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CONTENTS

ABSTRACT

The widespread adoption of compact fluorescent light bulbs (CFLs) have been advocated on the premise that it will result in significant savings in electricity and reduced carbon emissions. Using a household level survey of electrical lighting and usage in Pakistan, we examine the decision to adopt CFLs and the subsequent impact of CFL adoption on electricity usage. CFL adoption is significantly influenced by variables that proxy for income and the perceived expectations about the life span of CFLs. These findings indicate that policies that educate households on the lifespan of CFLs may prove effective in increasing CFL adoption. However, the savings in electricity usage from CFL adoption is less than expected. We find that 27%–41% of potential energy savings are offset through both enlarged bulb capacity and prolonged lighting time. This behavioral response to the energy efficiency improvement therefore diminishes some of the benefits of promoting CFLs as a means to reduce energy consumption and conserve the environment.

I. INTRODUCTION

Many countries, both developed and developing, have been in the process of trying to phase out incandescent bulbs (IBs) (Waide 2010). Multi-million dollar investment projects have been designed to procure and distribute free compact fluorescent lamps (CFLs) to replace IBs in millions of households in developing countries such as Bangladesh, Pakistan, the Philippines, and Rwanda. By increasing the prevalence of CFLs, it is expected that households will save energy and cut utility bills as CFLs provide significant energy savings over IBs. For countries, the large-scale switch to CFLs can aid in reducing carbon emissions or help in closing the gap between electricity supply and demand—an issue that is particularly critical in developing countries.

Successfully reducing energy demand, however, may require understanding factors that lead to higher adoption and ownership of CFLs. This will enable the creation of policies that can encourage CFL adoption as a utility-maximizing choice. Moreover, it requires understanding the behavioral response of households to the lower unit cost of obtaining electricity services from increased lighting efficiency. If households are price-sensitive or constrained by electrical supply, the benefits may be significantly less than expected due to a rebound effect that increases the demand for electricity services or lighting capacity, and may entail the creation of complementary policies that can further reduce electricity demand to policies that encourage replacement of IBs with CFLs.

This paper uses a household-level survey of electrical lighting choices and usage in Pakistan. We investigate household characteristics and behavioral factors that contribute to the adoption and ownership of CFLs within the context of a double hurdle model. We subsequently identify the relationship between CFL adoption and electrical usage with the aim of quantifying rebound effects that occur from CFL adoption.

While there are many studies involving adoption and rebound effect, this study fills an important gap in the literature. First, most studies have examined the adoption decision in the context of developed countries (e.g., Di Maria, Ferreira, and Lazarova 2010; Herberich, List, and Price 2011. Given that more households in developing countries are low-income and less educated, it is reasonable to expect to find significantly different factors driving the adoption decision that are examined in this paper. Second, the rebound effect in household lighting has largely been ignored with most studies typically focusing on automotive transport, heating, and other household appliances (Sorrell, Dimitropoulos, and Somerville 2009; Brohmann et al. 2009). An exception is Foquet and Pearson (2011), who look at the long-run demand for lighting in Europe using aggregate level data but are not able to attribute the rebound effect due to the adoption of a particular lighting technology. In contrast, we are able to attribute the rebound effect due to the adoption of CFLs and decompose it into the utility effect and capacity. Moreover, this rebound effect is computed based on relative energy efficiency measures as opposed to most estimates of rebound effects that are based on price elasticity, providing a better way to understand how improvements in technical efficiency rather than price of energy can influence the demand for energy. This analysis contains important insights for policy makers aiming to encourage CFL adoption and ownership without explicitly providing free CFLs. Moreover, it provides insights into how CFL adoption affects energy demand, which are important in assessing the expected benefits toward reducing energy demand from promoting wide-scale adoption.

The rest of this paper is outlined as follows. Section II provides an overview of the literature related to adoption of energy efficient lighting and electricity usage of lighting. Section III discusses the data that we use in our sample. Section IV presents the model and results for adoption. Section V discusses CFL adoption and its relation to energy usage. In particular, it focuses on quantifying the direct effect of CFL adoption on energy usage via the efficiency elasticity of demand. Section VI provides a discussion of the overall results. Section VII concludes.

II. BACKGROUND

A. Related Literature

Improving the energy efficiency of households is a critical component to reducing energy consumption or mitigating shortfalls in energy supply in relation to demand. While innovations in technology can improve energy efficiency, it relies heavily on adoption decisions. CFLs are an existing technological innovation that provides energy savings of 4–5 times that of an IB for the equivalent lumen output. The life span of CFLs lasts anywhere from 8–13 times that of an IB. Even at a price that is roughly five times that of an IB, a household should expect a rapid return on their investment in a CFL. Nevertheless, there is a significant amount of households that continue to use IBs. In the United States (US), for example, CFLs made up only 20% of the market for lighting in 2007.

The slow rate at which households have adopted CFLs is a commonly observed trend for cost-effective energy-efficient technologies and is driven by a variety of complex and interrelated factors driven by market failures, personal preference, and behavioral biases, among others (Jaffe and Stavins 1994). Thus, an increasing amount of research has been dedicated to identifying what drives and encourages adoption and prevalence of more energy-efficient technologies. The most common factors for adoption of energy-efficient technologies across studies are household income and the price of energy, with less definitive results on education, age, and household size (Brohmann et al. 2009). Ownership, age, and construction of the house have also factored prominently in driving the move toward greater energy efficiency of households in a variety of studies (Davis 2010, Di Maria, Ferreira, and Lagarova 2010; Mills and Schleich 2010) with principal–agent problems between renters and owners creating a situation where rented households have less energy-efficient technologies due to owners supplying cheaper, less efficient technologies, and renters paying for energy costs (Gillingham and Sweeney 2010).

Yet, while raising energy prices may curb demand for energy while speeding up adoption of technologies, such policies are often politically infeasible. This has resulted in research putting an increased emphasis on identifying behavioral and noneconomic factors that can encourage and increase the rate of energy efficiency adoption (Alcott and Mullainathan 2010). Social pressure and providing informational campaigns that will increase environmental awareness or allow households to make more informed choices from adopting energy-efficient technologies are shown to have substantial positive effects (Reiss and White 2008; Costa and Kahn 2010; Di Maria, Ferreira, and Lazarova 2010). In addition to behavioral factors, the relative price of the technology is also important in the proliferation of energy-efficient technologies. In an experimental setting in Chicago, social pressure was found to be the main aspect driving CFL adoption, while the price of the CFL was a significant driver of the number of purchases (Heberich, List, and Price 2010).

