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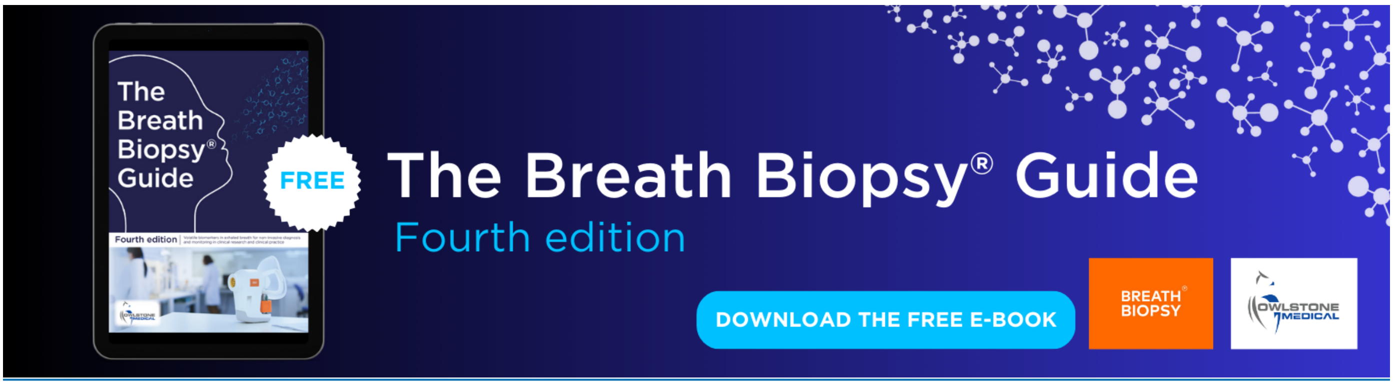

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LETTER

Replacement policy of residential lighting optimized for cost, energy, and greenhouse gas emissions

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Abstract

Accounting for 10% of the electricity consumption in the US, artificial lighting represents one of the easiest ways to cut household energy bills and greenhouse gas (GHG) emissions by upgrading to energy-efficient technologies such as compact fluorescent lamps (CFL) and light emitting diodes (LED). However, given the high initial cost and rapidly improving trajectory of solid-state lighting today, estimating the right time to switch over to LEDs from a cost, primary energy, and GHG emissions perspective is not a straightforward problem. This is an optimal replacement problem that depends on many determinants, including how often the lamp is used, the state of the initial lamp, and the trajectories of lighting technology and of electricity generation. In this paper, multiple replacement scenarios of a 60 watt-equivalent A19 lamp are analyzed and for each scenario, a few replacement policies are recommended. For example, at an average use of 3 hr day^{-1} (US average), it may be optimal both economically and energetically to delay the adoption of LEDs until 2020 with the use of CFLs, whereas purchasing LEDs today may be optimal in terms of GHG emissions. In contrast, incandescent and halogen lamps should be replaced immediately. Based on expected LED improvement, upgrading LED lamps before the end of their rated lifetime may provide cost and environmental savings over time by taking advantage of the higher energy efficiency of newer models.

1. Introduction

In the past two decades, light emitting diode (LED) lamps have reduced by 20-fold in cost and improved 40-fold in luminous flux [1, 2]. LED package efficacy could reach 200 lm W^{-1} by 2025 under the Department of Energy (DOE)'s solid-state lighting development goals [3]. In 2015, lighting accounted for 10% of the electricity consumption in the US [4]. By transitioning to energy-efficient lighting through market forces and federal mandates, such as the Energy Independence and Security Act (EISA), this consumption could be cut in half by 2050 [5], providing 261 terawatt-hours (TWh) of energy saving annually [3]. However, the transition has been slow so far as LED lamps still face major barriers to adoption, including high initial cost. With rising electricity prices and concerns for climate change and energy security, continued LED development and adoption is vital for realizing tremendous energy and carbon emission savings.

Lighting upgrades provide one of the easiest ways to cut household energy bills. Residential lighting service is provided mostly by A-type lamps, which include incandescent lamps (IL), halogen lamps (HL), compact fluorescent lamps (CFL), and LEDs. With over 3 billion units installed in the US, these round-shaped general service lamps represent over 147 TWh of energy saving potential for LEDs [6]. However, given the rapid improvement of LED technology and its cost reduction trajectory, when should LEDs be adopted from a consumer's perspective? What is the time-zero replacement decision in an average American household, i.e. should the household keep or replace the lamps they currently have? How does a decarbonizing electricity grid affect lighting replacement decisions that aim to minimize lighting expenditure and carbon footprints? This study juxtaposes the financial and environmental benefits of replacement today, and the advantages of adopting an improved and lower-cost technology later to provide guidance on residential lighting replacement.

1.1. Literature review

When making purchase decisions, consumers are encouraged to look past LEDs' high initial cost to the energy savings over their long life, and to consider financial assessment tools such as rate of return (ROR), return on investment (ROI), and payback period to illustrate all the benefits and costs. Alstone *et al* found that the energy 'debts' based on light output per unit of embodied energy plus energy consumption for off-grid LED lighting systems are paid back in just 20–50 days and have an energy ROI of 10–40 times [7]. Many studies have also demonstrated the competitive cost savings and environmental benefits of LEDs compared to incumbent lighting from a life cycle perspective [8–14]. However, without considering the timing of replacement, these methods alone cannot maximize the cost and environmental benefits of replacement.

