Improving Building Sustainability: Lighting Life Cycle Optimization and Management, and HVAC Demand Response

by

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Dedication

This dissertation is dedicated to my family – Aimei, Lihua, and Lishan – without whom I would not have been able to achieve what I have today; my partner, Alex, for supporting me through thick and thin; my dissertation committee – Professor Keoleian, Saitou, Reames, and Skerlos – for guiding me in my studies and challenging me to think critically and strive for excellence; staff at the Center for Sustainable Systems and the School for Environment and Sustainability – Geoff Lewis, Helaine Hunscher, and Sucila Hernandez – for the expertise, opportunities, assistance they graciously extended to me; my uncle, Kamsek, for making the American dream possible for my family and me; my friends old and new, near and far, who always inspire me and encourage me to keep going; and last but not least, my mentors from across all stages of my life, to whom I owe my successes.

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Table of Contents

Dedication ii

Acknowledgements iii

List of Tables viii

List of Figures xi

List of Appendices xv

Abstract xvii

Chapter 1 Introduction 1

- 1.1 Background and motivation 1
- 1.2 Research goal 5
- 1.3 Chapter overview 6
- 1.3.1 Chapter 2 summary 7
- 1.3.2 Chapter 3 summary 8
- 1.3.3 Chapter 4 summary 10
- 1.3.4 Chapter 5 summary 11

Chapter 2 Replacement Policy of Residential Lighting Optimized for Cost, Energy, and Greenhouse Gas Emissions 14

- 2.1 Introduction 15
  - 2.1.1 Literature review 16
  - 2.1.2 Study aims 17
- 2.2 Method 18
  - 2.2.1 Life cycle optimization 18
  - 2.2.2 Technology projections and life cycle impact profiles 18
  - 2.2.3 Decision variables 21
  - 2.2.4 Optimization model 23

2.3 Results 24

2.3.1 Baseline case results 25

2.3.2 Regional differences 27

2.3.3 Sensitivity analysis 28

2.4 Discussion 30

2.4.1 Case 1: purchase decision 30

2.4.2 Case 2: to keep or to replace? 30

2.4.3 Sensitivity and tradeoffs 31

2.5 Conclusion 32

2.6 Future work 33

Chapter 3 Life Cycle Cost Analysis of LED Retrofit and Luminaire Replacements for 4ft T8 Troffers Based on Market Data 35

3.1 Introduction 36

3.2 Method 39

3.2.1 Life cycle cost analysis 40

3.2.2 Replacement options 43

3.3 Results 50

3.3.1 Baseline 51

3.3.2 Sensitivity analysis 54

3.4 Discussion 56

3.5 Conclusion 58

Chapter 4 LCA of Rare Earth and Critical Metal Recovery and Replacement Decisions for Commercial Lighting Waste Management 60

4.1 Introduction 61

4.1.1 Material recovery opportunities from lighting waste 63

4.1.2 Study objectives 64

4.2 Background 65

4.2.1 Lighting technologies 65
4.2.2 End of life pathways 66
4.3 Goal and scope 68
4.4 Life cycle inventory 69
4.4.1 Rare earth element recovery from linear fluorescent fixtures 70
4.4.2 Critical metal recovery from linear LED fixtures 75
4.5 Limitations and future work 79
4.6 Results – part 1: Intermediate results at end of life 81
4.6.1 Linear fluorescent fixture waste management 81
4.6.2 Linear LED fixture waste management 81
4.7 Results – part 2: comparison of replacement-end of life pathways 82
4.7.1 Fluorescent-to-fluorescent replacement 83
4.7.2 LED-to-LED replacement 84
4.7.3 Fluorescent-to-LED replacement 84
4.8 Conclusion 86
Chapter 5 Assessing Residential Building Type Specific Heating and Cooling Demand Response Potentials Using Fourier Based Multiple Regression of Smart Meter Data 89
5.1 Introduction 90
5.1.1 Literature review 92
5.2 Method 96
5.2.1 AMI data 96
5.2.2 Seasonal definition 96
5.2.3 Piecewise log-linear-Fourier change-point regression 97
5.2.4 Demand response estimation 100
5.3 Results 102
5.3.1 Regression output 102
5.3.2 Load disaggregation 105
5.3.3 Demand response 109

5.4 Discussion 114
5.5 Conclusion 117

Chapter 6 Conclusion 119

6.1 Summary 119
6.2 Further Insights and Broader Context 122

6.2.1 Energy efficiency: opportunities and limitations 122
6.2.2 Energy efficiency vs. demand response 125
6.2.3 Deterministic vs. stochastic model 126

6.3 Recommendations for future research 127

Appendices 131
Bibliography 204

List of Tables

Table 1.1: Chapter overview. 6
Table 2.1: Technology projection and life cycle impact profiles of average 60W-equivalent 900 lumen A19 lamps. 21
Table 2.2: Life Cycle Cost-optimized policies under different initial lamp type and HOU. (Note: all life cycle impact values are normalized to 1 HOU.) 27
Table 2.3: Regional Life Cycle Cost-optimized policies at 3HOU under different initial lamp type. (Label in parenthesis represents NERC region.) 28
Table 2.4: Parameter values tested for sensitivity analysis. 29
Table 3.1: Replacement options for a 2x4 2-lamp F32 T8 recessed troffer. 43
Table 3.2: Baseline life cycle cost (LCC) and normalized life cycle cost (NLCC) comparison. 53
Table 3.3: Attribute comparison of different replacements for a fluorescent troffer luminaire. 57
Table 4.1: Comparison of global warming impact from different REE recovery methods from fluorescent lamp waste. 75
Table 5.1: Load information by service classes. 107
Table 5.2: Seasonal peak coincident DR potentials by service class type. 112
Table A.1: Definitions of impact functions per optimization objective. 133
Table A.2: 2015 electricity price [$/kWh] and annual growth rate to 2050 of selected state. 137
Table A.3: 2015 average per lamp transportation primary energy [MJ] and annual growth rate to 2050 for selected states. 140
Table A.4: 2015 average per lamp use phase primary energy [MJ] and annual growth rate to 2050 for selected states. 141
Table A.5: 2015 average per lamp transportation GHG emission [kg CO_2e] and annual growth rate to 2050 for selected states. 143
Table A.6: 2015 average per lamp use phase GHG emission [kg CO_2e] and annual growth rate to 2050 for selected states. 144

Table A.7: Percent value change in parameters compared to their baseline values. 149
Table A.8: Summary of LCC-optimized policies per parameter value change (listed in Table A.7) compared to Case 1 baseline scenario. 149
Table A.9: Summary of regional Cost-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.).. 153
Table A.10: Summary of regional Energy-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.).. 154
Table A.11: Summary of regional Emissions-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.).. 154
Table A.12: Fuel cycle primary energy factor, and GHG emission factor for alternative fuel mixes. Exponential growth is assumed between 2015 and 2050. 156
Table A.13: Summary of Life Cycle Energy-optimized replacement policies at 3 HOU under alternative fuel mixes. 156
Table A.14: Summary of GHG Emission-optimized replacement policies at 3 HOU under alternative fuel mixes. 157
Table A.15: Optimal replacement policy for typical US consumers (using US average grid mix and Kansas (US centroid) as the location). 158
Table A.16: Optimal replacement policy for consumers in DC (using RFCE grid mix). 160
Table A.17: Optimal replacement policy for consumers in Illinois (using RFCW grid mix). ... 161
Table A.18: Optimal replacement policy for consumers in Kansas (using SPNO grid mix). 163
Table A.19: Optimal replacement policy for consumers in Texas (using ERCT grid mix). 164
Table A.20: Optimal replacement policy for consumers in Wyoming (using RMPA grid mix).166
Table A.21: Optimal replacement policy for consumers in California (using CAMX grid mix). 167
Table A.22: Optimal replacement policy for consumers in Hawaii (using HICC grid mix)..... 169
Table A.23: Optimal replacement policy for typical US consumers if the grid mix becomes 100% coal by 2050. 170
Table A.24: Optimal replacement policy for typical US consumers if the grid mix becomes 100% natural gas by 2050. 172
Table C.1: Input-output for an 8” fluorescent linear fixture recycling with hydrometallurgical leaching of rare earth elements from its phosphor fraction. 185

Table C.2: Input-output for an 8” LED linear fixture recycling with hydrometallurgical leaching of rare earth elements from its phosphor fraction. 196
Table C.3: Life cycle inventory of Linear fluorescent fixture from Cradle-to-Gate. 197
Table C.4: Life cycle inventory of Linear LED fixture from Cradle-to-Gate. 199
Table C.5: Lighting system attributes. 201

List of Figures

Figure 2.1: An example of replacement ordering. 23

Figure 2.2: Optimized replacement policies (A-D) and burnout replacement policies (E1 and E2) for Case 1 baseline scenario. (Note LCC is the sum of Cost to Consumer and Social Cost of Carbon). 26

Figure 2.3: Breakdown of policy D (LCC-optimized) in Case 1 (baseline) per lamp contribution. 26

Figure 2.4: Change in Life Cycle Cost (objective value) per parameter value change. (Policy change indicators – ^: change in replacement timing from Lower Value, ^^: change in total number of lamps used from Lower Value, *: change in replacement timing from Higher 29

Figure 3.1: Life cycle cost product system boundary based on replacement lighting type. Within each system boundary, the component flows in black are common between systems, thus only those in blue are examined for each system. 40

Figure 3.2: System efficacy and material cost for 6 types of replacement lighting products. (Note: the system efficacies of LED troffers w/ RL are not plotted as they are the same as those of direct wire LED lamps. Material cost includes ballast for fluorescent lamps and plug & play LEDs.) (RL = with replaceable lamps, NRL = with non-replaceable lamps, Min. reqmt = minimum requirement, BF = ballast factor) 50

Figure 3.3: (Top left) life cycle cost (LCC) decomposition, (top right) system efficacy, (bottom left) total LCC in present value, and (bottom right) normalized LCC (per klm) of six replacement options for a 2x4 2-lamp F32 T8 recessed troffer. (Yellow diamonds represent mean value, RL = with replaceable lamps, NRL = with non-replaceable lamps) 52

Figure 3.4: Sensitivity of the mean normalized life cycle cost (NLCC: $/klm) to ballast factors, electricity prices, electrician rates, social cost of carbon, and annual operations. (RL = with replaceable lamps, NRL = with non-replaceable lamps) 55

Figure 4.1: LCA system boundaries. Part 1 presents the intermediate LCIA results at the end of life phase. Part 2 presents the final results across each system's life cycle(s). (*Waste treatment is necessary for fluorescent lamps before being disposed into landfills.) 69

Figure 4.2: Process flow diagram for the end of life management of a linear fluorescent fixture via: 1) recycling with REE recovery, and 2) landfill disposal. 73

Figure 4.3: Environmental impacts per 1 kg REE recovered from the phosphor fraction of the fluorescent lamp waste via mercury distillation, leaching, and solvent extraction. 74

Figure 4.4: Process flow diagram for the end of life management of a linear LED fixture via: 1) recycling with critical metals recovery, and 2) landfill disposal. 77

Figure 4.5: Environmental impacts per 1 kg gallium recovered from the LED fraction of linear LED lamp waste via leaching and solvent extraction. 79

Figure 4.6: Selected environmental impacts of recycling and landfilling a linear fluorescent fixture and a linear LED fixture in full vs. by lamps and electro. (electronics) only at end of life. (Note: results represent per materials discarded as a result of replacement.) 82

Figure 4.7: Selected environmental impact indicators compared across 16 different replacement-EOL pathways. (Functional unit: 1 Mlmh of lighting service, Extd. = Extended, Rep. = Replacement) 85

Figure 5.1: Data domain partitioning. 98

Figure 5.2: Examples of piecewise regression fit. 104

Figure 5.3: Distribution of r2 (top left), change-points (top right), slopes: mh, mc (bottom left), and intercepts: bh, bc (bottom right) from regressions, separated by service classes. (SF = single family, MF = multi-family, NE = non-electric, E = electric) 105

Figure 5.4: Average daily temperature profiles and average whole-home load profiles with disaggregated heating, cooling, and baseload (whole-home demand is from ground truth data). 106

Figure 5.5: Seasonal average diurnal temperature profiles and average whole-home load profiles with heating and cooling demand response potentials. (Bands represent 95% confidence intervals, whole-home demand is from ground truth data). 109

Figure 5.6: Average top 5 peak coincident heating DR potential in the winter and cooling DR potential in the summer in absolute term (left) and in relative term to total load during those hours (right), separated by service classes. 110

Figure 5.7: DR resource duration curves aggregated from all service class customers (red line is sorted by the same hour order as the black line). 111
Figure 5.8: DR profile (left axis) aggregated from all service class customers compared to ComEd's system load profile (right axis). Daily peak hour demand is shown. 112
Figure 5.9: Aggregated DR potentials (left axis) sorted by the same hour order as ComEd's load duration curve (right axis). 113
Figure 5.10: Box plot providing the 25th, 50th, and 75th percentile of aggregated heating DR potential throughout the day in the winter and aggregated cooling DR potential throughout the day in the summer. 114
Figure A.1: Comparison of projected rated lifetime of lamp by type. 132
Figure A.2: Comparison of projected purchase cost of lamp by type. 136
Figure A.3: Comparison of projected efficacy of lamp by type. 138
Figure A.4: Comparison of lamp purchase price per change in CFL & LED Base Price and LED Net Price Reduction (2015-2050). 147
Figure A.5: Comparison of LED efficacy per change in LED Net Efficacy Gain (2015-2050). 148
Figure A.6: Comparison of LED rated lifetime per change in LED Net Lifetime Gain (2015-2050). 148
Figure A.7: Pareto curve of Cost-Energy (left) and Cost-Emissions (right) for Case 1 baseline scenario. 150
Figure A.8: Trends in average electricity cost, grid primary energy factor, and GHG emission factor for selected regions. 152
Figure B.1: Lamp power rating and cost of fluorescent, plug & play LED, direct wire LED, and hybrid LED lamps. 174
Figure B.2: System power rating and cost of LED troffers with non-replaceable lamps. 175
Figure B.3: Comparison of system efficacy and material cost for 6 types of replacement lighting products at three ballast factors. (Note: the system efficacies of LED troffers w/ RL are not plotted as they are the same as those of direct wire LED lamps. Material cost includes ballast for fluorescent lamps and plug & play LEDs.) (RL = with replaceable lamps, NRL = with non-replaceable lamps, Min. reqmt = minimum requirement, BF = ballast factor) 176

Figure B.4: Life cycle cost (LCC) in present value of six replacement options for a 2x4 2-lamp T8 recessed troffer operating at 2000 hr/yr for 10 years, \$0.12/kWh, \$52.92/metric ton CO2, and three ballast factors (0.76, 0.88, 1.18). (LCC/klm means LCC normalized per thousand lumens. Bars represent the minimum and maximum of the LCC based on the surveyed retrofit products.) 180

Figure B.5: Wiring diagrams for single ended direct drive LED lamps. (Image credit: Atlanta Light Bulbs 2020) 181

Figure B.6: Wiring diagrams for double ended direct drive LED lamps. (Image credit: Atlanta Light Bulbs 2020) 181

Figure C.1: Proposed flow sheet for REE recovery from fluorescent lamp waste. (Adapted from Tunsu et al. 2016) 184

Figure C.2: Laboratory setup for REE recovery from fluorescent lamp waste. (adapted from Tunsu et al. 2016) 185

Figure C.3: Proposed process flow for Indium and Gallium recovery from LED waste dust through two-stage leaching and annealing. (Adapted from Swain et al. 2015) 188

List of Appendices

Appendix A Chapter 2 Supplemental Information 131
A.1 Model functions 131
A.1.1 Objective functions 131
A.1.2 Meta functions 133
A.1.3 Life cycle cost functions 135
A.1.4 Primary energy functions 139
A.1.5 Greenhouse gas emission functions 142
A.1.6 Social cost of carbon functions 145
A.2 Supplemental information on sensitivity analysis 146
A.2.1 Parametric assessment 146
A.2.2 Results from parametric assessment 149
A.3 Tradeoff between objectives 150
A.4 Regional differences in replacement policy 151
A.5 Alternative generation from coal and natural gas 155
A.6 Results by regions and fuel type 158
A.6.1 US average 158
A.6.2 DC: District of Columbia (NERC: RFCE) 160
A.6.3 IL: Illinois (NERC: RFCW) 161
A.6.4 KS: Kansas (NERC: SPNO) 163
A.6.5 TX: Texas (NERC: ERCT) 164
A.6.6 WY: Wyoming (NERC: RMPA) 166
A.6.7 CA: California (NERC: CAMX) 167
A.6.8 HI: Hawaii (NERC: HICC) 169
A.6.9 All coal scenario 170
A.6.10 US average in an all-natural gas scenario 172

Appendix B Chapter 3 Supplemental Information 174
B.1 Market information on commercial lighting replacement products 174
B.2 Life cycle cost analysis – mathematical formulation 177
B.3 Influence of ballast factor on life cycle cost 179
B.4 LED retrofit rewiring schematics 181
Appendix C Chapter 4 Supplemental Information 182
C.1 Rare earth element and critical metal recovery process modeling 182
C.2 Yttrium and europium recovery from linear fluorescent fixture waste 182
C.3 Gallium recovery from linear LED fluorescent fixture waste 186
C.3.1 Lixiviant requirement 189
C.3.2 Stage 1 leaching (Indium leaching) 190
C.3.2.1 Heat requirement 190
C.3.2.2 Electricity for stirring 191
C.3.2.3 Electricity for solid-liquid separation 192
C.3.3 Mixing with Na_2CO_3 192
C.3.4 Electricity for ball milling 192
C.3.5 Electricity for drying 193
C.3.6 Electricity for annealing 194
C.3.7 Stage 2-leaching: heating, stirring, & solid-liquid filtration 194
C.3.8 Additional considerations 195
C.3.8.1 Solvent extraction 195
C.3.8.2 Electricity for pumping 195
C.3.8.3 Infrastructural allocation 196
C.3.8.4 Transportation 196
C.4 Life cycle inventory of linear fixtures from cradle-to-gate 197
C.5 Equations for calculating the life cycle impacts per functional unit 201

Abstract

Residential and commercial buildings represent 39% of global energy carbon emissions. In the U.S., buildings consume 40% of the total energy consumption and thus represent a substantial energy saving opportunity. Additionally, building energy flexibility, or the ability to reduce or move demand to a different time, is playing an increasingly important role in grid modernization and renewable integration by helping to balance supply. Material efficiency is another foundation to sustainability, as many energy-efficient and renewable technologies depend on the use of specialty materials, which are dwindling in supply and many face geopolitical conflicts. This dissertation advances methods of life cycle analysis and data analytics while addressing some of these issues and opportunities in three key aspects – how to choose better products, how to better manage products at their end of life, and how to use energy more effectively.

Chapter 2 and 3 examine the *keep vs. replace* conundrum by studying the replacement of residential and commercial lighting, in which the rapidly changing LED technology creates unclear tradeoffs with incumbent lighting in terms of cost, energy savings, and emissions. The results suggest that while LED lighting offers competitive performance and life cycle cost as fluorescent lighting, there is less advantage (or benefit) for immediate LED adoption in a lower use, upfront cost-sensitive, or slowly decarbonizing grid situation.

Chapter 4 evaluates the life cycle impacts of recovering rare earth and critical metals from spent linear fluorescent and LED fixtures, respectively. This chapter also assesses the impacts of

extended use and modular (component) replacement to assess the value of reverse logistics (reuse, remanufacturing, and recycling). The results show that both types of metal extraction create net environmental impacts, which can be mitigated with process optimization and waste preprocessing to increase extraction efficiency. While modular replacement leads to overall lower environmental burdens, full replacement can offer incentive for LED recycling as their metal-heavy housing structure and heat sink are attractive to recyclers.

Chapter 5 performs piecewise log-linear-Fourier regressions on whole-home smart meter data and outdoor temperature data to disaggregate the thermostatically controlled loads from whole-home consumption and to estimate the technical thermal demand response potentials in the Midwest. The results suggest that single family buildings, being the higher energy users and larger customer base than multi-family, can provide higher per customer and aggregated demand flexibility. However, multi-family buildings, particularly those with a central HVAC system, may have the advantage of pooled demand across multiple units and should therefore be considered accordingly.

By examining the three decision-making questions related to technology and product selection (Chapter 2 - Chapter 3), waste management and material recovery (Chapter 4), and energy use and demand response (Chapter 5), the research helps inform decision making for building managers and energy consumers, and provide industry with insights regarding product design, reverse logistics, and demand response program recruitment.

Chapter 1 Introduction

1.1 Background and motivation

A low-carbon sustainable future necessitates a holistic blend of technologies and practices geared towards energy conservation, material efficiency, renewable resources, and more. To fully examine the tradeoffs and unintended consequences of different sustainable technology pathways, life cycle-based methods are necessary to account for the impacts from all the subsystems and processes within a specified system boundary (e.g. a product's life cycle), including the upstream (e.g. resource extraction, manufacturing) and downstream (e.g. end of life management) impacts from the use phase, as well as the interaction with auxiliary systems optionally (e.g. consequential methods). These methods include life cycle assessment, life cycle cost analysis, and life cycle optimization, the latter of which combines life cycle accounting methods with optimization to find the decision variables that enable the "best" outcome with respect to an objective (e.g. lowest cost).

Residential and commercial buildings represent 39% of global energy carbon emissions – 11% is embodied carbon (i.e. emissions from construction and material production) and 28% is from building operations (UN Environmental Program 2017, Davis et al. 2018). In order to curb global temperature rise, the UN environmental program (2017) suggests that the energy use intensity (EUI, energy use per floor area), needs to be reduced by 30% compared to 2015 and be net zero by 2050. In the U.S., buildings consume 40% of the total energy (US EIA 2020) and thus represent much energy saving potential. With the advent of smart controls, buildings also offer opportunity for grid modernization and renewable integration by operating as flexible loads to balance supply on the grid and location for distributed renewables (e.g. rooftop solar). Beyond energy, material use efficiency is another key consideration for sustainability. Many energy-efficient and renewable technologies depend on critical natural resources. For example, rare earth metals are used in magnets for electric motors, batteries, solar panels, as well as energy-efficient lighting. These resources are extremely limited in supply and often face geopolitical conflicts. It is therefore important to examine pathways for material efficiency as well as for reverse logistics such as reuse, remanufacturing, and recycling. *This dissertation advances methods of life cycle analysis (e.g. life cycle optimization, life cycle cost analysis, life cycle assessment) and data analytics while addressing some of these building sustainability issues in three key aspects – how to choose better products, how to better manage products at their end of life, and how to use energy more effectively.*

Building performance and energy efficiency can be improved through weatherization (i.e. changing the building envelope to increase its protection from the elements via air sealing, insulation, etc.) and the use of more energy efficient thermal systems and appliances. To this end, much attention and funding have been in place to advance the development of transformative and energy efficient technologies (e.g. light emitting diodes (LED) lighting, geothermal heat pumps) and to facilitate the adoption of these technologies through incentive programs, equipment standards, and building codes. For example, equipment and appliance standards and labels (e.g. Energy Star) help inform consumer purchase decisions and drive the adoption of energy efficient products. The cumulative savings from appliance standards is estimated to reach $2 trillion by 2030 since their inception in 1987 (US DOE 2020).

However, despite these top-down policies, evidence suggests that the adoption of energy efficient products is slow and often hindered by cost (US DOE 2016). In addition, many of these technologies are new to consumers and undergoing rapid development, which creates a consumer choice dilemma in terms of when to adopt them. A consumer can choose to purchase a new energy efficient replacement right away for its energy saving benefit. Or the consumer can defer the replacement to a future time when lower price, better performing, and more energy efficient versions of the product come along. The tradeoff in question is whether the cost and energy saving potentials of the future product is higher than those achievable by its incumbent counterpart today.

Chapter 2 addresses this *keep vs. replace* conundrum by examining the replacement of a commonly used household lamp – a 60W equivalent lamp available as an incandescent lamp, a halogen lamp, a compact fluorescent lamp (CFL), and a LED lamp. This chapter focuses on the transition timing between technologies, which takes into account the technology advancement and maturity. **Chapter 3** examines the replacement question in the context of linear troffers, one of the most common commercial lighting fixtures, and is focused on the differences between LED replacement options. Lighting is the largest (17%) electricity end use in US building sector, thus providing considerable opportunity for cost and energy savings. LED lighting products are becoming more energy efficient, cost-competitive, and numerous in options. The LED alternatives for linear troffers, for example, include direct wire, plug & play, hybrid retrofit lamps, and full LED troffers, which come at different purchase prices and require a varying degree of electrical modification. Hence LED lighting provides a suitable case study for examining the tradeoffs between different replacement technologies and options in terms of life cycle cost, carbon emissions, energy consumption, and carbon cost.

A low-carbon future requires closed-loop end of life (EOL) management pathways and material-efficient product designs. Replacement decisions affect EOL management in terms of what product systems or components are taken out of service, and when this decommissioning takes place. Replacement also affects future waste scenarios according to the products selected during replacement. How will the technology transition from fluorescent to LED affect future waste scenarios? Additionally, lighting waste represents a significant source of reusable rare earth elements and critical metals, which are vital to low-carbon technologies (e.g. electric motors, solar panels). These special metals face supply risk due to their dwindling stock relative to their growing demands and the geopolitical conflicts around them. Therefore, there is a growing interest in recovering these metals from waste electrical and electronic equipment, such as spent lighting.

Chapter 4 evaluates the life cycle impacts of recovering rare earth and critical metals from retired linear fluorescent fixture and linear LED fixture, respectively. Linear fixtures are used as the case study because they are among the most ubiquitous lighting type, with 1 billion installed in the U.S. (US DOE 2016). To understand different end of life management scenarios and the value of reverse logistics (i.e. the act of reusing and recycling products and materials), this chapter also assesses the impacts of extended use and modular (component) replacement relative to the benchmark of full luminaire replacement. By exploring these pathways, this chapter highlights opportunities for reducing the environmental impacts of specialty metal recovery from lighting waste as well as providing decision support to help businesses develop more sustainable programs regarding the replacement and EOL management of their lighting products.

Finally, in addition to energy efficiency and conservation, consumers can use their energy more effectively by making it flexible and responsive to the grid. This is known as demand response (DR), or demand flexibility in response to grid signal. It is a resource that allows for more effective balancing of supply and demand and, as a result, helps enhance grid resilience and reliability, increase renewable energy integration, defer capital expenditure for new power plants, and ultimately provide cost-savings to consumers. Among all building end uses, space heating and cooling represent a significant and effective DR resource. They account for 14% and 16% of the total building electricity expenditure, respectively. The large thermal inertia of buildings allows these thermostatically controlled loads to be changed intermittently (via a thermostat setpoint change) according to outdoor temperature without causing large deviation in the interior temperature and thermal discomfort (Mathieu et al. 2011).

Smart meter data are becoming more abundant, high quality, and high resolution. This enables an unprecedented level of load analysis, forecasting, and management geared towards understanding energy use behaviors and enhancing grid operations. **Chapter 5** performs piecewise log-linear-Fourier regressions on whole-home smart meter data and outdoor temperature data to disaggregate the thermostatically controlled loads from whole-home consumption and to estimate the technical HVAC DR potentials based on the load disaggregation. Leveraging the uniqueness of the ComEd smart meter dataset, which is predivided into service classes (categories) based on building types and space heating types, this chapter also compares the DR potentials between single and multi-family buildings, and electric and non-electric space heating buildings. The results help the utility to better understand their load end uses and to design more effective DR programs by recommending the type of customers to target for recruitment.

1.2 Research goal

As buildings represent a large portion of the total energy consumption in the U.S., the goal of this dissertation is to advance building sustainability by examining three decision-making questions related to technology and product selection (Chapter 2 - Chapter 3), waste management and material recovery (Chapter 4), and energy use and demand response (Chapter 5). The research findings help inform decision making for building managers, homeowners, and other energy consumers on how to choose better products, how to better manage products at their end of life, and how to use energy more effectively. They also provide manufacturers with insights on product design and material recovery, and utilities with insights on demand response program recruitment.

1.3 Chapter overview

The rest of the dissertation is arranged as shown in Table 1.1. Chapter 2 and **Error! Reference source not found.** are focused on equipment replacement policy, using residential lighting and commercial lighting, respectively, as their case study. Chapter 4 examines the environmental impacts of end of life treatment options as well as the implication of replacement choices, using commercial lighting as a case study. Chapter 5 performs load disaggregation on whole-home smart meter data to estimate the demand response potential from space heating and cooling. Chapter 6 synthesizes each of the four main chapters and, based on their findings, draws conclusions and recommends future work relevant to building energy use and sustainability that extends beyond this dissertation. Sections 1.3.1 to 1.3.4 provide a summary of each of the research chapters describing their research question, objective, novelty, and highlights.

Table 1.1: Chapter overview.

Chapter	Technology studied	Topic	Theme
1	Introduction, research goal, and overview of main chapters		
Chapter 2	Residential lighting	Replacement policy focused on inter-technology transition	How to choose better products
Chapter 3	Commercial lighting	Replacement policy focused on intra-technology options	
Chapter 4	Commercial lighting	LCA of end of life treatment and replacement implications	How to better manage products at end of life
Chapter 5	Residential space heating and cooling	Load disaggregation and demand response estimation	How to use energy more effectively
Chapter 6	Conclusion – chapter synthesis and future work		

The four research chapters in this dissertation have either been published or are in preparation for publication, as described below:

- **Chapter 2** : Liu L, Keoleian GA, Saitou K. 2017. Replacement policy of residential lighting optimized for cost, energy, and greenhouse gas emissions. *Environmental Research Letters.* 12, 114034. doi: 10.1088/1748-9326/aa9447

  Video abstract: https://youtu.be/l5kOxuiUUcc

- **Chapter 3** : Liu L, Keoleian GA, Lewis GM. Life cycle cost analysis of LED retrofit and luminaire replacements for 4ft T8 troffers based on market data (Under review by *Lighting Research and Technology*)
- **Chapter 4** : Liu L, Keoleian GA. 2020. LCA of rare earth and critical metal recovery and replacement decisions for commercial lighting waste management. *Resources, Conservation and Recycling*. 159, 104846. doi: 10.1016/j.resconrec.2020.104846
- **Chapter 5** : Liu L, Saitou K. Assessing building type specific residential space heating and cooling demand response potentials using Fourier based multiple regression of smart meter data (In preparation for *Energy & Buildings*)

1.3.1 Chapter 2 summary

Replacement Policy of Residential Lighting Optimized for Cost, Energy, and Greenhouse Gas Emissions

Research question: *Given LED's rapid improvement and cost reduction, when is it best to upgrade to LED lighting?*

Objective: This chapter: 1) develops optimal replacement policy for residential lighting that minimizes its life cycle cost, energy consumption, and GHG emissions; and 2) discusses insights on practical replacement strategies and inform SSL R&D priorities. To this end, multiple replacement scenarios incorporating different consumer locations, grid decarbonization assumptions, and future technology and cost projection for a 60 Watt-equivalent A19 lamp are analyzed. For each scenario, a few replacement policies are recommended.

