures on energy conservation through higher rents. The payback period of CFL's is relatively short and, in addition, renters could in principle take their bulbs with them when they move. From our dataset, we know whether the respondent owns the house that she inhabits and introduce a dummy to this effect, although its impact is not likely to be significant.

Table 1 contains the list and some descriptive statistics of the variables discussed above.

4 Empirical analysis

One of the implications of our theoretical model is that people with higher abilities to calculate the correct operating cost of the energy-saving device are more likely to adopt the new technology. Information deficiency is also pointed out as a key factor for non-adoption by the respondents of the survey described in Section 3. One of the questions of the survey asked respondents for their opinion on the main reason why people, in general (and not the respondent in particular), do not install energy-efficient measures in their homes.[14] Table 2 shows the breakdown of the responses. Notably, over fifty percent of the respondents mention unawareness of the benefits of energy-savings measures, or even their existence, as the main reason for not adopting them. Other important barriers to adoption of energy-saving technologies, as indicated by about 35 percent of the respondents, are financial constraints and affordability. This is consistent with many studies and reports that find purchase price to be the most important factor when buying household appliances, including CFL's (Bertoldi and Atanasiu, 2006). However, as the share of household income devoted to buying light bulbs is typically low and given the short payback period of the energy-saving light bulbs, financial constraints are likely to be less relevant for the adoption of CFL's as it is for other, more expensive, energy-saving appliances.

In our empirical investigation we use education as a proxy for a person's ability to evaluate the true operating cost of CFL's, captured by j in our theoretical model. Table 3 shows that, as predicted by the theory, the proportion of adopters of CFL's increases with education. Of those with primary education, only 13 percent report having installed CFL's in their dwelling. This proportion increases to 23 percent for those who have completed secondary education. For those with upper secondary or third level education, the proportion of adopters, 35 percent and 39 percent, respectively, is larger than the sample average reported in Table 1 (30 percent). The differences in proportions across the different consecutive education categories are statistically significant at 1 percent level, as indicated by the p-values in parenthesis, except for the last comparison of those in upper secondary and third level education. This may be explained by the fact that upper secondary education in our sample includes vocational training and people with technical vocational training might be better able to estimate the correct operating cost of the new technology than, say, a university graduate with a non-technical degree. In addition, even among those with the highest educational attainment, less than 40 percent

[14] In addition to the installation of CFL's, energy-savings measures include, for example, the installation of hot water cylinder lagging jackets; floor, roof, and wall insulation; double glazing; and draught-proofing on doors and windows.

have adopted the new technology. This indicates that education may be an imperfect proxy for one's ability to estimate operating costs. However, the trend in adoption rates found in our sample across educational achievement is consistent with the existence of an upward bias in the CFL's operating costs perceived by consumers.

The behavioural model in Section 2 also predicts that agents with low preferences for the environment may adopt CFL's if their perceived operating cost is sufficiently low, while agents with high preferences for the environment may not adopt them if they overestimate the operating costs too much. Table 4 demonstrates that, indeed, among the respondents in the survey, there are customers who have installed CFL's in each category of the three environmental attitudes variables. For example, among those who are not supportive of the Kyoto Protocol about 15 percent have installed a CFL in their dwelling, compared to 32, and 38 percent of those who are supportive and very supportive, respectively. Moreover, we see that as environmental attitudes become stronger, indicating higher preferences for the environment, the proportion of adopters increases for all three variables as implied by the theoretical model. These changes are statistically significant between all categories except the one between the categories 'non-important' (coded as 1) and 'important' (coded as 2) of the variable measuring the stated importance of environmental protection.

The answers summarized in Table 2 do not necessarily reflect the actual behaviour of the respondent; in addition, the descriptive statistics summarized in Table 3 and 4 only constitute a partial analysis of their actual behaviour. In order to investigate in more detail which factors determine the *individual* decision of adopting energy-efficient light bulbs, we estimate a probit model in which the probability of adopting CFL's is modelled as a function of (a vector of) environmental attitudes and awareness, education, logarithm of income, and other controls:

$$P(\text{adoption=1} \mid \mathbf{x}) = G(\beta_0 + \boldsymbol{\beta_1}\,\textbf{attitudes} + \beta_2\,\text{education} + \beta_3\,\log(\text{income}) + \boldsymbol{\beta_4}\,\textbf{controls})$$

where G is the standard normal cumulative distribution function. Table 5 reports the estimates of the coefficients, together with their standard errors, in the second column; the associated marginal effects – evaluated at the means of the independent variables) – are presented in the third column.

The variables we used to capture the environmental preferences of the respondent play a role in explaining the adoption of CFL's. People who support the Kyoto Protocol, believe in the importance of protecting the environment, and those more knowledgeable of the environment are, according to our results, more likely to adopt CFL's. The impacts are statistically significant and sizeable. For example an increase in the importance given to environmental protection is associated with an increase in the probability of adoption of CFL's of 0.10.

The largest marginal effects reported in Table 5 correspond to education. Having finished secondary and university education are each associated with an increase in the probability of CFL adoption of 12 percent. Notably, and consistently with the results in Table 3, the coefficient of these two variables have similar values and a test on their equality reveals that they are not statistically different from each other (p-value 0.97).

