Adoption of Energy Efficiency Technologies: A Review of Behavioral Theories for the Case of LED Lighting

Kelly Cowan and Tugrul Daim

Abstract What factors are most significant in understanding adoption behavior for energy efficiency technologies by commercial, residential, and industrial customers? The case of energy efficient lighting technologies is specifically examined. Several types of lighting technologies are compared to indoor LED lighting to determine how the technology meets the needs of the various user types. What factors are most significant in motivating technology adoption for such technologies, and preventing subsequent technology disadoption? This is particularly important for energy efficient lighting technologies, as both technology adoption and technology disadoption can be extremely rapid, and ongoing user involvement is often required to recognize full benefits from these technologies. The Unified Theory of Acceptance and Use of Technology (UTAUT) is useful in explaining adoption behavior related to stakeholder expectation and buy-in for the new technologies. UTAUT contains four elements that can be adapted to fit this research: (1) Performance Expectancy; (2) Effort Expectancy; (3) Social Influences; and (4) Facilitating Conditions. In the case of energy efficient lighting adoption, and LED adoption in particular, performance expectancy and effort expectancy can be related to factors such as future energy price expectancies, actual savings results, and ease of energy savings. Factors involving social influences include perceptions of environmental friendliness among different user groups, and facilitating conditions include policies, incentives, and educational programs to encourage adoption. Some conclusions are then drawn regarding adoption factors for emerging energy efficient lighting technologies.

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1 Introduction

1.1 Problem Statements

What factors are most significant in motivating technology adoption for energy efficiency technologies, and preventing subsequent technology disadoption? The later issue is particularly important for energy efficiency technologies, as both technology adoption and technology disadoption can be particularly rapid for these technologies, and ongoing user involvement is often required to recognize full benefits from adoption. Thus, it is important to study this form of technology adoption from a behavioral perspective to enhance current understanding of which factors are most important in motivating ongoing adoption. It is also important to be able to understand how these adoption factors affect specific user types. Commercial, residential, and industrial consumers are the main user types for energy efficiency technology. Of these user types, commercial users have the highest percentage of electricity use for lighting purposes. Commercial users will be the primary focus of this study, in order to obtain a detailed understanding of the factors affecting this largest segment of energy efficient lighting technology users.

To make this research manageable, it will focus on a special case of energy efficiency technology adoption regarding energy-saving solid-state lighting, which is produced by light emitting diodes, otherwise known as LEDs. The research will examine indoor solid state lighting to determine how well the technology fits the needs of the main user types. Conclusions can then be drawn regarding implications of this research for other examples of energy efficiency technology adoption.

1.2 Research Problem Description

The following section describes the current state of knowledge regarding this problem that has emerged from the academic literature. The Unified Theory of Acceptance and Use of Technology (UTAUT) is a key technology adoption theory that can be used for explaining adoption behavior related to stakeholder expectation and buy-in for the new technologies. UTAUT contains four elements that can be adapted to fit this research: (1) Performance Expectancy; (2) Effort Expectancy; (3) Social Influences; and (4) Facilitating Conditions. In the case of adoption of energy efficiency technologies, performance expectancy and effort expectancy can be related to factors such as future energy price expectancies, actual savings results, and ease of energy savings. Factors involving social influences include various perceptions of environmental friendliness among different user groups, and facilitating conditions include policies, incentives, and educational programs to encourage adoption.

1.2.1 Research Questions

Which adoption factors are most commonly cited in the literature on energy efficient lighting technologies?

Are there differences in the most commonly cited adoption factors for commercial, residential, and industrial users?

1.2.2 Significance of the Research

This research can provide insights regarding which factors are most likely to promote adoption of energy efficient lighting technologies, such as solid-state lighting. This can inform product design, as well as promotion, and business models that encourage adoption. It also has application to the development of policies to promote energy efficient lighting technology adoption.

2 Literature Review

2.1 History of Solid State Lighting Technologies

In 2008, lighting consumed approximately 17 % of total electricity usage in the United States [1]. Table 1 summarizes electricity use for the three key categories of lighting users.

While the residential sector is the largest in terms of total electricity used, only about 16 % of it goes toward lighting. The commercial sector consumes a much higher percentage, with approximately one quarter going to meet its lighting needs. Thus, electricity for lighting by commercial users is about 51 % higher than that of residential users. The industrial sector consumes about 3–5 times less electricity for lighting than commercial and residential users respectively, even though its total use of electricity is similar to the other sectors. In the future, transportation may constitute a fourth sector of electricity use, especially as the trend toward vehicle electrification continues. However, it currently consumes

Table 1 Percentage of US electrical use for lighting by sector

	Electrical use by sector (GWh/year)	Percentage of electrical use by sector for lighting (%)	Total electrical use for lighting (GWh/year)	Percentage of total US electrical use for lighting (%)
Residential	1,390,650	16	222,504	6
Commercial	1,343,200	25	335,800	9
Industrial	1,003,750	7	70,263	2
Total usage	3,737,600		628,567	17

Sources Calculated from Energy Information Administration (EIA) 2008 [1], and Shively 2008 [2] only 0.1 % of total US electrical load, so it was not included in this research at the present time.