Novelty: This chapter extends existing equipment replacement studies by: 1) considering the environmental impacts of replacement, which was seldomly studied, 2) examining how solid-state lighting technology improvement and grid decarbonization affect future replacement decisions for lighting, which have not been considered before, 3) and providing a novel framework for optimizing replacement policy in terms of replacement timing and technology type. By addressing these areas, this chapter aims to provide guiding policy for low-cost and low-impact residential lighting replacement across various regions of the U.S.

Highlights: Optimized replacement policies can help reduce cost and environmental impacts by 89-92% compared to the use of incandescent lamps only. In general, lamps with higher usage rates should be upgraded first and more frequently to provide the highest energy saving, and vice versa. At an average use of 3 hours/day (US avg), 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.

1.3.2 Chapter 3 summary

Life Cycle Cost Analysis of LED Retrofit and Luminaire Replacements for 4ft T8 Troffers Based on Market Data

Research question: *Given LED's rapid improvement, cost reduction, and variety in options, what are the tradeoffs between different LED replacement options?*

Objective: This chapter: 1) compares the cost benefits of different LED replacement options for a 2x4 T8 recessed troffer using market information; and 2) informs product selection based on the life cycle cost analysis. To this end, a life cycle cost (LCC) analysis is conducted to compare the cost-benefit of 5 LED replacement options (plug & play LEDs, direct wire LEDs, hybrid LEDs, LED troffers with replaceable lamps, and LED troffers with non-replaceable lamps) for a 2x4 T8 recessed troffer based on the data of 168 lighting products from an online vendor.

Novelty: With the cost and performance of linear LED lamps improving drastically in the past five years, this chapter reexamines the cost-benefit of LEDs based on current market and technology conditions so that building owners and managers can make better informed decisions regarding lighting replacement. Compared to existing studies, this chapter considers more lighting upgrade options, including hybrid LED lamps and LED replacement luminaires, some of which were not available before. The up-to-date market data highlights the latest development in lighting technologies and allows for the estimation of the range of expected life cycle costs by capturing the products' variation in lumen rating, lifetime, efficacy, and material cost. Other than cost, these attribute variations were not captured previously.

Highlights: Results of this chapter show that direct wire LED retrofits are the least-cost option to replacing fluorescent lamps in terms of normalized LCC. Plug & play lamps suffer from a lock-in with ballasts, but their ease of installation can help spur LED adoption. In cases where an existing ballast is still usable, hybrid LED retrofits provide the least upfront cost option by deferring the cost of rewiring. LED luminaires can offer improved aesthetics and reliability;

however, they have high upfront cost. Among them, luminaires with replaceable lamps offer lower cost than those without.

1.3.3 Chapter 4 summary

LCA of Rare Earth and Critical Metal Recovery and Replacement Decisions for Commercial Lighting Waste Management

Research question: *What are the environmental impacts of recovering specialty metal from lighting waste? How much environmental benefits can be achieved by reverse logistics levers such as extended use and modular replacement?*

Objective: This chapter: 1) quantifies the environmental impacts (per kg recovered) of recovering REE and CM from linear fluorescent fixtures and linear LED fixtures, respectively; and 2) compares the cost-benefit of extended use (by 25% of the luminaire's rated lifetime) and modular replacement (replacing components of the luminaire) with full luminaire replacement. To this end, an LCA is conducted by modeling 1 million lumen-hour of service from an 8ft T8 linear fixture across 16 pathways representing multiple replacement and waste management options.

Novelty: The environmental impacts at EOL are often neglected due to the dominance of the use phase impacts, as well as the paucity of economic and technical information on recycling processes. This chapter addresses the limited literature on lighting waste management by providing an LCA on the rare earth metal and critical metal recovery from spent fluorescent lighting and LED lighting, respectively, based on novel solvent extraction methods. Additionally, as waste management and material loop are a function of replacement decisions, this chapter compares the environmental impacts of three replacement pathways – extended equipment use, modular (component) replacement, and full (luminaire) replacement – to highlight opportunities for reducing the environmental impacts of specialty metal recovery from lighting waste as well as providing decision support to help businesses develop more sustainable programs regarding the replacement and EOL management of their lighting products.

Highlights: This chapter finds that recovering REE and CM from lamp waste via hydrometallurgical methods generally result in more environmental impacts than the primary production of the recovered materials. Per kg recovered, the global warming impact is 74kg and 3,687kg CO_2eq for REE and Ga, respectively. The high impacts for Ga recovery are due to Ga's low concentration (0.234 w/w%) in the LED waste. Intermediate results at the end of life stage show that recycling common metals (e.g. aluminum, copper, and sometimes steel) from fixtures can reduce or even completely offset the impacts of specialty metal recovery. Based on the end results, a mature technology like fluorescent fixtures can benefit from both extended use and modular product designs. The best strategy is to prioritize energy efficiency (e.g. by upgrading to new LED) and to choose full luminaire (lamps, electronics, and fixture) upgrades, which offer higher system efficacies, over retrofits (lamps and electronics only).

1.3.4 Chapter 5 summary

Assessing Residential Building Type Specific Heating and Cooling Demand Response Potentials Using Fourier Based Multiple Regression of Smart Meter Data

Research question: *How much demand response potential is available from residential space heating and cooling? How is demand response potential different between single family and multi-family buildings and between electric and non-electric space heating buildings?*

Objective: This chapter: 1) quantifies the technical HVAC (space heating and cooling) DR potentials from a utility's standpoint; 2) compares the DR potentials between building types (single/multi-family) and space heating types (electric/non-electric); and 3) discusses DR program design and policy implications based on the results. To this end, a piecewise log-linear-Fourier regression model is proposed to disaggregate the thermostatically controlled loads from whole-home smart meter data and to estimate the technical HVAC DR potentials.

Novelty: Compared to models with hidden Markov layers, the piecewise linear structure of the proposed model can keep the computation requirement low and offer an easy interpretation of the results. Compared to the change-point models with a prerequisite data classification step, the classification or domain partitioning is incorporated as a model constraint so that it can be optimized simultaneously with the regressions. Compared to the simple change-point models, this model uses Fourier fitting functions to capture the time-variant patterns in the baseload and time-variant demand-sensitivity to temperature to better estimate the HVAC demands. Additionally, this chapter compares the heating and cooling characteristics and potentials between different building types (single/multi-family) and space heating types (electric/non-electric), which was not examined before.

Highlights: Using smart meter data from ComEd, the model finds that space heating represents 17.4% of the winter load (7.8% annual load), and space cooling is 41.4% of the summer load (19.4% annual load). With a residential customer base of 3.69 million, the total instantaneous heating DR for the top 5 winter system peak hours is 0.93 GW and the total cooling DR for the top 5 summer peak hours is 3.6 GW. During the winter peaks, electric heat customers could on average shed 60% of their load instantaneously compared to 20% or less by their counterparts. During the summer peaks, non-electric heat customers could reduce their load by up to 61% on average, whereas electric heat customers could cut their demand by only half that. As ComEd is summer-peaking and cooling-dominant, its single family non-electric heat service class, which represents over 50% of its customer base and consumes 2-4 times more energy for cooling, is best suited to provide meaningful cooling DR during its system peak hours.

Chapter 2 Replacement Policy of Residential Lighting Optimized for Cost, Energy, and Greenhouse Gas Emissions

Abstract

Accounting for 10% of the electricity consumption in the U.S., 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 equipment 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 emission's 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 hours/day (US avg), 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.

Keywords: life cycle optimization, optimal replacement, residential lighting, light emitting diode, solid state lighting, compact fluorescent lamp energy efficiency

2.1 Introduction

In the past two decades, light emitting diode (LED) lamps have improved by 20-fold in cost and 40-fold in luminous flux (Tsao et al. 2010, Haitz and Tsao 2011). LED package efficacy could reach 200 lm/W by 2025 under the US Department of Energy (DOE)'s solid-state lighting development goals (US DOE 2016b). In 2015, lighting accounted for 10% of the electricity consumption in the U.S. (US EIA 2015). 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 (US EIA 2016), providing 261 terawatt-hours of energy saving annually (US DOE 2016b). However, the transition has been slow so far as LED still faces 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 LED. With over 3 billion units installed in the U.S., these round-shaped general service lamps represent over 147 terawatt-hours of energy saving potential for LED (US DOE 2015a). However, given the rapid improvement of LED technology and its cost reduction trajectory, when should LED 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 expenditures 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.

2.1.1 Literature review

When making purchase decisions, consumers are encouraged to look past LED's high initial cost to the energy savings over its 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. (2014) 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 to 40 times. Many studies have also demonstrated the competitive cost savings and environmental benefits of LEDs compared to incumbent lighting from a life cycle perspective (Slocum 2005, Quirk 2009, Tähkämö et al. 2012, 2013, US DOE 2012b, 2012c, IEA 2014). 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 (Regnier et al. 2004, Roger and Hartman 2005, Yatsenko and Hritonenko 2011, Hartman and Tan 2014). 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 (Kim et al. 2003, 2006, Horie 2004, Spitzley et al. 2005, Bole 2006, De Kleine et al. 2011, Tasaki et al. 2013, Mizuno et al. 2015). As the U.S. moves toward low-carbon power generation driven in part by the Renewable Portfolio Standards (DSIRE 2016, UNFCC 2015), the long-term benefits of energy efficiency gain will be lower due to an impact reduction in upstream energy and material production (Bergesen et al. 2015). With electricity accounting for most of the life cycle impacts of lighting (IEA 2014, US DOE 2012b, 2012c), 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 (2001) 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 (2014) on streetlight replacement on U.S. 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, 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 (US DOE 2013b), 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.

2.1.2 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 60W-equivalent (900 lumen)[1] lamps, which are commonly found in U.S. households, this paper seeks to provide guiding policy for low-cost and low-impact residential lighting replacement across various regions of the U.S.

2.2 Method

2.2.1 Life cycle optimization

This study uses life cycle optimization (LCO), a method that integrates life cycle assessment (LCA) with optimization analysis for enhancing product sustainability (Keoleian 2013), to construct a lighting replacement optimization model. The model draws data from LCA studies that follow ISO14040 as well as the outlook for LED technology (US DOE 2016b) and the grid (US EIA 2016). 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 (Kim et al. 2003, Spitzley et al. 2005), refrigerators (Horie 2004, Kim et al. 2006), washing machines (Bole 2006), and air conditioners (De Kleine et al. 2011).

2.2.2 Technology projections and life cycle impact profiles

LED lamps are expected to reach 150-180 lm/W in efficacy by 2020 and 50,000 hours in lifetime by 2025 (US DOE 2016b). Another study has the forecast at 250-300 lm/W and 80,000

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[1] Not all 60W-eq 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.

hours by 2050 (Bergesen et al. 2015). From 2015 to 2020, LED lamps would decrease by 40% in cost and lightweight by 33% in electronics mass and proportionally to wattage demand in terms of the heat sink (US DOE 2016b). Based on these projections, logistic models (see Appendix 0) 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 CFL is not expected to change significantly over time, improving at less than 1% annually (US DOE 2014). It is expected that both IL and HL are being phased out of operation by EISA (US DOE 2015a).

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 sub-stages from cradle-to-gate per DOE’s LCA studies (US DOE 2012b, 2012c, 2013a) 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 OEM suppliers (defined per DOE’s study) and the retailer (assumed at the geographical centroid of the continental U.S. – Kansas). It accounts for the LED weight reduction (US DOE 2016b), 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 (Nahlik et al. 2015).

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 hours per week), 1.5 (average A19 lamp usage rate in U.S. (US DOE 2015a)), and 12 HOU are also explored. Although lamp change-out is typically done by consumers themselves, an opportunity cost (Goldschmidt-Clermont 1993) equivalent to one third of the U.S. median wage of $17.40/hour (US DOL) is assigned to an estimated 9-minute 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 (US EIA 2016). 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 (US DOE 2007, 2013c, 2015a), the average primary energy factor and average GHG emission factor for the US grid are estimated to be 2.95 (kWh/kWh) and 0.647 kg $CO2_e$/kWh, 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 (Ryan et al. 2016). 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 Appendix 0 and 0.

In the EOL stage, 10% recycling is assumed for IL and HL, 20% for CFL and LED, and 30% for all lamp packaging (US DOE 2012b, US DOE 2012c). 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. Landfill cost is estimated at $45/ton (US EPA 2014, 2015a) and the same rate is applied to recycling packaging. The life cycle energy is estimated using the US Environmental Protection Agency (EPA) Waste Reduction Model (2015a) 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 2.1. 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 CO_2 in 2015 with an annual increase of 4.86% (US EPA 2015c).

Table 2.1: Technology projection and life cycle impact profiles of average 60W-equivalent 900 lumen A19 lamps.

Lamp Data	**IL**	**HL**	**CFL**		**LED**	
	2015	**2015**	**2015**	**2050**	**2015**	**2050**
Efficacy [lm/W]	15	20	70	83	78	298*
Lifetime [hr]	1,000	8,400	12,000	15,000	25,000	80,000*
Cost: Lamp	0.567	2.25	1.80 7.00 (dim.)	1.13 1.56 (dim.)*	$5.09 9.00 (dim.)	1.13* 2.00 (dim.)*
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 avg	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 avg	0.0754		0.226	0.0642	0.212	0.0409
End-of-Life	0.0128		0.0284		0.0150	0.0115

Note: All projections are modeled to grow exponentially except those marked with *, each of which follows a logistic curve as defined in Appendix 0 (Bergesen et al. 2015, Nahlik et al. 2015, US DOE 2012b, 2012c, 2013a, 2014, 2016, US DOL 2016b, US EIA 2014, US EPA 2014, 2015a).

2.2.3 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 $\boldsymbol{l}$ is defined as:

$$\boldsymbol{l} = (l_1, l_2, l_3) \tag{2.1}$$

where $l_i \in \{LED, CFL, HL, IL\}$. 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:

$$\boldsymbol{x} = (x_1, x_2, \dots, x_{n+m}) \tag{2.2}$$

where $x_i \in [0,35]$ is the number of years since 2015 when the i^{th} lamp replacement occurs. It is assumed that the total lighting service required during the time horizon is fulfilled by, in succeeding order, 1 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 2.1 shows the replacement order for an example where $n = 3$ and $m = 2$. Note that the first lamp (initial) is operated from 0 to x_1, the second lamp from x_1 to x_2, and so on.

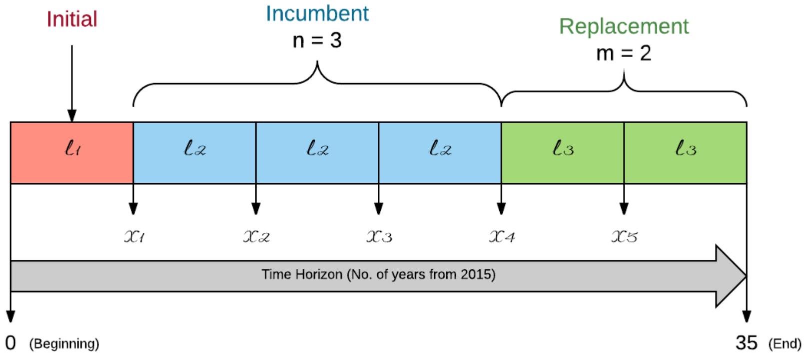

Figure 2.1: An example of replacement ordering.

2.2.4 Optimization model

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

$$\min_{\boldsymbol{x},n,m} f(M,U,W,\boldsymbol{l},\boldsymbol{x},n,m) = \min_{n,m}\left\{\min_{\boldsymbol{x}} f(M,U,W,\boldsymbol{l},\boldsymbol{x},n,m)\right\}$$

Subject to:

$$\begin{gathered}
x_1 \leq LT(l_1,0)\ ; \\
x_{i+1} - x_i \leq LT(l_2,x_i)\ ;\ \ i \in \{1,\dots,n\} \\
x_{i+1} - x_i \leq LT(l_3,x_i)\ ;\ \ i \in \{n+1,\dots,n+m-1\} \\
35 - x_i \leq LT(l_3,x_i)\ ;\ \ i = n+m \\
0 \leq x_i \leq 35 \\
n \in \{0,\dots,n_{max}\} \\
m \in \{0,\dots,m_{max}\}
\end{gathered} \tag{2.3}$$

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 (abbr. as Cost), 2) Primary Energy (abbr. as Energy), 3) GHG Emissions (abbr. 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 model functions can be found in 0.

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 (Wagner and Whitin 1958, Hartman and Tan 2014). 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 (2.3). This allows the inner optimization to 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.

2.3 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 (2.1), to obtain the optimal replacement policies among all possible upgrade scenarios.

2.3.1 Baseline case results

Figure 2.2 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 $l_2 = CFL$ and $l_3 = LED$. 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 2.3 shows a breakdown of the LCC-optimized policy (D) per individual lamp contribution.

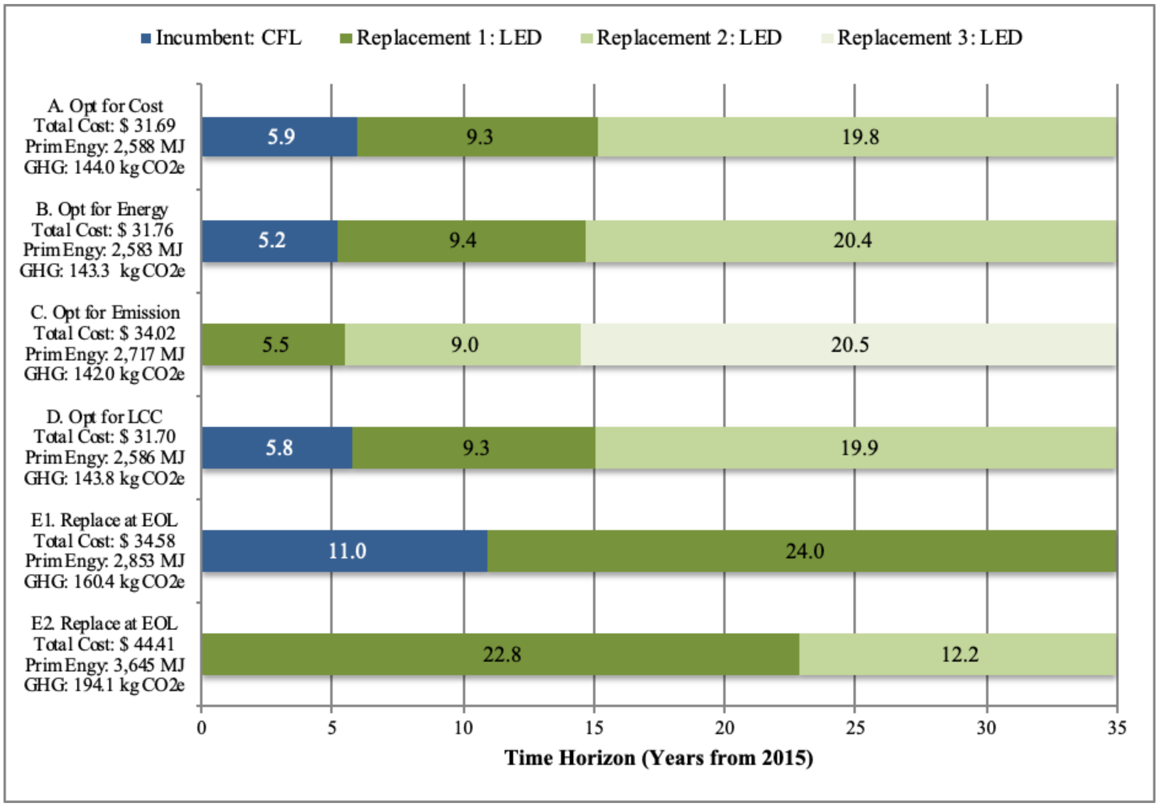

Figure 2.2: Optimized replacement policies (A-D) and burnout replacement policies (E1 and E2) for Case 1 baseline scenario. (Note LCC is the sum of Cost to Consumer and Social Cost of Carbon).

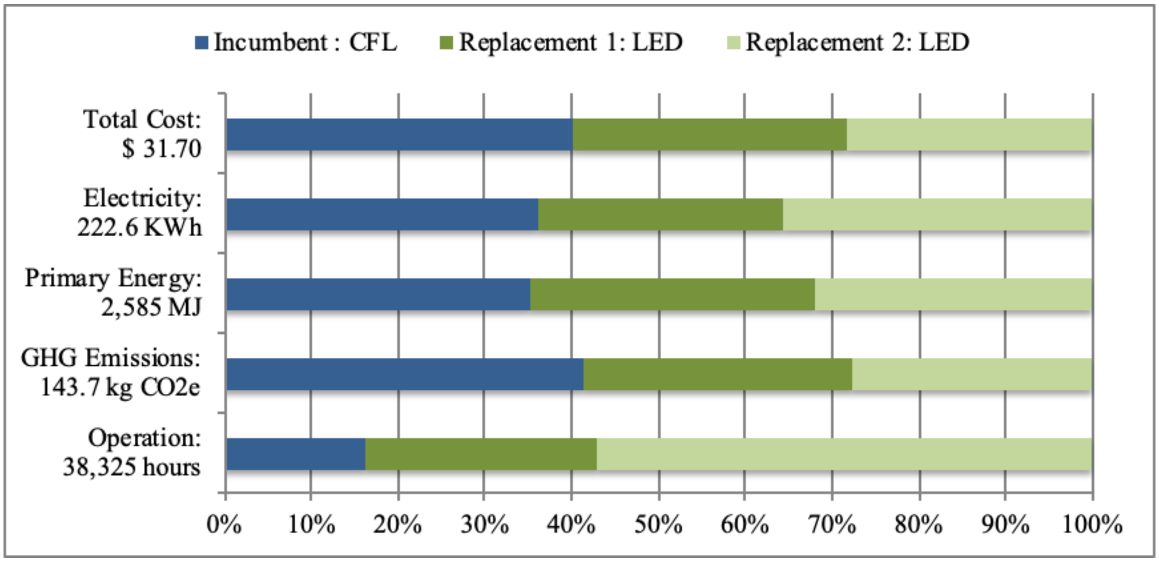

Figure 2.3: Breakdown of policy D (LCC-optimized) in Case 1 (baseline) per lamp contribution.

Table 2.2 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 $l_1 = IL$ and Case 2 with $l_1 = HL$ 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 Appendix 0.

Table 2.2: Life Cycle Cost-optimized policies under different initial lamp type and HOU. (Note: all life cycle impact values are normalized to 1 HOU.)

HOU [hr/day]	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO$_2$e/HOU]	Social Cost of Carbon [$/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

2.3.2 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 2.3 shows the 3HOU 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 Appendix 0, 0, and 0.

Table 2.3: Regional Life Cycle Cost-optimized policies at 3HOU under different initial lamp type. (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

2.3.3 Sensitivity analysis

Table 2.4 lists the parameter values used to test the sensitivity of the baseline scenario under the LCC objective. Each Lower and Higher Values from the 10 categories of parameters were tested one at a time. The sensitivity results, shown in Figure 2.4, 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 & EOL Cost* in Figure 2.4, the variation per unit of change is greater from the former parameter than from the latter. For reference, the baseline scenario yields an LCC of $40.15. A list of policies per parameter value change is available in Appendix 0.

Table 2.4: Parameter values tested for sensitivity analysis.

ID	Parameters	Units	Lower Value	Baseline Value	Higher Value
1	Ele. GHG Emission Factor (2015)[1]	kg CO2e/kWh	0.324	0.647	0.971
2	Electricity Base Price (2015)	$/kWh	0.0635	0.127	0.191
3	Discount Rate	%	1.50	3.00	6.00
4	Eletricity Price Annual Growth	%	0.00	2.30[3]	4.60
5	CFL & LED Base Price (2015)	$	1.80 & 3.00	1.80 & 5.09[2]	7.00 & 9.00[2]
6	LED Net Efficacy Growth (2015-50)	lm/W	122[3]	222[2,4]	N/A
7	Installation Cost	$	0.00	0.870	1.94
8	Ele. GHG Emiss. Annual Reduction	%	0.00	1.31[3]	2.61
9	LED Net Price Reduction (2015-50)	$	2.36	3.96[2,3]	N/A
10	LED Net Lifetime Growth (2015-50)	hrs	30,000[2]	55,000[4]	N/A

Notes: [1]US DOE (2015b); [2]US DOE (2016b); [3]US EIA (2014); [4]Bergesen et al. (2015) See Appendix 0 for additional details.

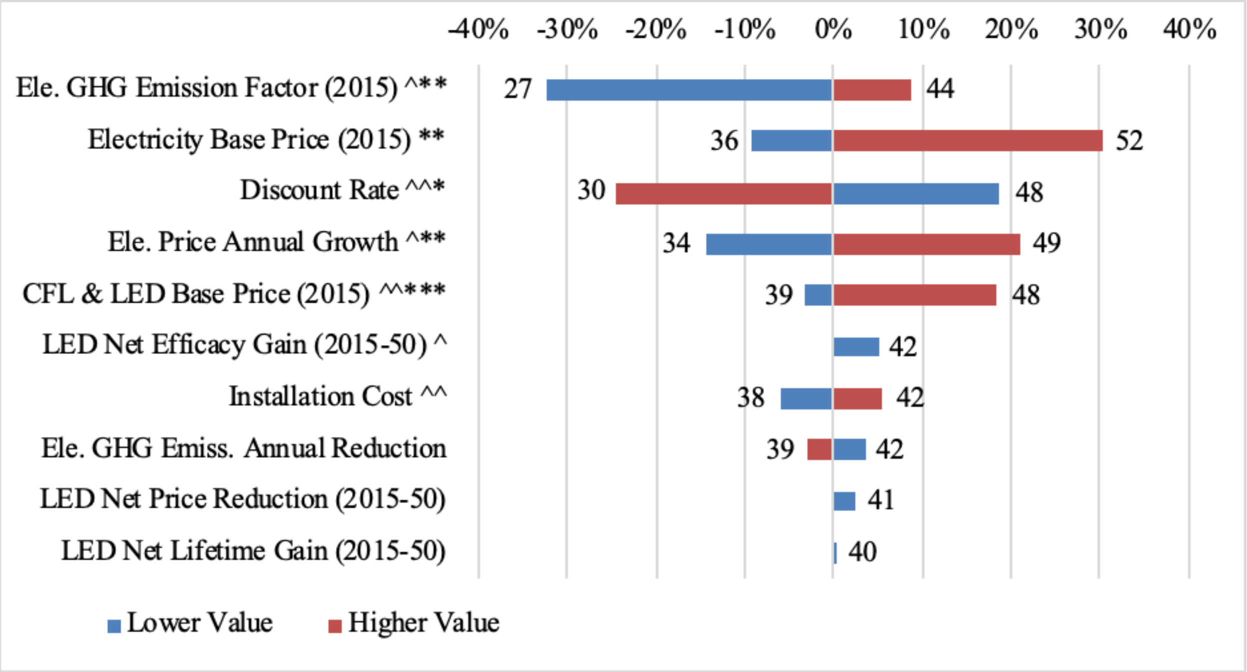

Figure 2.4: Change in Life Cycle Cost (objective value) per parameter value change. (Policy change indicators – ^: change in replacement timing from Lower Value, ^^: change in total number of lamps used from Lower Value, *: change in replacement timing from Higher

2.4 Discussion

2.4.1 Case 1: purchase decision

Figure 2.2 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 Emission's 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 Appendix 0.

A breakdown of the LCC-optimized policy (D) in Figure 2.3 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 2.2. 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.

2.4.2 Case 2: to keep or to replace?

Table 2.2 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 78lm/W), replacement to a newer model between 2020 and 2021is recommended. In general replacement depends on the lamp usage rate. As shown in Table 2.2, 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, which favor rapid replacement and adoption of more energy-efficient lamps, thereby lowering the per HOU use phase impacts.

2.4.3 Sensitivity and tradeoffs

Replacement policy depends on the fuel mix of the grid, which differs by region. Although DC and TX in Table 2.3 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 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 2.4 shows that the model is most sensitive to the base rates of electricity (e.g. cost and GHG 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 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 – 4 of those (marked by single indicators) have shifted slightly in replacement timing while 6 (marked by double indicators) have increased in the total number of lamps used.

2.5 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 provide the highest energy saving, and vice versa. If used 3 hours/day 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. (2010) US consumers may be better off purchasing LED lamps with shorter life spans at lower costs now.

2.6 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 LED technology adoption (US DOE 2015a). 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 (Min et al. 2015); Energy efficiency gain could increase lamp use, resulting in a rebound effect (Tsao et al. 2010); The integration of auxiliary electronics for LED (e.g. dimming controls, motion sensing, and timing schemes (US DOE 2016b)) could introduce additional power demands and supply chain impacts; Degradation in lighting (e.g. lumen depreciation, stochastic failure, and degradation from frequent cycling (US DOE 2013b)) 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 (US DOE 2014, 2016b). 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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Chapter 3 Life Cycle Cost Analysis of LED Retrofit and Luminaire Replacements for 4ft T8 Troffers Based on Market Data

Abstract

Lighting makes up 17% of electrical loads and the largest end use in commercial buildings. Linear fixtures are one of the largest opportunities for cost reduction through energy efficiency upgrades, given their long operating hours. With continued, rapid LED development and more LED replacement products on the market, lighting replacement decisions become more complex and warrant reexamination. With a goal to inform building managers and other decision-makers with practical guidance on lighting replacement, this study is a life cycle cost (LCC) analysis that compares the cost-benefit of 5 different LED replacement options for a 2x4 T8 recessed troffer based on the data of 168 lighting products from an online vendor. Results show that direct wire LED retrofits are the least-cost option to replacing fluorescent lamps in terms of normalized LCC. Plug & play lamps suffer from a lock-in with ballasts, but their ease of installation can help spur LED adoption. In cases where an existing ballast is still usable, hybrid LED retrofits provide the least upfront cost option by deferring the cost of rewiring. LED luminaires can offer improved aesthetics and reliability; however, they have high upfront cost. Among them, luminaires with replaceable lamps offer lower cost than those without.