Although *equipment replacement* with optimization has been widely researched, particularly for industrial equipment undergoing rapid technological change, many of the studies only focused on cost–benefit analysis [15–18]. A subset of replacement studies focused on automobiles, refrigerators, and other consumer products considers both cost and environmental benefits of replacement under technological progression but has not considered the social cost of carbon and variable electrical grid fuel mixes [19–26]. As the US moves toward low-carbon power generation driven in part by the Renewable Portfolio Standards [27, 28], the long-term benefits of energy efficiency gain will be lower due to an impact reduction in upstream energy and material production [29]. With electricity accounting for most of the life cycle impacts of lighting [8, 13, 14], it is imperative to consider changes to electricity fuel mix in lighting replacement decisions.

To the best of the authors' knowledge, there are only two studies that optimize the decision and/or timing of lighting replacement, but neither of the studies considered the environmental tradeoffs in replacement. Balachandra and Shekar [30] explored the replacement of residential IL with various fluorescent lamp types in India by comparing the relative annual ROR and investment risk of each alternative. However, this study was limited to fluorescent lighting and cost benefit considerations only. Ochs *et al*'s study [31] on streetlight replacement on US military bases found that delaying the switchover from high intensity discharge luminaires to LEDs achieves better performance and cost savings from future improved LED technology. However, it did not consider the potential savings from early replacement [32], i.e. from upgrading LED luminaires to newer, more energy-efficient models before they reach the end of their rated lifetime. With a longer service life and a parametric failure mode [33], LED replacement after adoption of the technology becomes less intuitive. A knowledge gap thus remains in understanding how technological changes in solid-state lighting (SSL) and power generation affects future replacement decisions for lighting.

1.2. Study aims

This study aims to conduct a comprehensive replacement analysis for residential lighting by considering several key parameters: environmental loads (primary energy and greenhouse gas (GHG) emissions), initial conditions (e.g. whether a luminaire is pending for replacement at the time of the decision), and technology improvement (to power generation and LED lighting). By studying the replacement of 60 W-equivalent (900 lm)[4] lamps, which are commonly found in US households, this paper seeks to provide guiding policy for low-cost and low-impact residential lighting replacement across various regions of the US.

2. Methods

2.1. Life cycle optimization

Life cycle optimization (LCO) is a method that integrates life cycle assessment (LCA) with optimization analysis for enhancing product sustainability [34] and is used to construct a lighting replacement optimization model. The model draws data from LCA studies that follow ISO 14040 as well as US Energy Information Administration outlook for LED technology [3] and the grid [5]. By considering how a product's life cycle impact profile changes over time with its design, the LCO framework determines an optimal replacement policy (characterized by timing of purchase and duration of use) in which the total life cycle impact (e.g. cost) of the product aggregated over a time horizon is minimized. This LCO framework has been used to study automobiles [22, 25], refrigerators [21, 23], washing machines [19], and air conditioners [20].

2.2. Technology projection and life cycle impact profiles

LED lamps are expected to reach 150–180 lm W^{-1} in efficacy by 2020 and 50 000 hours in lifetime by 2025 [3]. Another study has the forecast at 250–300 lm W^{-1} and 80 000 hours by 2050 [29]. From 2015–2020, LED lamps would decrease by 40% in cost, 33% by electronic mass and proportionally to wattage demand in terms of the heat sink [3]. Based on these projections, logistic models (see supplementary appendix A available

[4] Not all 60 W-equivalent lamps provide 900 lm of brightness, hence all lamp attributes (e.g. lamp price and power rating) are adjusted to 900 lm, which serves as the basis of comparison in this study.

Table 1. Technology projection and life cycle impact profiles of average 60 W-equivalent 900 lm A19 lamps. (Sources: Bergesen *et al* [29], Nahlik *et al* [37], DOE [3, 13, 14, 35, 36], DOL [39], EIA [47], EPA [44, 45])

	IL	HL	CFL		LED	
	2015	2015	2015	2050	2015	2050
Efficacy [lm W^{-1}]	15	20	70	83	78	298*
Lifetime [hr]	1000	8400	12 000	15 000	25 000	80 000*
Cost: lamp	0.567	2.25	1.80 (7.00)	1.13 (1.56*)	$5.09 (9.00)	1.13* (2.00*)
Cost: installation	0.870		0.870		0.870	
Cost: end of life	0.0287		0.0601		0.0589	0.0562
Primary energy [MJ]						
Manufacturing	1.90		65.0		281	172*
Transport—US average	0.679		2.03	1.10	1.88	0.544
End of life	0.00265		0.0219		0.0372	0.0204
GHG emissions [kg CO_2e]						
Manufacturing	0.948		8.99		12.5	8.10*
Transport—US average	0.0754		0.226	0.0642	0.212	0.0409
End of life	0.0128		0.0284		0.0150	0.0115

Note: Number in parenthesis represents dimmable lamp cost. All projections are modeled to grow exponentially except those marked with*, each of which follows a logistic curve as defined in supplementary appendix A.

at stacks.iop.org/ERL/12/114034/mmedia) are created to describe the future cost, efficacy, and rated lifetime of the LED lamps. Due to the maturity of the technology, the efficacy of CFLs are not expected to change significantly over time, improving at less than 1% annually [35]. It is expected that both IL and HL are being phased out of operation by EISA [6].