Encouraging greater adoption of energy efficient technologies will increase energy efficiency, but it is equally important to understand how much energy efficiency adoption actually results in decreases in energy demand. If shortfalls in energy are a major problem, or reduction in carbon emissions is the goal, then conversion to energy-efficient technologies may only partially resolve the problem. This is because there are often substantial rebound effects that result in increases in the demand for energy services due to the lower unit cost of energy services that arises when households convert to more energy-efficient technologies (Sorrell, Dimitropoulos, and Sommerville 2009). A study of lighting programs for buildings was found to have a rebound effect of around 30% (Nadel 1993), while household lighting has been estimated anywhere from 5%–12% (Greening, Greene, and Difiglio 2000) to 50%–200% in poor rural households (Roy 2000). In estimates of rebound effects over a long time horizon, it is found that in the most recent decade, a 10% increase in technical efficiency resulted in a 5% decrease in energy demand, implying a rebound effect of almost 50% (Foquet and Pearson 2011). Given the price sensitivity and constraints on energy consumption in developing countries, the evidence implies that the rebound effect may be quite substantial.

B. Energy and Electricity in Pakistan

In Pakistan, the issue of shortfalls in energy supply is especially severe. While Pakistan has experienced moderate increases in the supply of energy rising from 55.6 million tons-of-oil-equivalent (TOE) in 2004–2005 to 63.1 million TOE in 2009–2010, supply has not kept pace with the increases in demand that have grown on order of 7%–8% per annum (Jamil

2010).[1] Still, Pakistan has extremely low levels of energy consumption per capita at 436 kilowatt-hours (kwh) in contrast to the US, which consumes 13,647 kwh per capita. In the case of electricity, households comprised approximately 45.6% of electricity usage in 2008, with lighting estimated to account for 35% of total domestic electricity consumption (Tariq, Nasir, and Arif 2008).[2] However, approximately 40% of households are not connected to the electrical grid and the imbalance between supply and demand has led to frequent and unpredictable power cuts. This has led to concerns that sufficient electricity generation may be one of the major hold-ups to social stability and economic growth within the country (IEA 2008).[3]

Increasing adoption and proliferation of CFLs in households in Pakistan therefore may have potential for partially resolving the issue of insufficient electricity generation as almost 77% of households still use IBs. However, even with CFL prices that are around five times more than IBs, and potential inconsistencies in the supply of quality CFLs, CFLs have achieved a household penetration rate of 64% (ADB 2009). To speed up this switch, the $85 million Pakistan Sustainable Energy Efficiency Investment Program (SEEIP) was initiated to replace over 30 million IBs with CFLs. In this program, households are given up to two CFLs free of cost to replace existing IBs. Thus, understanding factors driving household adoption and ownership of CFLs and how CFL adoption is related to electricity usage is highly important especially given the large investments that are at a stake. At a more general level, our analysis provides valuable insights into the extent to which CFLs may actually provide a solution in developing countries that have severe shortages in electricity supply.

III. DATA AND DESCRIPTIVES

The Pakistan SEEIP Baseline Domestic Lighting Survey is used as the main basis for analysis. It contains a sample of 3,253 households in Pakistan conducted from 18 March 2009 to 10 April 2009 by Gallup Pakistan. It covers households from nine distribution utilities across 58 districts.[4] The survey collected basic demographic and housing characteristics. It conducted a detailed counting exercise of lighting equipment for the households sampled. In each household, the interviewers recorded the number, wattage, and average daily use in hour for each type of bulb in the living, dining, bedroom, and other rooms (i.e., study, kitchen, etc.). Two records were taken for each type of bulb to capture variations in bulb wattages.

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[1] Electricity supply comes from the following sources: 31.4% comprised of oil, 48.8% from gas, 7.3% from coal, and 11.8% from hydro, nuclear, and imported sources (IEA 2010).

[2] Domestic and commercial sectors in Pakistan account for 25% of total energy usage in 2009–2010 (HDIP 2010), but comprise a much larger portion of total electricity consumption.

[3] See *The Economist* (2011) and Kemal (2011).

[4] As the survey was conducted during the spring months, our analysis cannot capture the elasticity of demand and electricity usage during the winter months, which is when peak electricity demand occurs due to harsh weather conditions and the shorter number of daylight hours. However, the spring months may better capture what we could expect on average if we had lighting usage data over the course of the entire year for each household.

Basic descriptive statistics of the household in the sample are displayed in Table 1. Daily labor is the main source of income for the largest percentage of households at 34%. The average household has 1.69 workers and a household size of 6.9. Over 91% of households own their homes and 64% have a house constructed out of masonry with each house having an average of 2.71 rooms.

Table 1: Summary of Household Characteristics

Variable	Mean	SD
Respondent: Female	0.17	0.38
Respondent: Household Head	0.63	0.48
Income: Daily Labor	0.34	0.47
Income: Farming	0.14	0.35
Income: Government Work	0.15	0.36
Income: Business	0.19	0.39
Income: Private Service	0.18	0.38
Income: Other	0.00	0.05
Household Number of Workers (mean)	1.69	0.85
Household Size (mean)	6.92	3.01
Property Number of Rooms (mean)	2.71	1.41
Property: Own	0.91	0.29
Property: Rent	0.09	0.29
Property: Other	0.00	0.04
Property Type: Flat	0.02	0.14
Property Type: Building 1	0.94	0.24
Property Type: Building Multi-story	0.03	0.18
Property Type: Other	0.00	0.07
Property Construction: Adobe	0.16	0.37
Property Construction: Informal	0.20	0.40
Property Construction: Masonry	0.64	0.48
Observations	3,253	

Source: Authors' estimates.

