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Different schemes for replacing conventional light bulbs with LED bulbs for greatest return on investment

Tanwa Arpornthip*

Andaman Environment and Natural Disaster Research Center (ANED),
Faculty of Technology and Environment, Prince of Songkla University, Phuket Campus, Kathu, Phuket, 83120 Thailand

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Abstract

A country can reduce its energy consumption significantly by encouraging more LED lighting usage. To encourage LED transition, more information showing the light bulb transition scheme with minimum cost is needed. We propose three possible transition schemes and provide a method to choose the most profitable one in a specific market condition. The total cost of each scheme is calculated as the sum of the electricity payment incurred during the transition, the capital cost needed to purchase LED light bulbs, and the business loss from discarding unexpired conventional light. The utility of our analysis is shown by applying it to two markets: Bahrain and Thailand. The two markets are chosen because of the large difference in electricity rates. Our analysis shows that market conditions select the most profitable transition scheme. With our analysis, a consumer can choose the most profitable scheme that responds to changing market conditions and consumers' needs.

Keywords: decision making, LED technology adoption, energy conservation, profitability, sustainable energy consumption

1. Introduction

The importance of using more energy efficient products is recognized around the world. This is reflected in the Sustainable Development Goals (SDGs) of the United Nations (UN) (United Nations General Assembly (UNGA), 2015). Specifically, promoting resource and energy efficiency is a part of Goal 12 of the SDGs, which seeks to "ensure sustainable consumption and production patterns." The invention of LED light bulbs greatly facilitates reaching Goal 12. We shall describe two major reasons below.

First, more efficient lighting can significantly reduce energy usage. For a concrete example, we shall consider Thailand. The Energy Policy and Planning Office (EPPO) estimates that 49% of total energy is used to generate electricity (Energy Policy and Planning Office, 2016b). According to the Earth Policy Institute (2011), 19% of electricity consumption is used for lighting. From both figures, one can estimate that 9% of Thailand's total energy consumption is used for lighting. Since LED light bulbs consume only about 50% energy compared to conventional light bulbs, a total transition to LED technology would reduce Thailand's total energy consumption by almost 5% (Department of Energy, USA, n.d.). The reduction is a fifth of the energy consumption reduction goal outlined in Thailand's Energy Efficiency Development Plan (2016a).

Second, the energy consumption reduction can already be achieved through LED lighting, a technology that is available in the mass market and has been proven to work at least as well as conventional technology. LED lighting already has a significant market share at 12%, with compounded annual growth rate projected at 30% (Thailand LED Expo 2018, n.d.). LED technology has also been proven to be more efficient than conventional light bulbs in both commercial uses and academic research (Frei, 2018; Horgan & Dwan, 2014; Kerdlap, 2017).

Despite all the benefits of making an LED transition, both to the consumers and to the energy economy of a country, many factors hinder the LED transition rate. In the European Union, family-age composition and education level have a measurable effect on energy-efficient product purchase (Mills & Schleich, 2012). Increase governmental support and

*Corresponding author
Email address: tanwa.a@phuket.psu.ac.th

educational resources are recommended for Malaysia (Khorasanizadeh, Parkkinen, Parthiban, & David Moore, 2015). In Thailand, thirteen factors influence the adoption of LED lighting (Nuchprasert, 2016). A major factor hindering the LED transition rate of a consumer is the inventory loss of discarding unused or partially used conventional light bulbs. Because of its lower energy consumption and longer operation time, LED light bulbs are more profitable for newly-constructed buildings. However, the situation becomes more complex for consumers who currently use conventional light bulbs. The savings offered by LED light bulbs should be offset with the inventory loss of discarding conventional light bulbs. The complex calculation needed to estimate the offset could be a major factor hindering the transition rate (Nuchprasert, 2016; Wong, Turner, & Stoneman, 1996). To encourage faster LED transition, an analysis showing the most profitable scheme to make an LED transition is needed.

In our study, we propose a quantitative analysis of the profit, in the form of savings, associated with different schemes that consumers can use to make an LED transition. Our treatment considers the possibility of a consumer having to write off a large reserve of conventional light bulbs as a business loss. We will propose different LED transition schemes suitable for all consumers in any market conditions and demonstrate market conditions in which a preference for a specific scheme arises. The utility of our proposed schemes will be shown by using two example market conditions from Bahrain and Thailand. The two countries were chosen because of their large difference in electricity rates. The proposed transition schemes are applicable to all scales of consumers, from residential to large corporate.

2. Materials and Methods

We define the scope of our study in section 2.1. Any assumptions used are stated in section 2.2. The constraints and limitations beyond market assumptions are discussed in section 2.3. The definition of each transition scheme and how to calculate a scheme's profitability are given in section 2.4.