Given the amounts of electricity used for lighting in the commercial, residential, and industrial sectors, new energy saving lighting technologies have the potential to produce significant reductions in overall electricity usage. A number of emerging technologies appear promising for improving the efficiency of lighting technologies. Additional benefits to new lighting technologies include significantly longer service lifetimes, which reduce the need to replace bulbs, reduce the amount of electronics waste generated, and lower total cost of ownership (TCO).

One of the most rapidly developing new technologies for energy efficiency lighting technology is the light emitting diode, or LED. Currently, most LEDs produce under 100 Lm/W [3]. However, prototypes exist which produce over 200 Lm/W, and there are expectations of up to 280 Lm/W by 2015 [4]. Incandescent lights, the long-time dominant technology, typically produce only about 20 Lm/W [4]. Fluorescent lights are another well developed competing technology, especially in the commercial sector. They currently are less expensive than LEDs and produce up to 125 Lm/W [5]. However, fluorescent lights appear to be nearing the limits of their technical capabilities, and are not expected to improve significantly in coming years, as shown by Fig. 1. Furthermore, the service lifetimes for LEDs range from about 25,000 to 100,000 h [6]. This compares to only about 1,000–2,000 h for incandescents and 8,000–10,000 h for fluorescents [4].

LED lighting technologies offer a number of additional advantages, as well as certain disadvantages. Table 2 provides some additional details regarding the pros and cons of LEDs.

A number of questions remain regarding how rapidly LEDs and other energy efficient lighting technologies will be adopted. Much of this depends on the rate at which these technologies improve and costs are reduced. However, a great deal of the decision regarding the rate at which users adopt these technologies also depends upon specific factors regarding the type of end-user adopting the technology, the factors each user type considers important, and the level of importance and/or expectation that users associate with these factors. Several recent studies have examined these factors in relation to adoption of energy efficiency technologies in general, and to lighting technologies in particular.

Andrews and Krogmann used logistic regression modeling to analyze the adoption of energy efficiency technologies for commercial buildings in 2008 and found that locational factors, building use factors, and building-specific characteristics explained most of the adoption patterns for the leading energy efficiency technologies [9]. However, they concluded that their model only weakly explained the adoption of lighting technologies. Installation costs, energy prices, evolving standards, and other performance-related factors regarding new lighting technologies, which are just beginning to challenge the dominance of existing lighting technologies in the commercial sector, appear to have been major reasons why many users were reluctant to adopt these technologies. Unless decision makers were willing to incur large up front costs, typically in newer, owner-occupied buildings, it was found that they were unlikely to adopt advanced new lighting

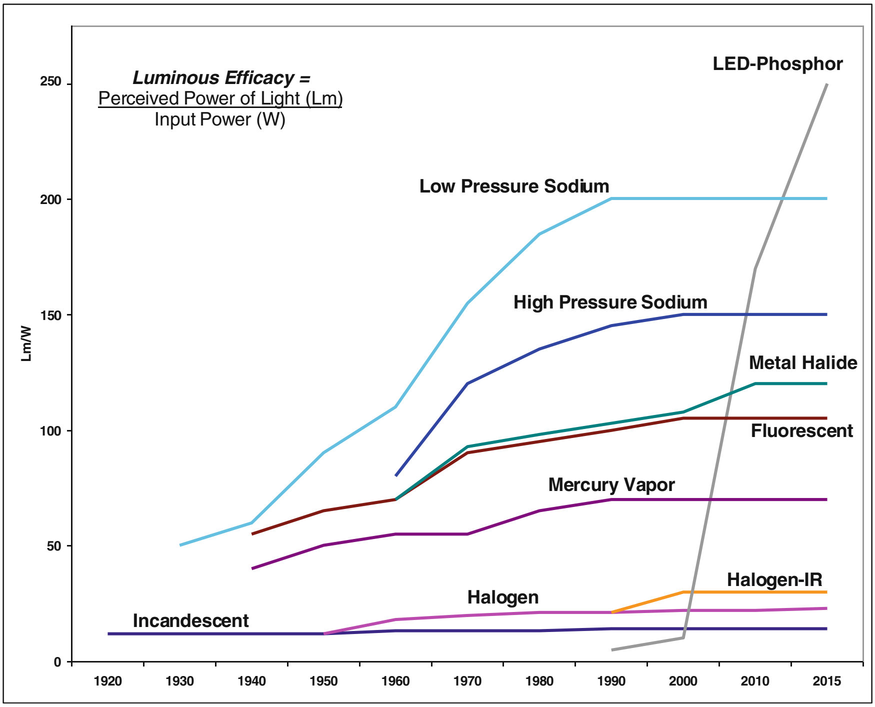

Fig. 1 Trend in efficacy of illumination technologies (Adapted from UCSB [4])

systems, largely due to the fact that it was unclear they would receive enough payback from savings on energy prices.

Anderson and Newell also examined the adoption of energy efficiency technologies in industrial manufacturing environments using similar logit modeling techniques and found adoption rates to be highest for projects with shorter payback times, lower costs, greater annual savings, higher energy prices, and greater energy conservation [10]. Manufacturing plants were 40 % more responsive to upfront costs versus annual energy savings. Therefore, subsidies were seen as a more effective policy instrument to promote adoption, rather than energy price increases. Fairly high hurdle rates of 50–100 % were found for investments in such projects.