For each lamp technology, data for cost, primary energy, and GHG emissions is collected for the production, transportation, use, and end of life (EOL) stages, where all GHG emissions are expressed in AR4 GWP-100. The production stage encompasses all substages from cradle-to-gate per DOE's LCA studies [13, 14, 36] and the production impact for LED is adjusted to reflect the actual LED efficacy improvement rate to-date. The transportation stage represents only the transportation between the original equipment manufacturer suppliers (defined per DOE's study) and the retailer (assumed at the geographical center of the continental US (Kansas). It accounts for LED weight reduction, [3] improved vehicle technology, and lower-carbon fuels, the latter two of which would decrease the life cycle energy factor and GHG emission factor by 57% and 91% respectively for bunker fuel container ships, and 58% and 56% respectively for diesel trucks by 2050 [37].

The use stage accounts for the purchase and installation of a new lamp when the incumbent lamp is ready for retirement and disposal. An average of 3 hours of use (HOU) per day is studied as a baseline condition while 1/7 (1 hour per week), 1.5 (average A19 lamp usage rate in US [6]), and 12 HOU are also explored. Although lamp change-out is typically done by consumers themselves, an opportunity cost [38] equivalent to one third of the US median wage of \$17.40 hr^{-1} [39] is assigned to an estimated 9 min labor time (which includes purchase and installation of the new lamp, and disposal of the old lamp). For lamps that are already in use at the start of the time horizon, both the lamp cost and installation cost are omitted from the calculation.

Between 2015 and 2040, the share of US electricity from natural gas and renewables are expected to increase by 6% and 13%, respectively, while the share from nuclear and coal decrease by 4% and 15%, respectively [5]. These fuel mix data are assumed valid for extrapolation until 2050. Using a bottom-up aggregation approach by generation type and accounting for the upstream impacts of power generation [40–42], the average primary energy factor and average GHG emission factor for the US grid are estimated to be 2.95 (kWh kWh^{-1}) and 0.647 kg CO_2e kWh^{-1}, respectively in 2015, with an annual growth rate of −0.385% and −1.31%, respectively. This study recognizes that the use of average generation factors may underestimate the potential savings from energy efficiency gain [43]. Although marginal generation factors may better capture the time-of-use impacts and savings, their projected changes from grid decarbonization cannot be estimated easily (due to lack of data), or with certainty (due to their temporal variability). To provide some insight on marginal generation impacts, replacement policies for coal, natural gas, and combinations of the two fuels are assessed and discussed in supplementary appendix E.

In the EOL stage, 10% recycling is assumed for IL and HL, 20% for CFL and LED, and 30% for all lamp packaging [13, 14]. Lamp recycling is assumed through mail-back programs (e.g. EasyPak and LampMaster), which offer prepaid recycling kits to send used lamps to recycling centers, at \$0.25 $lamp^{-1}$. Landfill cost is estimated at \$45 ton^{-1} [44] and the same rate is applied to recycling packaging. The life cycle energy is estimated using the EPA Waste Reduction Model [45] data for landfilling various materials, including aluminum, glass, copper, and corrugated containers. The recycled portion is assumed net zero energy given the unknown fate of the recycled materials.

The technology projections and life cycle impact profiles for all lamp types are summarized in table 1.

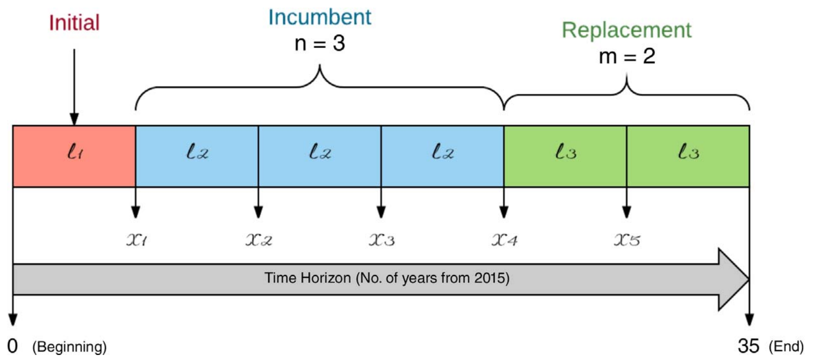

Figure 1. An example of replacement ordering.

HL is assumed to have the same non-use life cycle inventories as IL. In addition, this study assumes an annual discount rate of 3% and a social cost of carbon of $47.77 metric ton^{-1} CO_2 in 2015 with an annual increase of 4.86% [46].

2.3. Decision variables

The replacement model is constructed such that an initial lamp undergoes two technology upgrades during a time horizon of 35 years. Between each upgrade, retiring lamps are replaced with new and improved models of the same technology, purchased at the time of replacement. To explore different technology options for the upgrade, lamp type variable l is defined as:

$$l = (l_1, l_2, l_3) \tag{1}$$

where $l_i \in \{\text{LED}, \text{CFL}, \text{HL}, \text{IL}\}$. l_1 is the initial lamp type, and l_2 and l_3 are the lamp type in the first and second upgrades, respectively.