2.1 Scope

We will only focus on the financial impact of an LED transition on one consumer. The economic impact to the community and the broader economy will not be considered. Furthermore, even though the environmental impact of LED is an interesting aspect, we choose not to include it in our analysis because the subject has already been studied extensively in the literature (Arik & Setlur, 2010; Principi & Fioretti, 2014; Tähkämö, Puolakka, Halonen, & Zissis, 2012). Our general treatment is applicable to all types of light bulbs. However, for our application examples, we will only consider T8 fluorescence light bulbs and their equivalent LED replacements because T8 bulbs are widely used in commercial buildings in Thailand.

2.2 Assumptions

Several assumptions are used in our study. First, we assume that all consumers will eventually transition to all LED light bulbs. This is justified by the financial benefit obtained through making an LED transition and by national and international campaigns, such as the SDGs, advocating for more environmentally friendly technology. Additionally, as more manufacturers improve their processes for LED production, the price for the technology will be lowered enough that adopting the new technology will obviously be the more financially prudent choice.

Second, we assume that all consumers have not replaced any conventional light bulbs with LED. The assumption does not make our treatment less general, but it simplifies our calculations and makes our result easier to interpret. If a consumer has already made a partial transition to LED, the portion can be excluded from the calculation.

Third, if a consumer has to discard partially used or unused conventional light bulbs, the discounted original cost of the conventional bulbs is considered a business loss, also called a write-off, per International Accounting Standards (IFRS Foundation, 2016).

Lastly, for those consumers that purchase light bulbs to put in their reserve supply for quick repair work, we assume that they will aim for an identical reserve size even after the LED transition. Given the much longer lifetime of LED light bulbs, identical reserve amount might be unnecessary. However, lacking specific recommended number, the safest practice is to maintain the same level of reserve, the practice and assumption that we also follow here.

2.3 Constraints and limitations

Our analysis is based on undiscounted cash flow. Since an LED light bulb can last up to ten years, the most complete analysis would include the calculation of the net present value (NPV). However, calculating the NPV of an LED transition would require further analysis for some necessary parameters, such as the appropriate discount rate and inflation. Frequently, these parameters depend on each consumer's risk tolerance level, which is a business management decision. Including an NPV analysis would expand the scope of the study too much.

Our analysis is applicable to consumers that can fully fund any of the proposed schemes using existing assets. An analysis for consumers who finance an LED transition through loans needs an NPV calculation as described in the previous paragraph. A consumer is also assumed to have adequate market access to procure the amount of LED bulbs needed for the transition.

2.4 Methodology

In this section, different transition schemes are defined. Next, the total electricity payment needed during the transition period is calculated. The capital cost of the technology transition, consisting of the cost of acquiring new light bulbs and any write-off, is then estimated. The electricity payment and the capital cost are then added together to give the total cost for each transition scheme. Next, the total cost of each scheme is compared. Lastly, a parameter called cost differential is defined to aid us in comparing the profitability of all the schemes.

Based on our assumption stated in Section 2.2, a consumer starts an LED transition having only conventional light bulbs. The transition is complete when all the light bulbs are LEDs. The symbols used in our analysis are summarized in Table 1 for convenience. At the beginning of the transition,

Table 1. List of symbols used. The units are shown in parentheses behind the symbols. A consumer collects the market quantities by doing market research. The calculated quantities are derived from the market quantities.

	Market quantities	
$\boldsymbol{C}$	The price of a conventional light bulb	(local currency)
$\boldsymbol{C_L}$	The price of an LED light bulb	(local currency)
$\boldsymbol{f}$	Electricity rate	(local currency per kWh)
$\boldsymbol{P}$	Power consumption of a conventional light bulb	(kW)
$\boldsymbol{P_L}$	Power consumption of an LED light bulb	(kW)
$\boldsymbol{H}$	Expected lifetime of a conventional light bulb	(hours)
$\boldsymbol{H'}$	Average remaining lifetime of a conventional light bulb in use	(hours)
$\boldsymbol{N_{use}}$	The number of conventional light bulbs in use	(bulbs)
$\boldsymbol{N_{reserve}}$	The number of conventional light bulbs in reserve	(bulbs)
	Calculated quantities	
$\boldsymbol{C_1}$	The write-off cost of using a conventional light bulb, $(C - fPH)$	(local currency)
$\boldsymbol{\Delta P}$	The power consumption difference, $(P - P_L)$	(kW)
$\boldsymbol{\alpha}$	The fractional lifetime, (H'/H)	-
$\boldsymbol{r}$	The reserve fraction, $(N_{reserve}/N_{use})$	-
$\boldsymbol{L_S, L_D, L_P}$	Total electricity payment for scheme S, D, and P, respectively	(local currency)
$\boldsymbol{I_S, I_D, I_P}$	Total capital cost for scheme S, D, and P, respectively	(local currency)
$\boldsymbol{TC_S, TC_D, TC_P}$	Total cost of a transition for scheme S, D, and P, respectively	(local currency)
$\boldsymbol{\Delta TC_{x,y}}$	Cost differential between scheme X and Y. Defined as $(TC_y - TC_x)/N_{use}$. A positive cost differential means that Scheme X is more profitable compared to scheme Y. X and Y can be any of the schemes (S, D, or P)	(local currency)

conventional light bulbs are placed in two categories: those in use and those in reserve. The light bulbs in use are for day-to-day operation of the consumer's business. The light bulbs in reserve are kept unused as replacements for the light bulbs in use. For our analysis, we consider three different transition schemes as follows