Table 2 displays aspects of household CFL awareness and purchasing behavior. Over 89% of households are aware of CFLs and 64% claim to regularly purchase CFLs. However, only 51% bought CFLs in their last purchase while 56% bought an IB. Over 80% of all people made their last purchase of light bulbs within 2 kilometers of their home, and more than 42% cite availability as an important factor in getting them to switch to making more CFL purchases. Many respondents recognize the benefits of CFLs, with 87% stating that CFLs have significant energy savings, and more than 76% indicating that CFLs last at least two times longer than IBs. The stated average price of IB was Pakistan rupees (PRe) 15.7 (not displayed) in their last purchase versus PRe137.2, suggesting that CFLs are almost eight times more costly then IBs. This is potentially a major factor in the lack of greater CFL penetration, as only 58% of the population says they would buy a CFL if it is a higher price than an IB, despite a greater percentage of households recognizing that CFLs do have cost-savings and last longer than IBs. Moreover, of the people who do not frequently purchase CFLs, high cost is cited by 89% of households as the main reason for not purchasing a CFL, as seen in Table 3.

Table 2: Household Awareness, Purchasing Behavior, Perceptions of Lighting

Variable	Mean	SD
Aware of CFL	0.89	0.31
Last Buy IB	0.56	0.50
Last Buy CFL	0.51	0.50
Last Buy FTL	0.26	0.44
Last Buy Halogen	0.00	0.04
Distance Purchase Bulb > 2 kilometers?	0.20	0.40
Regularly Buy CFLs?	0.64	0.48
Reason to Switch to CFL: Energy savings	0.87	0.34
Reason to Switch to CFL: Light quality	0.43	0.49
Reason to Switch to CFL: Availability	0.42	0.49
Reason to Switch to CFL: Environment	0.06	0.24
Reason to Switch to CFL: Low Price	0.08	0.27
Perceived Life of CFL versus IB: Don't know	0.24	0.42
Perceived Life of CFL versus IB: 2 times	0.38	0.49
Perceived Life of CFL versus IB: 4 times	0.20	0.40
Perceived Life of CFL versus IB: 6 times	0.09	0.29
Person Life of CFL versus IB: 10 times	0.09	0.28
Buy CFL if price CFL > price IB?	0.58	0.49
Bulb Purchase: Hardware	0.55	0.50
Bulb Purchase: Grocery	0.45	0.50
Observations	3,253	

CFL = compact fluorescent lamp, FTL = fluorescent bue light, IB = incandescent bulb.

Source: Authors' estimates.

Table 3: Reasons for Not Buying CFLs (No-CFL Households)

Variable	Mean	SD
Reason Not Buy CFL: High cost	0.89	0.31
Reason Not Buy CFL: Doesn't look good	0.12	0.33
Reason Not Buy CFL: Bad light quality	0.07	0.25
Reason Not Buy CFL: Doesn't last long	0.15	0.36
Reason Not Buy CFL: Not available	0.09	0.28
Reason Not Buy CFL: Not suitable for fittings	0.10	0.30
Reason Not Buy CFL: Voltage fluctuations	0.03	0.16
Observations	1,166	

CFL = compact fluorescent lamp.
Source: Authors' estimates.

Table 4 provides statistics on lighting and lighting usage for households. In all, 64% of households have at least one CFL light bulb with 6.81 bulbs per households and average wattage of 315.90. The average household uses 1,305 watt-hours per day. The detail of the data allows us to focus more specifically on lighting choices and behavior in particular rooms. This captures the decision process behind lighting adoption and electricity usage, that it may be a two-part process, which takes into account overall electricity consumption of the household; and also electricity consumption within a particular room. In what follows, we focus on the living, dining, and bedrooms since most bulbs and lighting electricity usage are concentrated in these three rooms. We construct six variables in two sets for each room, focusing only on the lighting choices and usage of IBs and CFLs within the room.[5] The difference between the two sets is whether the variables take into account the actual lighting effects of different types of bulbs. Specifically, we have the average watt-hours per bulb, average wattage per bulb, and average daily hours used per watt as follows.

$$awh = \frac{\sum_{i=1,2} n_i^{cfl} w_i^{cfl} h_i^{cfl} + n_i^{ib} w_i^{ib} h_i^{ib}}{\sum_{i=1,2} n_i^{cfl} + n_i^{ib}}, \quad (1)$$

$$aw = \frac{\sum_{i=1,2} n_i^{cfl} w_i^{cfl} + n_i^{ib} w_i^{ib}}{\sum_{i=1,2} n_i^{cfl} + n_i^{ib}}, \quad (2)$$

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[5] In these calculations, we ignore information on the presence of other bulb types such as fluorescent tube lamps and halogen type bulbs. One justification for doing this is that CFL and IBs are interchangeable, while the same is not typically true for CFLs and other types of bulbs. At the same time, ignoring other types of bulbs may miss the fact that various types of lighting are substitutable, and households may trade off hours used for one type of bulb versus another depending on the cost of electricity.

and

$$ah = \frac{\sum_{i=1,2} n_i^{cfl} w_i^{cfl} h_i^{cfl} + n_i^{ib} w_i^{ib} h_i^{ib}}{\sum_{i=1,2} n_i^{cfl} w_i^{cfl} + n_i^{ib} w_i^{ib}}, \tag{3}$$

where n, w, and h are the number, wattage, and average daily use in hour for each type of bulb, the superscript indicates the bulb type, and the subscript represents one of the two records taken for one type of bulb. The average watt-hours per bulb is calculated as the sum of total watt-hours of CFL and IB divided by the total number of both types of bulbs, where the total watt-hours of CFL or IB is the product of number, wattage, and average daily use of the bulbs summed across records. The average wattage per bulb equals the sum of total wattage of CFL and IB divided by the total number of bulbs. The average daily hours used per watt is the total watt-hours in the room divided by the total wattage summed over bulb types and records of each type.

Table 4: Lighting and Lighting Usage of Households

Variable	Mean	SD
Have CFL?	0.64	0.48
Number of Bulbs IB	2.50	2.75
Number of Bulbs CFL	2.73	3.92
Number of Bulbs FTL	1.50	2.43
Number of Bulbs Other	0.07	0.49
Number of Bulbs All	6.81	5.66
Watts: IB	188.50	255.67
Watts: CFL	69.92	117.22
Watts: FTL	56.28	94.04
Watts: Other	1.19	11.41
Watts: All	315.90	302.83
Average Watts Per Day: IB	731.86	1345.48
Average Watts Per Day: CFL	308.30	745.24
Average Watts Per Day: FTL	259.48	572.81
Average Watts Per Day: Other	5.74	67.12
Average Watts Per Day: All	1,305.38	1,841.90
% Bulbs CFL	0.35	0.35

CFL = compact fluorescent lamp, FTL = fluorescent tube light, IB = incandescent bulb.