Decision variables specify the timing of lamp upgrades and replacements during the time horizon, defined as:

$$x = (x_1, x_2, \ldots, x_{n+m}) \tag{2}$$

where $x_i \in [0,35]$ is the number of years since 2015 when the ith lamp replacement occurs. It is assumed that the total lighting service required during the time horizon is fulfilled by, in succeeding order, one initial lamp of type l_1, n incumbent technology lamps of type l_2, and m replacement technology lamps of type l_3. The initial lamp is 'upgraded' to the incumbent technology at x_1 and to the replacement technology at x_{n+1}. In the case where an initial lamp does not exist, $x_1 = 0$. Operation of the last lamp is truncated at the end of the time horizon using a terminal value method. It should be noted that, in addition to x_i, n and m are also considered as decision variables in the model. Figure 1 shows the replacement order for an example where $n = 3$ and $m = 2$. Note that the first lamp (initial) is operated from $0 - x_1$, the second lamp from $x_1 - x_2$, and so on.

2.4. Optimization model

For a given combination of initial and upgrade technologies l, the optimization problem to find the optimal values of x, n, and m, can be formulated as follows:

$$\begin{aligned} &\min_{x,n,m} f(M, U, W, l, x, n, m) \\ &= \min_{n,m} \left\{ \min_{x} f(M, U, W, l, x, n, m) \right\}. \end{aligned} \tag{3}$$

Subject to

$$\begin{gathered} x_1 \le \text{LT}(l_1, 0). \\ x_{i+1} - x_i \le \text{LT}(l_2, x_i); i \in \{1, \ldots, n\} \\ x_{i+1} - x_i \le \text{LT}(l_3, x_i); i \in \{n+1, \ldots, n+m-1\} \\ 35 - x_i \le \text{LT}(l_3, x_i); i = n+m \\ 0 \le x_i \le 35 \\ n \in \{0, \ldots, n_{\max}\} \\ m \in \{0, \ldots, m_{\max}\} \end{gathered}$$

where f is the objective function composed of *impact functions* M, U, W, which represent the impacts before, during, and after the use-phase of the lamp, respectively. LT (l,x) is the rated lifetime (in years) of the lamp of type l in year x. The objective function f can take the forms of: (1) cost to consumer (abbreviated as Cost), (2) primary energy (abbreviated as Energy), (3) GHG emissions (abbreviated as Emissions), or (4) life cycle cost (LCC), which is defined as the sum of cost to consumer and social cost of carbon. The model is also used to optimize a 'burnout' replacement policy, in which each lamp is replaced explicitly at the end of its rated lifetime. This is done by turning the first four inequality constraints into equality constraints. Detailed definitions of the modeling functions can be found in supplementary appendix A.

Similar to the Wagner–Whitin approach in dynamic programming, this model allows the objective function to depend only on the decision epoch to replace, which determines the optimal useful lifetime of the lamps [15, 48]. Since n and m are the numbers of decision epochs to replace within each technology upgrade, the minimization of f with respect to x, n, and m is separable into a minimization with respect to x, nested within the minimization of n and m, as shown in equation (3). This allows the inner optimization to