Keywords: commercial lighting; life cycle cost (LCC); light emitting diode (LED); linear fixture; retrofit; replacement

3.1 Introduction

Electricity consumption for lighting has been on a steady decline, driven most recently by the adoption of LED, or light emitting diode, lighting. Today, lighting accounts for 6% of total US electricity consumption (US EIA 2019), down from 19% in 2010 (US DOE 2012). Lighting still makes up 17% of the electrical loads and remains the largest end use of electricity in commercial buildings (US EIA 2017). Linear fixtures are the most common lighting systems in commercial buildings, with nearly 1 billion units installed in the U.S. (US DOE 2015). Linear fixtures include "all troffer, panel, suspended, and pendant luminaires", as well as their lamps and retrofit kits (US DOE 2016). Troffers are rectangular fixtures that are typically recessed into the ceiling and are used in offices, schools, hospitals, retail, and industrial spaces. With their long operating hours, linear fixtures represent one of the largest opportunities for energy efficiency gain from LED retrofits. T8 or 1-inch diameter fluorescent linear lamps are currently the majority of linear fixture lighting. This study focuses on 32W fluorescent-equivalent (one of the most commonly used wattage ratings) T8 fluorescent recessed troffer lighting and examines the life cycle cost (LCC) and decision-making considerations for retrofit and replacement options for a 4ft 2-lamp system.

Since their inception, LED lighting technologies have undergone enormous change. The cost of LEDs has been decreasing tenfold per decade while their ability to produce light has increased by a factor of 20, a phenomenon that was first described by Haitz's Law (Haitz and Tsao, 2011). It is only in recent years that both the cost and performance of LED lighting have caught up with fluorescent lighting. For a long time, linear LED lamps struggled to compete with their fluorescent counterparts, which have efficacies[2] up to 108 lm/W (lumen/Watt) and costs as low as \$4/klm (\$/kilolumen) (US DOE 2015). By 2015, LED replacements began to exceed their fluorescent counterparts in efficacy, but cost remains a challenge. In the US Department of Energy (DOE) study (2014b), the cost of 4ft LED lamps was estimated to be \$11-33/klm (\$20-60/lamp), though the cost today is between \$2-9/klm (\$4-14/lamp) based on the market information collected in this study. Additionally, current LED lamps surpass fluorescent lamps in a number of performance attributes. They produce light without flickering, have higher energy efficiencies, and last longer. These translate into improved building ambiance, maintenance deference, and energy cost savings. LEDs also offer better dimming performance than fluorescent lamps. They have faster ramp-up to full brightness and are more energy-efficient at low dimming levels due to lower die (i.e., semiconductor base) temperatures (US NEMA 2015). Finally, LEDs do not contain mercury, making them safer for indoor use and at end-of-life.

Despite this recent progress, lighting replacement with LEDs is not an easy task. Lighting owners and contractors looking to make upgrades face several LED retrofit and replacement options that have unclear tradeoffs. Some lamps are directly usable with the existing fixtures and fluorescent lamp ballasts while others require retrofitting or rewiring the fixtures to bypass the ballasts. Hence, upfront costs and labor requirements differ depending on the complexity of the electrical modification required. Pairing with fluorescent ballasts can hinder the performance of LEDs, creating a tradeoff between convenience and energy efficiency. These tradeoffs must be resolved when scoping and executing lighting replacement projects.

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[2] Efficacy is a measure of energy efficiency of the lighting, defined as a ratio between its brightness output in lumen and power consumption in Watt.

The US DOE has invested in a number of efforts to aid the development and diffusion of LED lighting technologies. They have created programs, such as the Design Lights Consortium (DLC), a hub for product ratings and other technical resources (DLC 2020), and reports aimed at providing objective information and guidance on the technologies and their use. Among these reports is a series evaluating the performance of linear T8 LED lamps with troffers (US DOE 2014a) and the cost effectiveness of the lamps compared to the best-performing fluorescent counterparts (US DOE 2014b). DOE (2017) also published a practical guide to walk users through a series of important considerations for performance, cost, and safety when deciding between LED lamps, retrofit kits, and luminaire replacement. There is also a wealth of online resources from lighting suppliers to help users navigate through the vast and confusing replacement lighting market.

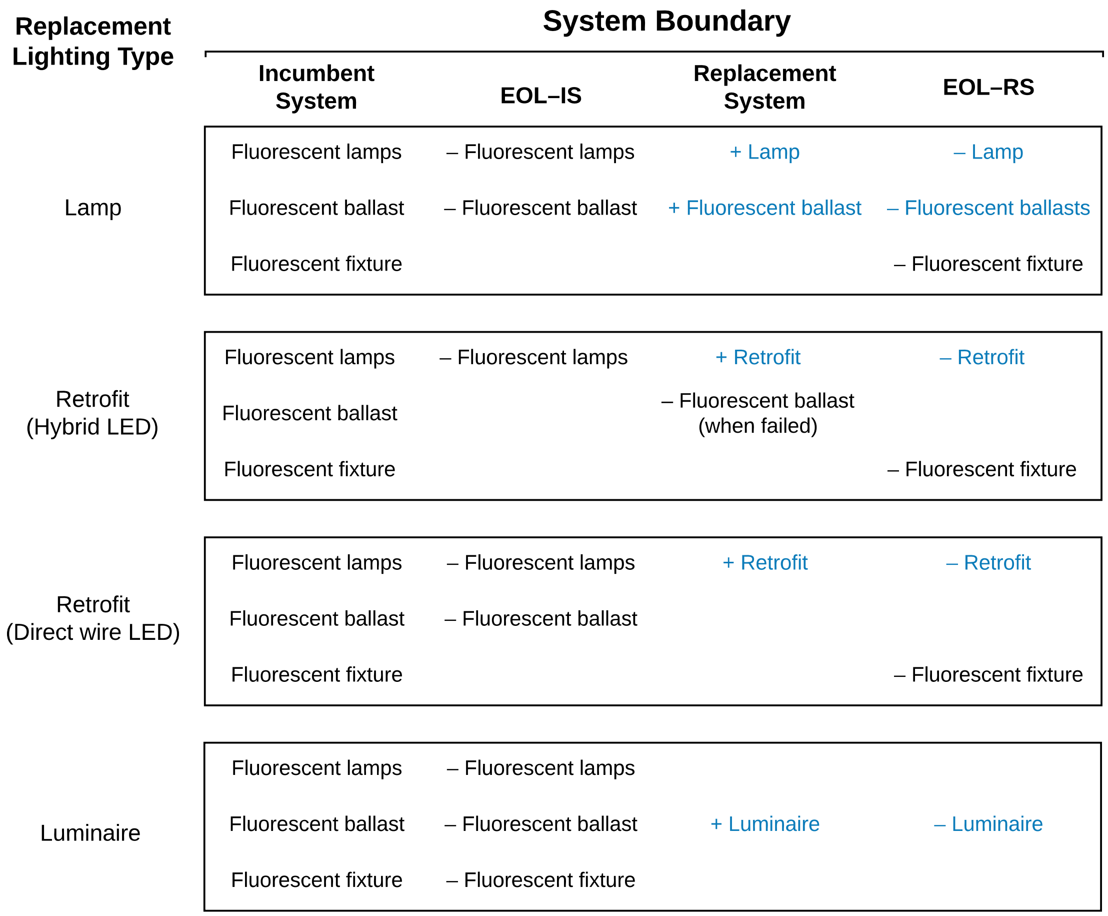
With the cost and performance of linear LED lamps improving drastically in the past five years, it is necessary to reexamine the cost-benefit of LEDs based on current market and technology conditions. This is especially important given that a third type of LED lamp, a hybrid that can be used as both ballast-compatible and ballast-bypass lamps, is now on the market. To include the environmental cost of retrofit and replacement decisions, the social cost of carbon should also be included. The social cost of carbon (SCC) is a carbon pricing structure developed by the US Environmental Protection Agency (US EPA 2016) to account for the long-term financial, social, and ecological damage from small incremental (marginal) changes in CO_2 emissions in the U.S.

With a goal to inform building managers and other decision-makers with practical guidance on troffer lighting replacement, this study evaluates the LCC and performance tradeoffs between six retrofit and replacement lighting options currently available in the market for a 2x4 (2ft x 4ft)

2-lamp F32 (32W fluorescent or equivalent) T8 recessed troffer. Compared to the DOE report (2014b), this study considers more lighting upgrade options, including hybrid LED lamps and LED replacement luminaires, some of which were not available before. The study also incorporates actual market data, which provide a snapshot of the latest development in lighting technologies relative to the projections assumed by DOE. Using market data also allows for the estimation of the range of expected LCC by capturing the products' variation in lumen rating, lifetime, efficacy, and material cost. Other than cost, these attribute variations are not captured in the DOE report. As LED technologies continue to improve rapidly and their costs continue to fall, it's important to keep track of these changes so that building owners and managers can make better informed decisions regarding lighting replacement.

3.2 Method

A detailed description of the six replacement lighting types and their attributes is included in Section 3.2.2 . Figure 3.1 shows the system boundary for the replacement product systems examined in this LCC analysis. Each system begins with a full fluorescent luminaire whose components are then retired and replaced according to the replacement lighting type requirement. A *luminaire* is a lighting system made up of *lamps* (light sources), *electronics* (ballast or driver), and a *fixture* (mechanical structure). For example, plug & play LEDs are a "lamp" type replacement, so they follow the top system boundary in Figure 2.1. The lamps and ballast from the fluorescent luminaire are replaced with new plug & play LEDs and a new ballast. At the end of the time horizon, all components including the incumbent fixture are retired to ensure functional equivalence. Since the flow of incumbent fluorescent components (black text in Figure 2.1) are common between the systems, they are excluded from the analysis and only the components in blue are examined.



Replacement Lighting Type	Incumbent System	EOL–IS	Replacement System	EOL–RS
Lamp	Fluorescent lamps	– Fluorescent lamps	+ Lamp	– Lamp
	Fluorescent ballast	– Fluorescent ballast	+ Fluorescent ballast	– Fluorescent ballasts
	Fluorescent fixture			– Fluorescent fixture
Retrofit (Hybrid LED)	Fluorescent lamps	– Fluorescent lamps	+ Retrofit	– Retrofit
	Fluorescent ballast		– Fluorescent ballast (when failed)	
	Fluorescent fixture			– Fluorescent fixture
Retrofit (Direct wire LED)	Fluorescent lamps	– Fluorescent lamps	+ Retrofit	– Retrofit
	Fluorescent ballast	– Fluorescent ballast		
	Fluorescent fixture			– Fluorescent fixture
Luminaire	Fluorescent lamps	– Fluorescent lamps		
	Fluorescent ballast	– Fluorescent ballast	+ Luminaire	– Luminaire
	Fluorescent fixture	– Fluorescent fixture		

Figure 3.1: Life cycle cost product system boundary based on replacement lighting type. Within each system boundary, the component flows in black are common between systems, thus only those in blue are examined for each system.

3.2.1 Life cycle cost analysis

This LCC analysis uses a similar method as that in DOE’s T8 LED cost-effectiveness report (2014b), as well as the same key parameters to maintain result comparability. Differences from the DOE method are: 1) actual product data are collected and used in this analysis, whereas estimated product attributes based on technology projections are used in the DOE report; 2) SCC is included in this study; and 3) in addition to total LCC, normalized LCC (NLCC) is assessed, allowing the comparison of products with different lumen ratings to be made per klm of light service delivered. For the LED options, simple cost payback relative to a fluorescent lamp and ballast benchmark system is also calculated.

The performance requirement for each lamp is at least 1,800 lm in luminosity and a CRI of at least 80. At a normal ballast factor of 0.88, the minimum luminous requirement for a 2-lamp system is 3163 lm. Data are collected from an online lighting vendor for 56 fluorescent lamps, 91 LED lamps and retrofits, 2 LED-ready fixtures, and 19 LED troffer luminaires (1000bulbs 2019). Of the LED lamps and retrofits, 54% are direct wire, 28% are plug & play, and 17% are hybrid lamps, indicating that the market is trending towards direct wire LEDs. All LED lamps have a rated lifetime of 50,000 hr. More information on the replacement products is in Appendix 0.

This analysis assumes a time horizon of 10-year at a discount rate of 3% which yields a capital recovery factor (CRF) of 0.114. Four annual operating hours are accessed – 1,000 hr (suitable for home setting), 2,000 hr (baseline, suitable for school setting), 4,000 hr (suitable for industrial spaces), and 8,760 hr (24/7 operation). The ballast factors examined are 0.76, 0.88 (baseline), and 1.18, which yield a minimum system lumen requirement of 2,727, 3,163, and 4,248 lm, respectively. These requirements govern the number of replacement lamps, retrofits, and luminaires used in the LCC calculations. The electrician labor cost rates examined are $50, $75 (baseline), $100, and $125 per hour. The electricity prices explored are $0.08/kWh, $0.11/kWh (baseline), $0.20/kWh, and $0.29/kWh. These reflect the range of state-average commercial electric rates in 2019, which was between $0.08 (Oklahoma) and $0.29 (Hawaii), with a national average of $0.11/kWh (US EIA 2019).

Tähkämö et al.’s study (2013) shows that the use phase of a fluorescent T5 fixture accounts for over 80% of its life cycle impacts. Liu and Keoleian (2020), in a comparison of the environmental impacts of reusing, recycling, and landfilling a fluorescent linear fixture and a LED linear fixture, also show the dominance of the use phase across all scenarios, particularly in terms of carbon emissions. Therefore, it is sufficient to consider the SCC only for the use phase electricity consumption in this study. The IPCC 2013 GWP 100a (V1.03) per kWh of US low voltage electricity is 0.699 kg CO_2eq. The SCC examined are $0, $26.46, $52.92 (baseline), and $154.98 (which corresponds to high impact at the 95th percentile in present value) per metric ton CO_2 equivalent. The SCC have an annual increase of $0, $0.50, $1.01, and $3.78, respectively, per metric ton CO_2. (US EPA 2016)

An electrician rate of $75/hr is used to estimate the labor costs. The cost of spot replacement (i.e. relamping) is $3.75/lamp and $15/ballast based on 0.05 and 0.20 hr of estimated labor, respectively. Recycling fee is $0.16/fluorescent lamp, $0.05/ballast, based on the quote for a recent commercial lighting project in Ann Arbor, Michigan (personal communication 2019). Since LED lamps and luminaires do not contain mercury like fluorescents, their recycling cost is assumed to be $0.05/lamp and $0.75/luminaire based on mass allocation.[3] The annual expected maintenance cost is the product sum of the annualized expected failure rates and their total replacement cost combining material, recycling, and labor costs. The annualized expected failure rate, or the probability that a component fails in a given year, is based on how much that component has been in use in that year relative to its rated lifetime (i.e., the more it is used, the more likely it is to fail). Additional costs, such as design & planning and inspections, which may be required in actual projects, are not included. See Appendix 0 for LCC equations.

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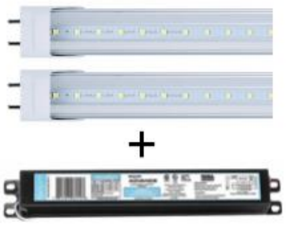
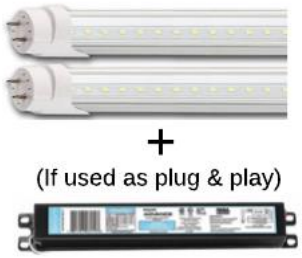
[3] For mass allocation, a LED lamp weighs roughly the same as the ballast whereas a LED luminaire weighs about 15 times more.

3.2.2 Replacement options

Six lighting product options for replacing a 4ft 2-lamp F32 T8 troffer are examined, which are summarized in Table 3.1. The lighting options can be categorized into three replacement types – lamp replacement, retrofits, and luminaire replacements. A *lamp replacement* is a change-out of the lamps only and does not require any electrical modification. Fluorescent lamps and plug & play LEDs fit this category. A *retrofit* involves modifying the existing fixture to accommodate a new light source and/or electronics. Retrofits include ballast-bypass LEDs and hybrid LEDs. *Luminaire replacement* is a full change-out of the lighting system, including the mechanical structure. This replacement type includes an LED troffer with replaceable lamps (RL) and LED troffer with integrated non-replaceable lamps (NRL). While lamp replacements and retrofits offer quick and lower-cost ways to upgrade to LEDs, full luminaire replacements are typically longer lasting and more energy efficient. However, higher material and labor costs are often required.

Table 3.1: Replacement options for a 2x4 2-lamp F32 T8 recessed troffer.

Type	**Name**	**Description**
Lamp (benchmark)	Fluorescent lamps 	Uses the existing fixture and a new ballast. Pro: convenience, easy change-out, no rewiring required, low cost Con: Least energy efficient
Lamp	Plug & play LED lamps	One-to-one replacement for fluorescent lamps. Uses the existing fixture and a new ballast. Pro: convenience, easy change-out, no rewiring required Con: get locked in on the use of ballast and fluorescent fixture

		
Retrofit	Direct wire LED lamps 	Each lamp contains an internal driver. Uses the existing fixture but rewiring is required to bypass the ballast. <u>Pro</u>: more energy efficient than plug & play LEDs since the ballast is bypassed, easy change-out once installed <u>Con</u>: higher labor cost than plug & play LEDs
Retrofit	Hybrid LED lamps 	Lamps are often used as plug & play lamps in the existing fixture until its ballast fails, after which point the lamps are directly wired to line voltage. <u>Pro</u>: utilize the remaining life of an existing ballast, flexibility in use mode <u>Con</u>: overall more labor-intensive than direct wire LEDs
Luminaire	LED troffer with replaceable lamps 	Existing fixture is discarded and replaced with a new LED troffer that uses replaceable lamps. This system is modelled as a LED-ready fixture with two direct wire LEDs. <u>Pro</u>: energy efficient, easy change-out once installed <u>Con</u>: high material costs

Luminaire	LED troffer with non-replacement lamps 	Existing fixture is discarded and replaced with a new LED troffer that has a non-replaceable, built-in LED arrays. Pro: longest-lasting, energy efficient, more design and aesthetic options Con: highest labor and material costs as the full luminaire is to be changed out upon failure

3.2.2.1 Lamps and retrofits

3.2.2.1.1 Fluorescent lamps

Linear fluorescent lamps are used as the benchmark for this study. The fluorescent lamps surveyed have an efficacy range between 62-100 lm/W, a price range between \$0.48-4.58/klm, and a rated lifetime between 20,000-84,000 hr. DOE (2014b) projected that 32W fluorescent lamps would be replaceable with 28W or 30W counterparts today given the minimum performance requirement of 1,800 lm and 80 CRI. However, contrary to this assumption, no 28W or 30W fluorescent lamps could meet these requirements. Therefore, 32W fluorescent lamps are surveyed in this study. Prior to their installation, a change-out of the ballast is assumed for two reasons: (1) a new ballast allows for energy efficiency gain, and (2) the existing ballast will most likely burn out before new lamps do. Thus, with both the lamps and the ballast, the total material cost is \$10.57-66.03 (\$28.46 avg), the installation cost is \$18.75 based on 0.25 hr labor, and the recycling cost is \$0.37 at end-of-life. The average material cost of this benchmark system is \$41.39 compared to \$30 in the DOE report (2014b). The system efficacy averages 91 lm/W compared to 88 lm/W assumed in the DOE report.

3.2.2.1.2 Plug & Play LEDs

As their name suggests, plug & play LED lamps (UL Type A) are designed to be a direct replacement for fluorescent lamps. They are ballast-compatible to allow for lamp swaps without having to rewire the fixtures. The system brightness is proportional to the ballast factor and the ballast increases the system energy demand by 2-3W per lamp (Pilner, 2019). Plug & play replacements are best suited for applications where fast replacement with minimal labor is desired, such as retail and limited access lighting.

The plug & play LEDs surveyed have an efficacy range between 127-164 lm/W and a price range between $2.08-5.20/klm. A change-out of the ballast is assumed prior to installation to enhance energy performance (as with fluorescent lamps). The total material cost for two lamps and a ballast is $15.43-66.47 ($34.82 avg), with $0.15 total in recycling cost at end of life. The cost to install the system is $18.75 based on 0.25 hr of labor.

3.2.2.1.3 Ballast-bypass LEDs (direct wire LEDs)

Ballast-bypass LEDs require the existing fixtures to be rewired, including disconnecting the ballast. Because the ballast is bypassed, the system performance is not subject to the ballast factor. Direct wire LEDs (UL Type B) are a type of ballast-bypass LEDs that have an internal driver built in and are among those surveyed in this study.

Direct wire LEDs are further categorized as single ended or double ended based on the number of pins on the ends of the tubes. This categorization is important for determining what type of sockets are required in the fixtures. Using the wrong sockets can cause short circuits and electrical fire as well as damage to the lamps. *Shunted* sockets supply line voltage to both ends of the lamps and only double-ended tubes can be used with them. *Non-shunted* sockets are compatible with either pin types as only one of the sockets supplies line voltage to the lamps. Retrofitted fixtures are often wired with non-shunted sockets for maximum compatibility. (See Appendix 0 for sample wiring diagrams.)

The direct wire lamps surveyed have an efficacy range between 113-150 lm/W and a price range between $2.22-8.47/klm. The total material cost for two lamps is $7.98-27.96 ($15.37 avg), along with $0.10 for recycling at end of life. The cost to install these lamps is $37.50 based on 0.5 hr of labor per fixture. Another type of ballast-bypass lamps are LED lamps that operate with an external driver (UL Type C). Since this type of lamp is not widely available currently, they are not modelled in this study.

3.2.2.1.4 Hybrid LEDs

This LED type is a hybrid of direct wire and plug & play (UL Type A&B) and is intended to offer upgrade flexibility. The LED lamp can be used as a plug & play to capitalize on the remaining life of an existing ballast before the fixture is rewired for ballast-bypass lamps. This replacement strategy, which distinguishes the hybrid option from that of a plug & play or a direct wire, is what is assumed in the LCC analysis.

The hybrid lamps surveyed have an efficacy range between 113-150 lm/W and a price range between $2.22-8.47/klm. The material cost for two lamps is $11.46-21.24 ($14.80 avg), and it costs $0.10 to recycle both lamps at end of life. The labor cost is estimated at $7.50 when installing them as plug & play lamps, plus an additional $37.50 to rewire the fixture when the ballast fails.

3.2.2.1.5 Ballasts

Ballasts and LED drivers serve the same purpose in lighting systems – they regulate the input electricity for the lamps to maintain light level and prevent damage by high current. Traditional magnetic ballasts naturally vibrate, which causes audible buzzing. They also cause visible light flicker because they modulate current at relatively low frequency. Electronic ballasts, which are the replacement technology, eliminate audible and visible artifacts by regulating the current and voltage at high frequency. In addition, electronic ballasts are more energy-efficient, longer lasting (by a factor of 2), and lighter weight.

Replacement F32 electronic ballasts include instant start and program ballasts, all of which have a rated lifetime of 150,000 hr. The ballasts can be further categorized into three groups based on their ballast factors. A ballast factor denotes how many lumens the lighting system will produce relative to the lamps' rated output when integrated with the ballast. For a fluorescent system, the ballast factor also affects the system wattage. Based on the ballasts surveyed, low, normal, and high ballast factors have an average value of 0.76, 0.88, and 1.18, respectively. Their cost ranges are $13.27-24.50 ($26.01 avg), $7.85-36.79 ($16.69 avg), and $13.99-15.86 ($18.18 avg), respectively. The cost to replace a ballast is $15 based on 0.20 hr of labor.

3.2.2.2 Luminaire replacements

3.2.2.2.1 LED troffers with replaceable lamps

This option is modelled as two direct wire LEDs paired with an LED-ready fixture. One potential advantage of this option compared to the direct wire retrofit LEDs is its less complex electrical modification. Hence, the amount of labor required is estimated to be 0.4 hr or $30.00 in cost. Only 2 LED-ready fixtures are available at the time of data collection. The average material cost of the fixture is $47.35, and the recycling cost is $0.70 on top of the costs of the direct wire LEDs.

3.2.2.2.2 LED troffers with non-replaceable lamps

LED troffer luminaires are designed to leverage the full benefits of LED packages. They are energy efficient, durable, and can last up to 100,000 hr, which is twice as long as LED lamps and retrofits. Since their light sources are integrated and non-replaceable, higher material and labor costs are required upon their failure or retirement.

The LED troffers with integrated lamps surveyed have an efficacy range between 102-140 lm/W and a price range between $12.09-54.17/klm. Their rated lifetime is between 50,000-100,000 hr. The material cost is $62.82-216.67 ($103.21 avg), and it costs $0.15 to recycle the luminaire at end-of-life. The cost to install the luminaire is $37.50 based on 0.50 hr of labor.

Figure 3.2 illustrates the system efficacy and material cost with respect to system brightness for the six replacement options. For the fluorescent and plug & play lamps, their system costs include the cost of the ballast. The dashed line is the minimum system luminous requirement for a troffer operating at a ballast factor of 0.88. For each LCC calculation, replacement lamps are excluded if their lumen outputs do not meet the minimum performance requirement. At a ballast factor of 0.88, 6 plug & play LEDs and 1 hybrid LED are excluded. The number of LED lamps and retrofits used in the LCC calculation decreases with a higher ballast factor (see Appendix 0).

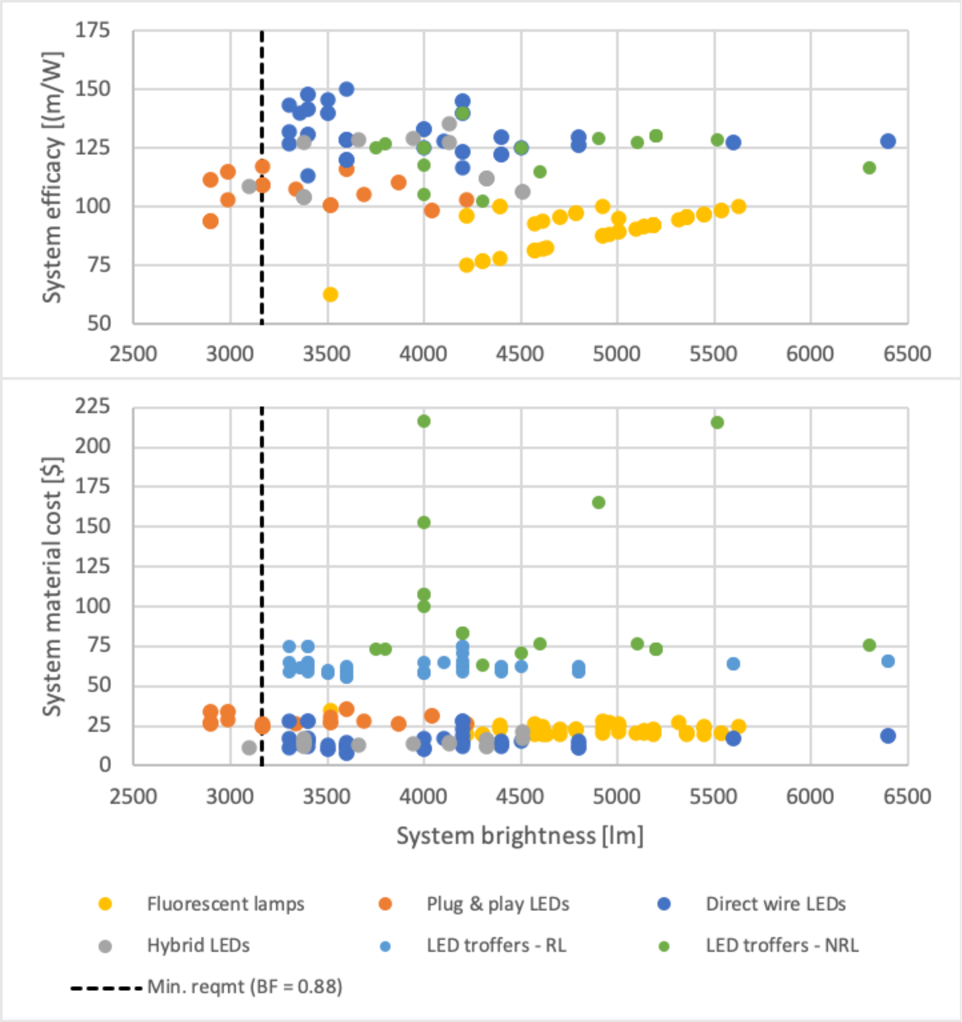


Figure 3.2: System efficacy and material cost for 6 types of replacement lighting products. (Note: the system efficacies of LED troffers w/ RL are not plotted as they are the same as those of direct wire LED lamps. Material cost includes ballast for fluorescent lamps and plug & play LEDs.) (RL = with replaceable lamps, NRL = with non-replaceable lamps, Min. reqmt = minimum requirement, BF = ballast factor)

3.3 Results

Section 3.3.1 presents results of the LCC analysis using the baseline values for ballast factor, electrician labor cost rate, electricity price, SCC, and annual operating hours. Section 3.3.2 presents the sensitivity analysis of those parameters, which are expected to have a strong influence on LCC.

3.3.1 Baseline

Figure 3.3 shows the average LCC decomposition, percentile range of system efficacy, range of LCC in present value, and percentile range of NLCC for each of the 6 replacement options – fluorescent lamp, 3 LED lamp/retrofits and 2 LED luminaires. The yellow diamonds in the boxplots are the mean values of the results. As expected, the contribution of upfront cost (material and labor) to LCC is higher for all LED options than for the fluorescent option. This is due to: 1) LED options are generally more energy efficient, which leads to lower electricity costs; and 2) LED options generally have higher upfront costs than fluorescent lamps. An exception to this is the hybrid LED option. On average, hybrid LEDs have the lowest material cost and labor cost of all replacement options, making them the most favorable from an upfront cost perspective. This makes sense as hybrid LEDs do not require a ballast and their initial change-out is similar to fluorescent lamps. However, the cost of direct wiring the hybrid lamps as the ballast burns out can increase the maintenance cost over time, making the option the highest in terms of total labor cost. Although the hybrid LED option provides flexibility, deferring electrical modification comes at the expense of higher labor cost over the life cycle.