1) Sudden transition (Scheme S): All conventional light bulbs, both in use and in reserve, are replaced with LED light bulbs immediately.
2) Discarding reserve transition (Scheme D): All conventional light bulbs in use are replaced by LED light bulbs until they burn out. All conventional light bulbs in reserve are discarded and replaced by LED light bulbs immediately. The discarded conventional light bulbs are written off as a business loss.
3) Passive transition (Scheme P): All conventional light bulbs, both in use and in reserve, are used until they burn out. All new bulbs are LED light bulbs.

Table 2 summarizes all the schemes and the actions taken toward conventional light bulbs for each scheme. Each scheme has its pros and cons. Scheme S offers the shortest transition period and zero electricity payment, but it also has the highest capital loss due to the write-off of discarded light bulbs. Scheme P has the longest transition period, but the lowest write-off loss. Because of its long transition period, scheme P also incurs the most electricity payment during the transition. Scheme D occupies the middle ground between the two extremes of scheme S and P.

The total cost of each transition scheme is the sum of the electricity payment during the transition period and the capital cost needed. We can calculate the electricity payment during the transition period by multiplying the total energy consumed with the electricity rate f. The total energy consumed is a product of the number of light bulbs in use, power consumption of one light bulb, and the expected lifetime of each bulb. The number of conventional light bulbs in use and in reserve are N_{use} and $N_{reserve}$, respectively. If used until burn out, the conventional light bulbs in use have the expected lifetime of H'. The expected lifetime of conventional light bulbs in reserve is H. The discarded light bulbs do not con-tribute to the energy consumption. The total electricity payment for each scheme is

Table 2. Proposed transition schemes and the actions taken toward conventional light bulbs. All the schemes must purchase $(N_{use} + N_{reserve})$ LED light bulbs to replace the conventional light bulbs.

Conventional light bulbs		Action
Scheme S	In use	Discard and write-off
	In reserve	Discard and write-off
Scheme D	In use	Use until burn out
	In reserve	Discard and write-off
Scheme P	In use	Use until burn out
	In reserve	Use until burn out

$$L_S = 0 \quad (1)$$
$$L_D = f[N_{use}P\alpha H] \quad (2)$$
$$L_P = f[N_{use}P(\alpha H + rH) + (1 - r)N_{use}P_L H] \quad (3)$$

where we have replaced two market quantities with two calculated quantities to simplify our calculation in the next steps. Preferred over $N_{reserve}$, the reserve fraction r is defined as the ratio between the number of light bulbs in reserve over the amount in use ($N_{reserve} = rN_{use}$). Defined as H'/H, the fractional lifetime α is used to remove H' from the expressions.

The last term of L_P reflects the fact that only scheme P employs a mixture of conventional and LED bulbs during the transition period. The number of LED bulbs used for the transition in scheme P plus the number of conventional bulbs in reserve must equal N_{use} to fulfill the total numbers of bulbs needed by the consumer.

The capital cost for each transition scheme can be calculated as the sum of the capital needed to purchase new LED light bulbs and any business loss incurred from writing off discarded bulbs. For each scheme, the total capital cost is

$$I_S = \alpha N_{use}C + rN_{use}C + (1+r)N_{use}C_L \quad (4)$$
$$I_D = rN_{use}C + (1+r)N_{use}C_L \quad (5)$$
$$I_P = (1+r)N_{use}C_L \quad (6)$$

Again, we prefer the use of r and α over $N_{reserve}$ and H'. The term involving C_L is the capital cost of buying LED bulbs, which is the same among all the schemes. The other terms are the business loss from write-off. In Scheme S, we have discounted the write-off cost by the fractional lifetime of the conventional light bulbs in use.