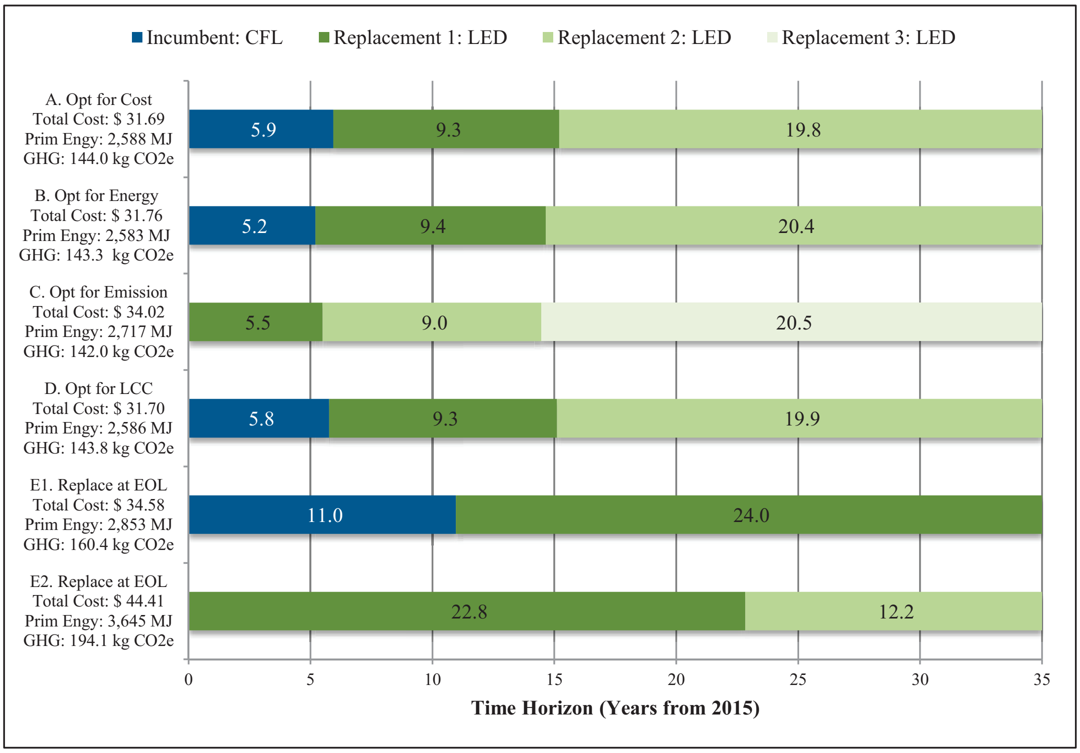

Figure 2. Optimized replacement policies (A–D) and burnout replacement policies (E1 and E2) for Case 1 baseline scenario. (Note that LCC is the sum of cost to consumer and social cost of carbon.)

be solved with respect to x using a nonlinear programming algorithm and repeated $n_{max} \times m_{max}$ times for all feasible combinations of n and m.

3. Results

In this section, the optimization results are presented for two representative cases—Case 1: a lamp is purchased at the start of the time horizon and Case 2: a lamp of either IL, HL, CFL, or LED is already in use at the beginning, assuming 100% of its service life remaining. Case 1 addresses the question of what to purchase given the decision to purchase while Case 2 explores the time-zero decision of whether to keep or replace a lamp that is still in working condition. By assuming a full service life for the initial lamp, the model can determine exactly at which point to favorably retire the lamp. In both cases, optimization runs are performed for all permutations of the lamp types, as defined in equation (1), to obtain the optimal replacement policies among all possible upgrade scenarios.

3.1. Baseline case results

Figure 2 presents the optimized replacement policies for Case 1 at 3 HOU under different objectives: (A) Cost, (B) Energy, (C) Emissions, and (D) LCC. For all objectives, the optimal policies occur under the upgrade scenario where $l_2 = \text{CFL}$ and $l_3 = \text{LED}$. Note that the initial lamp type does not affect the results since it is replaced immediately at the start of the time horizon. For comparison, two burnout replacement policies—E1 (an optimized solution where a CFL is purchased and later upgraded to an LED) and E2 (a suboptimal solution where an LED is purchased from the start) are also presented. Figure 3 shows a breakdown of the LCC-optimized policy (D) per individual lamp contribution.

Table 2 provides a summary of the LCC-optimized policies for both Case 1 and Case 2 under different initial lamp types l_1 and HOU rates. To compare across the lamp usage rate, all life cycle impact values in the table are normalized to 1 HOU. Note the optimized policies for both Case 2 with $l_1 = \text{IL}$ and Case 2 with $l_1 = \text{HL}$ recommend the immediate disposal of the initial lamp and placement policies same as those for Case 1, except for when HOU = 1/7. A complete set of results is available in supplementary appendix F.

3.2. Regional differences

Due to differences in the regional grid electricity and transportation in terms of cost, primary energy intensity, and carbon intensity, the policies are expected to vary by region. Table 3 shows the 3 HOU regional results for the District of Columbia (DC), Texas (TX), and California (CA), which provide a representation for the Eastern, Texas, and Western Interconnections, respectively. Each state's electricity profile (except for cost) is based on the North American Electric Reliability Corporation (NERC) region it is in. Detailed grid profiles and replacement policies for the three regions, as well as for Illinois, Kansas, Wyoming, and Hawaii can be found in supplementary appendices A, D, and F.

Table 2. LCC optimized policies under various l_1 and HOU. (Note that all life cycle impact values are normalized to 1 HOU.)

HOU [hr day^{-1}]	Cost to consumer [\$/HOU]	Electricity [kWh/HOU]	Primary energy [MJ/HOU]	GHG emissions [kg CO_2e/HOU]	Social cost of carbon [\$/HOU]	Replacement policy (2015–2050) [Purchase year]
Case 1						
1/7	20.00	149.8	1634	84.3	5.48	LED in 2015
1.5	12.27	75.0	956	54.3	3.14	CFL in 2015; LED in 2021 and 2030
3	10.57	74.2	862	47.9	2.82	CFL in 2015; LED in 2020 and 2030
12	8.53	64.1	729	39.4	2.35	CFL in 2015; LED in 2017, 21, 25, 30, and 39
Case 2 with l_1 = IL						
1/7	19.75	151.2	1634	86.4	5.38	Keep IL; LED in 2016
1.5	12.29	75.0	956	54.3	3.14	Discard IL; CFL in 2015; LED in 2021 and 2030
3	10.57	74.2	862	47.9	2.82	Discard IL; CFL in 2015; LED in 2020 and 2030
12	8.54	64.1	729	39.4	2.35	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
Case 2 with l_1 = HL						
1/7	18.47	144.7	1553	83.2	5.06	Keep HL; LED in 2017
1.5	12.29	75.0	956	54.3	3.14	Discard HL; CFL in 2015; LED in 2021 and 2030
3	10.57	74.2	862	47.9	2.82	Discard HL; CFL in 2015; LED in 2020 and 2030
12	8.54	64.1	729	39.4	2.35	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
Case 2 with l_1 = CFL						
1/7	11.02	89.2	936	50.7	3.07	Keep CFL; LED in 2024
1.5	10.49	75.0	911	48.2	2.84	Keep CFL; LED in 2021 and 2030
3	9.68	74.2	840	44.9	2.67	Keep CFL; LED in 2020 and 2030
12	8.31	64.1	724	38.7	2.31	Keep CFL; LED in 2017, 21, 25, 30, and 39
Case 2 with l_1 = LED						
1/7	10.42	84.6	886	47.8	2.91	Keep LED; LED in 2025
1.5	9.98	83.2	872	46.9	2.85	Keep LED; LED in 2025
3	9.30	71.8	811	43.3	2.59	Keep LED; LED in 2021 and 2030
12	8.13	63.2	712	38.0	2.28	Keep LED; LED in 2018, 21, 25, 31, and 39