Table 3.2 compares the mean and 95% confidence intervals of the baseline LCC and NLCC results. A one-tailed t-test is applied to compare whether the mean of each of the LED replacement options are significantly higher or lower (depending on the option) from that of the fluorescent benchmark system, using 0.05 as the threshold value to reject the null hypothesis that the means are not directionally different. Another metrics for measuring the difference between these means are how much the confidence intervals overlap.[4] Table 3.2 shows that, relative to the fluorescent option in terms of LCC, all three LED lamp and retrofit options are lower with high statistical significance,[5] while LED luminaire with nonreplaceable lamps are higher with high statistical significance, and LED luminaire with replaceable lamps were not significantly different. Relative to the fluorescent option in terms of NLCC, only direct wire LEDs are statistically lower; all other LED lamp and retrofit options are not meaningfully different; and both LED luminaire options are statistically higher.

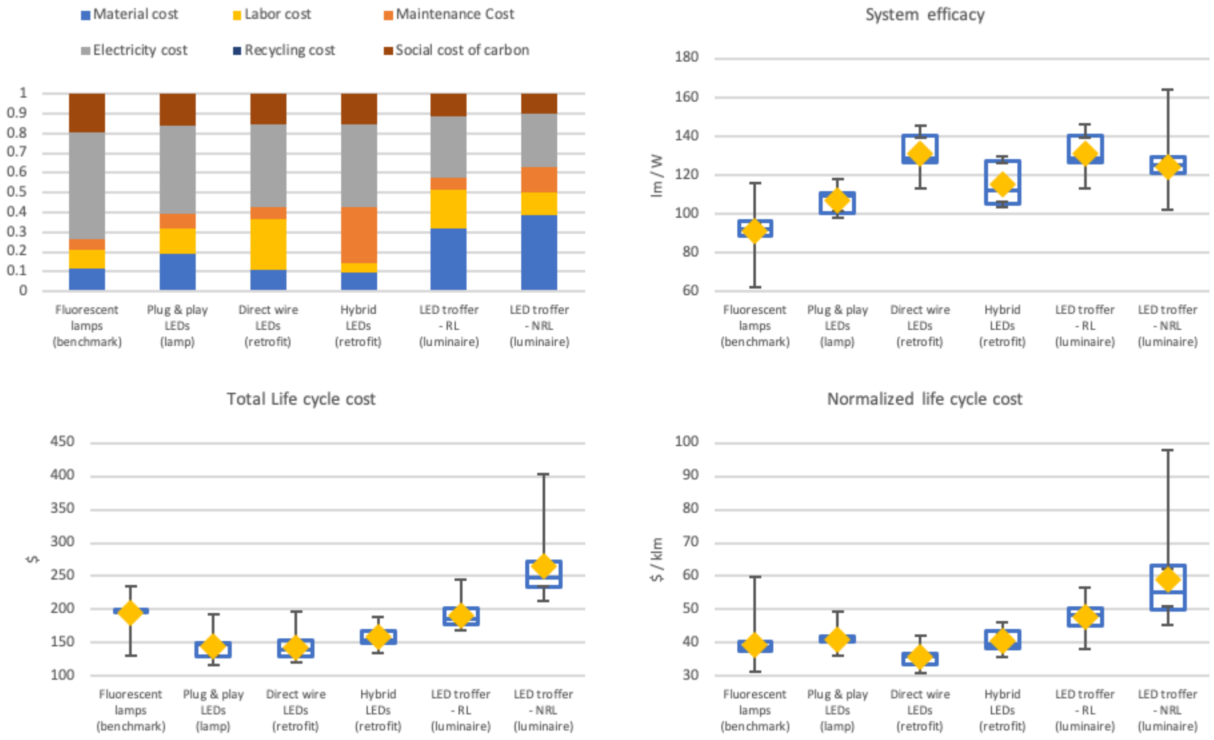


Figure 3.3: (Top left) life cycle cost (LCC) decomposition, (top right) system efficacy, (bottom left) total LCC in present value, and (bottom right) normalized LCC (per klm) of six replacement

[4] For example, although the NLCC of plug & play LEDs are higher than that of fluorescent lamps with statistical significance, since their confidence intervals overlap completely, the difference is not meaningful.

[5] Statistical significance corresponds to results with p value < 0.05; high statistical significance, p value < 0.01.

options for a 2x4 2-lamp F32 T8 recessed troffer. (Yellow diamonds represent mean value, RL = with replaceable lamps, NRL = with non-replaceable lamps)

All three LED lamp and retrofit options are among the lowest total LCC on average. while the LED troffer with replaceable lamps option is on par with that of fluorescent lamps. In terms of NLCC, direct wire LEDs score the best on average due to their system efficacies being among the highest of all replacement options, while plug & play and hybrid LEDs are on par with fluorescent lamps. The full luminaire replacement option with non-replaceable lamps have the highest LCC and NLCC, owing to their high upfront costs, which are also highly variable. Their average upfront cost is 33% higher than that of troffers with replaceable lamps.

Table 3.2: Baseline life cycle cost (LCC) and normalized life cycle cost (NLCC) comparison.

	LCC ($)				NLCC ($/klm)			
Replacement type	Mean	95% conf. intervals	Relative to BM	P value	Mean	95% conf. intervals	Relative to BM	P value
Fluorescent lamps (benchmark)	194	(168, 220)			40	(32, 47)		
Plug & play LEDs (lamp)	145	(118, 173)	Lower	1.49E-12***	41	(38, 44)	Higher	1.78E-2*
Direct wire LEDs (lamp)	143	(107, 179)	Lower	6.37E-28***	36	(30, 41)	Lower	2.12E-9***
Hybrid LEDs (lamp)	159	(129, 189)	Lower	4.86E-8***	41	(34, 47)	Higher	1.54E-1
LED troffer - RL (luminaire)	191	(155, 227)	Lower	1.98E-1	48	(39, 56)	Higher	4.54E-18***
LED troffer - NRL (luminaire)	265	(155, 376)	Higher	1.44E-5***	59	(32, 85)	Higher	3.18E-6***

BM = benchmark
* < 0.05
** < 0.01
*** < 0.001

From an upfront cost standpoint, plug & play LEDs and direct wire LEDs cost on average 14% and 29% more, respectively, than fluorescent lamps. However, they outperform fluorescent lamps in terms of operation (electricity) and maintenance costs. Their simple cost payback relative to the average cost of fluorescent lamps are 1.2 (plug & play) and 2.1 (direct wire) years. If the cost to rewire is included in the labor cost rather than the maintenance cost, the average simple cost payback for hybrid LEDs is 4.0 years. For LED luminaires with and without replaceable lamps, the average simple payback is 12 years and 76 years, respectively.

3.3.2 Sensitivity analysis

Figure 3.4: Sensitivity of the mean normalized life cycle cost (NLCC: $/klm) to ballast factors, electricity prices, electrician rates, social cost of carbon, and annual operations. (RL = with replaceable lamps, NRL = with non-replaceable lamps) displays how the NLCC varies with respect to: ballast factor, electrician rate, electricity price, SCC, and annual operating hours. The sensitivity of the NLCC to each parameter can be measured by comparing the slope of each line. Except for ballast factor, the NLCC increases linearly with all of the parameters. NLCC generally decreases with increasing ballast factors because at higher system lumen requirements, more low-lumen replacement products are excluded from the analysis, thus increasing the average lumen rating of those that are qualified. Plug & play LEDs are the most sensitive to the ballast factor, as their performance is regulated by both the ballast and their internal driver.

The direct wire LED option is the least cost option in terms of NLCC in nearly all cases. The only exception is when the high ballast factor is used. This LED option also shows the lowest sensitivity to all parameters except the electrician rate, since its installation is relatively more labor intensive. The LED luminaire with non-replaceable lamps is consistently the highest cost option, owing to its high material and maintenance costs. At or beyond 4,000 hr/yr operation, nearly all LED replacement options are more cost-effective than fluorescent lamps. This is also true when electricity price is at least $0.25/kWh or when SCC reaches $260/metric ton CO_2 (and increasing at $3.78 per year).

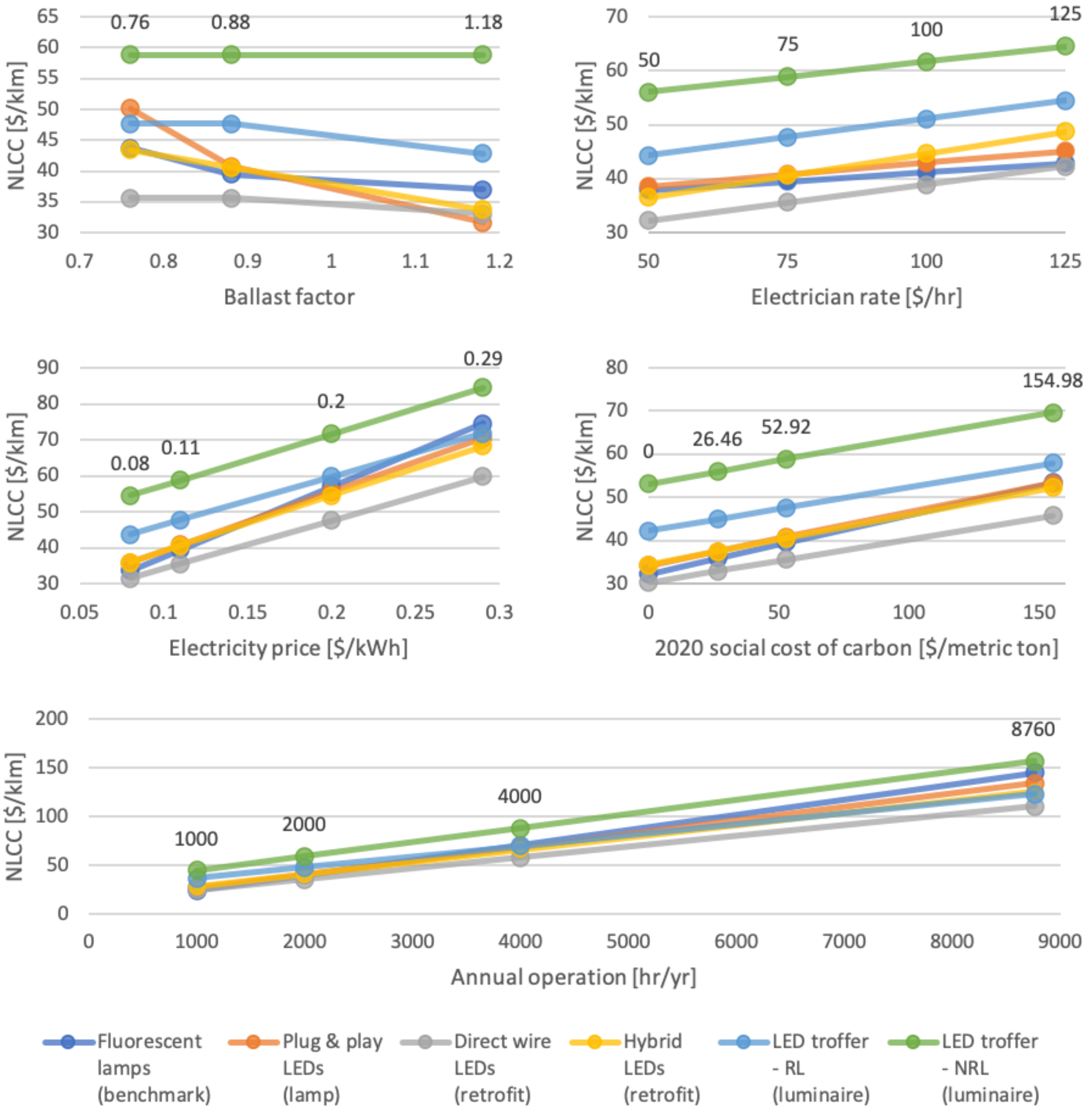


Figure 3.4: Sensitivity of the mean normalized life cycle cost (NLCC: $/klm) to ballast factors, electricity prices, electrician rates, social cost of carbon, and annual operations. (RL = with replaceable lamps, NRL = with non-replaceable lamps)

3.4 Discussion

Compared to the DOE report (2014b), the cost and efficacy of the fluorescent benchmark system are higher in this study by 30% and 3%, respectively. The higher cost difference is due to the fact that the 32W fluorescent lamps that are assessed in this study are the only lamps that meets the 1800 lumen requirement. DOE had assumed that high-efficiency fluorescent lamps meeting this requirement at a lower wattage would be available today. Additionally, the average efficacies of all LED options surveyed are higher by 7%-31% than projected by DOE. However, their relative efficacy difference from that of fluorescent lamps (18%-44% more) are consistent with DOE's assumption that the LED systems are 25% more energy efficient that the fluorescent benchmark.

A finding different from the DOE report is that fluorescent lamps may no longer be the least-cost option in terms of material cost and upfront cost (material and labor costs). Based on the products surveyed, hybrid LEDs and direct wire LEDs respectively cost 31% and 33% less on average than fluorescent lamps and ballast combined. This means that the costs of maintenance and subsequent replacement are also lower for these LEDs once the fixture has been retrofitted. In addition, hybrid LEDs offer lower upfront costs based on their ability to be used as plug & play LEDs to replace fluorescent lamps directly while the ballast is still functional. If the trend of cost reduction continues for LED lighting, it is likely that other LED lamps and retrofits will also reach upfront cost parity with fluorescent lamps.

This study shows that comparing LCC alone does not provide a full picture of the tradeoff between replacement options. While the LED lamp and retrofit options offer lower LCC on average, they deliver 7-28% less lumens than fluorescent lamps. The inclusion of NLCC as a metric helps capture this tradeoff. The results show that all three LED lamp and retrofit options are lower or on par with fluorescent lamps in terms of both average LCC and NLCC. Fluorescent lamps may still fill a niche in high lumen applications as most 32W-equivalent LED options are lower in rated lumens. Alternatively, higher wattage-equivalent LEDs or additional LED fixtures may be installed to compensate and meet the luminous requirement in this situation.

Table 3.3 summarizes and allows comparison of the attributes of the product systems. All LED options are more energy efficient and longer lasting on average than fluorescent lamps. The luminaire options offer more design flexibility. Because they are not constrained to fit incumbent fluorescent fixtures, their packaging can be optimized for energy efficiency, durability, and aesthetics, though often at the tradeoff of higher cost. The material costs of the LED luminaires surveyed are 1.2 to 11 times higher than the combined cost of fluorescent lamps and ballast, and 1.2-9.4 times higher than LED lamps and retrofits. Among the LED troffer luminaires, the options with replaceable light sources (e.g., direct wire LEDs with LED-ready fixtures) are lower cost. They can also offer environmental benefits by reducing the amount of waste generated at end-of-life and the amount of material produced for replacement (Liu and Keoleian 2020).

Table 3.3: Attribute comparison of different replacements for a fluorescent troffer luminaire.

	Fluorescent lamps	Plug & play LED lamps	Hybrid LED retrofits	Direct wire LED retrofits	LED troffer with replaceable lamps	LED troffer with non-replaceable lamps
High efficacy		X	X	X	X	X
Longer lasting		X	X	X	X	X
More design options					X	X
Quick change-out	X	X	X			
Lower upfront cost	X	X	X	X		
Lower life cycle cost	X	X	X	X	X	

LED lamps and retrofits are competitive options for replacing fluorescent lamps in an existing fixture. Plug & play and hybrid LEDs offer the same convenient change-out as fluorescent lamps, which makes them suitable for applications where access to lighting is limited (e.g., retail spaces and high ceilings) as well as niche markets where the lighting can be relocated with the owner when they vacate the property. Because of this convenience factor, plug & play and hybrid lamps may help spur LED adoption by acting as a gateway to ballast-bypass LEDs, which are meant for long-term use. In cases where an existing ballast is still usable, hybrid LEDs are the lowest upfront cost option; however, the cost of rewiring is only deferred as maintenance, which increases the overall labor cost over the life cycle. Direct wire LED retrofits are the lowest cost replacement for fluorescent lamps in terms of operation and maintenance costs and NLCC, despite their relatively high installation cost. Their high efficacy, low cost, and wide market availability suggest that direct wire LEDs have been a focal point of recent LED development and are currently a manufacturer-preferred replacement choice.

3.5 Conclusion

This study compared the LCC of six different replacement options for a 2x4 T8 recessed troffer with fluorescent lamps, based on a survey of 56 fluorescent replacement lamps, 91 LED lamps and retrofits, 2 LED-ready fixtures, and 19 LED troffer luminaires from an online lighting vendor. Some of the key findings include:

- Plug & play, direct wire, and hybrid LEDs are cost-effective and more energy efficient options to replacing fluorescent lamps.
- Plug & play LEDs suffer from a lock-in with ballasts, but their ease of installation can help spur LED adoption.
- Hybrid LEDs have the lowest upfront cost when an existing ballast is still useable.

- In terms of operation and maintenance costs and NLCC, direct wire LEDs are the lowest cost option despite their relatively high installation cost.
- LED luminaires with replaceable lamps are lower cost than those with integrated non-replaceable lamps though they offer fewer design options.
- In general, more lighting operational hours, higher electricity prices and social cost of carbon, and lower electrician labor cost rates lower the LCC of LED replacement products relative to fluorescent lamps, making them more cost-effective.

These findings provide guidance for commercial building owners and managers who are considering lighting replacement. They highlight the tradeoffs in lighting performance and cost between the six options considered. The results and findings are also applicable to residential buildings where 2x4 T8 lamps and troffers are commonly used particularly in workshops, basements, and garages.

Chapter 4 LCA of Rare Earth and Critical Metal Recovery and Replacement Decisions for Commercial Lighting Waste Management

Abstract

Lighting waste represents a significant source of rare earth elements (REE) and critical metals (CM), which are vital to low-carbon technologies. This research examines the environmental impacts of recovering REE (Yttrium and Europium) from linear fluorescent fixtures and CM (Gallium) from linear LED fixtures, as well as the implications of technology transition (e.g. from fluorescent to LED) and replacement decisions (i.e. extended use, modular replacement/retrofits, and full replacement) on waste management. An LCA is conducted by modeling 1 million lumen-hour of service from an 8ft T8 linear fixture across 16 pathways representing multiple replacement and waste management options. The study finds that recovering REE and CM from lamp waste via hydrometallurgical methods generally result in more environmental impacts than the primary production of the recovered materials. Per kg recovered, the global warming impact is 74kg and 3,687kg CO_2eq for REE and Ga, respectively. The high impacts for Ga recovery are due to Ga's low concentration (0.234 w/w%) in the LED waste. Intermediate results at the end of life stage show that recycling common metals (e.g. aluminum, copper, and sometimes steel) from fixtures can reduce or even completely offset the impacts of specialty metal recovery. Based on the end results, a mature technology like fluorescent fixtures can benefit from both extended use and modular product designs. The best strategy is to prioritize energy efficiency (e.g. by upgrading to new LED) and to choose full luminaire (lamps, electronics,

and fixture) upgrades, which offer higher system efficacies, over retrofits (lamps and electronics only).

Keywords: life cycle assessment; waste management; rare earth elements; gallium; light emitting diode (LED); fluorescent lighting

4.1 Introduction

Solid-state lighting technologies, such as light emitting diodes (LED), are improving the energy efficiency, comfort, and functions of our built environment. With its rapid improvement in luminous efficacy in the past decade, LED lighting has helped reduce lighting electricity consumption from 20% (Hendrickson et al. 2010) to less than 10% today (US EIA 2020). The annual saving from LED upgrades is expected to reach 260-400 TWh by 2030, or 40-60% of the total site energy when LED penetration reaches 88% (US DOE 2016b). Worldwide, LED adoption along with electricity decarbonization will reduce global carbon emissions in the lighting sector by more than a factor of 7 from 2010 to 2050 (Bergesen et al. 2016). How might the transition to LED affect the composition of waste generated from lighting, and are there any benefits from recovering rare earth and critical metals such as Yttrium, Europium, and Gallium? This study investigates the environmental impacts of recovering specialty metals (e.g. REE and CM) from lighting wastes as well as the implications of technology transition and replacement decisions on waste management.

Beyond energy efficiency, a low-carbon future requires closed-loop end of life (EOL) management pathways and material-efficient product designs. Low-carbon technologies often require novel materials, which can be energy-intensive to extract and limited in supply. Bergesen et al. (2016) found that increased LED lighting uptake may compete with low-carbon electricity generation for resources such as aluminum. As waste management is a multifaceted process that involves consumer decisions on product selection, a number of studies have examined product attributes (e.g. material criticality, recyclability) and proposed methods to help consumers choose more sustainable LED products (Jägerbrand 2015, Fang et al. 2018). With numerous different LED retrofit options available today to entice adoption, lighting waste management requires new scrutiny to understand the implications arising from the technology transition and replacement choices. Meanwhile, legacy lighting technologies, e.g. high intensity discharge lamps and fluorescent lamps (FL), have low recycling rates (30% for FL) despite disposal restrictions due to mercury (US NEMA 2019).

Studies focused on the waste management of lighting are limited. The environmental impacts at EOL are often neglected due to the dominance of the use phase impacts, as well as the paucity of economic and technical information on recycling processes (Mizanur Rahman et al. 2017). Apisitpuvakul et al. (2008) examined the life cycle impacts of increasing the recycling rate of spent FL tubes in Thailand. There, FL are either recycled for glass cullet or disposed of after mercury treatment. Their study found that recycling could reduce environmental impacts across all indicators by 85%, which is directly proportional to the reduced usage of sodium sulfide and cement in mercury treatment. Thavornvong et al. (2016) compared the environmental impacts of different waste management scenarios for a *T8 linear fixture*[6] fitted with either fluorescent lamps or LED lamps in Thailand. Similarly, Dzombak (2017) evaluated the environmental impacts of different EOL pathways for an LED streetlight, using a bill of materials created based on product teardowns.

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[6] A luminaire (either suspended or recessed) that is 8-foot long and traditionally uses four 4-ft linear fluorescent tubes that are 1 inch in diameter (T8), most often found in commercial spaces.

4.1.1 Material recovery opportunities from lighting waste

Lighting waste can provide a valuable stream of recovered rare earth elements (REE) and critical metals (CM). REEs are vital to the development of low-carbon technologies, (e.g. solar panels, magnets in electric motors, and batteries), whose demand is growing at 3-9% annually (Tan et al. 2015). Their limited global supply is at risk of geopolitical monopoly by China (Du & Graedel 2011) and stunted by a lack of recycling. Less than 1% of REE in 2011 were recycled from discarded waste electrical and electronic equipment (Binnemans et al. 2013). FL embody a significant source of REE (e.g. yttrium and europium) and make up 32% of the REE market in value (US DOE 2011, Binnemans et al. 2013, Tunsu et al. 2015). An average T8 fluorescent tube contains 5.8g of REE (Qiu & Suh 2019).

While LED lamps contain 1-2 orders of magnitude less REE than FL (Qiu & Suh 2019, US DOE 2011), they are rich in gallium (Ga) and indium (In), both of which are critical metals (CM) facing mounting supply risks (Swain et al. 2015, Graedel et al. 2015). Ga is vital to a rapidly growing Gallium Nitride (GaN) semiconductor industry that is expecting a $2.6 billion revenue by 2022 (Swain et al. 2015). According to Qiu and Suh (2019), the global REE flow in lighting waste is projected to peak between 2020-2027, following the peaking of lighting demand during 2014-2019. They found that despite the opportunity for cost optimization via economies of scale, REE prices would need to be 2.2-6.3 times higher than their 2018 levels for lamp recycling to be economic. In addition to the economic feasibility of REE and CM recovery from lighting waste, their environmental impacts are also important considerations.

Hu et al. (2017) analyzed the carbon footprint of two hydrometallurgical methods – acid extraction and solvent extraction – for recovering Y and Eu from FL phosphors. They found the two methods to result in a similar amount of carbon emissions based on inventories collected from lab-scale experiments, 9.3-10.6 kg CO_2eq per 16,100ppm REE recovered. This is equivalent to 578-658 kg CO_2eq per kg REE recovered and does not account for the avoided burdens of primary production. Amato et al. (2019) assessed the environmental impacts of recovering REE from several waste streams – fluorescent waste powder, fluid catalytic cracking catalysts, and permanent magnets. They found the carbon emissions to be 4 kg CO_2eq per kg fluorescent powder treated or 20 kg CO_2eq per kg REE recovered, after accounting for avoided primary production. As REE recycling becomes more technically available and more important in a resource-restrained, low-carbon economy, analysis is needed to examine the environmental burdens of new REE-recycling processes and their potential to displace primary production of REE.

4.1.2 Study objectives

Using linear fixtures as a case study, this study compares the environmental impacts of different waste management pathways, taking into account specialty metal recovery and replacement options such as LED retrofits. Namely, the objectives of the study are to: 1) quantify the impacts of recovering REE and CM from linear fluorescent fixtures and linear LED fixtures, respectively (given as per kg materials recovered); and 2) compare the option to extend the use of an existing luminaire, replace the luminaire *modularly* with an LED retrofit, and replace it *in full* with a new luminaire. By exploring these pathways, this study highlights opportunities for reducing the environmental impacts of specialty metal recovery from lighting waste as well as providing decision support to help businesses develop more sustainable programs regarding the replacement and EOL management of their lighting products.

4.2 Background

4.2.1 Lighting technologies

A “Luminaire” refers to an entire lighting system and consists of lamps, electronics (i.e. ballast or driver), and housing structure (i.e. fixture). “Linear fixtures” are a type of lighting commonly found in commercial spaces and consist of troffer, panel, suspended, and pendant type luminaires. Of the one billion linear fixtures installed in the U.S. (US DOE 2016a), over 90%[7] of them use replaceable fluorescent tubes. The most common tubes are T8 linear tubes, which are 1 inch in diameter. Due to their typically long operating hours, linear fixtures represent one of the largest energy-saving opportunities for LEDs – 44% of the total potential for indoor lighting (US DOE 2016a).

Fluorescent lighting is a mature technology with an industry-average efficacy of 108 lumen/Watt (lm/W) (US DOE 2016b). FL are typically made of a phosphor-coated linear glass tube with an electrode at each end. The tube contains a trace amount of mercury that emits UV light when energized by current. This UV light is absorbed by the phosphor, which then fluoresces to produce visible light (US NEMA 2001). Due to the presence of mercury in them, FL are mandated by law to be recycled or disposed of properly (US EPA 2019a). However, the mercury content in FL has been decreasing steadily under stricter regulatory standards over time. A 4ft linear tube manufactured in the 2000s contains 4-12mg of mercury, compared to 40-48mg when manufactured in the mid-1980s (US NEMA 2001, Aucott et al. 2004).

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[7] 5.6% LED is estimated for 2019 based on assumption of 100% LED penetration by 2040 and 3.2% in 2015.

4.2.1.1 LED lighting

A light emitting diode (LED) is a solid-state semiconductor device that converts electrical energy to visible light. LED lamps are about 40% more energy efficient than their FL counterparts and mercury-free. LEDs are expected to continue improving in the near future. US DOE projects that LED could surpass incumbent technologies by more than 100 lm/W in luminaire efficacy by 2025 (US DOE 2016b). The annual LED efficacy gain is slowing down, from 10 lm/W between 2012-2015 to 6 lm/W between 2015-2016 (US DOE 2016a).

4.2.2 End of life pathways

4.2.2.1 Replacement options

Waste management decisions are preceded by replacement decisions that consider what to retire (e.g. lamps or the entire luminaire) and what to replace it with (e.g. fluorescent or LED). To this end, three replacement options are explored – extended use, modular replacement, and full replacement. Liu et al. (2017) and Ochs et al. (2014) show that early retirement of incumbent lighting (i.e. replacing lighting systems ahead of their rated lifetimes) can maximize energy savings by leveraging the rapid advancement of LED technology. In theory, lighting units that have been retired early still retain their functionality and can therefore be reused. However, lighting reuse is uncommon, as used lighting units are perceived as less reliable and not worth the cost of installation. A more plausible scenario akin to reuse is extended use by the owner, i.e. continued usage beyond the product's rated lifetime. This is technically possible, particularly for LED lighting as its rated lifetime is estimated based on when its light output would dip below 70% of its initial level. In this study, extended use by 25% of the product's lifetime is explored.

Hendrickson et al. (2010) identified, via a product teardown of several residential bulbs, that product modularity and standardization promote ease of disassembly and hence more material recycling. Indeed, in the past decade the industry trend has been converging towards modular designs that allow the light source and electronics (e.g. driver) to be replaced. This led to a number of LED retrofit products as well as luminaire systems with replaceable parts designed to cater to a wide spectrum of consumer needs. LED retrofits (e.g. direct wire lamps, plug & play lamps) differ in packaging, equipment costs, and labor-intensity to install, but fundamentally they are the same and require a changeout of the lamps and electronics. Thus, a luminaire can be replaced either in full or modularly (with lamps and electronics). Modular replacement tends to suffer lower system efficacy due to integration losses from the use of the incumbent fixture. On the other hand, full replacement offers a higher system efficacy but at the expense of higher equipment costs and material requirements.

4.2.2.2 Waste management options

The Universal Waste Rule encourages the recycling of FL rather than disposal in landfills to reduce hazardous municipal solid waste. Meanwhile the US National Electrical Manufacturers Association (NEMA) (2001) suggests that landfilling FL is a safe and low-cost alternative to recycling, arguing that mercury from lighting sources is minimal and can be safely contained in a landfill. Therefore, both recycling and landfilling are examined in this study.

4.3 Goal and scope

The goal of this LCA is to evaluate and compare the environmental impacts of 16[8] different *replacement-EOL pathways* for commercial T8 linear fixtures. These pathways are made up by three replacement options (i.e. extended use, modular replacement, and full replacement), two waste management options (i.e. recycling and landfilling), and three technology transition pathways – fluorescent lighting replaced with fluorescent (FL-FL), fluorescent lighting replaced with LED (FL-LED), and LED replaced with LED (LED-LED). The LCA is conducted following ISO 14044 standards and using the *Allocation, default system model* in SimaPro 9.0.0.48 and the ecoinvent 3.5 v3 database. Environmental impact indicators — *IPCC GWP 100a*, *non-renewable fossil energy*, and the full suite of indicators from *ReCiPe endpoint (Hierarchist)* — are chosen for their comprehensiveness and relevance to impacts on the environment and human system.

The lighting systems modelled represent an 8-ft 2-lamp T8 (1 inch in diameter) luminaire. All systems are to deliver 8250 lumens over the course of their rated lifetimes, which vary by technology type. The functional unit of the analysis is 1 million lumen-hour (Mlmh) of lighting service. The results of the study will be presented in two parts, each part has a system boundary as illustrated in Figure 4.1. Part 1 presents the intermediate results at EOL for each of the four replacement systems (e.g. modularly replaced fluorescent components). To avoid duplication, these results are presented based on the materials discarded from each replacement system instead of per the functional unit of 1 Mlmh. The benefit of recycling is credited by means of avoided

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[8] The number of replacement-EOL pathways is 16 instead of 18 because two sets of pathways overlap, i.e. the extended use cases (with recycling or landfilling at EOL) of a linear fluorescent fixture in the FL-FL transition is the same as those in the FL-LED transition. Arguably, the FL-LED transition has no extended use cases.

primary production of the materials recovered at the EOL stage. Part 2 presents the final results per functional unit, which compare the different replacement-EOL pathways across their full life cycles.