Regarding energy efficiency adoption for residential users, Caird et al. also found considerable obstacles to the adoption of such technologies in UK households [11]. Even among environmentally conscious consumers, only about one-fifth of those who had seriously considered energy efficiency adoption actually reported having done so. Most who had adopted energy efficiency lighting technology had chosen compact fluorescent lights, and all but 7 % of the sample said that high prices and lack of information about LEDs had prevented them from adopting this technology. Some evidence also suggested that for environmentally conscious consumers, the adoption of high profile renewable energy technologies, such as solar panels, may confer a higher status than the adoption of more mundane and generally invisible

Table 2 Advantages and disadvantages of LED lighting technologies

Advantages	Disadvantages
Efficiency. LEDs can produce more light per watt than incandescents and many fluorescent bulbs. Their theoretical maximum efficiency is higher than any other current lighting technologies. Shape and size does not affect efficiency, unlike fluorescent bulbs. LEDs also radiate very little heat compared to incandescents and fluorescents	*Efficiency*. Although LEDs theoretical maximum efficiencies are very high, currently fluorescent bulbs are more efficient at producing light in the commonly desired daylight spectrum ranges
Lifetime. LEDs useful operating lives are estimated between about 25,000–50,000 h today to 100,000 h or more in the future. of useful life, though time to complete failure may be longer. Incandescent light bulbs last only about 1,000–2,000 h, while most fluorescents last about 8,000–10,000 h. LEDs also tend to slowly grow dimmer over time, rather than abruptly failing, like most other lighting technologies	*High Purchase Price*. The initial price of LED lighting is still considerably more expensive than other lighting technologies, however costs are projected to fall rapidly. The high energy efficiency of LEDs currently does not offset the higher purchase costs
Color. LEDs can produce colored light without the use of filters. Most current LEDs tend to produce cooler colors, however, than traditional light sources, leading some people not to choose LEDs for general illumination	*Light Quality*. The color spectra produced by LEDs can differ significantly from sunlight or incandescent light. The color of the light tends to be cooler and more blue. Although advances are being rapidly made to develop LEDs which produce natural light colors, it is unclear when such changes may occur
Cycling. LEDs can be turned on and off very quickly, and frequently cycling them does not cause premature failure, the way it does with fluorescents	
Low Toxicity. LEDs do not contain toxins like mercury that are found in fluorescent bulbs. This makes recycling easier	

Sources EERE [6], DoE [3], Azevedo [7], Mehta [8]

technologies associated with energy efficiency. Other surveys in the UK [12], and in the US [13] have also pointed to concern among potential adopters of residential energy efficiency technologies to avoid uncertainty before making major investment related to energy savings. One encouraging trend that emerged, however, from these studies was that many homeowners seemed committed to reducing energy use, and simple actions and/or behavioral changes to save energy. Nair et al. also found that among customers who perceived high energy prices to be a major problem, there was a much higher likelihood they would invest in energy efficiency technologies [14].

This research seeks to identify what is currently know about the most common factors influencing the adoption patterns of energy efficiency technologies in general and energy efficient lighting technologies in particular for commercial, residential, and industrial users. However, first, it is important to clarify several background points regarding the subjects of energy efficiency and energy conservation, as well as relevant theories regarding the adoption of technology. Behavioral theories of technology acceptance and use will be specifically considered, since energy efficiency technologies often require extensive understanding of user perceptions, both before and after adoption. Caird points out that there has been a lack of research on how energy efficiency technologies are actually used by consumers [11]. Without a full understanding of these processes and motivations, there is a risk that users who have adopted energy efficiency technologies may later choose to reject, or disadopt them. This research will examine such behavioral factors in order to get a better understanding of what influences the acceptance and use of such technologies.

2.2 Energy Efficiency and Energy Conservation Technologies

Energy efficiency involves decreasing the amount of energy input required to achieve a unit of desired output, such as light, heat, or other useful functions [2]. The goal of energy efficiency programs and technologies is to enable the effective use of energy to create products, perform work, and achieve all the necessary goals for which energy use is required, while minimizing the amount of energy that is wasted in the process. Another way of expressing this is to say that energy efficiency reduces the energy intensity of processes. Energy conservation is a closely related concept, but it seeks to reduce the total amount of energy consumed, rather than trying to increase the effectiveness with which it is used [15]. Energy efficiency and energy conservation are often used in concert with one another and can be important components of strategies to insure adequate energy supplies are available to meet the needs of growing populations. In practice, the terms energy efficiency and energy conservation are often used interchangeably, since there are often significant overlaps in these functions. For the purposes of this paper, energy efficiency will be the preferred term. Energy efficiency is also considered a form of alternative energy, since it is an alternative to building and using conventional energy sources, such as fossil fuel-based power generation.

Policies and programs to promote the adoption of energy efficiency technologies and practices have a long history. Many countries around the world established energy efficiency and energy conservation programs starting after the 1970's oil crisis. According to a report by the International Energy Agency (IEA), without the energy savings that have been achieved since 1973, the total amount of energy required in 1998 would have been at least 50 % higher [16, 17]. The agency further predicts that future growth rate of world energy consumption can be cut another 50 % by 2030, using new and existing energy efficiency and energy conservation technologies. Figure 1 summarizes the expected improvement of the various types of energy efficiency lighting technology by 2015 [18].