As we would expect from the results in Table 2, where financial constraints are singled out as a key barrier for adoption of energy savings measures, income has a significant and positive impact also on the probability of adoption of energy efficient light bulbs. We find that a one percent increase in income[15] is associated with an increase in the probability of adoption of 0.095 percent. While the impact of income on the adoption of CFL's is statistically significant, it doesn't seem economically important. This is hardly surprising, however, given the low price

[15]As mean income in our sample is close to €23,000, this corresponds to an annual increase of €230.

of CFL's compared to other appliances, and the typically low share of the household's income used up in their purchase.

Further, the dummy variable for rural households is significant and negative. This result is similar to Scott's (1997). Compared to people living in urban areas, living in a rural area decreases the probability of installing energy-efficient light bulbs by 0.07. We hypothesize that this could be related to the reduced accessibility to the market for CFL's in remote areas at the time of the survey.

Finally, the dummy variable capturing appropriability is also statistically significant at the 95 percent confidence level. People who own the dwelling in which they reside are shown to be more likely to install a CFL than those who are renting. None of the remaining socio-economic regressors is statistically significant. The test for joint significance of age, male, married, and number of dependent children indicates that they can be dropped from the regression model as a group (p-value 0.4438).

As robustness checks we first estimated the marginal effects associated with the coefficients in Table 5 at different levels of income (1^{st}, 25^{th}, 50^{th}, 75^{th}, and 99^{th} percentile) and educational attainment. The marginal impacts discussed above increase monotonically with the level of income and education, but these increases are not statiscally significant. Second, we analyzed the robustness of our results to the inclusion in the model of dwelling characteristics in addition to the socio-economic and socio-demographic characteristics of the household. Previous research has pointed at a positive association of the size of the residence with greater lighting needs and CFL adoption (Mills and Schleich, 2008). Our dataset does not contain information on floor space but has a variable capturing the number of rooms in the house. We also included dummies indicating whether the house is detached or semidetached (with apartments as the reference category). Mills and Schleich (2008) argue that a detached house may be associated with greater lighting needs and that households living in such dwelling may perceive the lighting costs more accurately due to greater involvement in home maintenance. Finally, to account for the possibility that the age of the residence influences adoption through the difficulty of fitting CFL's in older lighting fixtures, especially with first-generation CFL's (Menanteau and Lefebvre, 2000), we included a dummy for dwellings built prior to the 1960s. The results are robust to the inclusion of these additional variables; see columns 4 and 5 of Table 5. The coefficients on the education and environmental awareness variables retain their magnitude and significance levels. Only the dummy capturing whether the respondent owns his house (whose correlation with 'number of rooms' and 'detached house' is 0.31 and 0.25, respectively) stops being significant at the conventional levels. Living in a rural area (whose correlation with detached house is 0.53) is now associated with a larger drop in probability of CFL adoption (11 percent vs. 7 percent). Of the new dwelling characteristics variables, only 'detached house' has a significant positive impact in the probability of CFL adoption.

5 Conclusions

Despite being a good investment both from the environmental and the economic point of view, the adoption of energy-efficient lighting in many OECD countries has been sluggish. This is even more surprising in a country like Ireland, where it is estimated that a CFL operating for 2,000 hours per annum would pay back its upfront cost in just about two months. Despite this, only 38 percent of Irish households (30 percent at the time of the survey, in 2001) use CFL's.

In this paper we have developed a simple theoretical framework to investigate this puzzle. Transparently, the model indicates that the crux of the adoption decision is in the trade-off between the higher purchasing cost of CFL's and their lower operating cost. As the purchasing price is observed, while the operating costs are difficult to estimate for the average user, a major source of hold-up is identified. The model thus shows that the agent's ability to correctly gauge the operating costs, income and environmental preferences are expected to be the key determinants of the adoption decision.

Using survey data collected in 2001 for a representative sample of 1,500 Irish households, we have tested the implications of the theoretical model. Our empirical findings confirm the insights from the theory. We find that education and environmental attitudes play, together with income, a key role in the adoption of CFL's. When asked about the barriers for adoption of energy-saving measures, over 50 percent of the households surveyed pointed at the lack of awareness of the benefits and the lack of awareness of even the existence of such measures. Financial constraints were also mentioned and income is found to play a significant role in the decision of adopting CFL's. Moreover, agents who declare to have strong environmental preferences on a number of different accounts are also much more likely to have at least one CFL in their residence. Overall, however, the low adoption rate found in or sample is consistent with the existence of an upward bias in the estimate of operating costs by consumers.

The recent focus of the policy debate has been on banning IL's to increase efficiency in residential lighting. A generalized ban, however, is an inefficient instrument and would certainly impose an unnecessary burden on consumers by forcing the adoption of CFL's also at low usage lighting points. Given that with the current market conditions a much higher rate of CFL adoption would be rational, resorting to pigouvian instruments such as taxes and subsidies should be also ruled out as unnecessarily expensive.