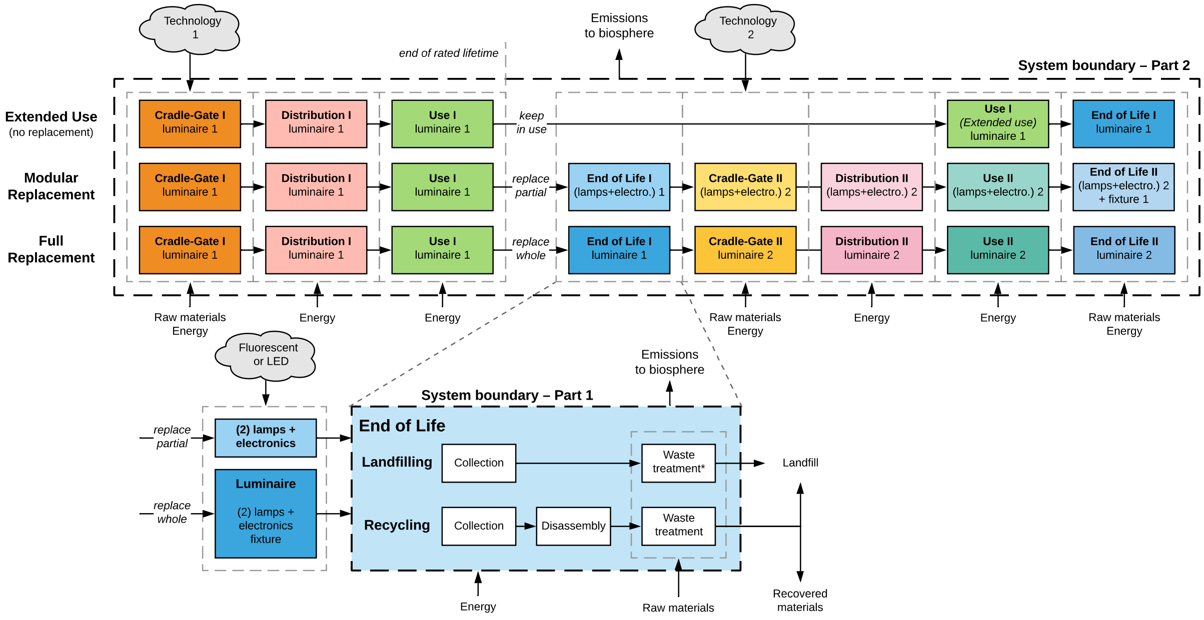

Figure 4.1: LCA system boundaries. Part 1 presents the intermediate LCIA results at the end of life phase. Part 2 presents the final results across each system's life cycle(s). (*Waste treatment is necessary for fluorescent lamps before being disposed into landfills.)

4.4 Life cycle inventory

The life cycle inventory of the linear fluorescent fixture is obtained via a product tear-down analysis, while the linear LED fixture is modeled based on shared industry information. The luminaires modeled are a direct replacement of each other in real life. The FL and LED luminaire weigh 6.83kg and 8.65kg, respectively, and are manufactured in China and Mexico, respectively, with final assembly in the U.S. Transportation is assumed to be 15km for landfill disposal and 30km for recycling on a 21ton lorry, and 300km for distribution on a >32ton freight lorry. For the electricity in use phase, the US average grid mix is assumed. The luminaire system efficacy takes into account the replacement type (modular or full) and technology transition (e.g. from FL to LED). An FL has an efficacy of 104.6 lm/W while the system could reach 128.5 lm/W when retrofitted with LED. For a full list of life cycle inventories, see supporting information.

The material recovery processes are modeled based on the hydrometallurgical methods described by Tunsu et al. (2016) for fluorescent tubes and by Swain et al. (2015) for LED manufacturing waste dusts. These laboratory-level methods are scaled up commercially using a framework proposed by Piccinno et al. (2016) along with their expert insights on average industrial process parameters. Their engineering-based framework is designed for LCA modeling purposes and has been used to estimate the environmental impacts of various emerging technologies, including battery materials, geopolymer concrete, recycling methods, and biofuel production. For details on the scaling process and derivation of the parameters, see 0.

4.4.1 Rare earth element recovery from linear fluorescent fixtures

FL contain about 2-3% of phosphor powder by mass (Binnemans et al. 2013, Tähkämö et al. 2014). The phosphor fractions vary by lamp manufacturers. They are generally made up by a combination of heavy and critical REE – yttrium (Y), europium (Eu), and terbium (Tb), and lighter REE in smaller quantities – cerium (Ce), lanthanum (La), and gadolinium (Gd). In this study, only Y and Eu are considered as they are the primary REE in the phosphor. The recovered phosphor fractions often vary in composition and quality depending on lamp design and recycling method. Common recycling processes for REE include acid leaching followed by purification.

Retired lamps are collected either whole or pre-crushed to contain mercury, prevent accidental breakage (US NEMA 2001) and reduce waste volume (US EPA 2016). Lamps that are not pre-crushed are often disassembled using a cut and blow method, where the metal electrode ends are cut off so that the phosphor powder can be "blown out" (Apisitpuvakul et al. 2008). Another method involves crushing lamps in a machine that vacuums the waste dusts through a series of filters to capture the mercury and phosphor powder (Binnemans et al. 2013). Crushed particulates can be shaken, washed, and separated into recyclates rich in metals, plastics, and glass. The separation efficiency for metal ranges from 72-99% depending on the type of crusher used (Rhee 2017).

Compared to glass cullet recycling, reclaiming REE is a much harder process. One major barrier is the incomplete removal of mercury and fine glass particles from phosphor fractions. Much of the mercury in spent lamps is chemically bound to the phosphor powder (89%) and glass particles (8%) (Jang et al 2005). Its distribution does not vary significantly with the age of the lamps (Hobohm et al. 2017). Mercury can be removed via acid leaching (e.g. I_2/KI solution) (Tunsu et al. 2016), followed by precipitation using mercury-binding resins (e.g. sodium hydrosulphite, Cyanex 923) (Tunsu et al. 2015). The most common method to remove mercury is by heating the phosphor mixture at 400-600°C for several hours, even to 800°C for higher removal rates, a process known as distillation (Binnemans et al. 2013, Fujiwara and Fujinami 2007). Direct reuse of the phosphor fractions retrieved after mercury removal is possible but often very difficult due to contamination and quality deterioration from exposure to UV and mercury over time (Binnemans et al. 2013). Instead, the phosphor fractions often are recovered by chemical extraction, with optional thermal pretreatment, followed by purification (Amato et al. 2019).

For REE recovery, this study uses a flowsheet for processing FL waste dusts (i.e. phosphor fraction) proposed by Tunsu et al. (2016). The waste treatment process flow is illustrated in Figure 4.2, along with preceding steps such as waste collection and disassembly. The sieved waste dust collected from crushed fluorescent tubes contains 17% REE (primarily Y and Eu) and 40-50%

glass and non-soluble particles. The leaching method leverages a two-step approach to isolate different materials from the phosphor mixture. First metal impurity is removed via a mild acid (1M HNO_3 for 10 min), then a REE leachate rich in Y and Eu is extracted via a stronger acid (2M HNO_3 for 24h). Both acid extractions are carried out at a 10% weight-to-volume (w/v) ratio and a 400rpm mixing rate. The REE leachate (aqueous) undergoes solvent extraction by mixing with an organic solvent containing 35% vol Cyanex 923[9] in kerosene, at a 2:1 organic-to-aqueous (O:A) feed ratio. A REE-rich aqueous solution is stripped from the organic phase using 4M HCl in a mixer-settler system at 700rpm and 1:1 O:A ratio. The solution is then treated with oxalic acid[10], followed by thermal treatment at 800°C for 2h. The final product obtained is 95:5 weight-to-weight (w/w) Y and Eu, at an overall recovery efficiency of 91%.

The depleted organic phase is regenerated by washing with water at a 1:1 feed ratio for 1 min (to remove HCl) and reused again as a Cyanex solvent. A 90% efficiency is assumed for the organic phase regeneration process. The FL modeled is assumed to have 5mg mercury, which represents the industry average today. Prior to REE leaching, the phosphor fraction undergoes distillation to remove mercury (Binnemans et al. 2013). The thermal treatment is also useful for improving the leaching kinetics (Amato et al. 2019). Outside of the leaching process, inventories are collected from a number of other studies, including Apisitpuvakul et al. (2008) on the inventory

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[9] Cyanex 923 weighs 348g/mole and contains 93% trialkylphosphine oxides ($C_{18}H_{39}OP$), which can be produced by the oxidation of tertiary phosphines (Ahmed et al. 2013). The inventory for Cyanex 923 is approximated based on the molar mass distribution of different compounds, i.e. 9.8% phosphine (i.e. phosphane), 4.6% oxygen, and 85.6% organic compounds in SimaPro 9.0.0.48.

[10] Oxalic acid is modeled as a product synthesized using sugar and nitric acid, aided by a vanadium pentroxide catalyst.

for FL disassembly and thermal treatment, Amato et al. (2019) on oxalic acid use, and Tähkämö et al. (2014) on the FL bill of materials.

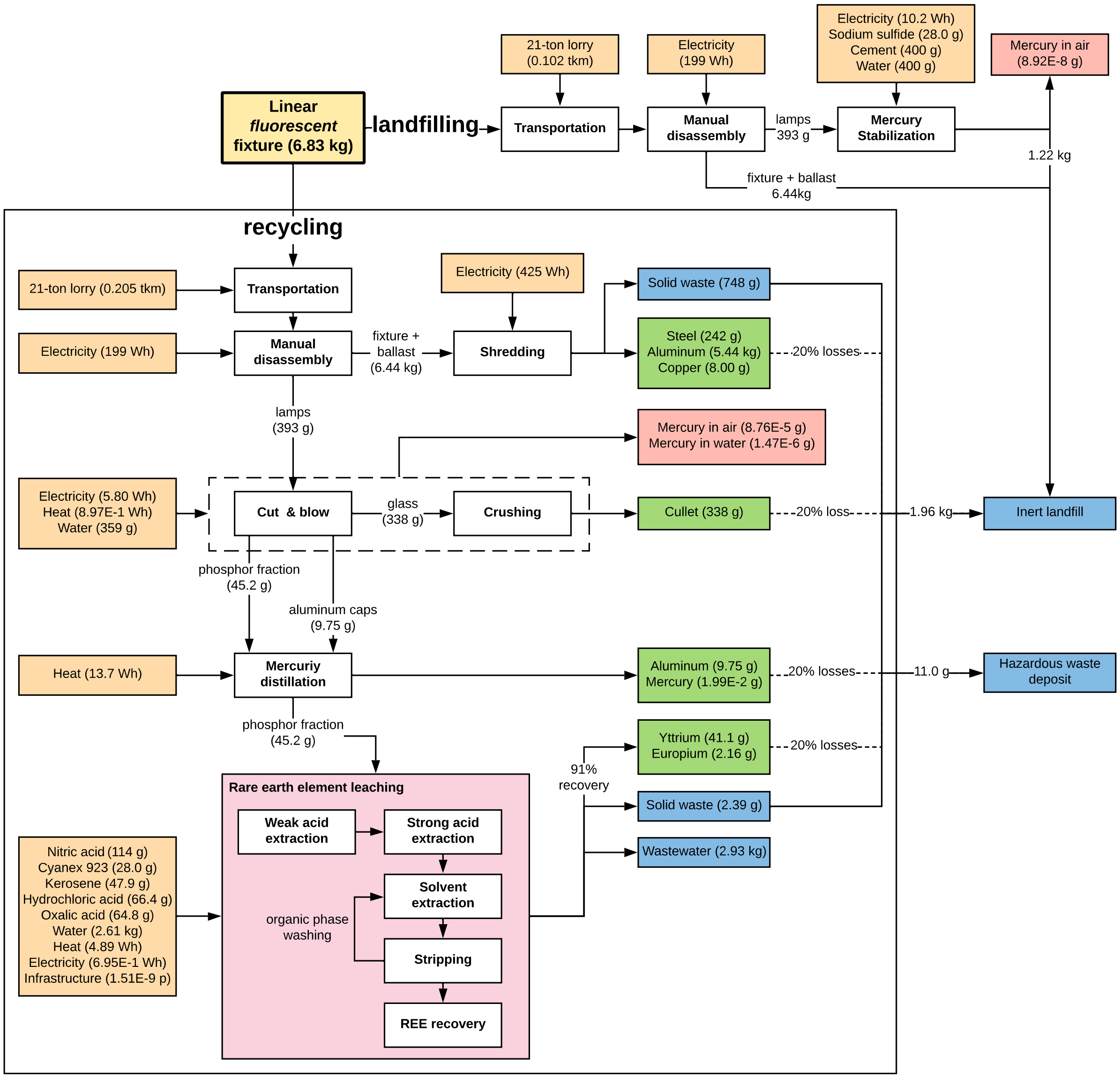

Figure 4.2: Process flow diagram for the end of life management of a linear fluorescent fixture via: 1) recycling with REE recovery, and 2) landfill disposal.

Figure 4.3 shows the environmental impacts of recovering 1kg REE (95%Y and 5%Eu) from FL waste. The recovery processes involved are outlined by the pink box in Figure 4.2 and include an allocation of the mercury distillation by the REE weight and avoided REE primary production. The REE recovery results in substantially more environmental impacts than the avoided REE primary production across all indicators, owing to the consumption of large amounts of chemicals, which together contribute to 71-100% of the impacts. Oxalic acid is the largest contributor across all but one impact indicator, despite its consumption being nearly the same as HCl. HNO_3 consumption contributes heavily to ozone depletion.

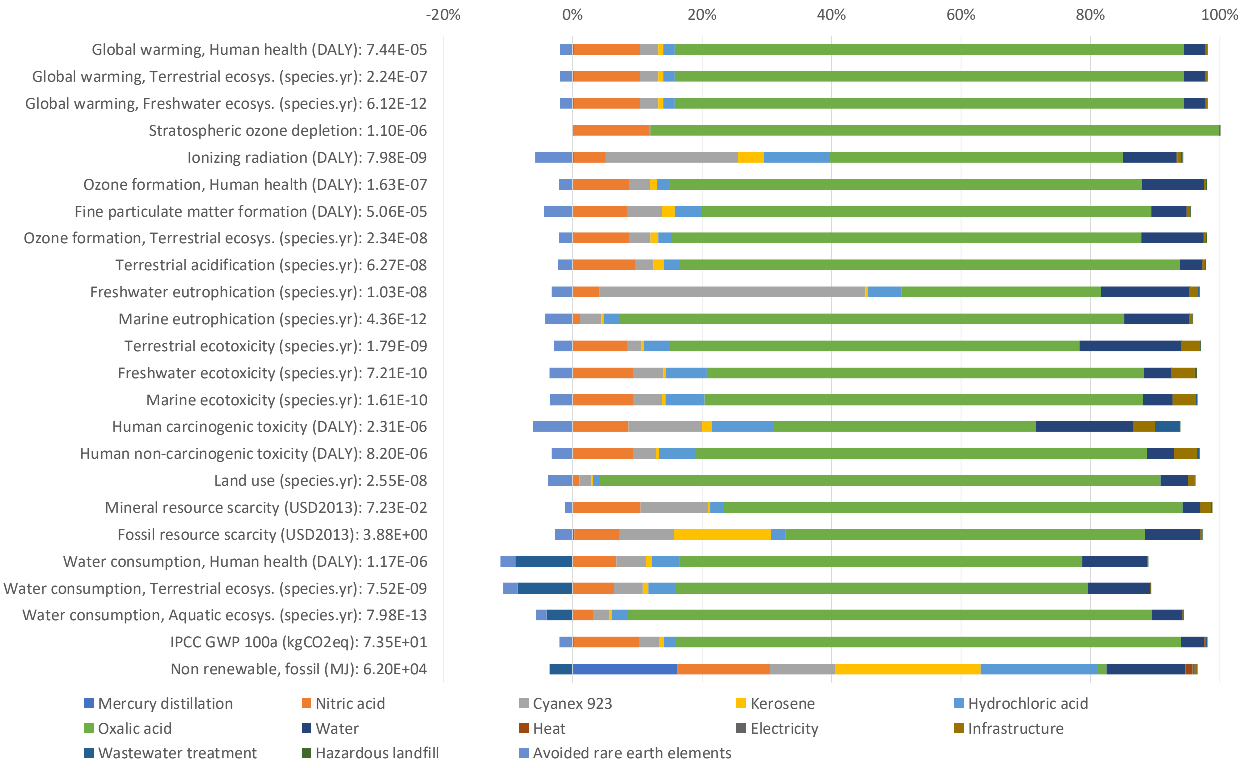

Figure 4.3: Environmental impacts per 1 kg REE recovered from the phosphor fraction of the fluorescent lamp waste via mercury distillation, leaching, and solvent extraction.

The net carbon emission and fossil energy consumption per kg REE recovered is 74 kg CO_2eq and 61,982 MJ, respectively. Table 4.1 compares the carbon emission result with values from two studies that are normalized to the same unit. To make a more consistent comparison, a new value is calculated based on Amato et al. (2019)'s process flow sheet using SimaPro (9.0.0.48) and the US grid mix. The carbon emissions result from this study is within the same order of magnitude as that from Amato et al. (2019)'s study but smaller by one order of magnitude compared to that from Hu et al. (2017)'s study. This could be attributed to the fact both this study and Amanto et al. modelled the REE recovery processes at the commercial scale while Hu et al. used inventories collected at the laboratory level.

Table 4.1: Comparison of global warming impact from different REE recovery methods from fluorescent lamp waste.

Study	Recovery Method	kg CO_2eq/kg REE recovered	System and boundary conditions
Hu et al. (2017)	Sulfuric acid extraction	608.1-623.6	Lab-scale inventories; REE extraction stage only and does not include REE purification and recovery, waste treatment, and avoided REE primary production; Taiwan grid at 0.532kg CO2eq/kWh; SimaPro (8.0.2, ecoinvent v3)
	Hydrochloric acid extraction	575.8-593.2	
	Solvent extraction	658.4	
Amato et al. (2019)	Sulfuric acid extraction	20 (38*)	Commercially scaled inventories at 4,000t/yr waste treatment; from thermal pretreatment to waste treatment; European average grid mix; GaBi (7.3.3.153, database version 6.115)
This study	Nitric acid and solvent extraction hybrid method	73.5	Commercially scaled inventories at 1,200t/yr waste treatment; from thermal pretreatment to waste treatment, including infrastructure); US average grid mix at 0.667kg CO2eq/kWh; SimaPro (9.0.0.48, ecoinvent 3.5 v3)

*new value calculated in SimaPro 9.0.0.48 using ecoinvent 3.5 v3 database and US average grid mix based on literature's process flow. Oxalic acid is remodeled as a product synthesized from sugar, nitric acid, and vanadium pentroxide rather than from *Aspergillus niger* fermentation.

4.4.2 Critical metal recovery from linear LED fixtures

To recover the critical metals from LED lamps, the LED packages need to be liberated physically from other lamp components (Nagy et al. 2017). The rest of the fixture can be dismantled in a conventional shredder, where the particulates are sorted via a series of separation steps (e.g. magnetic separators for ferrous metals, eddy current separators for non-ferrous metals).

The LED packages are crushed and sieved to produce three fractions of different ranges of particulate size (Nagy et al. 2017). The medium coarse fraction (of 106-1,000μm) contains the highest concentration of Ga as GaN and, in some cases but to a lesser extent, Indium (In) (Swain et al. 2015). This fraction further undergoes three stages of electrostatic separation to remove conductive particulates and increase the concentration of Ga from 250-350ppm to 510-710ppm (Nagy et al. 2017). At this point the waste dust is ready for critical metals recovery processing. The LED packages modeled in this study contain 0.234% w/w Ga and no In. Since the Ga concentration can only be increased up to 0.256% when all conductive materials (e.g. Al, Cu, Au) are removed, the electrostatic separation steps are not necessary and thus not included in the model.

A number of studies have been undertaken to examine different mechanochemical ways of recovering Ga from manufacturing waste containing GaN. These include leaching methods by acids (e.g. HCl, H_2SO_4) and bases (NaOH, HNO_3) as well as waste pretreatment by ball milling and annealing. Swain et al. (2015) found that pretreating LED waste prior to leaching can drastically improve Ga recovery and leaching using HCl has the best recovery rate. The effectiveness of HCl as a leaching agent for GaN recovery has also been confirmed in a study by Chen et al. (2018).

The process to recover Ga from LED phosphor waste dust is modelled after two studies. First Swain et al. (2015)'s two-stage hydrometallurgical scheme using 4M HCl is used to produce a Ga-rich liquor. Then the liquor undergoes a solvent extraction method using organophosphorus compounds proposed by Ahmed et al. (2013) to recover the Ga. These methods are chosen for their high leaching or recovery efficiencies. The waste treatment process flow is illustrated in Figure 4.4, along with preceding steps such as waste collection and disassembly.

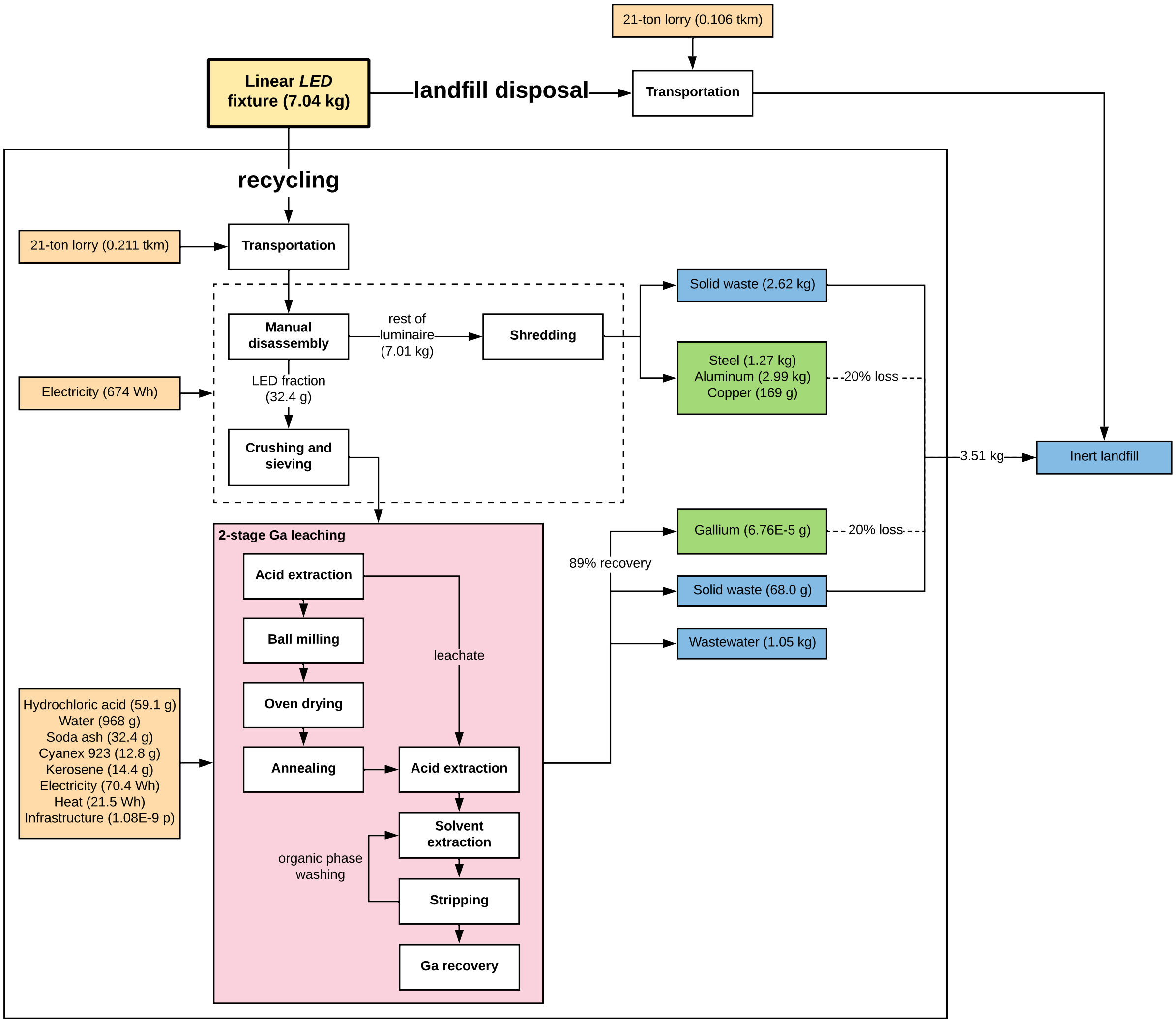

Figure 4.4: Process flow diagram for the end of life management of a linear LED fixture via: 1) recycling with critical metals recovery, and 2) landfill disposal.

First the LED waste dust is leached in 4M HCl at 100°C, 100g/L pulp density, and 400 rpm mixing rate. Then the residue is mixed with Na_2CO_3 at 1:1 w/w ratio, ball-milled in a grinding bowl at 150 rpm for 24h, dried in an oven at 60°C for 4h, and annealed in a furnace at 1,000°C for 4h. The residue then undergoes a second stage leaching, using the same 4M HCl leachate recovered from the first stage, at 100°C for 1h this time to recover Ga. The leachate reuse captures some of the Ga dissolved during the first leaching stage, bringing the overall leaching efficiency to 97%. The Ga-rich aqueous liquor is then extracted with a Cyanex 923 in kerosene organic solvent at a 1:1 O:A ratio. The molarity of the Cyanex solvent is five times the molarity of Ga in the liquor. Finally, the extracted organic phase is stripped from the solution using 1M HCl at 1:1 O:A ratio to obtain Ga at 92% overall solvent extraction efficiency. Similar to the solvent extraction process for REE recovery from FL waste, the depleted organic phase is assumed to be reused at 90% efficiency after washing with water to remove HCl. The overall Ga recovery efficiency from the acid and solvent extraction hybrid method is 89%.

Figure 4.5 shows the environmental impacts of recovering 1 kg Ga from LED lamp waste. These impacts represent the total impacts from the processes outlined by the pink box in Figure 4.4. Except for *mineral resource scarcity*, the recovery process results in substantially more environmental impacts than the avoided Ga primary production, owing to the consumption of large amounts of chemicals, which together embody 41-87% of the impacts. HCl and water consumption are among the largest impact contributors. Note the impacts of Ga recovery are one to two orders of magnitude greater than those of REE recovery from FL waste. The net carbon emissions and fossil energy consumption per kg Ga recovered is 3,689 kg CO_2eq and 63,352 MJ, respectively. These large impacts are due to the extremely low concentration of Ga (0.234 w/w%) in the LED chips, which are already small and lightweight compared to the rest of the luminaire.

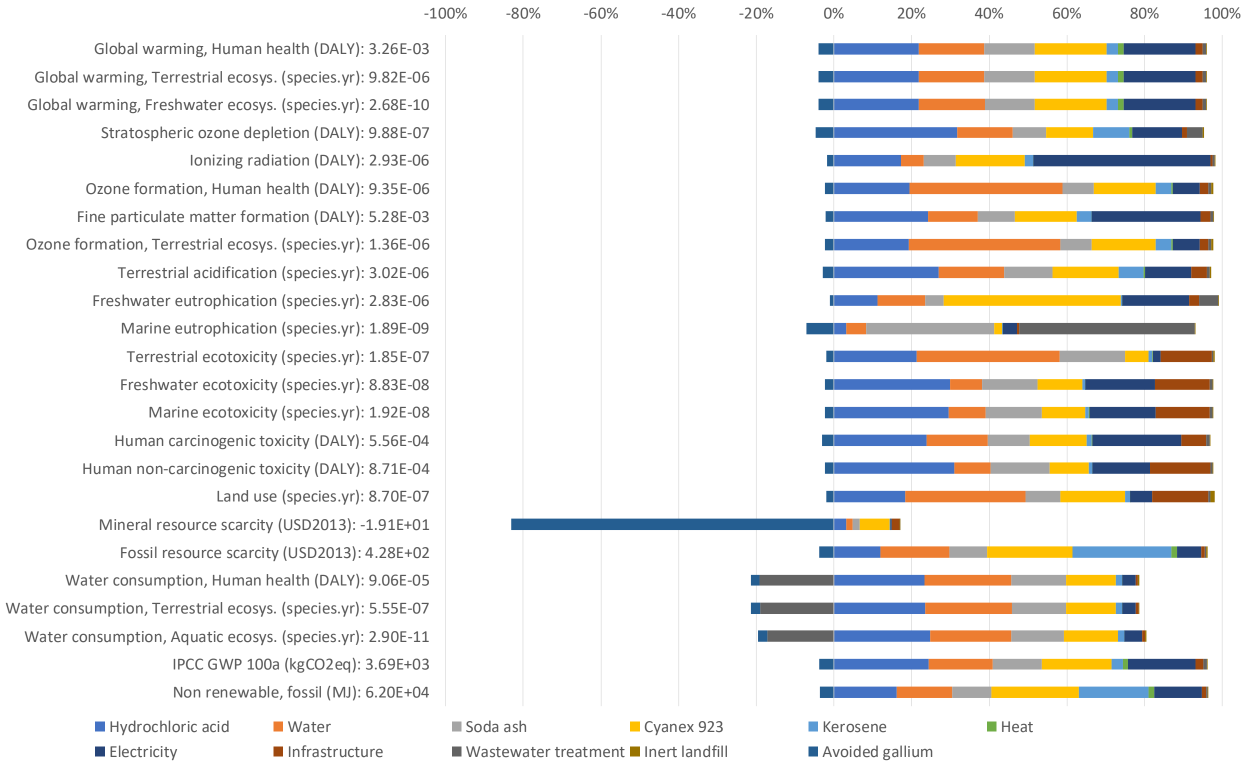

Figure 4.5: Environmental impacts per 1 kg gallium recovered from the LED fraction of linear LED lamp waste via leaching and solvent extraction.