Source: Authors' estimates.

The other set of three variables we construct take into account the efficiency improvement of CFLs, and could be used to proxy for the lighting output and lighting intensity produced by an average bulb. To yield the same level of lighting output, usually measured in lumens, the IB consumes 4–5 times energy than does CFL.[6] For simplicity,

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[6] See, for example, http://en.wikipedia.org/wiki/Compact_fluorescent_lamp

we conservatively assume a capacity-adjusted wattage equivalent to four times of its real wattage for CFL, i.e., $\vec{w}_i^{cfl} = 4w_i^{cfl}$. Put differently, $\vec{w}_i^{cfl}$ may be viewed as the wattage of an IB bulb to replace a CFL bulb to produce approximately the same lighting. Then, we have the variables, as defined below based on the capacity-adjusted wattage, corresponding to those in equations (1)–(3).

$$\overrightarrow{awh} = \frac{\sum_{i=1,2} n_i^{cfl}\vec{w}_i^{cfl}h_i^{cfl} + n_i^{ib}w_i^{ib}h_i^{ib}}{\sum_{i=1,2} n_i^{cfl} + n_i^{ib}}, \tag{4}$$

$$\overrightarrow{aw} = \frac{\sum_{i=1,2} n_i^{cfl}\vec{w}_i^{cfl} + n_i^{ib}w_i^{ib}}{\sum_{i=1,2} n_i^{cfl} + n_i^{ib}}, \tag{5}$$

and

$$\overrightarrow{ah} = \frac{\sum_{i=1,2} n_i^{cfl}\vec{w}_i^{cfl}h_i^{cfl} + n_i^{ib}w_i^{ib}h_i^{ib}}{\sum_{i=1,2} n_i^{cfl}\vec{w}_i^{cfl} + n_i^{ib}w_i^{ib}}. \tag{6}$$

$\overrightarrow{awh}$ and $\overrightarrow{aw}$ can be interpreted as virtual average watt-hours and average wattage per bulb, respectively, when all CFLs were replaced with IBs in the room to produce the same lighting. While $\overrightarrow{awh}$ and $\overrightarrow{aw}$ are not intended to measure the actual lumens-hour or lumens yielded, they may proxy for the average lighting output and lighting intensity per bulb, respectively, since what really matters is the relative efficiency of CFL to IB in the formulas.

Table 5 presents descriptive statistics of lighting bulbs in the living, dining, and bedrooms, respectively. Among the entire sample of 3,253 households reporting presence of lighting bulbs (any kind), 1,026 were in the living rooms; 685 in the dining rooms; and 2,466 households in the bedrooms. Given that the average number of rooms across the sample is less than three, it is expected that a number of households do not have all three rooms. For households where dining, living, and/or sleeping are in one room, interviewers might have the freedom to categorize the type of the room.

Table 5: Lighting and Lighting Usage By Room

Variable	Living Room		Dining Room		Bedroom	
	Mean	SD	Mean	SD	Mean	SD
CFL in room	0.74	0.44	0.64	0.48	0.57	0.50
Number of IB	0.49	0.75	0.54	0.73	0.91	1.12
Number of CFL	1.08	0.95	0.97	1.05	0.99	1.44
Average watt-hour per bulb	205.43	185.85	188.07	195.98	232.42	226.88
Average wattage per bulb	42.37	29.04	44.83	29.14	53.54	33.58
Average hours used per watt	4.93	2.41	4.14	2.42	4.29	2.40
Average watt-hour per bulb (lumen adj)	474.08	311.09	389.73	305.72	406.21	278.82
Average wattage per bulb (lumen adj)	93.23	34.92	90.63	38.86	91.41	32.30
Average hours used per watt (lumen adj)	4.95	2.40	4.16	2.41	4.31	2.38
Observations	1,026		685		2,466	

CFL = compact fluorescent lamp, IB = incandescent bulb, SD = standard deviation.

Source: Authors' estimates.

Rooms with at least one CFL bulb account for 74%, 64%, and 57% of the living, dining, and bedrooms, respectively. The living room has the highest CFL penetration probably because on average, more time was spent in it than in other rooms. The average numbers of CFL and IB are 1.1 and 0.5, respectively, in the living room; 1.0 and 0.5 in the dining room, and 1.0 and 0.9 in the bedroom. The data suggest that the CFL has dominated the IB in both extensive margin (penetration) and intensive margin in the main rooms of a typical household in Pakistan. People tend to use more CFL bulbs than IB in the living and dining rooms, but not in the bedrooms.

The sample mean of the average energy consumption of one bulb, computed with equation (1), is 205, 188, and 232 watt-hours in the living, dining, and bedrooms. The energy consumption per bulb can be decomposed into average wattage per bulb, indicated by equation (2); and average daily use in hours per bulb, by equation (3). The means of average wattage and daily use are 42.4 wattage and 4.9 hours, respectively, for the living room; 44.8 wattage and 4.1 hours for the dining room, and 53.5 wattage and 4.3 hours for the bedrooms. On average, the living room has the longest daily use of lighting, while the bedroom has significantly higher wattage per bulb than do other two room types. The latter, however, does not hold when we account for the different lighting capacities of CFL and IB of the same wattage.

The virtual average watt-hours, wattage, and daily use per bulb defined by equations (4)–(6) are presented in the bottom of each panel in Table 5. The means of these variables are: 474.0 watt-hours, 93.2 wattage, and 5.0 hours in the living room, 389.7 watt-hours, 90.6 wattage, and 4.2 hours in the dining room, and 406.2 watt-hours, 91.4 wattage, and 4.3 hours in the bedroom, respectively. A few interesting points are noted in comparing the actual and virtual measures. First, the virtual watt-hours and wattage are more than twice as big as the actual ones for the living and dining room, and nearly twice for the bedrooms. This illustrates the substantial energy saving brought by the CFL if the households would like to pursue the same level of lighting in the presence and absence of CFL. Second, the average wattage per bulb in the bedroom is 20%–25% higher than those in the living and dining rooms. However, the difference vanishes in terms of lighting capacity per bulb measured by the virtual average wattage. On the other hand, people still seem to prefer a brighter bedroom since there are two bulbs on average in the bedroom while only 1.5 bulbs exist in other room types. The case may be explained if the bedrooms are generally bigger than living or dining rooms in Pakistan. Third, the two measures of the average daily use per bulb are almost the same in means across rooms.