Table 3. Regional LCC-optimized policies at 3 HOU under various l_1. (Label in parenthesis represents NERC region.)

Region	Cost to consumer [\$]	Electricity [kWh]	Primary energy [MJ]	GHG emissions [kg CO_2e]	Social cost of carbon [\$]	Replacement policy (2015–2050) [Purchase year]
Case 1						
DC (RFCE)	34.32	222.9	2844	126.5	7.49	CFL in 2015; LED in 2020 and 2030
TX (ERCT)	30.78	223.0	2472	147.1	8.66	CFL in 2015; LED in 2020, and 2030
CA (CAMX)	38.18	207.5	2412	88.9	5.07	CFL in 2015; LED in 2019, 2025, and 2034
Case 2 with l_1 = IL or Case 2 with l_1 = HL						
DC (RFCE)	34.35	222.9	2844	126.5	7.49	Discard IL/HL; CFL in 2015; LED in 2020 and 2030
TX (ERCT)	30.81	223.0	2472	147.1	8.66	Discard IL/HL; CFL in 2015; LED in 2020 and 2030
CA (CAMX)	38.21	207.5	2412	88.9	5.07	Discard IL/HL; CFL in 2015; LED in 2019, 25, and 34
Case 2 with l_1 = CFL						
DC (RFCE)	31.65	222.9	2777	117.2	7.05	Keep CFL; LED in 2020 and 2030
TX (ERCT)	28.11	223.0	2407	137.9	8.22	Keep CFL; LED in 2020 and 2030
CA (CAMX)	35.51	207.5	2347	79.8	4.63	Keep CFL; LED in 2019, 2025, and 2034
Case 2 with l_1 = LED						
DC (RFCE)	30.45	215.5	2684	113.3	6.84	Keep LED; LED in 2021 and 2030
TX (ERCT)	27.03	215.6	2324	133.1	7.96	Keep LED; LED in 2021 and 2030
CA (CAMX)	34.33	214.8	2233	73.4	4.31	Keep LED; LED in 2021 and 2030

3.3. Sensitivity analysis

Table 4 lists the parameter values used to test the sensitivity of the baseline scenario under the LCC objective. Each of the lower and higher values from the ten categories of parameters were tested one at a time. The sensitivity results, shown in figure 4, are ordered in terms of the changes in the objective value normalized to a unit of change in the parameter, compared to the baseline scenario. Thus, even though the variation from *LED Net Price Reduction* seems smaller than that from *Fixed Installation and EOL Cost* in figure 4, the variation per unit of change is greater from the former parameter than from the latter. For reference, the baseline scenario yields a LCC of \$40.15. A list of policies per parameter value change is available in supplementary appendix B.

Table 4. Parameter values tested for sensitivity analysis. (See supplementary appendix B for additional details.)

ID	Parameters	Units	Lower value	Baseline value	Higher value
1	Electricity GHG emission factor (2015)	$kg\,CO_2e\,kWh^{-1}$	0.324	0.647	0.971
2	Electricity base price (2015)	$\$\,kWh^{-1}$	0.0635	0.127	0.191
3	Discount rate	%	1.50	3.00	6.00
4	Eletricity price annual growth	%	0.00	2.30[c]	4.60
5	CFL and LED base price (2015)	$	1.80 and 3.00	1.80 and 5.09[b]	7.00 and 9.00[a,b]
6	LED net efficacy growth (2015–50)	$lm\,W^{-1}$	122[c]	222[b,d]	N/A
7	Installation cost	$	0.00	0.870	1.94
8	Electricity GHG emissions annual reduction	%	0.00	1.31[c]	2.61
9	LED net price reduction (2015–50)	$	2.36	3.96[b,c]	N/A
10	LED net lifetime growth (2015–50)	hrs	30 000[b]	55 000[d]	N/A

[a] represent dimmable lamp prices.
[b] based on DOE [3].
[c] based on EIA [47].
[d] based on Bergesen *et al* [29].