4.5 Limitations and future work

The LCAs are conducted using SimaPro (9.0.0.48) and the ecoinvent database (3.5 v3). Despite the large inventory in the ecoinvent database, process data on REE primary production is limited and cannot be broken down into individual REE, owing to disclosure restrictions on this proprietary information. These generic REE inventories may impair the quality of the results, especially in terms of credits given to avoided primary production. However, ongoing effort to map REE primary production processes by production origins and REE grades, and to do so with increased accuracy and granularity (e.g. Lee & Wen 2016) will help fill this data gap. Although both types of luminaire contain plastic (mostly polycarbonate and glass fiber-reinforced polyamide) and circuit components (e.g. resistors), which could be recycled, their recycling is difficult and generally not common in the U.S. Therefore, these components are considered solid waste in this study. The recycling of plastic and circuit components will be left for future studies as the technology becomes more widespread.

This study recognizes that lighting replacement decisions are multidimensional, and the considerations are specific to the decision-maker. Factors such as labor, cost, light quality, and dimming requirement are not considered in this study. Interested parties can refer to factsheets from DOE’s lighting program for additional guidance on linear troffer upgrades (US DOE 2017). The 25% extended use pathway is hypothetical in that it is conditional on the health and performance of the incumbent luminaire. However, the primary purpose of the extended use case is to serve as a basis of comparison for other EOL scenarios.

Although conventional approaches, such as pyrometallurgical (melting) and hydrometallurgical (leaching) techniques, are proven to be efficient, many of them are not commercially viable (due to high energy requirement and consumption of large amounts of chemicals) and can cause secondary pollution (e.g. slags, toxic wastewater) (Priya & Hait 2017). As a result, there is a growing effort to improve the economics and scalability of these leaching methods (Tan et al. 2015), as well as increasing the amount and type of REE (e.g. Tb, Ce, La, Gd) or CM (e.g. In) that can be recovered from lamp waste. Another research focus is on developing and improving the efficiency and reliability of greener recovery methods, such as microbiological leaching (Priya & Hait 2017) and supercritical fluid extraction (Shimizu et al. 2005). Future research can examine and compare the life cycle performance and cost of different recovery methods to provide more timely and comprehensive recommendations.

4.6 Results – part 1: Intermediate results at end of life

Figure 4.6 compares the impacts of recycling and landfilling materials discarded from the modular replacement and the full replacement of a linear fluorescent fixture and a linear LED fixture, focusing on three environmental impact indicators – *global warming potential (GWP)*, *stratospheric ozone depletion*, and *mineral resource scarcity*.

4.6.1 Linear fluorescent fixture waste management

When considering only the components from the modular replacement (i.e. the FL and ballast), the recycling option results in more environmental impacts than landfill disposal across all impact indicators except *freshwater* and *marine ecotoxicity*, driven primarily by contribution from the REE recovery process. However, when the whole luminaire is considered, recycling become much more favorable and results in net beneficial impacts across all indicators except *stratospheric ozone depletion*, which appears to be dominated by REE leaching (and oxalic acid based on Figure 4.3). The benefits of luminaire recycling are driven by an avoided primary production credit from the recovery of Al, which is prominent in the housing structure and can more than offset the REE recovery impacts.

4.6.2 Linear LED fixture waste management

Despite the net harmful environmental impacts of Ga recovery across all but one impact indicator (Figure 4.5), they are dwarfed by the benefits of recycling metals from the LED fixture, as shown in Figure 4.6. For both the modular replacement and the full replacement cases, recycling results in net beneficial environmental impacts thanks to the avoided primary production of Al, Cu, and, in some cases, steel. This is true even for modular replacement, since the LED lamps contain a large of amount of metals (e.g. Al heat sink), which can be recycled.

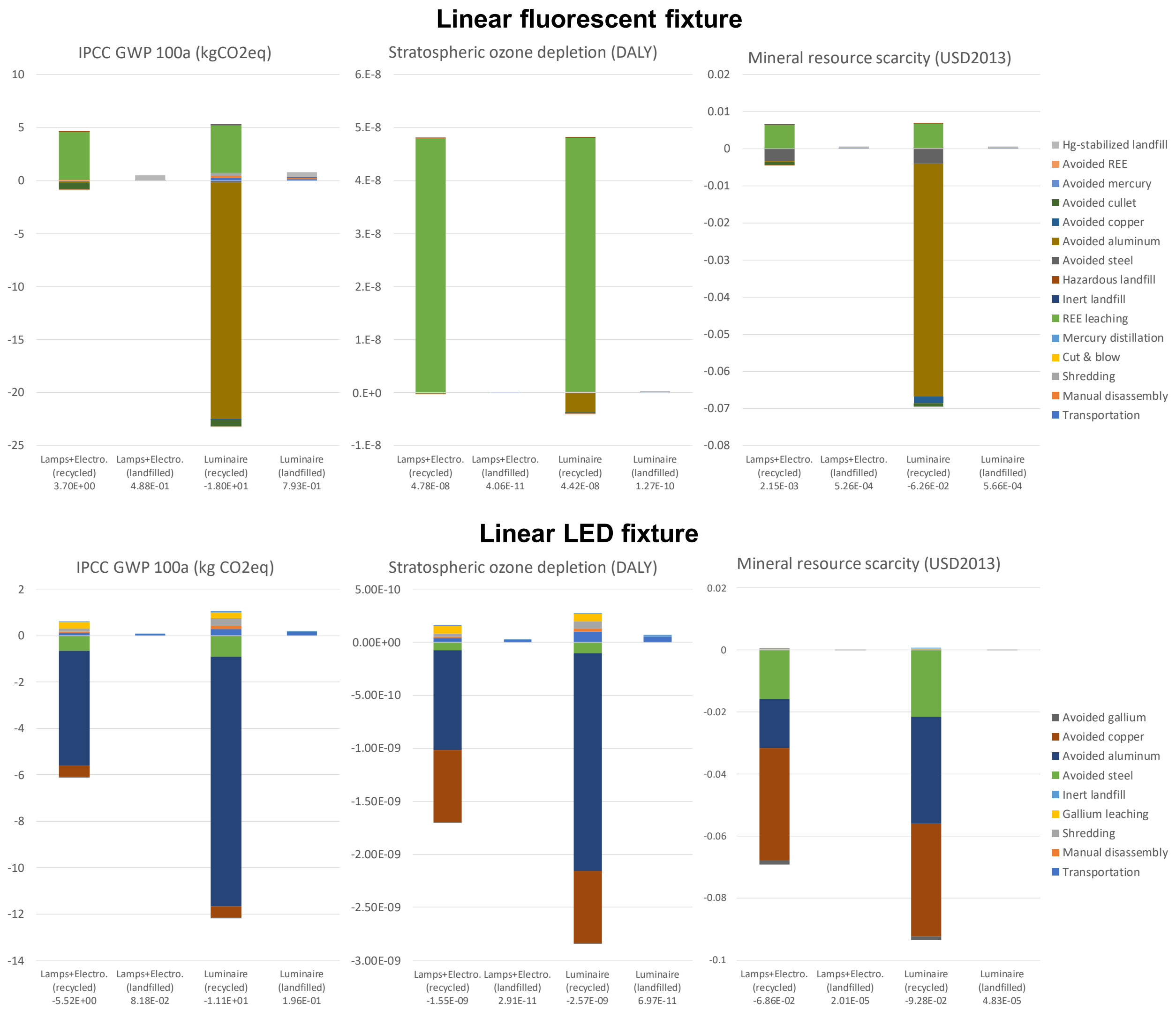

Figure 4.6: Selected environmental impacts of recycling and landfilling a linear fluorescent fixture and a linear LED fixture in full vs. by lamps and electro. (electronics) only at end of life. (Note: results represent per materials discarded as a result of replacement.)

4.7 Results – part 2: comparison of replacement-end of life pathways

To examine the full extent of waste management under different conditions, 16 unique replacement-EOL pathways are constructed based on two waste management options (recycling, landfilling), three replacement options (extended use, modular replacement, and full replacement), and three technology transition pathways (FL-to-FL, LED-to-LED, FL-to-LED). The system boundary and definition of the pathways are shown in Figure 4.1. Differences in the overall system efficacy with respect to the replacement type and technology are taken into account. For fluorescent lamps, the lamp efficacy stays constant as the technology is mature and no further improvement is expected. For LEDs, the system efficacy is higher for a full replacement than a modular replacement as integration losses with the incumbent fixture are avoided. Figure A.7 presents the results for three selected environmental impact indicators – *GWP*, *stratospheric ozone depletion*, and *mineral resource scarcity*. As expected, the use phases embody the majority of the impacts across all replacement-EOL pathways and the EOL phase impacts become relatively insignificant. All else equal, recycling results in lower environmental impacts than landfill disposal.

4.7.1 Fluorescent-to-fluorescent replacement

When the total life cycle impacts are considered, the difference between the FL-FL pathways is trivial (within 5% of one another) for 18 out of the 24 impact indicators, including *GWP*. Across all but one of the indicators, the full replacement with landfilling at EOL result in the highest environmental impacts due to the need to produce the most components and a lack of material recovery. The only exception is *ozone depletion*, in which category the impacts from the use of oxalic acid in REE leaching adversely affected the overall recycling impacts. Surprisingly, it is not the extended use cases that generally have the lowest overall impacts despite their 25% longer lifetime, but it is instead the modular replacement cases. This is because the modular components (from the second product life cycle) have much lower cradle-to-gate impacts than the luminaire. Thus, when normalized to the functional unit, the total cradle-to-gate impacts for the modular replacement cases are lower than those of the extended use cases. Another interesting finding can be obtained by comparing the case of modular replacement with landfilling and full replacement with recycling. The results show generally lower environmental impacts for the former case, suggesting that making the lamps and electronics replaceable can be a more environmentally benign strategy than enforcing recycling alone.

4.7.2 LED-to-LED replacement

The overall environmental impacts of the LED-LED pathways are generally lower than those of the FL-FL pathways, since LED have higher efficacies than FL and hence lower energy consumption. For the LED-LED pathways, full luminaire replacement (with either recycling or landfilling) results in the lowest environmental impacts across all indicators except *mineral resource scarcity*. This is due to two factors: 1) full replacement allows for the highest system efficacy gain and 2) the cradle-to-gate burden of the entire luminaire is not much more than that of the modular components (i.e. lamps and driver). Extended use has the opposite effect by making no replacement and is therefore the most impactful across all indicators. In terms of *mineral resource scarcity*, any replacement with recycling has the least environmental impacts.

4.7.3 Fluorescent-to-LED replacement

The FL-LED pathways provide the most reduction in environmental impacts by leveraging LED's increasing efficacy and longevity, compared to the extended use of an incumbent linear fluorescent fixture. Among these pathways, it is interesting to compare the impacts of retrofitting the fluorescent fixture with LED lamps and a driver (modular replacement) or replacing it completely with a new LED fixture (full replacement). The retrofit option is modelled as being 5% less efficient and shorter lasting than the full replacement option, due to the use of the incumbent fixture which is not designed for LED.

The results show that full replacement, particularly when coupled with recycling, has the lowest environmental impacts across all indicators, hence a full fixture upgrade to LED is a more environmentally benign choice than a LED retrofit for the linear fluorescent fixture.

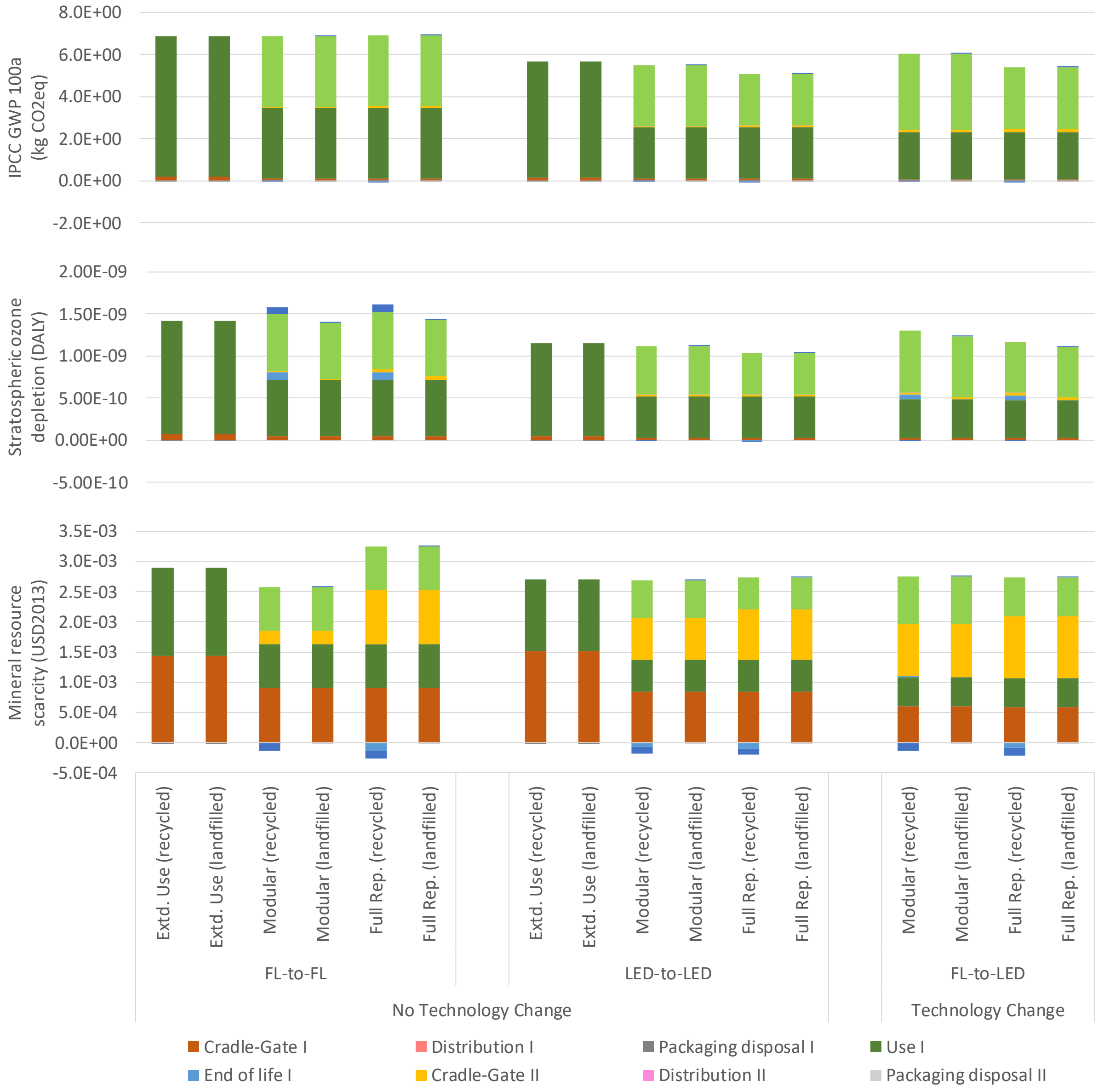

Figure 4.7: Selected environmental impact indicators compared across 16 different replacement-EOL pathways. (Functional unit: 1 Mlmh of lighting service, Extd. = Extended, Rep. = Replacement)

4.8 Conclusion

Post-consumer lighting represents an important opportunity for REE and CM recovery. With nearly 1 billion linear fixtures in the U.S., of which over 90% still use fluorescent technologies (US DOE 2016b), the overnight potential to recover REE from legacy FL[11] is roughly 20,000 metric tons, along with 9 metric tons of mercury. However, based on current acid extraction technologies, REE recovery from FL waste has harmful environmental impacts, driven by the large amount of chemicals used. Compared to REE recovery, the net environmental impacts of Ga recovery from LED waste (except in terms of *mineral resource scarcity*) are even higher by 1-2 orders of magnitude due to the low concentration of Ga in LED chips. The net carbon emissions per kg material recovered are 74 kg and 3,687 kg CO_2eq for REE and Ga, respectively.

To this end, REE and CM recovery methods may benefit from process optimization. For example, oxalic acid, which is used to recover REE in the final step and contributes majority of the impacts of REE recovery, can be recycled internally, similar to the regeneration of the Cyanex solution used during solvent extraction. As metal dilutions in waste directly impact the economics of recycling (Johnson et al. 2007), Ga recovery from LED waste can undergo preprocessing to increase its concentration of Ga, thereby improving its recovery efficiency and costs. Greener recovery approaches, such as microbiological leaching and supercritical fluid extraction using CO_2, may provide alternative recovery pathways in the future as they become more developed and commercially viable.

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[11] The calculation assumes 4ft FL on average, which is the standard practice and its impacts are half of those of the 8ft FL modeled in this study.

Additionally, the impacts of REE and CM recovery from lighting waste can be reduced by recovering other valuable materials simultaneously. For example, the LED waste in this study contain 0.29 w/w% Y and 0.41 w/w% Lutetium, which may be recovered as coproducts of the Ga recovery process. The recycling of common metals, such as Al, Cu, and steel, from lighting fixtures can also reduce or even completely offset the burdens of hydrometallurgical processing, thus helping to lower the environmental and economic barriers for REE and CM recovery efforts in recycling. In the case of FL recycling, the benefits of metal recovery from the lamp and ballast alone are not enough to offset the REE recovery burdens. However, for LED lamp recycling, the high metal concentration in the LED light sources (i.e. from the heat sink) can more than offset the burdens from Ga recovery, despite it being orders of magnitude more impactful than REE recovery.

As more and more lighting transition from fluorescent to LED, there will be reduction in environmental impacts, primarily driven by the efficacy gain from LED. However, since LED is not subjected to the Universal Waste Rule, recycling rates could decrease, leading to less material recovery and more solid waste. In terms of replacement decisions for waste management, the benefits of extended use and modular product design are not as clear-cut as expected. A mature technology like fluorescent can benefit from extended use as well as product modularization, which can be a more environmentally benign strategy than enforcing recycling alone (as illustrated in the FL-FL pathways). However, the most important strategy is prioritizing energy efficiency by replace old lighting with new LED. To this end, full luminaire replacement may be better than modular replacement for leveraging the full efficacy of new LED lighting as integration losses from the use of the legacy fixture can be avoided.

As lighting technologies mature and energy sources become less carbon intensive, EOL management will play an increasingly important role in reducing pollution, increasing resource utilization efficiency, and facilitating a circular economy. While it is possible for individual consumers to make better product selection (Jägerbrand 2015, Fang et al. 2018) and waste management decisions (Dzombak 2017), lighting system sustainability will require systemic changes from the industry. To this end, lighting design and material selection need to take place with disassembly and recycling in mind, as material liberation is key to higher recovery efficiencies and lower recycling costs (Reuter & van Schaik 2015, Johnson et al. 2007). In addition to product design and material recovery process improvements, recycling channels need to be optimized through waste collection strategies (Von Gries and Wilts 2015), economies of scale, and be in line with REE and CM pricing to facilitate more investment and momentum in this area (Qiu & Suh 2019).

Chapter 5 Assessing Residential Building Type Specific Heating and Cooling Demand Response Potentials Using Fourier Based Multiple Regression of Smart Meter Data

Abstract

Demand response (DR) estimation is useful to utilities in understanding their load end uses and designing more effective DR programs. In this study, a piecewise log-linear-Fourier regression model is proposed to disaggregate the thermostatically controlled loads from whole-home smart meter data and to estimate the technical thermal DR potentials. The model uses Fourier fitting functions to capture the time-variant patterns in the baseload and time-variant demand-sensitivity to temperature to better estimate the HVAC demands. Using smart meter data from ComEd, the model finds that space heating represents 17.4% of the winter load (7.8% annual load), and space cooling is 41.4% of the summer load (19.4% annual load). With a residential customer base of 3.69 million, the total instantaneous heating DR potential for the top 5 winter system peak hours is 0.93 GW and the total cooling DR potential for the top 5 summer peak hours is 3.6 GW. During the winter peaks, electric heat customers could on average shed 60% of their load instantaneously compared to 20% or less by their counterparts. During the summer peaks, non-electric heat customers could curtail their load by up to 61% on average, whereas electric heat customers could cut their demand by only half that. As ComEd is summer-peaking and cooling-dominant, its single family non-electric heat service class, which represents over 50% of its customer base and consumes 2-4 times more energy for cooling, is best suited to provide meaningful cooling DR during its system peak hours.

Keywords: demand response; load disaggregation; smart meter data; multiple regression; Fourier transform

5.1 Introduction

Building consumption represented one fifth of the global delivered energy in 2018 and projected to grow at 1.3% annually (US EIA 2019a). As more end uses are shifting toward electricity (US EIA 2019a), buildings represent an important demand response resource for electric grid operation. Enabled by smart meters and home energy management systems, demand response (DR) is achieved when consumers reduce or shift their electricity usage in response to grid signals or incentives during peak periods (US DOE 2020). Within building end uses, thermostatically controlled loads (TCL) or Heating Ventilation and Air Conditioning (HVAC) loads account for some of the largest end uses and hence DR potentials. This study presents a framework for estimating DR potential for space heating and cooling using large samples of residential smart meter data collected in the US Midwest region.

In the U.S., about 25% of the total electricity delivered in 2019 are consumed by residential buildings (US EIA 2020). Within them, space heating and cooling accounts for 14% and 16% of the total electricity expenditure, respectively. The demand for electric space heating is will decrease at 1% per year to 2050, whereas air conditioning will undergo the largest growth of all end uses and increase at 1.6% annually (US EIA 2020). TCL is highly dependent on geographic location and climate and space heating is more prevalent in colder climate regions such as the US Northeast and Midwest. The large thermal inertia of buildings allows TCL to be an effective DR resource by allowing the control setpoint to be changed intermittently according to outdoor temperature without causing large deviation in the interior temperature and thermal discomfort

(Mathiew et al. 2011). This, combined with their large energy expenditures, makes space heating and cooling a significant DR resource.

Estimating the technical DR potentials from residential building stock is important to utilities' resource planning as well as to distribution system operators and DR aggregators[12]. DR can help utilities balance supply and demand more effectively, reduce operating cost by reducing peak demand, and defer the construction of new power plants. These cost reductions, in turn, are transferred to consumers as cost savings. Unlike the use of AC, which tends to coincide well with solar resource (Dyson et al. 2014), space heating demand tends to be higher during the night and in winter months when solar resource is lowest and cannot be leveraged fully to displace peak demands. Therefore, DR in space heating would serve a non-trivial role, particularly in heating-dominant regions.

Advanced Metering Infrastructure (AMI) or smart meter data is becoming more abundant, high quality, and high resolution, thanks to the exponential growth in smart meter deployment, which have more than doubled in the U.S. in the last decade (US EIA 2017). By 2018, smart meter deployment has reached nearly 90 million, covering over half of all US electric customers (US EIA 2017, 2019b). Smart meter data enables a variety of data analytics (e.g. load analysis, forecasting, and management) useful for understanding energy use behaviors and enhancing grid operations (Wang et al. 2020). In this study, an AMI dataset containing sub-hourly whole home electric demands for over 2.75 million accounts in the Midwest is assessed. This dataset provides a unique opportunity to understand: 1) the difference in HVAC DR potentials between single and

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[12] they aggregate DR from customers to sell in the ancillary market. (Wang et al. 2020)

multi-family buildings, and 2) whether households with high space heating demand are also those with high space cooling demand.

5.1.1 Literature review

HVAC DR potentials can be estimated by electric demand sensitivity to outdoor temperature, assuming this thermal response rate is equivalent to demand change in response to a broadcast of setpoint change. Methods for capturing the nonlinear relationship between demand and temperature include non-parametric and parametric regressions. Non-parametric regressions describe the relationship between predictors and response without a parametrized function (e.g. moving average). These regressions often use a smoothing method (e.g. Kernel density estimation) to obtain the locally weighted averages (Härdle, 1990) or collapse the continuous variables into bins (Aroonruengsawat and Auffhammer 2011, Deschenes and Greenstone 2011, Berkouwer 2020). Parametric regressions are those defined by a parametric function (e.g. a linear model). Compared to non-parametric regressions, which rely on the entire dataset to make predictions, a fixed parametric model uses only the predictor estimates. The simplicity and interpretability of parametric models may better lend themselves to utilities as these models can eliminate the need to store large amounts of data, which is resource-constrained and difficult; and they can provide more insights on how the response is affected by the predictors than non-parametric models.

Henley and Peirson (1997) demonstrated that space heating energy (explicitly metered) is best described by a quartic (4th order) function of the difference between indoor and outdoor temperatures based on heat transfer principles. They noted that while the quartic model provides better fit than linear models, the fit compared to Kernel regression is less reliable on either end of the temperature range, where the data points are less dense. The Kernel regression reveals the relationship to more closely follow a logistic curve, in which demand plateaus to a maximum at extremely low temperatures and vice versa. This makes sense as the heating system would cycle more and more frequently until it is on at full capacity as temperature drops. However, many studies have demonstrated that linear regression is enough to capture the relationship between TCL and temperature.

One of the widely used parametric methods for extracting TCL from whole home energy demand is the simple linear change-point (or break point) models. (Kissock et al. 1998, 2002, Mathieu et al. 2011, Birt et al. 2012, Burke and Emerick 2016, Perez et al. 2017, Waite et al. 2017, Chen et al. 2019, Berkouwer 2020). These models are based on the observation that demand tends to have piecewise linear correlation with temperature, whereby TCL associated with cooling increases linearly with rising temperature above a changepoint (temperature threshold) and TCL associated with heating increases with falling temperature below the same or a different changepoint. The best-fit lines are constrained to join at the changepoint(s). When there are two HVAC changepoints, the middle line segment represents the dead band, or a range of temperatures for which HVAC is off. By regressing demand with the temperature difference between outdoor and HVAC changepoint(s), average thermal response rates and non-temperature dependent load (i.e. baseload) are obtained. However, the variability in responses are not captured in these models as they assume that baseload, temperature sensitivity, and HVAC changepoints are all static (constant).

In second group of change-point models, the regressions are performed within divided domains, which are based on the classification of data points as temperature and non-temperature dependent. To this end, Dyson et al. (2014) used linear regression of daily aggregation and an unsupervised method to successively separate the data. Liang and Ma (2019) used a pattern similarity search method that compares temporally adjacent time segments to extract temperature-dependent loads for the regression. Compared to the simple change-point models, this group of models can capture instances when demand is decoupled from temperature, such as buildings with manual or scheduled HVAC operation that does not always follow temperature.[13]

Demand is inherently influenced by activity patterns, which depend on time. To control for the fixed effects of time, previous studies have separated the regressions by time periods (e.g. Henley and Peirson 1997, Mathieu et al. 2011, Liang and Ma 2019) or incorporate time variables (e.g. hour of day, weekdays) directly into the models (Dyson et al. 2014). To our knowledge, no studies have considered the interaction between temperature and time. Interaction effects can be thought of as the deviation from the mean temperature effect on demand with respect to time. This time-variant temperature fluctuation is important for load disaggregation as well as for improving model fit.

Another group of models aim to incorporate flexibility not found in the simple change-point model by capturing the dynamics in temperature sensitivity, setpoint preference, and activity pattern. To this end, Hidden Markov models (HMM) are used to identify when and how long a heating appliance is on (Huang et al. 2013), or when and how much heating energy is used (Albert and Rajagopal 2015) based on whole home energy data. A n_{th} order Markov process describes the transition process in which the state of a system only depends on its current state and $n-1$ previous states. A hidden Markov model is one where the current state is not observed and only the sequence of transitions is. A disadvantage of this group of models is computation requirement compared to change-point models. For example, computing a system with m stages (e.g. time steps) and n states

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[13] An example is when HVAC is turned off during the shoulder season when temperature still fluctuates widely throughout the day.

requires a memory usage proportional to mn and time proportional to mn_2. Whereas the time complexity of a linear regression with m samples is proportional to m.

In this study, a piecewise log-linear-Fourier regression model is proposed to quantify the technical space heating and cooling DR potentials as a function temperature using whole-home smart meter data. DR estimation is useful to utilities to understand their load end uses and design more effective DR programs. Fourier transform, or spectral analysis, is commonly used to capture periodicity, such as diurnal cycles (Smith 1998). A piecewise linear structure is chosen to keep the computation requirement low and to offer an easy interpretation of the results. Compared to the change-point models with a prerequisite data classification step, the classification or domain partitioning is incorporated as a model constraint so that it can be optimized simultaneously with the curve fit. Compared to the simple change-point models, the model proposed captures the time dynamics in the baseloads using Fourier fitting functions as well as the time-variant temperature effects.

This study aims to extend existing demand-temperature changepoint regression models for load disaggregation and apply the new model to ComEd's AMI data to: 1) evaluate the technical space heating and cooling DR potentials from a utility's standpoint; 2) compare the DR potentials between building types (single/multi-family) and space heating types (electric/non-electric); and 3) discuss DR program design and policy implications based on the results. The objective of the model is to estimate 1) the HVAC loads, and 2) the sensitivity of HVAC loads to the temperature as the DR potential from broadcasting an HVAC setpoint change.

5.2 Method

5.2.1 AMI data

This study uses an AMI energy dataset from Commonwealth Edison (ComEd), an electric utility that operates primarily in the state of Illinois (IL). This ground truth dataset contains half hourly electricity usage time series from October 2015 to March 2017 and represents over 2.75 million accounts in 375 zip codes. The data is pre-divided into four service classes which are classified by building type (single/multi-family) and space heating type (electric/non-electric). Majority (about 95%) of the customer base have non-electric space heating. Due to regulation in IL around data privacy protection, the account IDs are anonymized and reshuffled each month, hence zip code level aggregated data is used. The completeness of the data (i.e. whether it has missing time steps) per zip code varies due to meter deployment, which increased over time. In December 2016, there was a significant drop in the meter readings, therefore the dataset is truncated between December 2015 and November 2016 to obtain one full year (leap year) of data. Within that year, there are 11678-15242 Heating Degree Days (under 65°F), and 745-2412 Cooling Degree Days (over 65°F) based on the data from all relevant weather stations. Only zip codes containing at least 95% complete data are used. The number of accounts represented in the processed dataset is 2.27 million.

5.2.2 Seasonal definition

Hourly TMY3 outdoor temperature from weather station closest to each zip code (linear distance based on the latitude and longitude of its centroid) is obtained from EEWeather (2019). The temperature dataset is interpolated to match the half-hourly intervals for the AMI data. The seasonal segmentation is obtained by performing a multiple change-point detection over each zip code level time series using a Python package called *Ruptures* (Truong et al. 2020). This program aims to locate the time steps between which demand is most similar to its neighbors in an optimization framework. The four most occurring change-points are selected from the distribution of the results to inform the beginning of each seasons. The seasonal definition obtained and used in this study is that winter ends on 2016-04-11 and begins again on 2016-11-17 and summer occurs between 2016-05-26 and 2016-09-28.