To calculate the total cost of a transition for each scheme, we add the electricity payment to the capital cost. For each scheme, the total cost per one light bulb in use is

$$TC_S/N_{use} = \frac{L_S+I_S}{N_{use}} = \alpha C + rC + (1+r)C_L \quad (7)$$

$$TC_D/N_{use} = \frac{L_D+I_D}{N_{use}} = \alpha fPH + rC + (1+r)C_L \quad (8)$$

$$TC_P/N_{use} = \frac{L_P+I_P}{N_{use}} = f[(\alpha+r)PH + (1-r)P_LH] + (1+r)C_L \quad (9)$$

To facilitate the comparison between different schemes, we will define two new variables. We define the cost differential between scheme X and scheme Y as

$$\Delta TC_{x,y} = (TC_y - TC_x)/N_{use} \quad (10)$$

where x and y represent one of the three schemes (S, D, and P). The cost differential is the amount of money saved by using scheme x instead of scheme y per one light bulb in use. We also define the write-off cost of using a conventional light bulb, which is the price of one conventional light bulb less the electricity payment over its usage lifetime, as

$$C_1 = C - fPH \quad (11)$$

Using the newly defined variables, we can write the cost differential between all the transition schemes as

$$\Delta TC_{D,S} = \alpha C_1 \quad (12)$$

$$\Delta TC_{P,S} = \alpha C_1 - fP_LH + [C_1 + fP_LH]r \quad (13)$$

$$\Delta TC_{P,D} = -fP_LH + [C_1 + fP_LH]r \quad (14)$$

If $\Delta TC_{x,y} > 0$, a consumer should prefer scheme x over scheme y for its lower cost and higher profitability. A negative $\Delta TC_{x,y}$ suggests the opposite.

3. Results and Discussions

The most profitable scheme has the least total cost for a specific market condition. Having the cost differential (Equation 12-14), we can find specific market conditions that make a transition scheme more profitable compared to the other two schemes. In general, we will pick the scheme that yields the most profit in a market condition. If more than one scheme yields the same profit, we will pick the scheme that completes the LED transition sooner. From Eq. 12, finding the more profitable scheme between scheme D and S is straightforward. Since α is always greater than zero, the sign of C_1 dictates the preferred scheme. For the market in which $C_1 \geq 0$, it is obvious from Equation 11-12 that $\Delta TC_{D,S} > 0$. A consumer should prefer Scheme D over Scheme S. The opposite is true for $C_1 < 0$; Scheme S is more profitable than scheme D. Knowing the value of C_1, we can find the most profitable scheme by considering $\Delta TC_{\mathrm{P,X}}$ where X is the more profitable scheme between scheme D and S, as chosen by the criteria described in the preceding paragraph. For the market in which $C_1 < 0$, scheme S is more profitable than scheme D. We consider $\Delta TC_{\mathrm{P,S}}$. We note that the quantity in the square brackets of Equation 13 can be rewritten as

$$C_1 + fP_LH = C - fH\Delta P \quad (15)$$

where ΔP is the difference in power consumption of a conventional light bulb compared to its LED-equivalent counterpart $(P - P_L)$. If the above quantity is less than on equal to zero, $\Delta TC_{\mathrm{P,S}} \leq 0$ and scheme S is preferred. This condition is equivalent to $\Delta P \geq C/fH$. This is shown graphically in Figure 1a. However, if $\Delta P < C/fH$, then $\Delta TC_{\mathrm{P,S}}$ starts in the negative for zero reserve size $r = 0$. Scheme P is only more profitable than scheme S when the positive term in the square bracket of Equation 13 is larger than the two negative terms in front. The turning point occurs when the reserve fraction grows larger than

$$r > \frac{fP_LH - \alpha C_1}{fP_LH + C_1} \quad (16)$$

This case is shown graphically in Figure 1b.

For the market in which $C_1 \geq 0$, Scheme D is always more profitable than scheme S. We now consider $\Delta TC_{\mathrm{P,D}}$. The quantity in the square bracket of $\Delta TC_{\mathrm{P,D}}$ is the same as the quantity described by Equation 15. For $\Delta P \geq C/fH$, the quantity in the square bracket of $\Delta TC_{\mathrm{P,D}}$ is always negative, which leads to $\Delta TC_{\mathrm{P,D}} < 0$ and a preference for scheme D over P. This case is shown graphically in Figure 1c. However, if $\Delta P < C/fH$, $\Delta TC_{\mathrm{P,D}}$ starts in the negative for $r = 0$. Scheme P is only more profitable than scheme D when the positive term in the square bracket of Equation 14 is larger than the first negative term. The turning point occurs when r grows larger than

$$r > \frac{fP_LH}{fP_LH + C_1} \quad (17)$$

This case is shown graphically in Figure 1d. The entire analysis of this section can be summarized as a decision flowchart