Our results paper suggest that, perhaps surprisingly, the most effective way to increase the adoption of CFL's might be to make consumers grasp that there are financial gains to be reaped from switching to CFL's. Simple nudges, in the spirit of the 'libertarian paternalism' advocated by Thaler and Sunstein (2003), could work well in this sense. The introduction of clearer energy labels, educational campaigns aimed at teaching consumers how to read them, or simply agreements with supermarkets and other retailers to clearly indicate the average cost *per lumen* of different types of light-bulbs, as commonly done for other products, would all speed the adoption of CFL's.

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A Appendix: Tables

Table 1: Descriptive statistics

Variable	N	Mean	Std. Dev.	Min	Max
Adoption of energy-efficient light bulbs	1392	0.30	0.46	0	1
Support Kyoto	1469	2.08	0.71	1	3
Importance of Environment	1496	2.51	0.59	1	3
Knowledge of Environment	1500	0.85	0.35	0	1
Education (reference = primary education)					
Low secondary	1500	0.19	0.39	0	1
Upper secondary	1500	0.47	0.50	0	1
University Degree	1500	0.17	0.38	0	1
Income	1497	22,987	11,644	1,852	57,138
Rural dwelling	1500	0.38	0.49	0	1
Own House	1480	0.78	0.41	0	1
Age	1492	43.61	17.10	18	90
Sex (1=male)	1500	0.48	0.50	0	1
Marital Status (1=married)	1500	0.52	0.50	0	1
Number of dependent children	1500	0.88	1.29	0	8

Table 2: Reasons for not installing energy-savings measures

	Frequency	Percent
Can't afford/don't want to borrow	502	34.53
Not aware of benefits	470	32.32
Not aware of existence	276	18.98
Higher priorities	80	5.50
Not own house	49	3.37
Don't want disruption	44	3.03
Other	33	2.27
Total	1,454	100

Table 3: Proportion of adopters across different education categories

	Educational attainment			
	Primary	Lower Sec.	Upper Sec.	Third Level
Proportion of adopters	0.129	0.234	0.352	0.385
		(0.002)	(0.003)	(0.176)

Note: p-values of test for the difference in proportions in parenthesis. Values refer to differences between consecutive categories.

Table 4: Proportion of adopters across different environmental attitudes categories

	Attitudes Indicator		
	Support of Kyoto Protocol		
	1	2	3
Proportion of adopters	0.146	0.321	0.381
		(0.000)	(0.021)
	Importance of Environment		
	1	2	3
Proportion of adopters	0.206	0.208	0.371
		(0.484)	(0.000)
	Knowledge of Environment		
	0	1	
Proportion of adopters	0.136	0.329	
		(0.000)	

Note: p-values of test for the difference in proportions in parenthesis. When there are three categories the two p-values refer to differences between consecutive categories.

Table 5: Adoption of energy-efficient light bulbs, probit regressions

Variable	Coefficient	Marg. Effects	Coefficient	Marg. Effects
Support Kyoto	0.156***	0.053***	0.164***	0.053***
	(0.060)	(0.020)	(0.064)	(0.021)
Importance of environment	0.292***	0.098***	0.296***	0.097***
	(0.072)	(0.024)	(0.077)	(0.025)
Knowledge of environment	0.326**	0.102***	0.371**	0.110***
	(0.138)	(0.039)	(0.146)	(0.039)
Lower secondary school	0.154	0.053	0.250	0.085
	(0.144)	(0.051)	(0.155)	(0.546)
Upper secondary school	0.344***	0.117***	0.389***	0.128***
	(0.133)	(0.045)	(0.144)	(0.047)
University degree	0.348**	0.124**	0.413**	0.145**
	(0.156)	(0.058)	(0.168)	(0.062)
log(Income)	0.282***	0.095***	0.225**	0.073**
	(0.087)	(0.030)	(0.952)	(0.0311)
Rural	-0.199**	-0.066***	-0.359***	-0.113***
	(0.079)	(0.026)	(0.102)	(0.031)
Own house	0.245**	0.079**	0.108	0.034
	(0.110)	(0.033)	(0.118)	(0.037)
Age	0.003	0.001	0.003	0.001
	(0.003)	(0.001)	(0.003)	0.001
Male	-0.076	-0.025	-0.107	-0.035
	(0.076)	(0.026)	(0.082)	(0.027)
Married	0.072	0.024	0.033	0.106
	(0.098)	(0.033)	(0.1035)	(0.033)
Number of dependent children	-0.032	-0.011	-0.016	-0.005
	(0.035)	(0.012)	(0.037)	(0.012)
Detached			0.0365***	0.122***
			(0.129)	(0.044)
Semidetached			0.084	0.027
			(0.115)	(0.038)
Number of rooms			0.034	0.011
			(0.042)	(0.013)
Built before 1960's			0.094	0.031
			(0.092)	(0.030)
Constant	-5.176***		-4.976***	
	(0.923)		(0.921)	
N	1339	1339	1219	1219
Pseudo-R^2	0.08		0.09	

Notes:

a. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

b. Standard errors are given in parenthesis.