IV. DETERMINANTS OF CFL ADOPTION

Our goal is to investigate the factors determining adoption and ownership of CFLs within the household as it conveys important information on how to increase the efficiency of lighting systems that may lead to reductions in demand for energy. We use a double hurdle model to examine a household's decision to adopt and own CFLs. This model assumes that the CFL adoption decision is a two-stage process where a household first decides to adopt a CFL (extensive margin) and then decides the number of CFLs that they want to own (intensive margin). The CFL adoption decision is modeled as a binomial process while the number of CFLs that are then owned by the household is modeled as a truncated Poisson process.

Let *i* represent the household and *j* the district. The dependent variable, Y_{ij}, captures the number of CFLs owned by the household, while, x_{ij}, captures household characteristics that influence the decision to purchase CFLs, such as gender, household size, proxies for income, property characteristics, and variables that capture price of bulbs and awareness of the life span of CFLs. This model is estimated via maximum likelihood, where the likelihood function is expressed as follows:[7]

$$\ln L = ln\left\{\prod_{Y_{ij}=0} \exp\left(-\exp\left(x_{ij}\beta_1\right)\right) \prod_{Y_{ij}>0} \left(1-\exp\left(-\exp\left(x_{ij}\beta_1\right)\right)\right) * \frac{\exp\left(yx_{ij}\beta_2\right)}{\left(\exp\left(\exp\left(x_{ij}\beta_2\right)\right)-1\right)y!)}\right\} \tag{7}$$

Estimates from the adoption and ownership decision are displayed in Table 6. Many of the factors that drive initial adoption are shown to also drive the number of CFLs that are owned. Household characteristics appear to have very little bearing on the initial adoption of CFLs, but do factor significantly into the number of bulbs contained within the household. The wealth of a household, captured by proxies for main income source, number of workers, household ownership, and sturdiness of the housing structure, is positively correlated with greater ownership of CFLs. Greater household size also leads to significantly more positive

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[7] http://www.stata-journal.com/sjpdf.html?articlenum=st0040

purchases of CFLs. The lower relative price of CFLs to IBs and closer proximity appear to increase initial CFL adoption, but has no effect on the number of bulbs owned.

Table 6: Double Hurdle Model Estimates of CFL Adoption and Ownership

Variables	Logit	Truncated Poisson
# Bulbs	0.0820***	0.0361***
	[0.0128]	[0.00152]
Price of CFL to IB	–0.0630***	0.00
	[0.0192]	[0.00576]
Distance Last Bulb Purchase: > 2km	0.338***	–0.02
	[0.0944]	[0.0276]
Not Aware of CFL	–1.263***	–0.595***
	[0.167]	[0.123]
Life CFL versus IB: Don't Know	–1.430***	–0.190***
	[0.121]	[0.0676]
Life CFL versus IB: 2 times	–0.201**	–0.106***
	[0.0855]	[0.0316]
Life CFL versus IB: 6 times	0.483***	0.03
	[0.147]	[0.0396]
Life CFL versus IB: 10 times	0.15	0.214***
	[0.135]	[0.0384]
Cite: Cost of CFL as Barrier	–2.115***	–0.301***
	[0.0900]	[0.0566]
Respondent: Female	–0.04	0.194***
	[0.116]	[0.0350]
Respondent: HH Head	–0.187**	0.0769***
	[0.0860]	[0.0278]
Main Income: Farming	0.10	–0.213***
	[0.109]	[0.0461]
Main Income: Government	–0.13	0.02
	[0.0953]	[0.0280]
HH # Workers	–0.03	0.0493***
	[0.0494]	[0.0141]
HH Size	0.00	0.00932**
	[0.0135]	[0.00385]
# Rooms in HH	–0.01	–0.01
	[0.0379]	[0.00994]
Property Own	–0.10	0.174***
	[0.132]	[0.0392]
Property Type: Flat	–0.13	0.259***
	[0.245]	[0.0607]
Property Type: Building Multi-story	–0.27	0.217***
	[0.169]	[0.0489]
Property Type: Other	–1.206*	0.46
	[0.731]	[0.309]
Construction: Adobe	–0.15	–0.535***
	[0.105]	[0.0514]
Construction: Informal	–0.208**	–0.275***
	[0.0929]	[0.0411]
Log Avg HH Income in City	–0.02	–0.06
	[0.173]	[0.0607]
Constant	1.61	1.086**
	[1.278]	[0.446]
Observations	3,243	3,243

CFL = compact fluorescent lamp, HH = household, IB = incandescent bulb.

Notes:
1. Standard errors in brackets; *** p<0.01, ** p<0.05, * p<0.1, DISCO dummies included but not shown.
2. Omitted dummies are Life CFL versus IB: 4 times; Main Income: Self-Employed/Business/Private Service/Other; Property: Rent/Other; Property Type: Single Building; Construction: Masonry.

Source: Authors' estimates.

As income and household characteristics are difficult to change, the inclusion of the awareness and perception characteristics are the most useful in informing policy. Awareness of CFLs and higher expectations on the life span of CFLs leads to both higher adoption and ownership of CFLs. However, as reported in Table 2, almost 89% of households in Pakistan report that they are aware of CFLs, so running standard campaigns promoting CFLs will probably have little effect on increasing adoption and ownership of CFLs in the aggregate. Cost does prove to be a significant barrier for many households as almost 40% of the population stated they would not purchase a CFL if the price was lower than an IB. Still, this may largely be driven by lack of awareness or misperceptions regarding the life of the CFL versus an IB. Almost 82% of the population assumes that the lifespan of a CFL bulb is at most four times that of an IB, with 24% of households claiming that they are unaware of the life of a CFL versus an IB. This results in significantly lower probabilities in adopting and owning multiple CFLs.

Given that the rated life span of CFLs in developed countries is estimated to be at least eight times that of an IB, the majority of the population appears to assume that the life span is considerably lower. This suggests that ensuring a minimum quality standard on CFL life span accompanied with information campaigns on the life span of a CFL bulb relative to an IB could be highly productive in influencing households in Pakistan to adopt and own more CFLs.