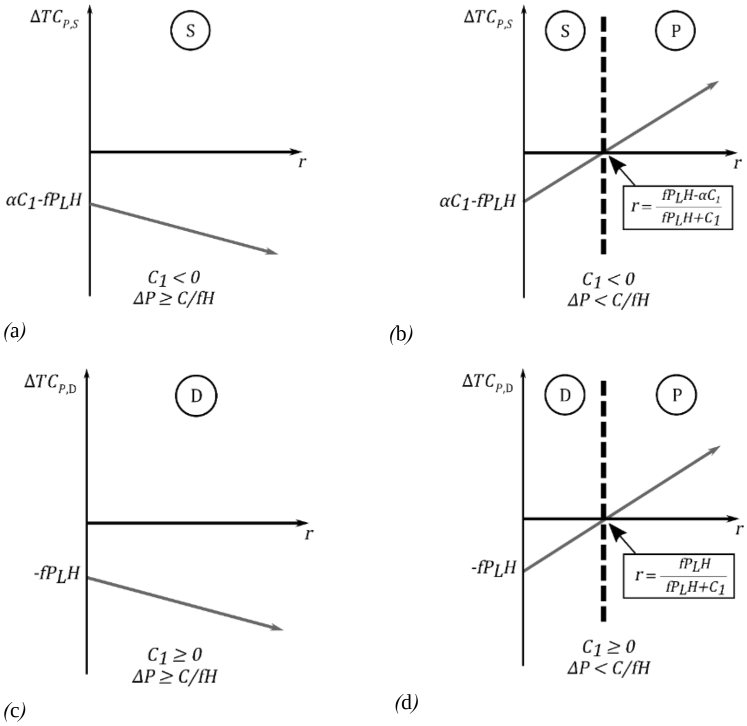

Figure 1. Most profitable LED transition schemes in different market conditions. The cost differential between Scheme P and the other two schemes in different market conditions is shown. Circled letters show the most profitable transition scheme for that specific market condition. (a-b) Comparing scheme P to scheme S for $C_1 < 0$. (c-d) Comparing Scheme P to Scheme D for $C_1 \geq 0$

shown in Figure 2. Consumers who are mathematically inclined can follow Figure 2 to select the most profitable transition scheme.

In addition to helping a consumer pick the most profitable scheme, our analysis can also provide cost comparison between different schemes. This is done through the $\Delta TC_{x,y}$ variables. For example, $\Delta TC_{D,S}$ gives the cost difference between using scheme D and scheme S per one light bulb. A positive value suggests that scheme D is cheaper than scheme S by that amount per light bulb, while a negative value shows the opposite. In general, $\Delta TC_{x,y}$ gives the amount of money saved per light bulb to use Scheme X instead of Scheme Y.

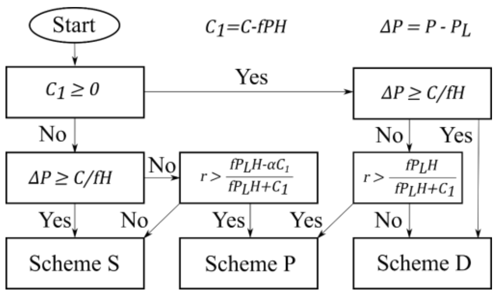

Figure 2. Decision flowchart to find the most profitable LED transition scheme.

4. Application Examples

While Figure 2 provides good mathematical summary of our analysis, it might be inaccessible to typical consumers. To increase the reach and utility of our analysis, a worksheet (shown in Table 3) has been developed to help a consumer select the most profitable transition scheme based on a market condition. The worksheet is a more user-friendly representation of Figure 2. The conversion between the worksheet and the flowchart is shown in Table 4.

The worksheet's design is based on typical tax forms found in many countries. Consumers' familiarity with tax forms should make the worksheet more accessible. The language used in the worksheet is simplified. Moreover, the mathematical operations involved are reduced to small and simple steps. Each line of the worksheet corresponds to either a quantity or a term of a quantity shown in Table 1. To use the worksheet, a consumer needs the data for the market quantities shown in Table 1.

Two market conditions are selected to showcase the utility of the worksheet: Bahrain and Thailand. The two countries are chosen because of the large difference in their electricity rates. For a concrete example, we look for a transition scheme to replace T8 fluorescent light bulbs, a common type of light bulbs found in commercial buildings, with equivalent LED light bulbs. The market quantities for the two markets are shown in Table 5.

First, we consider Bahrain, a country that has cheaper electricity rate compared to Thailand. The market quantities shown in Table 5 are used to fill out the worksheet in Table 3. The filled-out worksheet for Bahrain market is Table 6. The worksheet suggests that scheme D is the most profitable transition scheme for the market condition shown in Table 5.

Table 3. LED transition scheme worksheet. Designed to resemble a typical tax form, the worksheet helps consumer select the most profitable LED transition scheme.

LED transition scheme worksheet

Objective: The worksheet helps determine the most profitable light bulb replacement scheme in transitioning from conventional light bulbs to LED light bulbs.
Instructions: Fill out the following worksheet. Using the units provided in the parentheses. Use your local currency for units denoted "LC" (Local Currency). To avoid rounding error, at least four decimal places of accuracy is recommended, when applicable.