5.2.3 Piecewise log-linear-Fourier change-point regression

The electric demand is log-transformed so that: 1) the effect of outliers is dampened (data is right-skewed); and 2) the model parameters can approximate the percent change in HVAC demand per degree change in temperature. The log transformation helps improve the model fit by allowing the model residuals to be more normally distributed, which enforces the use of the statistical modeling framework. The data domain Ω has the following dimensions:

$$\Omega = \left[x^{min}, x^{max}\right] \times \left[y^{min}, y^{max}\right] \times \{0, 0.5, 1, \ldots, t^{max}\} \tag{5.1}$$

where x is the temperature in °C, y is ln(demand) in W, and t is the time index, or the number of hours from the start of the time horizon. The super scripts min and max represent the minimum and maximum of the range of each predictor variable, respectively. The partitioned domains are shown in Figure 5.1, where the heating domain (shown in magenta), $\Omega^h = \{(x, y, t) \in \Omega \mid x \leq x^h, y \geq y^{hf}, t \in T^h\}$, is a subset domain with an x upper-bound defined by the heating change-point x^h (i.e. where space heating ends) and a y lower-bound by y^{hf}, which represents the cut-off between loads with heating and without. Similarly, the cooling region (shown in cyan) is defined as $\Omega^c = \{(x, y, t) \in \Omega \mid x \geq x^c, y \geq y^{cf}, t \in T^c\}$, where x^c is the cooling change-point (i.e. where space cooling begins) and $x^h \leq x^c$. Both heating and cooling domains are constrained to within a subset of time indices, which represents season. This is to ensure that the model considers only the datapoints occurring in the winter for heating and those in the summer for cooling. The non-HVAC (non-temperature dependent) domain is that outside the heating and cooling domains, $\Omega^f = \Omega \setminus (\Omega^h \cup \Omega^c)$. The fitting parameters for domain partitioning are x^h, x^c, y^{hf}, and y^{cf}.

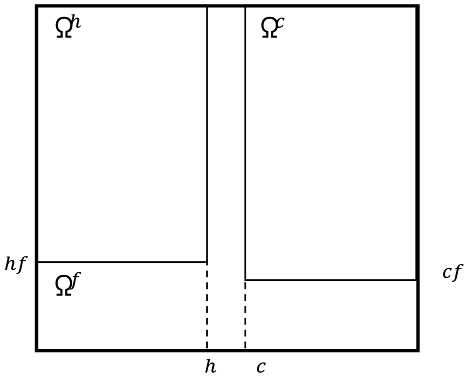

Figure 5.1: Data domain partitioning.

The estimated log demand $\ln(\hat{y})$ is provided by the domain-wise linear-Fourier regressions as follows:

$$\ln(\hat{y}) = \begin{cases} F^h(t)\left(b^h + m^h(x - x^h)\right) + F^0(t) & if\ (x, y, t) \in \Omega^h \\ F^c(t)\left(b^c + m^c(x - x^c)\right) + F^0(t) & if\ (x, y, t) \in \Omega^c \\ F^0(t) & if\ (x, y, t) \in \Omega^f \end{cases} \tag{5.2}$$

$$F^d(t) = a_0^d + a_1^d\, cos(\omega t) + a_2^d\, sin(\omega t) + a_3^d\, cos(2\omega t) + a_4^d\, sin(2\omega t) \tag{5.3}$$

$$\begin{aligned} F^0(t) = {} & a_0^0 + a_1^0\, cos(\omega t) + a_2^0\, sin(\omega t) \\ & + \sum_{i=2}^{8} a_{2i-1}^0\, cos(k_i \omega t) + a_{2i}^0\, sin(k_i \omega t) \end{aligned} \tag{5.4}$$

where F^h, F^c, and $F^0$are the Fourier transform of t for heating, cooling, and non-HVAC domain, respectively. The Fourier functions for the HVAC domains are generalized by a $F^d(t)$, where $d =$

$\{h, c\}$. $a_i^d, i = 0,1, \ldots, 4$ are the fitting Fourier parameters for t, and ω is the fundamental frequency of the Fourier transform given by $\frac{2\pi}{p}$ at $p = 24$h. Effectively, the Fourier components capture the 24h and 12h cycle patterns,[14] which are among the top 8 strongest cycles (denoted by high magnitudes) based on the FFT of different zip code aggregated demands. The effect of time of day on demand is often included in demand regression models to control for daily activity patterns and temperature cycle at this frequency. b^h, b^c, m^h, m^c are the fitting linear parameters for x centered at their domain-specific changepoints. The Linear-Fourier portion describes temperature as a mix of mean and time-variant effects.

The non-HVAC domain aims to capture the baseload, which consists of constant appliance loads (e.g. refrigerators, phantom plug loads) and non-temperature dependent activity loads (e.g. typical occupancy and use pattern of appliances that are more schedule based). To this end, an 8-frequency Fourier function $F^0(t)$ is used to capture these major cyclical patterns. The number of Fourier components to include in the model comes at the tradeoff of improved fit and computation time. ω and the Fourier term multipliers, $k_i, i = 2, \ldots, 8$, as well as the initial parameter fits are informed by the FFT of demand in the shoulder seasons. The HVAC domains also contain $F^0(t)$ so that 1) the function can be regressed across all datapoints; and 2) the Linear-Fourier portion of their models can capture the temperature dependent effects as an addition to the baseload.

The regression model is an ordinary least squares regression solved by minimizing the sum square of residuals (RSS) using a python package called *lmfit* (Newville et al. 2020). A local search method, *powell*, is used to iterate over a number of partitioned domains to obtain the global

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[14] a_1^d and a_2^d give the coefficients for the 24h cycles and a_3^d and a_4^d, 12h cycles.

solution. The search is partitioned based on bounds applied to the domain-partitioning parameters: x^h, x^c, y^{hf}, and y^{cf}. First a simple change-point regression is performed over a set of smoothed-out demand by temp bins to get a best guessed value for the HVAC change-point (e.g. 21°C). This value is then used to inform the bounds for the change-points (e.g. three sets of bounds would be constructed: [13.5, 18.5], [18.5, 23.5], [23.5, 28.5]). These bounds are applied to x^h for zip codes with electric space heating, and to x^c for those with non-electric heat. A constraint parameter, $\Delta x = x^h - x^c$, which is used to enforce $x^h \leq x^c$, has an upper bound of 5 and of the width of Ω. For y^{hf} and y^{cf}, three equal length bounds are constructed between y^{min} and y^{max}. The maximum number of iterations per zip code is, therefore, 3(3)(2) = 18. Three FFT performed over the winter, summer, and shoulder season demands are used to inform the initial values of the Fourier components for the heating, cooling, and non-HVAC domain models, respectively.

5.2.4 Demand response estimation

5.2.4.1 Instantaneous demand response potential

An assumption to the regression model is that HVAC domain demands are made up by the baseload and HVAC loads. The instantaneous (very short term and time-limiting) HVAC DR potential $InstDR_t^d$ is estimated based on the disaggregation of these HVAC demands from the whole-home loads in the HVAC domains, given as follows:

$$InstDR_t^d = e^{F^d(t)\left(b^d + m^d(x - x^d)\right) + F^0(t)} - e^{F^0(t)} \quad if\ (x, y, t) \in \Omega^d \tag{5.5}$$

where $d = \{h, c\}$, and the terms are the estimated back-transformed HVAC domain demands and baseload, respectively, from (5.2. The results can be interpreted as the expected DR or curtailment (load reduction) potential by shifting the HVAC changepoints entirely to match the outdoor temperature. If $D^d(x,t) = F^d(t)\Big(b^d + m^d(x - x^d)\Big)$, then the estimated HVAC domain demand can be rewritten as:

$$\hat{y}^d = e^{D^d(x,t)+F^0(t)} = e^{D^d(x,t)}e^{F^0(t)} = e^{D^d(x,t)}\hat{y}^f \tag{5.6}$$

where $\hat{y}^f$ is the baseload. This means the HVAC domain load is an exponential multiple of the baseload and $D^d(x,t)$ is an HVAC effect factor and is 0 when HVAC is off and > 0 when HVAC is on. For example, if $D^h(x,t)$ is 0.5, then demand during the hours in which heating is on is $e_{0.5}$ or 1.65 times the baseload and the heating portion of the demand is 65% of the baseload.

Due to the nature of the Linear-Fourier model $D^d(x,t)$, many of its fitting parameters cannot be interpreted alone. If $F^d(t) = a_0^d + F_1^d(t)$, then $D^d(x,t)$ can be rewritten as:

$$D^d(x,t) = \underbrace{a_0^d b^d}_{\substack{geometric\\ mean}} + \underbrace{b^d F_1^d(t)}_{\substack{main\ effect\\ of\ time}} + \underbrace{a_0^d m^d(x - d^d)}_{\substack{main\ effect\\ of\ temp.}} + \underbrace{F_1^d(t) m^d(x - d^d)}_{\substack{interaction\ between\\ temp.\ and\ time}} \tag{5.7}$$

where each of the terms describes the HVAC load as a relative difference between the baseload and the overall demand in the HVAC domain. The first term is the geometric mean of the HVAC demand when the effects of time and temperature are all zero. This can be thought of as the minimum percent increase from baseload when heating or cooling is turned on. The second term captures the main effect of time, or the time-variant deviation from the mean percent increase in load from the HVAC start-up. The third term is the main effect of temperature. The composite slope $a_0^d m^d$ represents demand sensitivity to temperature, i.e. the mean percent increase in demand due to a unit shift in HVAC setpoint to match the outdoor temperature, all else being equal. For example, if the composite slope is 0.01, it means shifting the setpoint by 1°C will increase demand by $e_{0.01}$-1=1%. On the other hand, a zero slope means the HVAC-domain loads do not have a clear relationship with temperature alone. The fourth term describes the interaction between temperature and time. It can be thought of as the fluctuations of the demand sensitivity to temperature with respect to time.

5.2.4.2 Average demand response potential

The average (steady-state) space heating and cooling DR potential, $AvgDR_t^h$ and $AvgDR_t^c$, are defined as the half-hourly mean curtailment potential from a broadcast of HVAC setpoint change to match outdoor temperature by up to 2.5°C (~4°F) (Dyson et al. 2014), given as:

$$AvgDR_t^h = e^{a_0^h m^h \cdot \max(x-d^h,-2.5)+F^0(t)} - e^{F^0(t)} \quad if\ (x,y,t) \in \Omega^h \tag{5.8}$$

$$AvgDR_t^c = e^{a_0^c m^c \cdot \min(x-d^c,2.5)+F^0(t)} - e^{F^0(t)} \quad if\ (x,y,t) \in \Omega^c \tag{5.9}$$

The terms are again back-transformed from the log domain.

5.3 Results

5.3.1 Regression output

Figure 5.2 shows four examples of the regression results. The top panels show two zip codes that have only one type of HVAC demand, while the bottom two panels show zip codes with dual HVAC modes that are either heating or cooling dominant. Within each panel, the left column subplots are in the temperature domain while the right column subplots are in the time domain. The magenta, cyan, and blue colored dots in the first row of subplots represent the best fit demands in the heating, cooling, and non-HVAC domain, respectively. The middle row subplots provide the residuals of the fit (yellow dots) and the temperature time series (green) for reference. The third row of subplots provide the back-transformed disaggregated heating and cooling demands in the temperature and time domain. The plots show that the regression model can adequately characterize the loads and/or identify the change-points in different load patterns. For example, in the top left plot, the change-points are overly shifted to the left, but the cooling loads were correctly identified. In the top right plot, the data seems more underfitted than other data sets but the general trend between temperature and demand is captured.

Figure 5.3 shows the distribution of r_2 values and selected HVAC domains model parameters – change-points: x^h, x^c, slopes: m^h, m^c, and intercepts: b^h, b^c, separated by service classes. The range of r_2 (with means between 0.7-0.8) is on par with or better than that of other demand-temperature regression studies (Dyson et al. 2014, Liang and Ma 2019). There is a considerable spread in the change-points. However, for the electric space heating customer classes, their mean values are within expectation. The mean change-points are considerably lower for the non-electric heat service classes, due their low electricity demand in the winter. The distributions of the heating and cooling change-points nearly coincide completely. This indicates that the shoulder season or HVAC setpoint dead band is either short or not detectable in the model. The distribution of the heating slopes and cooling slopes show that cooling demand has a higher sensitivity to temperature than heating demand. The combination of the HVAC slope and intercept being zero indicates a lack of heating or cooling for some of the zip codes. Indeed, for the non-electric heat classes, there are 2-3% zip codes without any heating load; and 20-23% zip codes in the electric heat classes are without cooling.

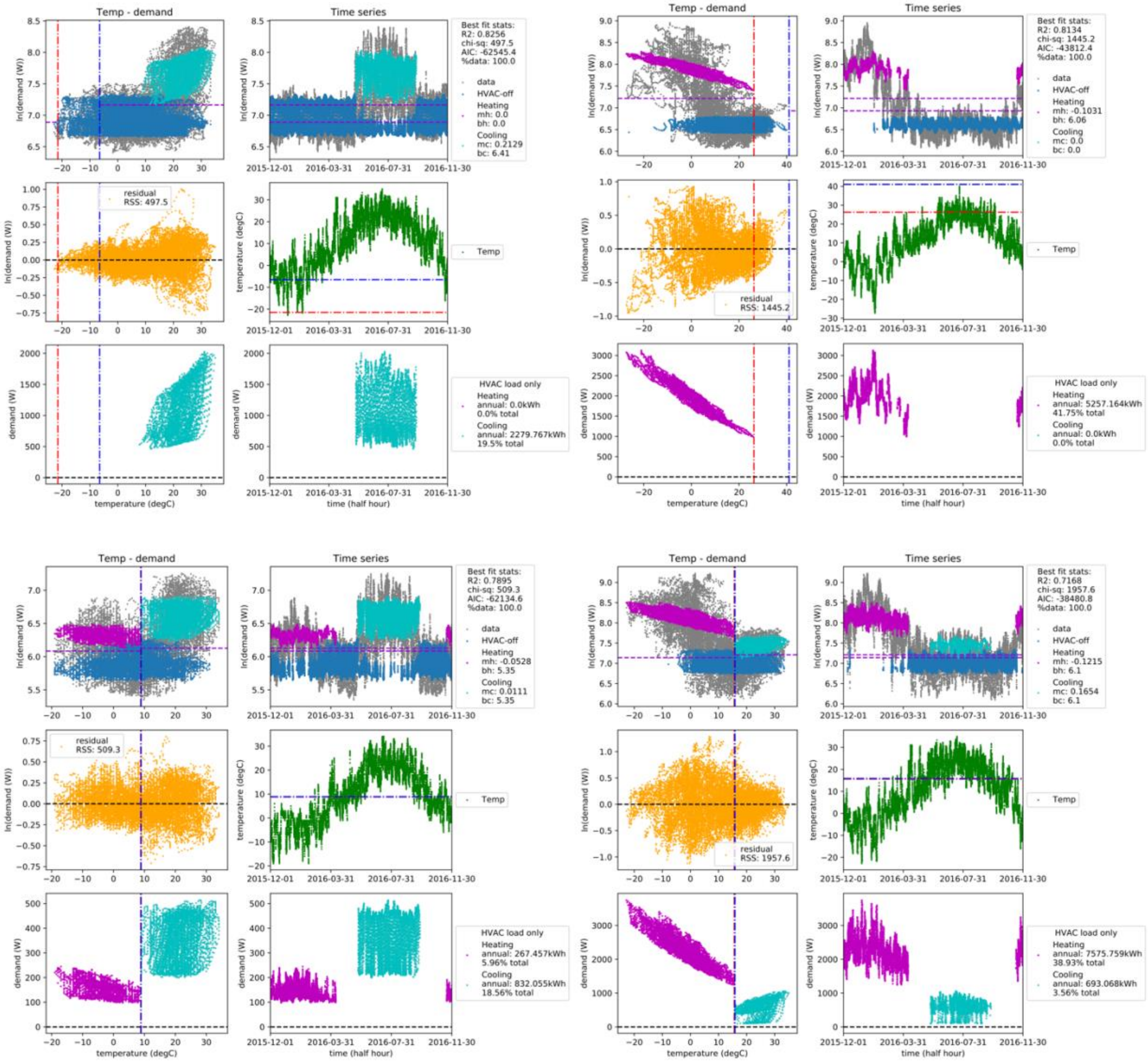

Figure 5.2: Examples of piecewise regression fit.

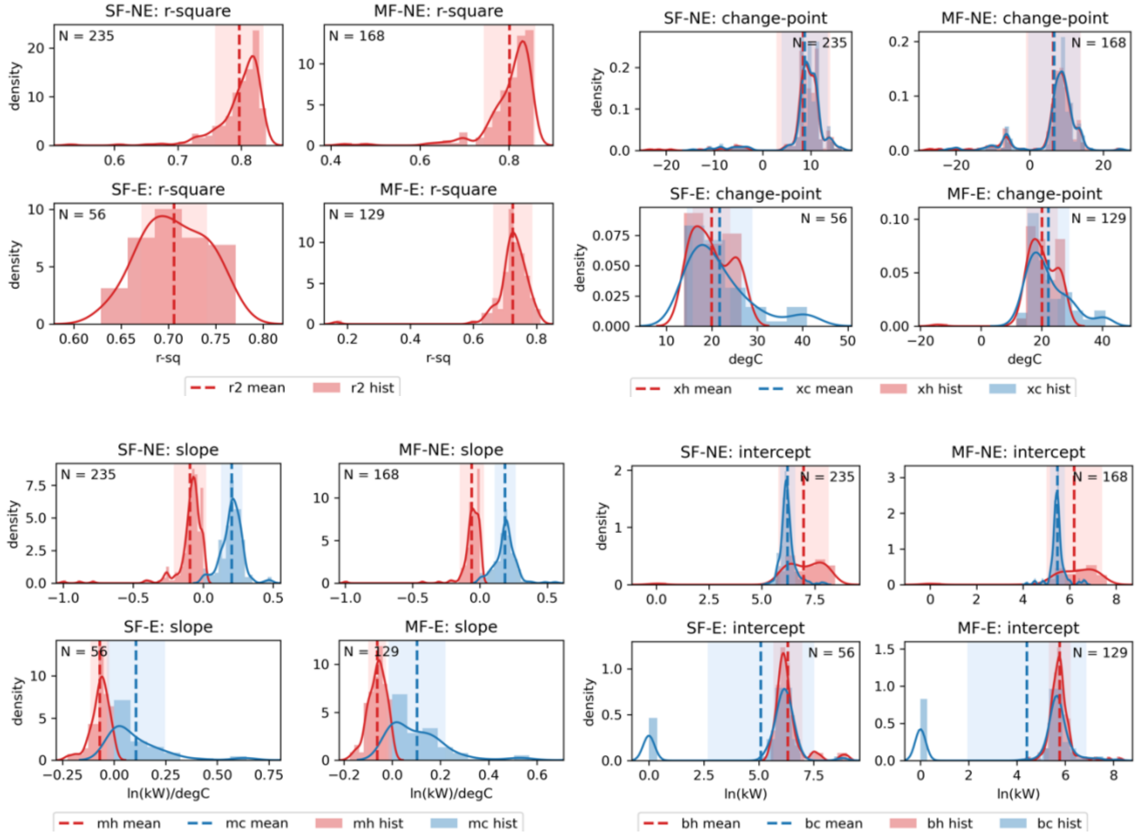

Figure 5.3: Distribution of r2 (top left), change-points (top right), slopes: m^h, m^c (bottom left), and intercepts: b^h, b^c (bottom right) from regressions, separated by service classes. (SF = single family, MF = multi-family, NE = non-electric, E = electric)

5.3.2 Load disaggregation

Figure 5.4 shows the average daily whole-home load profile disaggregated into heating, cooling, and baseload per service class. The disaggregated loads are from the regression model and the whole-home demand (black line) is from the AMI ground truth data. The load disaggregation is fairly accurate compared to the ground truth data, with the exception of the peak winter hours for the electric heat customer classes. These unmodeled demand peaks (i.e. the gap between the magenta region and the black line) do not fully coincide with the temperature dips (green line), indicating that: 1) there are non-temperature dependent behaviors that are not periodic and are thus not captured by the baseload model (e.g. holidays) [15], and/or 2) that under extreme temperatures, the relationship between demand and temperature may be beyond linear or log-linear.

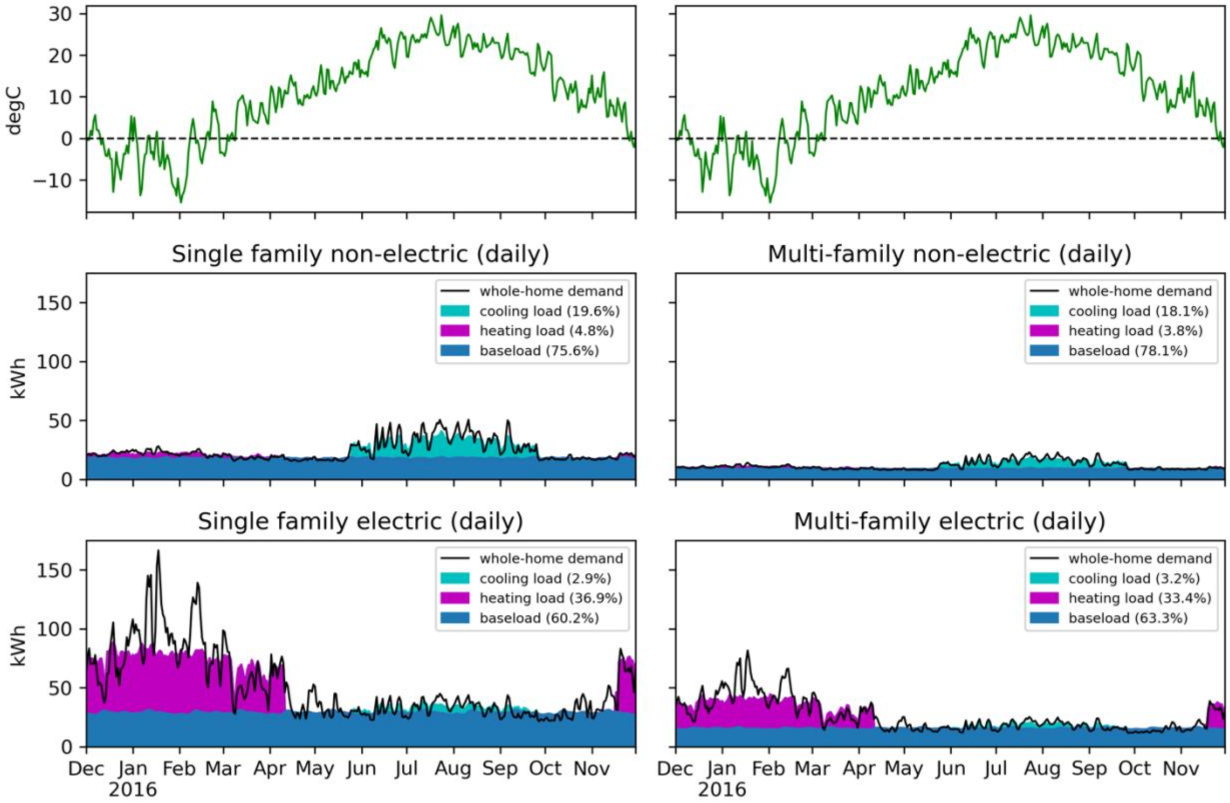

Figure 5.4: Average daily temperature profiles and average whole-home load profiles with disaggregated heating, cooling, and baseload (whole-home demand is from ground truth data).

In terms of total consumption and end uses, single-family premises have roughly doubled the amount of electricity consumption as multi-family. The electric space heating service classes also consume roughly twice as much electricity as their non-electric counterparts, primary due to

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[15] Martin Luther King Day (national holiday) and Valentines' Day are among the winter peak days for which their demands are not fully captured.

their large heating loads. In contrast, their cooling loads are substantially smaller, which indicates a sparsity of AC usage. Electric space heating is considered an inefficient heating source and could be tied to older, underdeveloped housing regions, whereas natural gas furnace is used more often in newer constructions and tends to be paired with central AC in a forced air system. Non-electric service classes contain a small percent of heating load, which could be due to increased fan load for heat distribution, the use of secondary electric heating, increased time spent at home during the winter, or a combination of the above.

Table 5.1 summarizes the HVAC load disaggregation by service class along with their customer counts and whole-home annual loads. The values given in bracket represent the weighted (by zip code customer counts) 5th, 50th, and 95th percentiles of the zip code average values within each service class. The HVAC loads are given as a percent of the annual load and of the total load during the season in which the HVAC load occurs. The latter is useful for understanding how much whole-home load could be curtailed on average when HVAC is used. These observations are consistent with findings from the 2015 US EIA Residential Energy Consumption Survey (RECS), which finds that single-family uses 3 times more energy on average than multi-family (of 5 units or more), and the heating load ranges between 25% for large apartment buildings and 46% for single family detached homes. The heating loads for 95% of the electric heat single and multi-family customer classes in this study are between 27-44%.

Table 5.1: Load information by service classes.

Service type	% by premise count	No. zip codes analyzed	Whole-home annual load MWh	**Heating** % annual load (% winter load)	**Cooling** % annual load (% summer load)
Single family non-electric	54.6	235	[7.04, **8.36**, 11.78]	[2.5, **6.1**, 8.9] [5.9, **14.1**, 19.6]	[13.1, **20.9**, 25.8] [30.6, **43.6**, 50.5]
Multi-family non-electric	40.8	168	[3.54, **4.18**, 5.14]	[0.2, **4.2**, 8.6] [0.4, **9.8**, 19.0]	[9.4, **19.8**, 24.7] [23.4, **42.0**, 49.0]

Single family electric	0.3	56	[13.81, **18.08**, 21.93]	[31.0, **38.8**, 41.0] [53.0, **61.4**, 65.6]	[0, **5.9**, 10.3] [0, **15.4**, 25.2]
Multi-family electric	4.3	129	[6.70, **8.84**, 12.64]	[27.5, **34.3**, 44.4] [48.8, **56.8**, 66.6]	[0, **5.3**, 10.0] [0, **14.1**, 24.6]

Note: annual consumption is for a leap year; Values in brackets represent 5th, 50th, and 95th percentiles.

Figure 5.5 shows the diurnal load disaggregation along with their 95% confidence intervals (given by the band) for winter and summer. At this temporal scale, the aggregation of the modelled end uses closely matches the ground truth data (dash-dotted line). As shown in the table, heating and cooling become a higher percent of the daily load during winter and summer. For the electric heat customer classes, their heating loads are relatively constant throughout the day, peaking slightly at 7am and 7-8pm. Within the non-electric heat customers, the single family class has a large cooling ramp in the summer afternoon, peaking at 3pm. This cooling peak is slightly ahead of the whole-home peak, which is at 4pm. In contrast, multi-family homes experience more even cooling throughout the day. This makes sense as multi-family buildings tend to have more centralized cooling that operates on a constant schedule during the summer. The average daily summer cooling peak for multi-family is also at 3pm, however their whole-home load peak is at 8pm due to activity patterns.

The diurnal plots in Figure 5.5 are useful for understanding load flexibility for accommodating renewable integration into the grid on a daily basis. The baseload profile provides a reference for how much the demand can be shed when instantaneous HVAC DR is applied. Solar insolation and cooling demand tend to coincide – they are the highest during the day and in the summer. Thus, cooling demand can be moderated in the late afternoon as solar resources ramp down (Dyson et al 2014). Wind and heating load also share similar characteristics – they are more consistent across the day and are more useful in the winter when solar is less available. Further research is needed to understand the extent to which HVAC DR can provide this grid service.

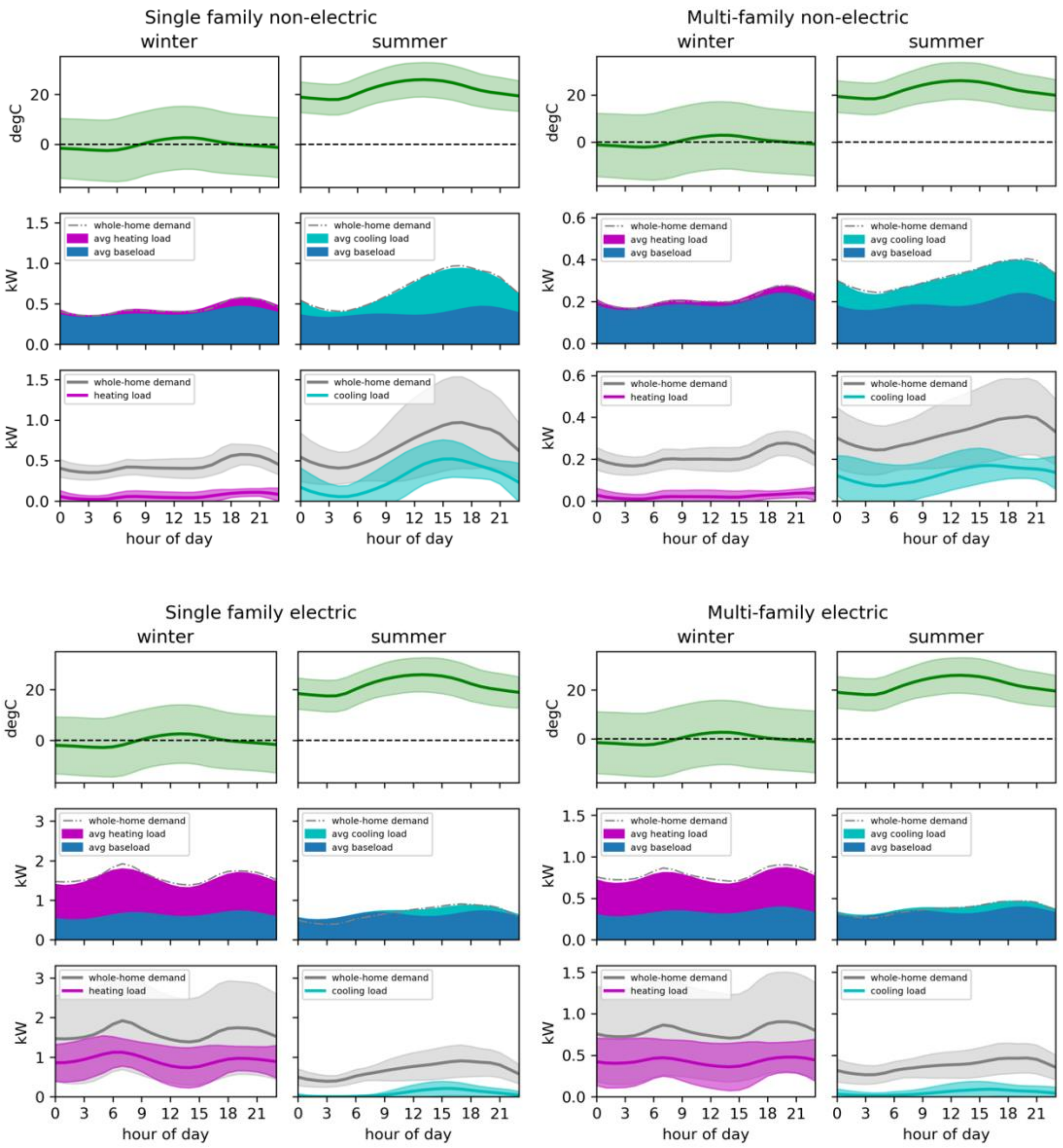

Figure 5.5: Seasonal average diurnal temperature profiles and average whole-home load profiles with heating and cooling demand response potentials. (Bands represent 95% confidence intervals, whole-home demand is from ground truth data).