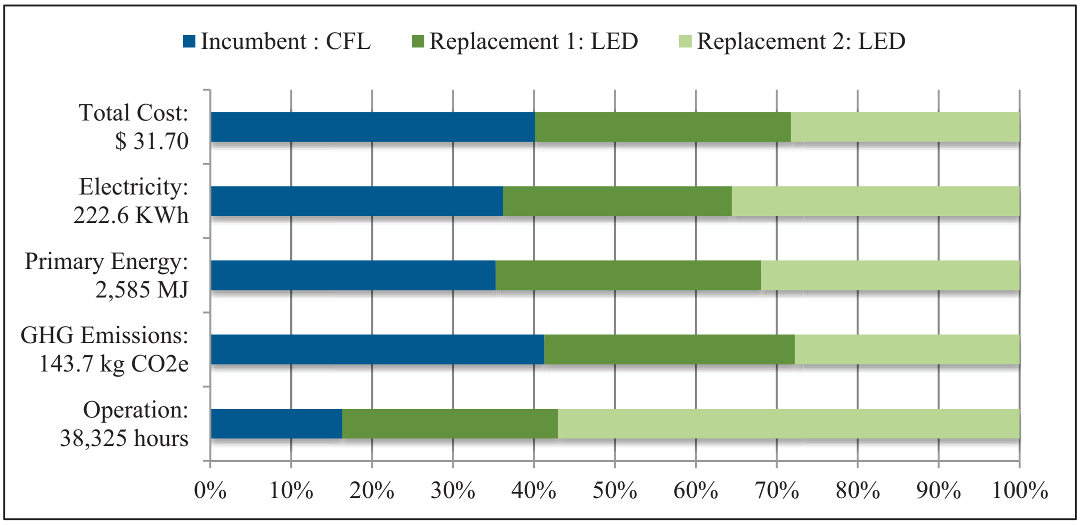

Figure 3. Breakdown of policy D (LCC-optimized) in Case 1 (baseline) per lamp contribution.

4. Discussion

4.1. Case 1: Purchase decision

Figure 2 shows that the policy depends on the objective of replacement. For example, it is optimal to delay the adoption of LED lamps until 2020 by purchasing a CFL first in terms of both Cost (policy A) and Energy (policy B). However, purchasing an LED lamp from the start is recommended from an Emissions perspective (policy C), indicating that the emission saving from using less electricity with the LED lamp outweighs the production emissions of the lamp. Two Pareto curves comparing the tradeoffs between the three objectives are available in supplementary appendix C.

A breakdown of the LCC-optimized policy (D) in figure 3 shows that the CFL contributes the least lumen-hours but the most in Cost, electricity consumption, Energy, and Emissions. However, the CFL provides both energy and cost savings overall by allowing for the adoption of lower cost and more energy-efficient LED lamps later. This is also supported by the comparison of E1 and E2 in figure 2. In addition, it is not recommended to keep any of the lamps to the end of their rated lifetime (burnout), as doing so would increase the total life cycle impacts by 9%–41%. However, given that consumers generally do not replace their lamps until burnout, consumers may still achieve 84%–86% in life cycle impact savings by following E1, compared to using ILs only.

4.2. Case 2: To keep or to replace?

Table 2 shows that the decision to keep or replace depends on the type of lamp used initially. In the baseline scenario at 3 HOU, if the initial lamp is an IL or HL, immediate disposal is recommended as well as the purchase of new lamps following the same policies as Case 1. If the initial lamp is a CFL, upgrading it to an LED is recommended in 2018 for Emissions and 2 years later for other objectives. If the initial lamp is an LED (assumed with the 2015 efficacy of 78 $lm\,W^{-1}$), replacement to a newer model between 2020 and 2021is recommended. In general replacement depends on the lamp usage rate. As shown in table 2, all life cycle impacts decrease on a per HOU basis as the lamp usage rate increases. This is a result of an increase in the utilization of each lamp in the policy, which lowers the per HOU non-use phase impacts. Another factor is increased dominance of the use-phase impacts,

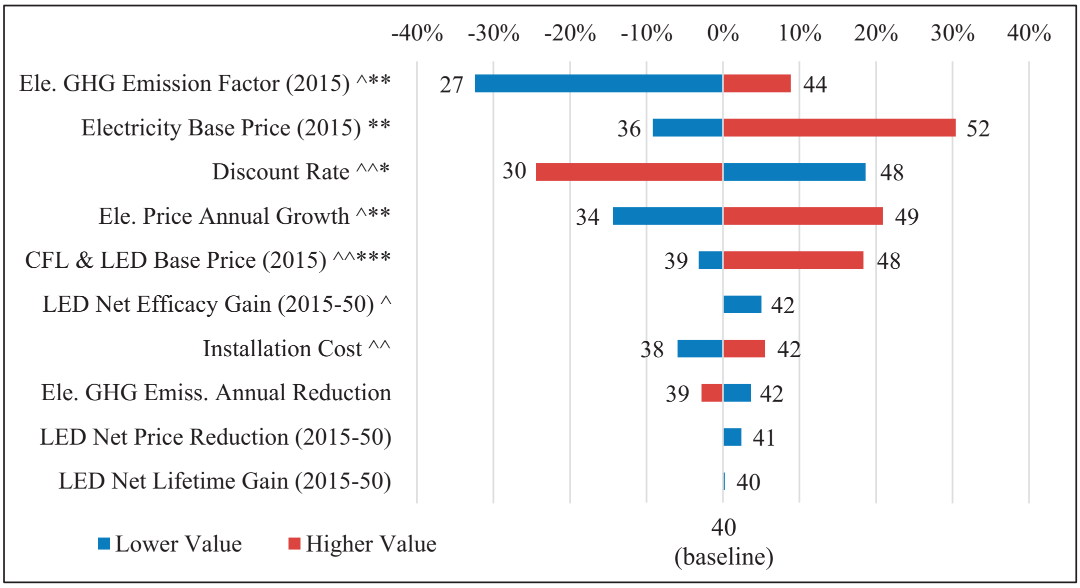

Figure 4. Change in LCC (objective value) per parameter value change. (Policy change indicators—ˆ: change in replacement timing from lower value, ˆˆ: change in total number of lamps used from lower value, *: change in replacement timing from higher value, **: change in total number of lamps used from higher value, ***: change in type of first lamp purchased.)

which favor rapid replacement and adoption of more energy-efficient lamps, thereby lowering the per HOU use phase impacts.