V. CFL ADOPTION AND ENERGY USAGE

The interest in increasing CFL adoption is primarily based on the assumption that CFL adoption will lower overall energy usage. To assess how household adoption of CFLs in each room affects energy usage for lighting, we use the empirical regression model as follows:

$$y_i = \beta_0 + \beta_1 CFL_i + X_i \mathrm{B} + D_i + \varepsilon_i \, , \tag{8}$$

where, i indices household, $y = awh, aw, ah, \overrightarrow{awh}, \overrightarrow{aw},$ or $\overrightarrow{ah}$, and CFL = 1 if there is one or more CFL in the room, and 0 otherwise, X is the vector of respondent and household characteristics such as main income sources, household size and number of workers, number of rooms, property type, etc., D is the dummy for Discos. The model is estimated for each room type.

While β_1 is the key parameter of interest, estimation of β_1 is subject to potential bias arising from the endogeneity of *CFL*. First of all, adoption of the more energy efficient bulbs and electricity consumption are both influenced by energy supply and price of electricity. The Disco dummy is used to control for potential supply side effects as well as electricity price variations across regions. Secondly, some unobserved household characteristics, such as lighting needs and concerns about the environmental footprint of energy use, may have impacts on both CFL adoption and electricity use. In addition to the basic respondent and household characteristics, we add variables with respect to the awareness of CFL, the understood life span of CFL relative to IB, self-reported major barrier for adopting CFL, and convenience to purchase CFL in an augmented model. These variables are assumed to proxy for the household's attitude toward and knowledge about the CFL, thus controlling for the unobservables. Robust standard errors are estimated with clusters by city to account for heterogeneity and intracity correlations among the model residuals.

Table 7 reports the estimated β_1 in the baseline models (odd columns) and models augmented with proxies for CFL attitude and knowledge (even columns) for different dependent variables and rooms. Columns 1–6 display estimates for the actual average watt-hours, wattage, and hours used daily per bulb; and the columns 7–12 display the corresponding variables adjusted with lighting capacity. The living, dining, and bedrooms are displayed in the top, middle, and bottom panels, respectively. Due to space limitations, the estimated coefficients for other control and dummy variables are omitted in the table.

First of all, the baseline models and augmented models yield highly consistent estimates. The sign and significance of the estimates are the same and the magnitudes are sufficiently close between the two models for most variable-room cells. This implies that a household's knowledge and attitude regarding CFLs do not generate significant co-movements of CFL adoption and lighting consumption of electricity. The endogeneity of CFL adoption due to unobserved household preference with respect to lighting and environment, though existing in theory, is unlikely to be the driving force of our results. On the other hand, we note that the impact of the attitude and knowledge proxies is bigger for some lighting-adjusted variables, e.g., watt-hours in the living and dining rooms, than the corresponding actual measures. Given the greater explanatory power of the augmented models, we focus our following discussions on the estimates of the augmented models.

On average, the CFL-adopting rooms consume about 200 watt-hours less per bulb per day than the zero-CFL rooms across room types. The reduction is largely attributable to the reduction in average bulb size, as shown in columns 3 and 4. The coefficient estimates are all statistically significant at 1% level. As far as the length of use is concerned, the bulbs are used 0.73 hour (44 minutes) more every day in the living rooms with CFLs as opposed to without CFLs. Nevertheless, this estimate for the dining rooms or bedrooms is smaller and statistically insignificant. The results suggest a strong rebound effect in the living rooms in terms of increased usage of lighting resulting from efficiency improvement, but not in the dining and bedrooms.

Table 7: Effects of CFL Adoption on Energy Usage Estimates

Dependent Variables	Avg Watt-Hr per Bulb	Avg Watt-Hr per Bulb	Avg Wattage per Bulb	Avg Wattage per Bulb	Avg Hrs Used per Watt	Avg Hrs Used per Watt	Avg Watt-Hr per Bulb (lumen adj)	Avg Watt-Hr per Bulb (lumen adj)	Avg Wattage per Bulb (lumen adj)	Avg Wattage per Bulb (lumen adj)	Avg Hrs Used per Watt (lumen adj)	Avg Hrs Used per Watt (lumen adj)
CFL in Living Room	−216.4***	−206.8***	−51.65***	−51.19***	0.651***	0.727***	127.2***	141.6***	14.21***	14.54***	0.679***	0.762***
	[24.51]	[22.74]	[3.094]	[3.233]	[0.215]	[0.239]	[33.59]	[33.75]	[4.494]	[4.235]	[0.213]	[0.235]
Observations	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025
R-squared	0.48	0.50	0.69	0.69	0.16	0.19	0.32	0.34	0.30	0.33	0.17	0.19
CFL in Dining Room	−212.2***	−192.7***	−48.27***	−44.20***	0.11	0.07	94.08***	122.3***	23.53***	28.96***	0.15	0.12
	[27.34]	[26.73]	[4.083]	[4.472]	[0.166]	[0.197]	[28]	[34.51]	[7.723]	[8.007]	[0.165]	[0.193]
Observations	685	685	685	685	685	685	685	685	685	685	685	685
R-squared	0.54	0.55	0.69	0.70	0.32	0.33	0.38	0.40	0.31	0.35	0.32	0.32
CFL in Bedroom	−212.1***	−218.1***	−50.04***	−50.35***	0.437**	0.37	81.74**	79.75*	14.81**	15.69**	0.479**	0.410*
	[32.78]	[37.78]	[3.394]	[4.154]	[0.198]	[0.233]	[35.23]	[41.97]	[5.735]	[7.284]	[0.195]	[0.23]
Observations	2460	2460	2460	2460	2460	2460	2460	2460	2460	2460	2460	2460
R-squared	0.33	0.34	0.64	0.65	0.17	0.19	0.16	0.17	0.22	0.24	0.17	0.19
HH Char.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Disco Dummy	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Knowledge and Attitude	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y

CFL = compact fluorescent lamp, HH = household, N = No, Y = Yes.

Note: Standard errors in brackets; *** p<0.01, ** p<0.05, * p<0.1, DISCO dummies included but not shown.

Source: Authors' estimates.