Conventional light bulb

1	The price of a conventional light bulb (LC)	....
2	Electricity rate (LC/kWh)........	....
3	Power consumption of a conventional light bulb (kW)	....
4	Expected lifetime of a conventional light bulb (hours)........	....
5	Multiply lines 2 through 4 (line 2 × line 3 × line 4). This is the cost of using a conventional light bulb (LC)........	....
6	Subtract line 5 from line 1 (line 1 – line 5). This is the write-off cost of using a conventional light bulb (LC)........	....
7	Divide line 5 by line 3 (line 5 ÷ line 3). (LC/kWh)........	....
8	Divide line 1 by line 7 (line 1 ÷ line 7). This is the break-even power consumption difference (kW)........	....

LED light bulb

9	Power consumption of an LED light bulb (kW)........	....
10	Subtract line 9 from line 3 (line 3 – line 9). This is the power consumption difference (kW)	....
11	Multiply line 2, line 4, and line 9 together (line 2 × line 4 × line 9). This is the cost of using an LED light bulb for one conventional lifetime (LC)	....

Individual considerations

12	Average remaining lifetime of a conventional light bulb in use. If unsure, use the value from line 4 (hours)	....
13	Amount of conventional light bulbs being used currently (bulbs)........	....
14	Amount of unused conventional light bulbs in inventory (bulbs)........	....
15	Divide line 12 by line 4 (line 12 ÷ line 4). This is the fractional lifetime........	....
16	Divide line 14 by line 13 (line 14 ÷ line 13). This is the reserve fraction	....

Choosing transition scheme

17	Add line 6 and line 11 together (line 6 + line 11)........	....
18	If line 6 is greater than or equal to zero, go to line 24. Otherwise, go to the next line.	
19	If line 10 is greater than or equal to line 8, go to line 27. Otherwise, go to the next line.	
20	Multiply line 6 by line 15 (line 6 × line 15)........	....
21	Subtract line 20 from line 11 (line 11 – line 20)........	....
22	Divide line 21 by line 17 (line 21 ÷ line 17)	....
23	If line 16 is greater than line 22, go to line 28. Otherwise, go to line 27	
24	If line 10 is greater than or equal to line 8, go to line 29. Otherwise, go to the next line.	
25	Divide line 11 by line 17 (line 11 ÷ line 17)	....
26	If line 16 is greater than line 25, go to line 28. Otherwise, go to line 29	
27	Use SCHEME S, see the description below	
28	Use SCHEME P, see the description below	
29	Use SCHEME D, see the description below	

Scheme S	Scheme P	Scheme D
Sudden transition: Replace all conventional light bulbs with LED bulbs immediately.	Passive transition: Use all conventional bulbs until burn out prior to replacing them with LED bulbs	Discarding reserve transition: Discard all unused conventional light bulbs. Replacing burnt out conventional bulbs with LED ones.

Bahrain market is a good example to show the utility of our analysis and the worksheet. If r is greater than 7.2%, or equivalently $N_{reserve} > 72$, line 16 would be larger than line 25 in Table 6. In this case, the most profitable transition is scheme P. A business that needs to ensure constant optimal lighting condition on its premise (such as hospitals, operation theatres) can have r higher than 7.2% and scheme P would be more profitable. The example shows the versatility of our

Table 4. Conversion between the worksheet shown in Table 3 and the quantity being calculated on each line of the worksheet

Line	Quantity	Line	Quantity	Line	Quantity
1	C	11	fP_LH	21	$fP_LH - \alpha C_1$
2	f	12	H'	22	$\frac{fP_LH - \alpha C_1}{fP_LH + C_1}$
3	P	13	N_{use}	23	$r > \frac{fP_LH - \alpha C_1}{fP_LH + C_1}$
4	H	14	$N_{reserve}$	24	$\Delta P \geq \frac{C}{fH}$
5	fPH	15	α	25	$\frac{fP_LH}{fP_LH + C_1}$
6	$C_1 = C - fPH$	16	r	26	$r > \frac{fP_LH}{fP_LH + C_1}$
7	fH	17	$fP_LH + C_1$	27	-
8	C/fH	18	$C_1 \geq 0$	28	-
9	P_L	19	$\Delta P \geq \frac{C}{PH}$	29	-
10	ΔP	20	αC_1		