Energy efficient lighting technologies appear to offer significant potential for improvement in the near future. Figure 1 shows that LEDs offer the greatest potential for improving the amount of light output produced per unit of energy used. Thus, the adoption of LEDs offers an opportunity for major saving in the energy needed for lighting, and could play an important part in future efforts to shrink the growth of energy use. However, in order to better understand this opportunity, it is important to examine how the process of technology adoption works.

2.3 Theories of Technology Adoption

In order for a new technology to be utilized, an innovation-decision process must occur whereby the individual or decision-making unit moves from the point of first knowledge of a technology to a decision to accept and implement the innovation. Rogers defines technology adoption as the stage in the innovation-decision process where the choice is made to "make full use of the innovation as the best course of action available [19, 20]." Rogers further defines five stages in the adoption process: (1) Knowledge; (2) Persuasion; (3) Decision; (4) Implementation; and (4) Confirmation [21]. An individual may choose **not** to adopt an innovation at any stage in this process, including disadopting an innovation after initially accepting it.

The issue of disadoption is particularly important for energy efficiency technologies. Many energy efficiency technologies are high involvement products that require considerable ongoing commitment by users after the initial adoption decision, in order to continue receiving the benefits the technologies confer. While this may not be true of simple, low cost interventions like weather proofing a house, more advanced energy efficiency products often involve larger investments, longer time to learn how to use them, customized them, and/or decide if the user is willing to continue accepting the performance factors of the new technology in return for the tradeoff of energy savings. An advantage of energy efficiency technologies is that many of them can be adopted very rapidly. This can occur, for example, as quickly as it takes to put in a new light bulb. At the point where a decision has been made to retain energy efficiency technologies, the energy saving benefits continue to occur constantly and permanently, unless a disadoption occurs.

Technology adoption is a process which can occur through a variety of mechanisms. The Technology Adoption Lifecycle [22], originally developed as a sociological model, examines how information about novel products, or ideas, can spread throughout a network of potential adopters. The model was later generalized in Roger's widely read textbook, *Diffusion of Innovations* [19]. The Bass Model of Diffusion [23] is another common method for studying the introduction of new products by forecasting adoption based on coefficients of innovation and imitation.

The Theory of Reasoned Action (TRA) [24] examines adoption from a behaviorist perspective, proposing that "the individual's positive or negative feelings about performing a behavior" create a behavioral intention, which is comprised of attitudes and subjective norms regarding the behavior for the individual's social group. A diagram of this model is provided in Fig. 2.

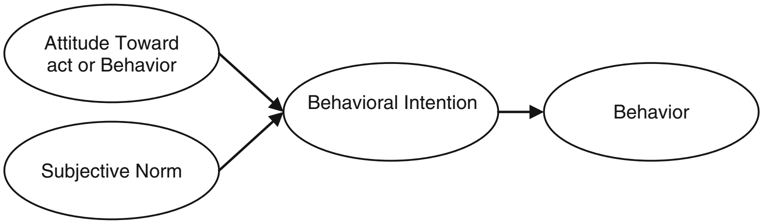

Fig. 2 Theory of reasoned action (Adapted from [24])

The Theory of Planned Behavior (TPB) [25] addresses a number of limitations of TRA, such as overlap between attitudes and norms, and adds the dimension of perceived behavioral control, which contributes to actual behavior. Decomposed TPB (DTPB) [26], further breaks down the precursors which lead to the variables of attitude, subjective norms, and perceived behavior control. The Technology Acceptance Model (TAM) [27, 28] also deals with limitations of TRA by identifying perceived ease of use and perceived usefulness of technology as factors which contribute to the formation of an attitude, and ultimately a behavior. The model was extended as TAM2 [29, 30]. A diagram of this model is provided in Fig. 3.

TAM was refined into a new theory called the Unified Theory of Acceptance and Use of Technology (UTAUT) [31, 32], which includes the elements of performance expectancy, effort expectancy, social influence, and facilitating conditions. A diagram of this theory is provided in Fig. 4.

UTAUT has largely been applied to projects involving the implementation of Information and Communication Technologies (ICT). User participation in new ICT systems after implementation is critical, just as it is with energy efficiency technologies, in order to realize the full benefit of the system. Attitudes within a social network are also important in determining continued use of a system. As previously noted by Nair et al., social effects, including status and prestige, can also be relevant to the adoption of energy efficiency technology [14]. Perceptions regarding needs, such as views on the need for a new ICT system, or views regarding the high cost of energy, can drive buy-in by potential adopters on the choice of a solution to meet those needs. Likewise, expectations on the

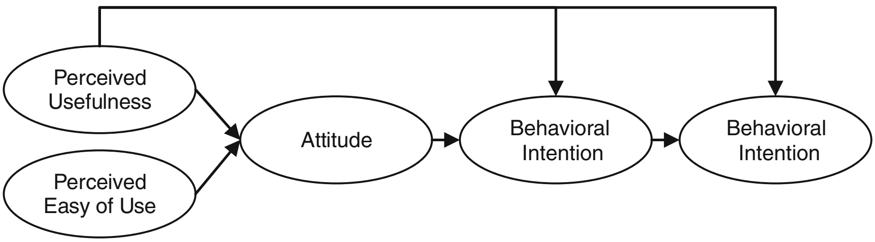

Fig. 3 Technology acceptance model (Adapted from [27, 28])