When the dependent variables are adjusted with their lighting capacity, we obtain some interesting, contrasting estimates. Adopting CFLs clearly causes increases in watt-hours per bulb per day and average wattage of each bulb, after the lumen outputs in the CFL-adopting rooms and zero-CFL rooms are equalized. The effects are statistically significant at the 1% level except for the bedroom models, which display 10% and 5% significance with respect to lumen-adjusted watt-hours and wattage, respectively. These results again point to existence of strong rebound effects across different rooms, and the enhanced lighting capacity per bulb may be another channel, in addition to prolonged use, that gives rise to the rebound effect. Using the sample statistics and regression estimates, we conduct an exercise to estimate the size of the rebound effect in household lighting in the next section.

VI. REBOUND EFFECT IN ELECTRICAL LIGHTING USAGE FROM CFL ADOPTION

A. Theoretical Concept

When technical efficiency of some energy service improves, consumers may increase the demand for this service since the unit cost of obtaining the service is essentially lowered. As a result, the actual energy savings from the technical progress is less than proportional to the efficiency improvement. This offsetting effect is referred to as the rebound effect. Considered more broadly, efficiency improvement in one type of energy service may lead to increase in effective income of consumers and thus higher demand for other types of energy services. It will also reduce the prices of intermediate and final goods that use this type of energy service as inputs in production, and thus increase consumption of these goods. The latter two effects are termed indirect and economywide rebound effects, respectively, as opposed to the direct rebound effect in the former case (Sorrell and Dimitropoulos 2008). The existence of rebound effects suggests that estimating economic benefits of energy efficiency improvement must go beyond simple engineering calculation.

While the three kinds of rebound effects differ in mechanisms and share common or uncommon policy implications, more studies are focused on the direct rebound effect. Following Sorrell and Dimitropoulos (2008), the energy efficiency (ε) of an energy service is defined as

$$\varepsilon = \frac{S}{E}, \tag{9}$$

where *S,* is the amount of energy service produced per unit of device such as lumen-hours per bulb in the case of lighting, and *E* is the amount of energy input used to produce *S*, e.g., electricity in watt-hours.

Since $\frac{\partial \varepsilon}{\varepsilon} = \frac{1}{\varepsilon}\left(\frac{\partial S}{E} - \frac{S\partial E}{E}\right) = \frac{\partial S}{S} - \frac{\partial E}{E}$, the efficiency elasticity of demand for energy is

$$\eta_\varepsilon(E) \equiv \frac{\partial E}{E}\frac{\varepsilon}{\partial \varepsilon} = \frac{\partial S}{S}\frac{\varepsilon}{\partial \varepsilon} - 1, \tag{10}$$

which indicates that if the demand for energy service goes up due to energy efficiency improvement, i.e., $0 < \frac{\partial S}{S}\frac{\varepsilon}{\partial \varepsilon} < 1$, the efficiency elasticity of demand for energy is actually smaller than 1 in absolute value. In other words, higher energy efficiency would not lead to proportional reduction in energy consumption. The rebound effect can be calculated as

$$1 + \eta_\varepsilon(E) \equiv \frac{\partial S}{S}\frac{\varepsilon}{\partial \varepsilon}. \tag{11}$$

Further, we assume that the amount of energy service is the product of the size or capacity of the device (*C*) and the utilization (*U*), i.e., $S = C \cdot U$. The lighting capacity may be measured in lumens, and utilization in hours. Thus,

$$\frac{\partial S}{S}\frac{\varepsilon}{\partial \varepsilon} = \frac{\partial C}{C}\frac{\varepsilon}{\partial \varepsilon} + \frac{\partial U}{U}\frac{\varepsilon}{\partial \varepsilon}, \tag{12}$$

which shows that the direct rebound effect can be decomposed into two effects: the enlarged capacity of the energy device and prolonged use of the device in response to energy efficiency improvement.

The direct rebound effects on cars, heating system, etc. have been identified and measured in the literature (Sorrell, Dimitropoulos, and Sommerville 2009). These studies have found rebound effects for energy services over a large range of values even for a particular use. For example, the personal transport literature has found rebound effects ranging from a low of 3% to 87%, while space heating has found rebound effects of between 0.6% to 60%. This indicates that one can find very different rebound effects depending on the context as well as estimation method used.

B. Empirical Estimates of the Rebound Effect

The coefficients from variations in the regression equations in Section V can be used to compute the rebound effect from CFL adoption that occurs due to the lower unit cost of energy services under having adopted CFLs compared to no CFLs. We first distinguish the coefficient, β_1, with superscript corresponding to the equation defining the dependent variable. That is, $\beta_1^{(1)}$ represents the estimated β_1 (of the augmented model) for *awh*, $\beta_1^{(2)}$ for *aw*, and so on. Therefore,

$$\frac{\partial S}{\partial CFL} = \frac{\partial \overrightarrow{awh}}{\partial CFL} = \beta_1^{(4)}, \tag{13}$$

$$\frac{\partial E}{\partial CFL} = \frac{\partial awh}{\partial CFL} = \beta_1^{(1)}, \tag{14}$$

$$\frac{\partial C}{\partial CFL} = \frac{\partial \overrightarrow{aw}}{\partial CFL} = \beta_1^{(5)}, \tag{15}$$

and

$$\frac{\partial U}{\partial CFL} = \frac{\partial ah}{\partial CFL} = \beta_1^{(3)}. \tag{16}$$

The average efficiency improvement from zero-CFL room to CFL room is

$$\frac{\partial \varepsilon}{\varepsilon \partial CFL} = \frac{\partial S}{S \partial CFL} - \frac{\partial E}{E \partial CFL} = \frac{\beta_1^{(4)}}{S} - \frac{\beta_1^{(1)}}{E}. \tag{17}$$

The efficiency elasticity of energy demand can be obtained as follows,

$$\eta_\varepsilon(E) = \frac{\varepsilon \partial E}{E \partial \varepsilon} = \frac{\partial E}{E \partial CFL} / \frac{\partial \varepsilon}{\varepsilon \partial CFL} = \frac{\beta_1^{(1)}}{E} / \left(\frac{\beta_1^{(4)}}{S} - \frac{\beta_1^{(1)}}{E} \right). \tag{18}$$