Table 5. Example market conditions from Thailand and Bahrain

Quantity	Thailand		Bahrain	
	Value	Source	Value	Source
$\boldsymbol{C}$	59 Baht	Quotes from three vendors[1]	14.5 Dinar	Quotes from three vendors[1]
$\boldsymbol{C_L}$	115 Baht	Quotes from three vendors[1]	18.3 Dinar	Quotes from three vendors[1]
$\boldsymbol{f}$	2.7124 Baht/kWh	MEA[2] (2018) and PEA[3] (2018)	0.003 Dinar/kWh	EWA[4] (2018)
$\boldsymbol{P}$	36 Watts	Quotes from three vendors[1]	36 Watts	Quotes from three vendors[1]
$\boldsymbol{P_L}$	18 Watts	Quotes from three vendors and (Kerdlap, 2017)[1]	18 Watts	Quotes from three vendors and (Kerdlap, 2017)[1]
$\boldsymbol{H}$	18000 hours	Quotes from three vendors[1]	18000 hours	Quotes from three vendors[1]
$\boldsymbol{H'}$	9000 hours	See footnote[5]	9000 hours	See footnote[5]
$\boldsymbol{N_{use}}$	1000 bulbs	See footnote[6]	1000 bulbs	See footnote[6]
$\boldsymbol{N_{reserve}}$	40 bulbs	See footnote[6]	40 bulbs	See footnote[6]

[1] When multiple sources exist, the median value is used.
[2] Thailand's Metropolitan Electricity authority (MEA). Small general services consumer
[3] Thailand's Provincial Electricity Authority (PEA). Small general services consumer
[4] Bahrain's Electricity and Water Authority (EWA). Domestic customer with one account
[5] Assuming 50% average lifetime for light bulbs in operation
[6] Enough reserve for one month of operation assuming uniform distribution of lifetime left in light bulbs in use. A thousand light bulbs is appropriate for a small to medium-size business.

analysis in picking the most profitable scheme in changing market conditions.

In contrast, consider Thailand's market condition as shown in Table 5. Table 7 shows the filled-out worksheet for Thai market. We find that line 6, corresponding to c_1, is negative. Consequently, line 10 is greater than line 8 ($\Delta P > c/fH$) and line 19 is true. Lastly, the worksheet suggests scheme S as the most profitable scheme. Because of the high electricity rate, writing off all conventional light bulbs immediately is a sensible transition scheme for Thailand. Using conventional light bulbs longer would incur more electricity payment compared to a one-time investment in energy-saving LED light bulbs. While Scheme S is recommended here, the implementation varies between different consumers. The scheme would be more suitable for consumers that have dedicated personnel for the repair work, as well as enough funding to buy a large amount of LED light bulbs in one purchase. If Scheme S is proven to be impractical, Scheme D would be the next best alternative. As stated in the constraints and limitations section, a detailed analysis of Scheme S's practicality is beyond the scope of our study as it would involve logistics and management decision analysis of consumers. Both examples above demonstrate the utility and the application of the worksheet shown in Table 3.

5. Conclusions

Three schemes for replacing conventional light bulbs with LEDs are proposed. Sudden transition scheme (scheme S) discards all conventional light bulbs and replaces them with LED light bulbs immediately. Discarding reserve transition

Table 6. Example worksheet for Bahrain's market condition. The worksheet suggests scheme D for Bahrain consumers.

LED transition scheme worksheet		
Objective: The worksheet helps determine the most profitable light bulb replacement scheme in transitioning from conventional light bulbs to LED light bulbs. Instructions: Fill out the following worksheet. Using the units provided in the parentheses. Use your local currency for units denoted "LC" (Local Currency). To avoid rounding error, at least four decimal places of accuracy is recommended, when applicable.		
Conventional light bulb		
1	The price of a conventional light bulb (LC)........	14.5
2	Electricity rate (LC/kWh)........	0.003
3	Power consumption of a conventional light bulb (kW)........	0.036
4	Expected lifetime of a conventional light bulb (hours)........	18000
5	Multiply lines 2 through 4 (line 2 × line 3 × line 4). This is the cost of using a conventional light bulb (LC)........	1.944
6	Subtract line 5 from line 1 (line 1 – line 5). This is the write-off cost of using a conventional light bulb (LC)........	12.556
7	Divide line 5 by line 3 (line 5 ÷ line 3). (LC/kWh)........	54
8	Divide line 1 by line 7 (line 1 ÷ line 7). This is the break-even power consumption difference (kW)........	0.2685
LED light bulb		
9	Power consumption of an LED light bulb (kW)........	0.018
10	Subtract line 9 from line 3 (line 3 – line 9). This is the power consumption difference (kW)........	0.018
11	Multiply line 2, line 4, and line 9 together (line 2 × line 4 × line 9). This is the cost of using an LED light bulb for one conventional lifetime (LC)........	0.972
Individual considerations		
12	Average remaining lifetime of a conventional light bulb in use. If unsure, use the value from line 4 (hours)........	9000
13	Amount of conventional light bulbs being used currently (bulbs)........	1000
14	Amount of unused conventional light bulbs in inventory (bulbs)........	40
15	Divide line 12 by line 4 (line 12 ÷ line 4). This is the fractional lifetime........	0.5
16	Divide line 14 by line 13 (line 14 ÷ line 13). This is the reserve fraction........	0.04
Choosing transition scheme		
17	Add line 6 and line 11 together (line 6 + line 11)........	13.528
18	$\boxed{\text{If line 6 is greater than or equal to zero, go to line 24.}}$ Otherwise, go to the next line.	
19	If line 10 is greater than or equal to line 8, go to line 27. Otherwise, go to the next line.	
20	Multiply line 6 by line 15 (line 6 × line 15)........	
21	Subtract line 20 from line 11 (line 11 – line 20)........	
22	Divide line 21 by line 17 (line 21 ÷ line 17)........	
23	If line 16 is greater than line 22, go to line 28. Otherwise, go to line 27	
24	If line 10 is greater than or equal to line 8, go to line 29. $\boxed{\text{Otherwise, go to the next line.}}$	
25	Divide line 11 by line 17 (line 11 ÷ line 17)........	0.0719
26	If line 16 is greater than line 25, go to line 28. $\boxed{\text{Otherwise, go to line 29}}$	
27	Use SCHEME S, see the description below	
28	Use SCHEME P, see the description below	
29	$\boxed{\text{Use SCHEME D, see the description below}}$	