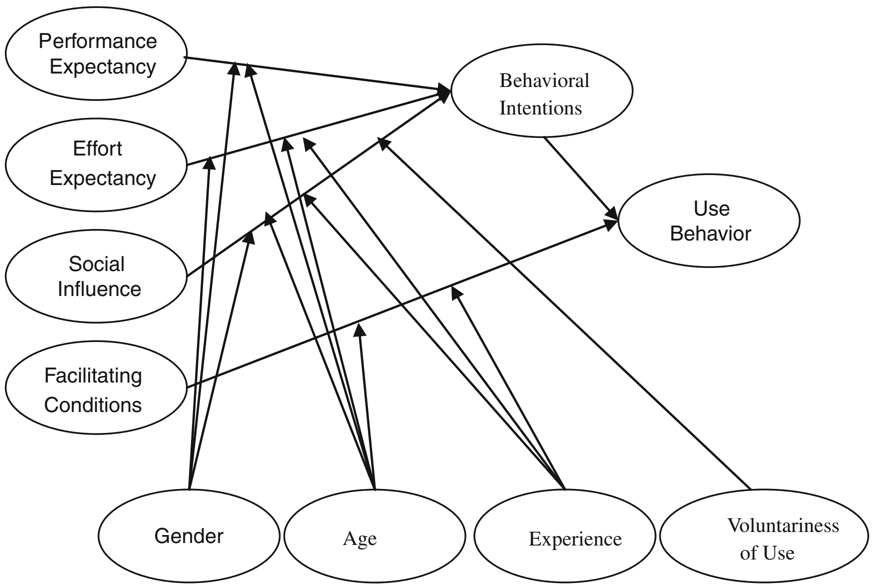

Fig. 4 Unified theory of acceptance and use of technology (Adapted from [31, 32])

performance and quality of a solution can influence adoption for both ICT and energy efficiency. Thus, UTAUT appears to have strong applicability for energy efficiency technologies.

3 Model Development

To better understand the application of behavioral adoption theories, such as UTAUT, to energy efficient lighting technologies, and to determine which factors are most commonly cited as significant in influencing adoption for each user type, a literature review was performed. To identify these factors, a search of academic articles was conducted in the Compendex database for terms related to "technology adoption" and "energy efficiency." The search was further narrowed to articles involving lighting technologies. This initial search resulted in 79 articles relating to these topics. After careful review, however, 49 articles were selected that were deemed to be specific and relevant enough to the exact topic of this research to be included in this analysis. Adoption factors identified from the literature on energy efficient lighting technology are summarized in Table 3. They have also been categorized according to the four elements of UTAUT.

References in the literature are given next to each of the adoption factors in the table. The research questions below then focus in on the following aspects of energy efficient lighting technologies:

Table 3 Factors driving technology acceptance and use of EE lighting by behavioral category

Behavioral category		Technology acceptance and use factors
Performance expectancy	Relative advantage and outcome expectations	Installation cost [7, 33–38]
		Energy cost savings [7, 33, 35, 37–45]
		Payback time [35, 46]
		Maintenance cost [39, 47, 48]
		Total cost of ownership [7, 9, 33, 38, 39, 41, 42, 45, 47–52]
	Perceived usefulness and fitness for purpose	Brightness [37, 45, 53]
		Light color [7, 41, 54, 55]
		Start-up speed [38, 42, 45]
		Flicker [41, 55]
Effort expectancy	Ease of operation	Ease of use [52, 54, 56, 57]
		Ease of maintenance [38, 42, 58]
		Ease of recyclability [34, 41, 59]
Social influences	Subjective norms and image	Perceived greenness of product [7, 9–14, 33, 34, 48, 59–61]
		Social Status/Significance of Adoption [8, 33, 36, 39, 52, 56, 62, 63]
		Importance of recyclability [34, 41]
Facilitating conditions	Compatibility	Standards/Compatibility [47, 57, 64]
		Recycling infrastructure [34, 35, 38]
	Perceived behavioral control	Taxes or tariffs [39]
		Energy prices [40, 65]
		Incentives or promotional policies [40, 48, 57, 63]
		Public environmental consciousness [9, 41, 56, 59, 66]

Which adoption factors are most commonly cited in the literature on energy efficient lighting technologies?

Are there differences in the most commonly cited adoption factors for commercial, residential, and industrial users?

Each category of these adoption factors is described below. An explanation is then provided for how each of these factors relate to technology adoption for energy efficient lighting technology.

Performance Expectancy

Performance Expectancy is the degree to which individuals feel using a new technology or system will help them achieve personal or organizational goals more effectively. In the original UTAUT studies applied to ICT, performance expectancy could be divided into categories, or constructs, related to adopting computer hardware and software systems, such as perceived usefulness/extrinsic motivation, job-fit, relative advantage, and outcome expectations. These constructs can be further decomposed into specific, measurable adoption factors. In the case of technology adoption for energy efficient lighting, similar categories can be used. However, categories like job-fit can be redefined as fitness for purpose and combined with perceived usefulness, since goals here can be defined more broadly than simply for employees who are using a technology for one specific job use. “Relative Advantage and Outcome Expectations” can also be combined here, since the advantages that the technology is expected to provided closely match the expected outcomes. Table 3 then lists specific technology acceptance and use factors that can measure various aspects of performance.