4.3. Sensitivity and tradeoffs

Replacement policy depends on the fuel mix of the grid, which differs by region. Although DC and TX in table 3 have different total life cycle impacts, their LCC-optimized replacement policies are similar due to their individual tradeoff between Cost and Emissions (e.g. high Cost is balanced by low Emissions in DC and vice versa in TX). Compared to DC and TX, CA benefits from an earlier adoption of LED and more frequent replacements thereafter, driven primarily by its high electricity cost. Although LED upgrade is less urgent for CA in terms of emissions due to its cleaner grid compared to DC and TX, the cost saving from rapid replacement outweighs the emission benefit from delayed replacement for CA under the LCC objective.

Figure 4 shows that the model is most sensitive to the base rates of electricity (e.g. cost and emission factor in 2015) and least sensitive to improvement to the service life of LEDs (due to early replacement). Although the variations in LED cost and efficacy are less significant than the variations in electricity attributes at affecting the objective value, they still led to important changes in the policy. For example, the lower efficacy gain resulted in the purchase of an LED lamp immediately in 2015 due to the reduced benefit from waiting. Overall, 11 out of the 17 parameter value changes led to a shift in policy—four of those (marked by single indicators) have shifted slightly in replacement timing while six (marked by double indicators) have increased in the total number of lamps used.

5. Conclusion

This study offers guidelines for lamp replacement and purchase decisions aimed at reducing cost, primary energy, and GHG emissions, as well as insights for lighting design and development priorities. Overall, optimized replacement policies can help reduce cost and environmental impacts by 89%–92% compared to the use of ILs only. The time-zero decision to keep or replace an existing lamp depends on lamp usage rate, replacement objective, and the characteristics of available replacement alternatives relative to the existing lamp. In general, lamps with higher usage rates should be upgraded first and more frequently to achieve the highest possible cost, energy, and emission savings, and vice versa. If used 3 hr day^{-1} on average, existing ILs and HLs should be replaced immediately while existing CFLs and LEDs should be kept. For purchase decisions today, it may be optimal economically and energetically to delay the adoption of LED lamps until 2018–2021 by purchasing CFLs today, unless the LEDs are price-competitive with CFLs through retail discounts or incentives. From a GHG emission's perspective, the delay in LED adoption is shorter and adoption is optimal today for the US average, DC, Texas, and Hawaii.

In all the optimized replacement policies, all lamps are replaced before the end of their rated lifetime (burnout), indicating that early replacement can take advantage of technology improvements and price reductions. For LED lamps, the average utilization rate is only 30% for 3 HOU and up to 78% for 12 HOU. Lamp utilization increases and replacement frequency decreases as lamp cost and efficacy reach steady states and the grid decarbonizes over time. Therefore, lamp manufacturers and developers may be better off maximizing the efficacy of the lamps and luminaires before durability in their designs. Given the high replacement frequency, manufacturers may want to set up low-cost and convenient recycling programs as well as pursuing strategies to dematerialize and modularize design for easy disassembly and component replacement, such as those suggested by Hendrickson *et al* [49]. US consumers may be better off purchasing LED lamps with shorter life spans at lower costs now.

6. Future work

The LCO framework in this study can be applied to evaluate linear fixture and high bay/low bay luminaires replacement in commercial/industrial indoor applications, which represent over 60% of the potential market for LEDs [6]. Meanwhile, future work can benefit from refining the modeling of key parameters (e.g. SSL technology development, time-of-use electricity cost and impacts, grid decarbonization) as new data becomes available, and capturing additional performance-related parameters that may affect replacement. For example, the heat placement effects of LEDs could alter the heating/cooling requirement in buildings [50]; energy efficiency gain could increase lamp use, resulting in a rebound effect [1]; the integration of auxiliary electronics for LED (e.g. dimming controls, motion sensing, and timing schemes) [3] could introduce additional power demands and supply chain impacts; degradation in lighting (e.g. lumen depreciation, stochastic failure, and degradation from frequent cycling) [33] may not increase replacement costs directly but may affect productivity over time; consumers may be concerned with quality variability and tradeoffs between product retail cost and performance, resulting from manufacturers' design choices in, for instance, the number of LED chips, heat sink size, and driving current [3, 51]. The deterministic model in this study provides a basis for estimating the optimal replacement timing for lighting upgrades. However, given the high degrees of uncertainty in the future state of SSL, the quality of the results can be improved by applying stochastic modeling techniques, such as Monte–Carlo simulation, on the sensitive parameters identified in this study.

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