A capacity effect and a utilization effect, into which the rebound effect is decomposed, are respectively

$$\frac{\partial C}{C} \frac{\varepsilon}{\partial \varepsilon} = \frac{\partial C}{C \partial CFL} / \frac{\partial \varepsilon}{\varepsilon \partial CFL} = \frac{\beta_1^{(5)}}{C} / \left(\frac{\beta_1^{(4)}}{S} - \frac{\beta_1^{(1)}}{E} \right), \tag{19}$$

$$\frac{\partial U}{U} \frac{\varepsilon}{\partial \varepsilon} = \frac{\partial U}{U \partial CFL} / \frac{\partial \varepsilon}{\varepsilon \partial CFL} = \frac{\beta_1^{(3)}}{U} / \left(\frac{\beta_1^{(4)}}{S} - \frac{\beta_1^{(1)}}{E} \right). \tag{20}$$

Table 8 exhibits calculation of the rebound effects for each type of room. The lumen-adjusted watt-hours, watt-hours, lumen-adjusted wattage, and daily use per bulb are averaged across zero-CFL rooms for *S,E,C,* and *U* (numerically equal between *S* and *E* for zero-CFL rooms). Given our central estimates, the energy efficiency for lighting improves by 96%, 102%, and 83% on average for the living, dining, and bedrooms, respectively, for the CFL-adoption rooms as opposed to zero-CFL rooms. The efficiency elasticity of energy demand, however, is estimated at 59%, 61%, and 73%, respectively, which imply a considerable rebound effect in household lighting regardless of the room type. For every possibility of saving 10% of energy due to advanced lighting technology, only 6%–7% of energy would actually be saved as households tend to choose brightening rooms and/or longer lighting time. This offsetting effect is estimated at about 27%–40% depending on room type.

Table 8: Energy Efficiency Improvement and Rebound Effects

	Living Room	Dining Room	Bedroom
S and E (average of zero-CFL rooms)	362.7	310.3	358.8
C	80.2	74.46	82.56
U	4.36	3.87	4.04
$\beta 1^{(1)}$	–206.8	–192.7	–218.1
$\beta 1^{(3)}$	0.73	0.07	0.37
$\beta 1^{(4)}$	141.6	122.3	79.75
$\beta 1^{(5)}$	14.54	28.96	15.69
$\partial\varepsilon/\varepsilon\partial CFL$	0.96	1.02	0.83
$\eta\varepsilon(E)$	–0.59	–0.61	–0.73
Rebound Effect	0.41	0.39	0.27
Capacity Effect	0.19	0.38	0.23
Utilization Effect	0.17	0.02	0.11

Source: Authors' estimates.

Decomposing the rebound effect shows interesting variations across room types in the household behavioral response to efficient lighting. In other words, the rebound effect in household lighting takes place through both capacity and use channels. The relative importance of each channel, however, differs with room type. For the living room, where the largest rebound effect is identified, capacity effect and utilization effect account about equally for the rebound. A 10% efficiency increase could result in 2% increase in lighting capacity of bulbs and another 2% or so increase in time of use of the living room. The results imply that availability of more efficient lighting induces people to stay longer in a brighter living room, where a variety of family activities are carried out. The dining room has a rebound effect of comparable size with that of the living room. However, it is dominated by the capacity effect, which suggests that households prefer to eat in a brighter environment but are unlikely to prolong the meal time when CFLs are adopted. Bedrooms have relatively smaller rebound effect and, similar to the dining room, tend to have more lighting than longer stay time in the presence of CFLs.[8] This stark difference between living rooms, and dining and bedrooms, may be explained by the fact that living rooms can serve multiple functions while dining and bedrooms' functions are relatively unique.

Our estimation is subject to bias due to endogeneity of the *CFL* variable not fully addressed by the model. It is possible that households adopting the CFL bulbs consume more electricity or demand more lighting than those not adopting. $\beta_1^{(1)}$ would be underestimated in the former case and $\beta_1^{(4)}$ would be overestimated in the latter, both of which result in an

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[8] Note that the estimate of $\beta_1^{(3)}$ for the bedroom is insignificant despite the utilization effect calculated based on the point estimate is as high as 11%.

underestimation of the efficiency elasticity of energy demand and an overestimation of the rebound effect. In contrast, if households care more about energy savings are more likely to adopt the CFLs, $\beta_1^{(1)}$ would be overestimated leading to overestimation of the efficiency elasticity and hence underestimation of the rebound effect.

VII. CONCLUSION

The ability to increase the adoption and ownership of CFLs within households can play an important role in closing the shortfall in electricity supply relative to demand in developing countries. The high cost of CFLs and lack of awareness or misperceptions on the life span of CFLs versus IBs are major factors preventing greater adoption and ownership of CFLs as a utility maximizing choice of the household. This suggests that households may be uninformed about the true savings that can arise from switching to CFLs from IBs. Ensuring minimum quality standards and carrying out informative campaigns on the life span of CFLs relative to IBs can have significant effects in influencing a much greater number of households in Pakistan to adopt and own more CFLs.

While greater adoption and ownership of CFLs can help reduce electricity shortfalls, the extent of the benefits achieved through increased adoption, ownership, or replacement of CFLs depends on how overall efficiency of the lighting system affects household demand for energy. Households in Pakistan may not only be constrained by the price of electricity, but also by the supply of electricity. Our finding that CFL adoption results in a sizable rebound effect on the order of 27%–41% for households in Pakistan, significantly diminishes how much can be achieved in closing the gap between demand and supply of electricity through CFL adoption and ownership. Additional research is needed to understand whether informational campaigns and social pressure can also be used to reduce energy consumption as suggested by previous research (Reiss and White 2008, Allcott and Mullainathan 2010, Costa and Kahn 2010). Nevertheless, even with substantial rebound effects, in countries where households are relatively poor, the ability to improve the household environment and lengthen the hours of productive activities may have significant and positive impacts on increasing household welfare.

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Adoption of CFLs and Electrical Lighting Usage in Pakistan

A household level survey of electrical lighting and usage in Pakistan is used to examine the decision to adopt compact fluorescent lamps (CFLs) and the subsequent impact of CFL adoption on electricity usage. Adoption and ownership of CFLs are significantly influenced by variables that proxy for income and the perceived expectations about the life span of CFLs. However, the savings in electricity usage from CFL adoption is less than expected, with a significant amount of potential energy savings being offset through both enlarged bulb capacity and prolonged lighting time.

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