Effort Expectancy

Effort Expectancy is the degree of ease associated with the use of a new technology or system. Typical construct categories related to this in the ICT literature include perceived ease of use and complexity. For adoption of energy efficient lighting, a single category called ease of operation can be defined that fits the adoption factors found in the literature and listed in Table 3.

Social Influences

Social Influences are the degree to which individuals perceive that “important others” believe they should use the new technology or system. For the adoption of ICT systems, “important others” are generally defined as powerful people, such as managers and influential individuals who can exert authority over employees in an organization. For adoption of energy efficient lighting, the definition of authority figures can be much broader, including managers, customers, and other stakeholders who are impacted by the adoption decision. Construct categories in the ICT literature include subjective norms, social factors, and image. For adoption of energy efficient lighting technology, a single category called “Subjective Norms and Image” can be defined that fits with the adoption factors found in the literature and listed in Table 3.

Facilitating Conditions

Facilitating Conditions are the degree to which individuals perceive that a technical and organizational infrastructure exists to support the use of the new technology or system. Typical construct categories related to infrastructure in the ICT literature include perceived behavioral control and compatibility. In the technology adoption literature for energy efficient lighting, the same constructs can be defined. Table 3 then lists adoption factors from the literature that fit with these constructs and measure their relevant aspects.

Most Common Adoption Factors in the Literature

After defining the construct categories and adoption factors for energy efficient lighting technologies in the previous section, the literature was then examined to determine what was currently known about these adoption factors, and whether some of the factors were considered more common or significant factors for commercial, residential, or industrial users of energy efficient lighting technologies. Table 4 shows a list of the most common adoption factors for each user type. This is based purely upon a review of literature in which researchers referred to specific adoption factors as being more common or significant for various users of these technologies. An explanation is then provided for the reasoning behind these factor assessments. The goal of these assessments is simply to gain a basic understanding of which adoption drivers have been considered the most common or significant for each user type by a subset of experts. Future research will attempt

Table 4 Technology acceptance and use factors for EE lighting by sector

Commercial	Residential	Industrial
Installation cost	Installation cost	Installation cost
Energy cost savings	Energy cost savings	Energy cost savings
Total cost of ownership	Greenness of product	Payback time
Light color	Standards/Compatibility	Light color
Start-up speed	Light color	Start-up speed

to more precisely quantify the exact levels of importance for these and many other adoption factors regarding energy efficient lighting technologies.

An analysis of the most common factors for **commercial users** is provided below. Andrews and Krogmann [9] found that installation cost/upfront implementation cost is the dominant factor driving adoption for commercial users considering energy efficiency lighting technology. The next most significant factor identified was energy cost savings, which was confirmed by a number of other researchers in the commercial lighting sector [7, 39]. Andrews and Krogmann relied on the US DOE's Commercial Building Energy Consumption (CBEC) survey, which is conducted every 4 years [67]. It contains a great deal of information related to energy efficiency, but a limited amount of data related to lighting. So, a number of the factors identified in the literature in Table 3 as important for energy efficient lighting were not specifically analyzed for commercial adopters of energy efficient lighting technology. However, several lines of research mentioned that commercial users, such as those in owner occupied building, considered TCO, as well as issues regarding lighting quality, to be significant adoption factors [8, 37, 43, 47]. Thus, TCO is listed as the third most commonly mentioned factor in the research regarding adoption of energy efficient lighting technologies. TCO can encompass a variety of costs, including initial set up costs, energy costs, and maintenance costs, such as those due to the longer operating lifespan of LED lights. Issues of lighting quality were addressed at various other points in the literature. The most frequently cited issues are solving problems with light color [7, 41] and start up time [38, 45]. So, those qualitative characteristics were rated as the fourth and fifth most commonly mentioned factors that are important for commercial users.

An analysis of the most common factors for **residential users** is provided below. Many studies of factors for energy efficient lighting technology for residential users did not go into as much detailed analysis, particularly on financial and quantitative measures. However, they often did cite qualitative issues affecting consumer intention for adoption. Caird [11] found that installed cost/upfront implementation cost is the main factor of concern for residential users and noted that it is currently perceived as the main disincentive for adopting. The next most frequently discussed adoption factor was energy savings, which, again, consumers perceived skeptically and wondered if the energy savings produced by LEDs was worth the additional cost [14, 36, 66]. Consumers did note, however, that environmental concern was a major factor in considering the adoption of energy efficient lighting technologies, so perceived greenness of the product is listed as the third most commonly mentioned factor [34, 42, 63]. The next most common factor was standards/compatibility. It was noted that LED lighting is perceived as not being widely available for residential use, or that there are concerns it will not be compatible with existing fixtures [7, 12, 13, 47]. Lastly, residential users expressed concern about the light color or quality of energy efficient lighting alternatives [7, 55].