Scheme S	Scheme P	Scheme D
Sudden transition: Replace all conventional light bulbs with LED bulbs immediately.	Passive transition: Use all conventional bulbs until burn out prior to replacing them with LED bulbs	Discarding reserve transition: Discard all unused conventional light bulbs. Replacing burnt out conventional bulbs with LED ones.

scheme (scheme D) uses all the conventional light bulbs currently installed until they burn out, discards all the unused light bulbs, then replaces with LEDs. Lastly, passive transition scheme (scheme P) uses all light bulbs until burn out before replacing them with LEDs. Each scheme incurs expenses and generates savings through different mechanics. We provide a method for consumers to choose the most profitable LED transition scheme. Our analysis responds to changing market

Table 7. Example worksheet for Thailand's market condition. The worksheet suggests scheme S for Thai consumers. Unrelevant lines and scheme descriptions have been omitted to save space.

	LED transition scheme worksheet	
	Conventional light bulb	
1	The price of a conventional light bulb (Baht)...	59
2	Electricity rate (Baht/kWh)...	2.7124
3	Power consumption of a conventional light bulb (kW)	0.036
4	Expected lifetime of a conventional light bulb (hours)...	18000
5	Multiply lines 2 through 4 (line 2 × line 3 × line 4). This is the cost of using a conventional light bulb (Baht)..	1757.64
6	Subtract line 5 from line 1 (line 1 – line 5). This is the write-off cost for one conventional light bulb (Baht)..	-1698.64
7	Divide line 5 by line 3 (line 5 ÷ line 3). (Baht/kWh)..	48823.33
8	Divide line 1 by line 7 (line 1 ÷ line 7). This is the break-even power consumption difference (kW)..	0.0012
	LED light bulb	
9	Power consumption of an LED light bulb (kW)...	0.018
10	Subtract line 9 from line 3 (line 3 – line 9). This is the power consumption difference (kW).........	0.018
11	Multiply line 2, line 4, and line 9 together (line 2 × line 4 × line 9). This is the cost of using an LED light bulb for one conventional lifetime (Baht)..	878.82
	Individual considerations	
12	Average remaining lifetime of a conventional light bulb in use. If unsure, use the value from line	9000
	4 (hours)	1000
13	Amount of conventional light bulbs being used currently (bulbs)..	40
14	Amount of unused conventional light bulbs in inventory (bulbs)...	0.5
15	Divide line 12 by line 4 (line 12 ÷ line 4). This is the fractional lifetime.......................................	0.04
16	Divide line 14 by line 13 (line 14 ÷ line 13). This is the reserve fraction	
	Choosing transition scheme	
17	Add line 6 and line 11 together (line 6 + line 11)..	-819.82
18	If line 6 is greater than or equal to zero, go to line 24. Otherwise, go to the next line.	
19	If line 10 is greater than or equal to line 8, go to line 27. Otherwise, go to the next line.	
	....(Unrelevant lines are omitted.)	
27	Use SCHEME S.	
Scheme S	Scheme P	Scheme D
Sudden transition	Passive transition	Discarding reserve transition

conditions and consumers' different needs. A user-friendly worksheet is designed to aid consumers in collecting market data, calculating relevant quantities, and selecting the most profitable scheme. Knowing the most profitable scheme for an LED transition could entice consumers into using more eco-friendly products sooner, which has both economic and environmental benefits to the economy. Furthermore, realizing specific transition scheme helps streamline other business decisions such as logistics and labor cost planning in order to make an LED transition.

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