An analysis of the most common factors for **industrial users** is provided below. Anderson and Newell [10] found that industrial users were considerably more responsive to upfront installed cost, rather than energy cost savings when making decisions about the adoption energy efficient lighting technologies. The next most common factor identified was payback time. Industrial users strongly favored short payback times for recovering energy efficiency investments. Many additional factors identified in the literature in Table 3 as significant for energy efficient lighting were not specifically analyzed for industrial adopters of energy efficient lighting technologies. However, various sources in the literature point to similarities in the concerns of commercial and industrial users, since they both need to meet requirements in a business environment, rather than meeting the types of personal preferences often cited by residential users [38, 49]. Therefore, light color [7, 41] and start up time [38, 45], the same qualitative issues as expressed by commercial users, were rated as the fourth and fifth most significant factors for industrial users.

While the studies above present some interesting results, they also need to be examined cautiously. Such literature based assessments often compare studies by researchers using different methods and assumptions, examining industries of different make-ups, and are often conducted in different parts of the world. Clearly this would not offer the ideal framework for readily comparing or robustly analyzing such factors. It simply tries to get the best general consensus from the literature examined in current search. It also offers a baseline, as more data is collected regarding the importance of adoption factors for different user types to compare the similarities or differences in that data to what was previously through a study of the literature.

There are many issues that would need to be addressed to more precisely quantify the relative significance of these adoption factors for commercial, residential, and industrial users. The next section begins the examination of the research needed to more fully quantify the relative differences between the priorities for each of these adoption factors. A variety of methods are anticipated for performing this importance quantification, including expert interviews, surveys, analysis of trade-offs, and dynamic modeling.

4 Results

To begin the process of better quantifying the significance of these adoption factors, an important first step is verifying that the variables identified in the literature are seen as significant by experts in the field. A small group of nine experts was contacted to validate the factors presented in Table 3 and determine which ones looked most promising to focus on in further studies. The group consisted of nine experts, who were drawn from a variety of backgrounds, including: Electrical Engineering (2); Mechanical Engineering (2); Lighting Design/Manufacturing (2); Lighting Installation (1); and Architecture (2). All experts were familiar with the application of lighting technologies in commercial, residential, and industrial settings, although a number of them specialized primarily in one or another of these sectors. Overall, there were a roughly equal number of experts who specialized in areas related to each sector.

The experts began with the start concepts derived from the literature, but they were free to add factors if they felt additional concepts were important or to indicate if they felt any of the factors were inappropriate or not significant. One additional factor, Programmability/Energy Management, was identified through this process, bringing the total number of factors examined to 22. To rapidly gather input from this group of experts, which was composed of people from many different backgrounds, a charrette technique was used to allow them to quickly validate and prioritize variables through the use of a voting process [68]. Each expert was allowed to cast a total of five votes, assigning no more than one vote to a single factor. This permitted the experts to identify the set of five factors they considered to be most significant, without worrying about exactly how the factors ranked in terms of relative importance. All votes were then tallied to reveal the consensus regarding the factors that the most experts considered significant. These results are presented below.

A number of interesting results are evident from the expert judgment data. First, there are some similarities with results from Table 4. The largest number of votes in all sectors went to Installation Costs and the second largest number to Energy Cost Savings. However, in the Industrial sector, there was a tie for second place, between both Energy Cost Savings and Payback Time. Because of the possibility of ties, the third, fourth, and fifth highest choices become more complicated and are not always easy to spot on a tabular data format. Therefore, Fig. 2 below attempts to summarize the data in a more graphical format where the highest choices for each sector stand out a little more prominently. For example, the third highest choice for the Commercial sector is TCO, which is consistent with Table 4. For Residential sector, however, it includes Greeness of Product, which is consistent with Table 4, but it is also in a three-way tie for third place with Light Color and Standards/Compatibility. For the Industrial sector, there is also a three-way tie for third place between TCO, Standards/Compatibility, and Maintenance Costs. This is somewhat different that Light Color and Start-up Speed, which were found to be the third and fourth highest factors on Table 4 for the Industrial sector. However, those factors are listed as one several different choices rates as the fourth highest for this sector on Table 5. A number of other similarities and differences can be observed on Fig. 5 regarding the shape of the data patterns between the various industries.

The goal of the expert judgment data contained in Table 5 and summarized in Fig. 2 was not to establish an exact or definitive measurement of the rankings of adoption factors, it does provide a general picture of the significance of different

Table 5 Expert judgment—technology acceptance and use factors for EE lighting by sector

Commercial	Count	Residential	Count	Industrial	Count
Installation cost	6	Installation cost	5	Installation cost	6
Energy cost savings	5	Energy cost savings	4	Energy cost savings	5
Total cost of ownership	4	Total cost of ownership	2	Total cost of ownership	3
Light color	3	Light color	3	Light color	2
Standards/ Compatibility	3	Standards/ Compatibility	3	Standards/ Compatibility	3
Start-up speed	3	Start-up speed	2	Start-up SPEED	2
Maintenance cost	2	Maintenance cost	2	Maintenance cost	3
Ease of maintenance	2	Ease of maintenance	2	Ease of maintenance	2
Payback time	2	Payback time	2	Payback time	5
Incentives or promotional policies	2	Incentives or promotional policies	2	Incentives or promotional policies	2
Taxes or tariffs	2	Taxes or tariffs	2	Taxes or tariffs	2
Brightness	2	Brightness	2	Brightness	2
Importance of recyclability	2	Importance of recyclability	2	Importance of recyclability	1
Programmability/ Energy management	2	Programmability/ Energy management	1	Programmability/ Energy management	2
Ease of use	1	Ease of use	2	Ease of use	1
Flicker	1	Flicker	2	Flicker	1
Public environmental consciousness	1	Public environmental consciousness	1	Public environmental consciousness	1
Greenness of product	1	Greenness of product	3	Greenness of product	1
Energy prices	1	Energy prices	1	Energy prices	1
Recycling infrastructure	0	Recycling infrastructure	0	Recycling infrastructure	0
Ease of recyclability	0	Ease of recyclability	1	Ease of recyclability	0
Social significance of adoption	0	Social significance of adoption	1	Social significance of adoption	0

factors in each of the sectors and shows some results that both support and diverge from the results in Table 4. Although some factors, such as Recycling Infrastructure received no votes, and Ease of Recyclability received only one, that does not necessarily mean those factors are not important or should be excluded from future studies. Importance of Recycling was listed as a significant factor in all sectors. The expert panel was provided an opportunity to say if they believed any factors should be excluded, and none were identified. However, one way to interpret factors with a low number of votes is to say that those aspects of recyclability were not clearly top of mind for many experts. Therefore, they may not be listed as start concepts on future measurement instrument, and there may instead be clarifying questions about recyclability asking if the current factors adequately address the issues related to recyclability that respondents consider important. If they do not, additional terms can be proposed which may better express

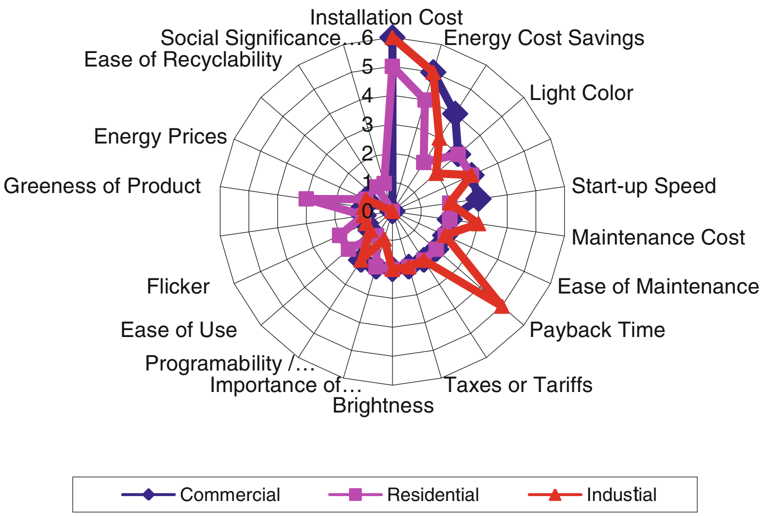

Fig. 5 Polar chart—technology acceptance and use factors for EE lighting by sector

concerns related to these issues. The next step in this research will then be to create a survey to more precisely measure the relative importance of the various factor affecting the acceptance and use of technologies for energy efficient lighting.

5 Conclusions

This research used several methods to determine what is currently known about the factors that are thought to most commonly influence adoption behavior for energy efficient lighting technologies in the commercial, residential, and industrial sectors. Literature was reviewed regarding the adoption of energy efficient lighting technology, and the most commonly used terms were identified and sorted according to the UTAUT framework. LED lighting was a specific focus among the energy efficient lighting technologies, as a number of studies identified it as a promising new lighting technology, which offers many advantages in terms of energy savings and long operating life of the product.

An initial review analyzed several groups of studies from the commercial, residential, and industrial sectors to determine if there was consensus on some of the factors most common to each industry. Installed Cost and Energy Cost Savings were found to be the factors most commonly considered significant in motivating adoption in all three sectors. Other factors varied in each sector, though the Commercial and Industrial sectors were believed to be the most similar. It was difficult to reach a clear consensus on the top five factors in each sector, so a group of experts was contacted for an exploratory study to validate and prioritize the wider set of factors identified in the literature, as well as determine if they felt specific factors should be added or removed. This research also found that Installed Cost and Energy Cost Savings were the two most common factors for all three sectors. However, among the third, fourth, and fifth level choices, there were many ties for the most common factors. While this did not establish precise rankings for these factors, it provided some initial insights into the complex set of factors influencing each sector. It is valuable to see that there may be a number of factors which are significant at each level. The next step in this research will be to create data collection instruments to more precisely quantify the relatively importance of different factors in each of these industries.

Behavioral theories of technology adoption, such as UTAUT, were discussed in this paper to explain how stakeholder expectation and buy-in could influence the acceptance and use of new technologies. This was seen as being particularly important for the adoption of energy efficiency technologies, because these technologies tend to be very dependent on continued acceptance and involvement by users in order to realize the full benefits they can deliver. The literature reviewed in this study identified adoption factors associated with each of the four key construct categories of UTAUT and explained how these constructs could be applied to understanding energy efficient lighting technologies. However, customization of these constructs would be necessary to operationalize them for measuring specific aspects of these technologies in future research.

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