5.3.3 Demand response

Figure 5.6 shows the average top 5 peak coincident heating DR potential in the winter and cooling DR potential in the summer by each zip code in each service class. Top 5 (seasonal) peak coincidence refers to the top 5 peak hours for the ComEd system load in the winter and summer. The DR potentials are given in absolute term (left subplot) and in relative term as a percent of total load during those hours (right subplot). The size of the bubbles is related to the number of premises in a zip code. Within each service class, there is a spread in the amount of DR potential available, particularly in single family classes. However, DR potential as a percent of seasonal load is much more clustered, indicating that DR potential is highly correlated with whole-home consumption. The single family non-electric heat service class is slated to provide the most cooling DR potential based on their large cooling loads as well as large customer counts (see Figure 5.8 and Table 5.2). The non-electric service classes have high heating DR potential as well as some cooling DR potential but make up only 5% of the customer base combined. Very few zip codes offer high DR potential in both heating and cooling (i.e. those close to the dotted line). This means that majority of the premises is contributive to only one type of HVAC DR.

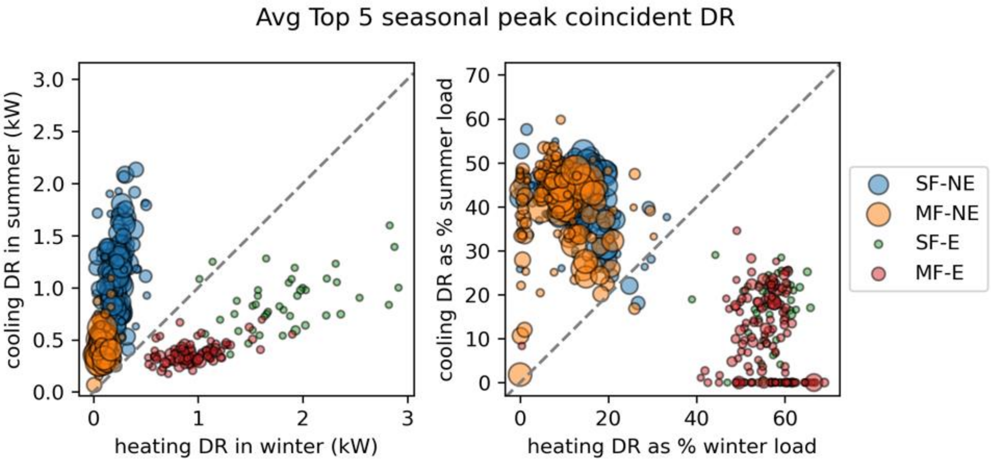

Figure 5.6: Average top 5 peak coincident heating DR potential in the winter and cooling DR potential in the summer in absolute term (left) and in relative term to total load during those hours (right), separated by service classes.

In 2019, ComEd had 3.69 million residential customers and nearly 100% penetration in AMI implementation (US EIA 2020). Figure 5.7 shows the duration curves of the aggregated DR resources. When extrapolating the service class distribution to this customer count, the aggregated instantaneous DR potential peaks at 3.8 GW. The heating DR potential totals 0.93 GW for the top 5 system peak winter hours and the cooling DR potential is 3.6 GW for the top 5 peak summer hours. The aggregated steady-state curtailment potential from a 2.5°C setpoint change peaks at 103.6 MW, which is an order of magnitude smaller than the instantaneous DR potential. The DR resources are non-zero for about 6,500 h. Figure 5.8 shows the breakdown of the instantaneous DR profile by service classes relative to the utility's system load profile of the same time period (PJM 2020). Daily system peak hour demands (grey line plotted against the right y-axis) and the HVAC DR available during those hours (left y-axis) are shown. Table 5.2 summarizes the DR potential breakdown by service classes.

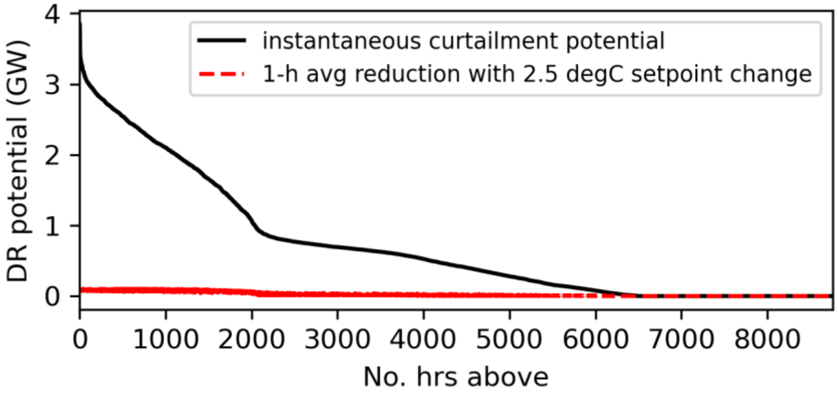

Figure 5.7: DR resource duration curves aggregated from all service class customers (red line is sorted by the same hour order as the black line).

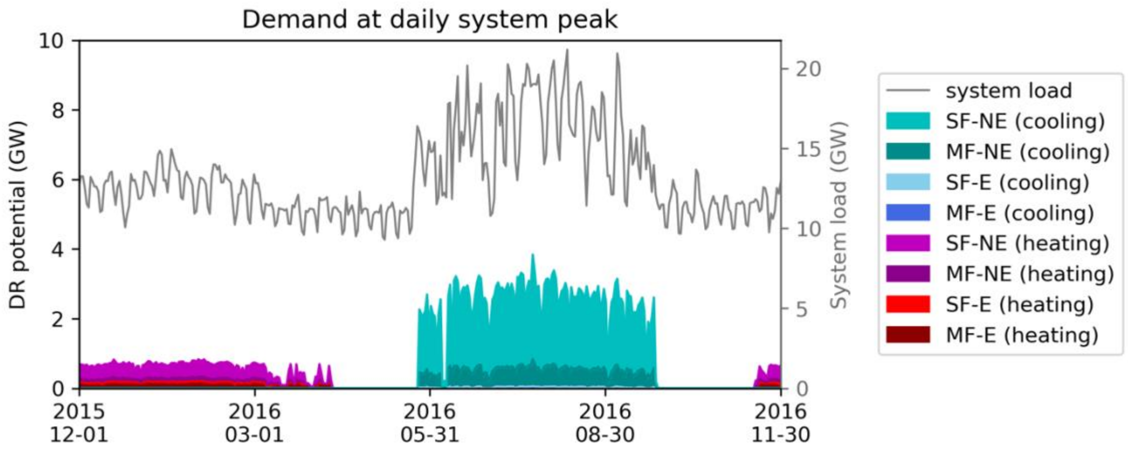

Figure 5.8: DR profile (left axis) aggregated from all service class customers compared to ComEd's system load profile (right axis). Daily peak hour demand is shown.

Table 5.2: Seasonal peak coincident DR potentials by service class type.

	Average top 5 seasonal peak coincident DR					
	Heating in winter			**Cooling in summer**		
Service type	kW per home	% whole-home demand	% total DR	kW per home	% whole-home demand	% total DR
Single family non-electric	0.22 ± 0.06	20.4 ± 0.1	59.6	1.11 ± 0.31	60.1 ± 0.1	77.7
Multi-family non-electric	0.07 ± 0.04	13.8 ± 0.1	14.7	0.40 ± 0.12	51.8 ± 0.2	20.7
Single family electric	2.14 ± 0.47	60.5 ± 0.1	2.9	0.51 ± 0.27	28.1 ± 0.2	0.2
Multi-family electric	1.07 ± 0.46	57.7 ± 0.2	22.8	0.27 ± 0.10	28.4 ± 0.2	1.4

Note: mean ± delta represents the 95% CI range of average DR potentials by zip code within a service class. *% total DR* column sums to 1 and is the relative contribution that all combined customers in a service class have toward the total DR.

The system load is summer peaking and cooling dominant. Non-electric customer classes provide virtually all of the cooling DR potential in the summer with single family making up over ¾ of it. The single family non-electric heat service class has both high cooling demand per premise

(2-4 times higher than other classes) and high customer counts (represent over half of the customer base). In terms of aggregated heating DR potential, the single-family non-electric heat service class still dominates and makes up nearly 60% of the share due to its sheer customer base. Although electric heat customers can curtail up to 60% of their whole home loads during peak winter hours, their overall contribution to the aggregated heating DR potential is only 26% combined.

Figure 5.9 shows the system load duration curve (right y-axis) along with the aggregated HVAC DR potentials (left y-axis) sorted by the same hour order. For the top 1000 hours, high and fairly consistent cooling DR potentials can be expected. Beyond that, the cooling DR potential begins to fluctuate more widely. Heating DR is not available for the first 782 peak hours as they do not occur in the winter. Figure 5.10 shows the 25th, 50th, and 75th percentile range of aggregated heating and cooling DR potentials that can be expected throughout the day in the winter and summer, respectively. As expected, the hour-to-hour heating DR potential is relatively consistent. Whereas the cooling DR potential climbs during the day, peaking at 3pm, and dips during early morning.

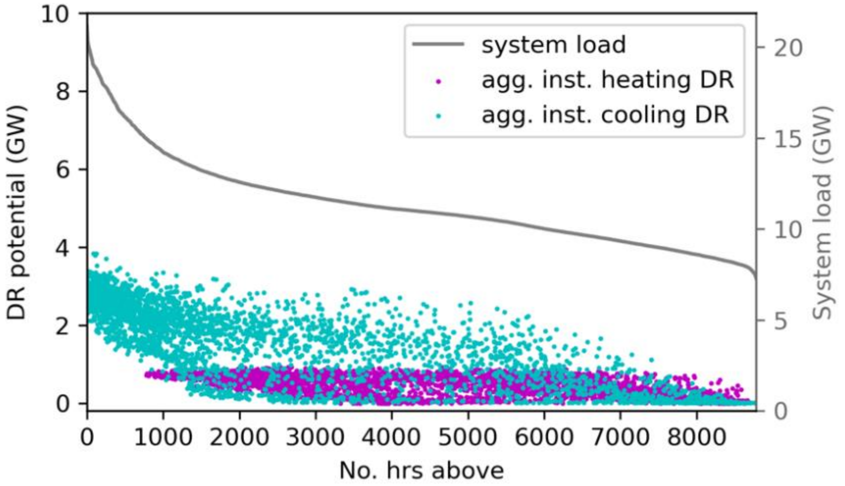

Figure 5.9: Aggregated DR potentials (left axis) sorted by the same hour order as ComEd’s load duration curve (right axis).

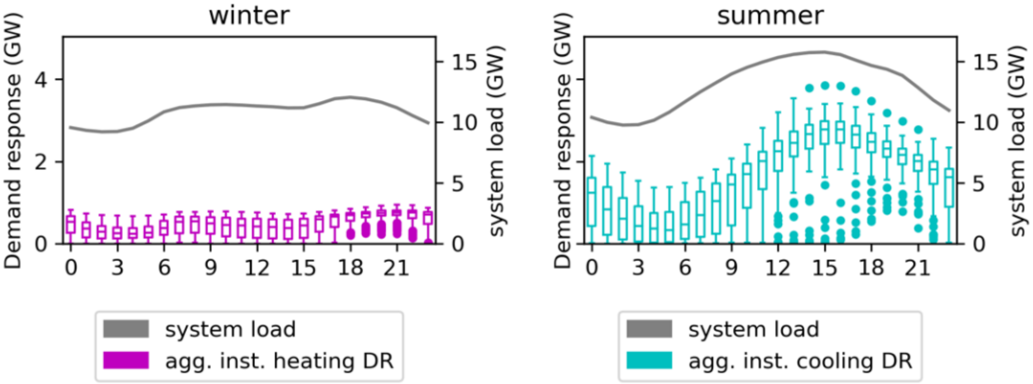

Figure 5.10: Box plot providing the 25th, 50th, and 75th percentile of aggregated heating DR potential throughout the day in the winter and aggregated cooling DR potential throughout the day in the summer.

5.4 Discussion

Figure 5.6 shows that the HVAC DR potentials do not tend to coincide in ComEd's customer base, i.e. very few zip codes have both high heating and cooling DR potentials. Single family non-electric heating customers have the highest cooling DR potential and single family electric heat customers have the highest heating DR potential. Dyson et al. (2014) show that recruitment targeting users of high DR potential is more cost-effective than random recruitment due to the concentration of high cooling loads on few users and the diminishing marginal return on recruitment. Given that ComEd is summer-peaking and cool-dominant, recruitment should focus on the single family non-electric heat customers with high cooling DR potential, (i.e. customers in the blue bubble zip codes highest on the y-axis in Figure 5.6). Within them, those with considerable heating DR potential can also be recruited to provide heating DR to save on equipment costs, since those customers would already be equipped, and the probability of a heating DR event is lower.

For additional heating DR, single family electric heat customers can be recruited first. However, the total heating DR potential is low given their low customer counts. Multi-family buildings with central HVAC controls may also be contenders as the HVAC loads across multiple units can be easily aggregated and controlled. While this study is restricted to zip code averaged load data, the method or other similar regression models can be applied to premise or building level smart meter data to easily identify those with high cooling DR and/or high heating DR potentials. Additional consideration for recruitment includes electric space heating types, which have different response times and dynamics. For example, thermal comfort would be less affected by the intermittent on-off cycling of resistance baseboards than forced air electric furnaces because water has a higher thermal inertia than air and can therefore retain more heat. Similar to resistance baseboards, geothermal heat pumps provide thermal stability but lower DR potential as they leverage the ground for thermal reservoirs and are therefore more energy efficient.

In this study, the estimation of the instantaneous HVAC DR potential is conservative because the model did not fully capture the heating demand in the winter peak hours. However, since the size of electric heat service classes is relatively small, this underestimation is not significant at the system level. Secondly the data anonymity rule, by design, excludes large electric consumers as well as customers living in very low-density areas (e.g. countryside) from the AMI data. Hence the zip code average profiles analyzed may be biased towards lower values. Finally, the averaging process dilutes the response of individual premises. The zip code averages are affected by differences in the HVAC equipment (equipment type, efficiency), behaviors (setpoint preference, activity pattern), and missing timesteps from premises. For example, for a zip code that contains two premises, with one of very high heating load and the other of very low heating load, if the latter lacks data for December, then the zip code average would have a very high load in that month and an average heating load in other months. This can affect the log-linearity between demand response to temperature and hence the quality of the model fit.

Future work on this model can focus on improving the HVAC domain model to better capture the peak hour HVAC demands. This is important as the value of DR to manage contingency events is related to the peak hours. To this end, additional variables affecting electricity consumption can be incorporated (e.g. solar heat gain, infiltration, and humidity). Holidays and other demand discord days can be excluded or isolated and examined separately. Another aspect to consider for the model is the lagged response of demand to outdoor temperature change as a result of building thermal inertia. This can be easily tested with time shifts in the data.

Additionally, the model can be extended with Monte Carlos simulations to obtain the range of expected DR potentials given different weather conditions and/or participation rates, and to quantify the robustness of the model. Results of the load disaggregation can be correlated with renewable generation or resources to understand the value of DR in helping to balance different renewable energy supplies. Carbon accounting can be employed to evaluate the carbon emission reduction potential when using DR to provide different grid services. Finally, a correlation study can be conducted to better understand the socioeconomic backgrounds between different service classes relative to their DR potentials. This may be useful to the utility in terms of recruiting customers for energy efficiency improvement vs. DR and for income-based efficiency programs. For example, the electric heat service classes exhibit traits that suggest energy inefficiencies and a lack of adequate cooling – they have slightly higher baseload than their non-electric counterparts on average (as shown in Fig 4) and they have half the cooling load as their counterparts. These findings warrant further investigation. Understanding the drivers for these energy consumption differences can better inform decision regarding program design for DR as well as for energy efficiency and how to prioritize customers between these programs.

5.5 Conclusion

DR estimation is useful to utilities in understanding their load end uses and designing more effective DR programs. In this study, a piecewise log-linear-Fourier regression model is proposed to disaggregate the thermostatically controlled loads from whole-home AMI data and estimate the technical HVAC DR potentials. This is an improved model compared to typical change-point models in that: 1) domain partitioning is optimized and takes place simultaneously as the domain-specific model; 2) the model provides a better fit (with 95% of r_2 between 0.65 and 0.90) with the data by capturing both the mean and time-variant temperature effects on demand using Fourier transform functions; and 3) the sum of the disaggregated end uses matches the AMI data with high accuracy.

Leveraging the uniqueness of the AMI dataset from ComEd, this study examines the difference in HVAC DR potentials between building types (single/multi-family) and space heating types (electric/non-electric). On average, single family buildings consume twice as much electricity as multi-family buildings, overall and by HVAC end uses. Electric heat customers also consume twice as much as their non-electric heat counterpart, largely due to their space heating requirement being an order of magnitude greater. Heating and cooling DR potentials do not coincide in ComEd’s customer base. Non-electric heat customers tend to be cooling-dominant while electric heat customers tend to be heating-dominant by definition. During winter peaks, electric heat customers could shed on average 60% of their load instantaneously compared to 20% or less by those without. During summer peaks, non-electric heat customers could curtail their load by up to 61% on average, whereas electric heat customers could cut down their demand by half that.

Overall, space heating represents 7.8% of the annual total load and 17.4% of the total winter load. Space cooling represents 19.4% of the annual total load and 41.4% of the total summer load. When projecting the distribution of service classes out to the 2019 customer count, the total instantaneous heating DR potential for the top 5 system peak winter hours is 0.93 GW and the total cooling DR potential for the top 5 peak summer hours is 3.6 GW. As ComEd is summer peaking and cooling dominant, its single family non-electric heat service class, which represents over 50% of its customer base and consumes 2-4 times more energy for cooling, is best suited to provide meaningful cooling DR during its system peak hours. In addition, multi-family buildings, particularly those with central HVAC systems, may have the advantage of pooled demand across multiple units and should therefore be considered accordingly. This DR trend likely applies to the rest of the U.S. as single family is the most prevalent building type (RECS 2015) and most regional grids are summer peaking (Cappers et al. 2009). Utilities can apply the method developed in this study or other similar regression models to their smart meter data to easily identify premises or buildings with high cooling DR (or summer peak shaving) potential.

Acknowledgement

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Chapter 6 Conclusion

6.1 Summary

This dissertation provides pathways for improving building sustainability by examining three decision-making questions related to technology and product selection (Chapter 2 - Chapter 3), waste management and material recovery (Chapter 4), and energy use and demand response (Chapter 5). From the perspective of consumers, Chapter 2 and Chapter 2 examine residential and commercial lighting replacement policy, respectively, with the former focused on the timing of inter-technology transition and the latter on the differences between intra-technology (LED) options. Chapter 4 assesses the environmental impacts of specialty metal recovery from commercial lighting waste and other end of life treatment options as well as the implication of extended use and replacement choices. The results are informative to consumers making individual choices regarding replacement and waste management as well as manufacturers and recyclers regarding recycling and material recovery opportunities. Chapter 5 conducts load disaggregation on whole-home smart meter data to estimate the demand response potential from space heating and cooling from the utility's standpoint, using a large smart meter dataset collected in the Midwest. The chapter also explores the differences in load profile and demand response between single family, multi-family, electric, and non-electric space heating buildings.

Findings from this dissertation research help inform decision making for building managers, homeowners, and other energy consumers on how to choose better products, how to better manage products at their end of life, and how to use energy more effectively. Key findings include:

- For a technology that is rapidly improving in terms of energy efficiency, frequent upgrade (i.e. replacing before the end of rated lifetime) can provide overall cost and environmental benefits because the energy savings outweigh the cost of replacement. Conversely, for a mature technology that is no longer changing, prolonged or extended use is favorable.
- Equipment with higher usage rates should be replaced first and more frequently to obtain the highest energy savings, and vice versa. For instance, a lamp that operates for 12 hr per day would see 3-5 replacements optimally over the course of 35 years compared to 1-2 replacements for a lamp that operates at 1.5 hr per day.
- In terms of residential lighting, LEDs were largely not positioned to replace fluorescent lamps in the past 5 years. Between 2015-2020, deferring LED adoption by using CFL could provide energy, cost, or emissions benefits at least 50% of the time. This is based on simulations with different amounts of coals in the grid mix, different consumer locations, and different frequency of operating the lamps.
- Spent products, especially those retired early, offer opportunity for material recovery. Both fluorescent and LED lighting can be recycled for rare earth and critical metal concentrates, respectively. Choosing products with modular design that allows for the exhaustible, energy-consuming components to be replaced directly is ideal from an environmental standpoint.
- Building energy can be controlled and used for demand response (DR) to provide relief during grid system peaks and help balance renewable supply. Heating, Ventilation, and Air Conditioning (HVAC) load is especially useful as a DR resource because it is a large share of the total building consumption, contributes to the system peaks, and can be adjusted instantaneously and intermittently without causing thermal discomfort due to the building's

large thermal inertia. Therefore, consumers, particularly those with large space heating and cooling loads, should be encouraged to support and participate in their local DR programs.

The research findings also provide manufacturers with insights on product design and material recovery, as well as utilities with insights on program design for demand response. For example:

- Product efficacy (inverse of energy efficiency) should be prioritized over product longevity as rapid improvement in this area encourages more frequent upgrades and replacement. For instance, LEDs are used 30-80% of their rated lifetime before they are optimally replaced. Consequently, dematerialization, modular product design, and close loop manufacturing (e.g. product buybacks, trade-ins, and recycling) can allow for frequent replacement without high purchase cost for consumers, generating an excess amount of waste, or depleting the resource stock.
- Specialty metals recovery from lighting waste has net environmental burdens due to the large consumption of chemicals (e.g. oxalic acid) for solvent extraction and the low concentration of these metals in the waste. Thus, these material recoveries can benefit from extraction efficiency improvement (e.g. optimize processes to decrease the chemical and energy input, support lamp and luminaire design for disassembly and material liberation, and incorporate waste preprocessing to increase the specialty metals concentration) and alternative extraction methods (e.g. microbiological leaching, supercritical fluid extraction).
- As more lighting transitions from fluorescent technologies to LED, there will be a reduction in environmental impacts, primarily due to the efficacy gain and energy savings from LED. However, without a waste restriction on LED like its mercury-containing

fluorescent counterpart or a proper recycling infrastructure, more lighting solid waste is expected. To facilitate more recycling in this area, recycling channels need to be optimized with effective waste collection strategies, economies of scale, and be in line with specialty metal pricing to facilitate more investment and momentum in this area. The recycling of lighting for metal-heavy components such as housing structure and heat sink, can facilitate the recovery of rare earth and critical metals from lighting waste by sharing the collection and disassembly costs.

- For demand response recruitment, buildings with the largest HVAC loads should be targeted first. Change-point regressions of smart meter data can identify such customers or clusters of customers quickly. They also eliminate the need for large data storage by reducing the smart meter data to model parameters, which can be easily interpreted. Generally, single family buildings, being the larger energy users and customer base, can provide higher per customer and aggregated DR capability. However, multi-family buildings, particularly those with a central HVAC system, may have the advantage of their DR being easily pooled across multiple units and should be considered accordingly.

6.2 Further Insights and Broader Context

6.2.1 Energy efficiency: opportunities and limitations

The prospect of energy efficiency to reduce energy use, energy cost, and energy-related carbon emissions is paramount. By reducing the amount of energy consumed per unit of service or output, energy efficiency can help counter the effects of global population and affluence growth, as well as increasing the economic competitiveness of sectors and countries. It is often a more cost-effective approach to carbon reduction than renewable integration, which requires infrastructural changes (Molina and Relf 2018). By reducing grid demand and capacity expansion needs, energy efficiency helps society achieve 100% clean and renewable energy faster.

Sustainable products and technology must meet four necessary conditions: 1) they must address an important unmet societal problem; 2) they must not cause more environmental or social harm than benefit; 3) they must be economically successful to be self-sustaining in the market, but 4) not overly that they cause rebound effects (Skerlos 2015). While energy efficiency could help curb carbon emissions, its success depends on several key factors. Under-adoption, energy rebound, and other unintended consequences from energy-efficient technologies can both impede or negate their savings. Although what and how much consumption are considered excessive and a rebound is debatable, it is important to recognize these potential shortfalls.

Energy-efficient technologies may not be well adopted due to several reasons – economic barrier from a lack of a viable business model, the technologies lacking intrinsically attractive attributes to diffuse in the market, and psychological barriers from the consumers (common with new technologies). Strategies that can help drive adoption include top-down regulations (e.g. appliance standards, product bans), economic incentives (e.g. product rebates, alternative financing), and consumer education (e.g. product labels, information that promotes energy efficiency or aids decision-making). Until recently, the adoption of LED lighting has been lukewarm despite its rapid technology advances (US DOE 2016). Chapter 2 and Chapter 2 show the optimal replacement pathways for LED lighting that can maximize environmental and economic benefits.

Energy rebound describes the phenomenon in which the expected energy saving from a new or improved product is negated due to a behavioral rebound in energy consumption, either directly or indirectly (Day 2014). This could come from: 1) more consumption and/or more ownership of the product (e.g. installing more LED fixtures, leaving the light on longer after an LED upgrade); or 2) the consumption of other more carbon- or energy-intensive products and/or activities (e.g. energy cost savings being spent on travel). These rebounds can cause more energy and environmental burdens than if the energy-efficient product was never introduced.

However, there is no consensus regarding the size of the rebound on energy efficiency and the value of energy efficiency in decarbonization for climate change (Day 2014, Shellenberger and Nordhaus 2014). This is in part because what is considered a rebound (excess vs. necessary consumption) is debatable and new technologies could support climate mitigation in new ways (e.g. demand response), which are difficult to assess. Saunders and Tsao (2012) estimate the direct rebound effect for solid-state lighting to be 100%, i.e. the total efficacy gain in solid-state lighting was completely offset by the growth in global lighting demand. However, they attribute some of this rebound to necessary welfare gain and argue that new opportunities from smart LED to balance grid supply could outweigh this energy rebound.

Finally, it is imperative to ensure that energy-efficient products do not cause more environmental or social burdens in their life cycles than their incumbent counterparts. Chapter 4 shows that the life cycle impacts of LED and the environmental impacts of material recovery from LED waste are comparable with those of incumbent lighting technologies. That said, LED lighting is meeting all but one necessary condition for sustainability – energy rebound. However, energy efficiency policies and technology development should not be discouraged or impeded on the basis of rebound effects. Instead, mitigation strategies can be deployed, such as consumer education aimed at breaking down cognitive biases to promote energy conserving behaviors and proper market incentives to prevent over-adoption and consumption.

6.2.2 Energy efficiency vs. demand response

Energy efficiency and demand response (DR) present interesting tradeoffs in that high building energy consumers are good candidates for demand response programs as well as weatherization and energy efficiency improvement. But as a building's energy efficiency increases, its DR capability decreases. So how should utilities prioritize between building energy efficiency and DR?

The choice between energy efficiency and DR will depend on the unique conditions of a region's grid. Generally, energy efficiency improvement is a more attractive target for regions where electricity prices are high, or power generation are largely fossil fuels. Energy efficiency can reduce both net and peak demand. However, the value of energy efficiency for decarbonization decreases with more and cheaper renewable energy supply. On the other hand, DR is more attractive for regions with time of use or critical peak electric rates, high renewable penetration, or high peak-to-baseload ratio. In terms of program recruitment, households with high energy use intensity (per floor area) are best suited for energy efficiency, whereas households with high net energy use or high energy use during peak hours are best for DR.

In the US, both lighting and HVAC hold great potential for energy efficiency improvement and DR. Lighting represents 10% of building energy use (US EIA 2019). LED is projected to reduce building energy use by 40-60% (3-4.5 quads in primary energy) by 2030, compared to scenarios with no LED adoption (US DOE 2016). HVAC constitutes 40% of building energy use (US DOE 2012). Depending on the replacement technology (e.g. ceiling fan control, geothermal heat pump), commercial HVAC upgrade can provide 0.75-17% (0.05-1.11 quads) in energy saving per year (US DOE 2011), while residential HVAC upgrade saving is 0.25-20% (0.02-1.62 quads) (US DOE 2012) compared to 2011 codes and standards. Both lighting and HVAC are key end uses for commercial building DR and represent the majority of the potential, irrespectively of the program cost (Alstone et al. 2017). In the residential sector, HVAC is one of the largest DR end uses and represent over half of the potential at low program costs (the rest being plug-in hybrid and electric vehicles). For example, at a DR program cost of less than $50/kWh-year, the potential to use commercial HVAC for load shifting is 3GWh-year in Southern California Edison under a medium penetration scenario.

6.2.3 Deterministic vs. stochastic model

Deterministic models produce outcomes that are determined entirely by the parameter values and the initial conditions. Without any randomness involved, the outcomes from these models are reproducible and always the same for a given set of model conditions. They are easy to understand and can be used to describe systems with specific conditions (e.g. average) and predictable behaviors. To this end, deterministic models can support individual decision-making by capturing the unique conditions decision-makers are facing. They are also suitable for understanding system responses based on average conditions. In Chapter 2 , lighting replacement is modelled deterministically. The results are specific to the average parameter values and initial conditions used.

However, most systems in real life are not deterministic as many environmental and behavioral factors cannot be accounted for and are instead more probabilistic in nature. One way to assess these uncertainties in a deterministic model is to conduct a parametric study. To this end, Chapter 2 analyzes scenarios with different customer locations, grid mixes, and lamp operation hours. Chapter 3 incorporated market data on lighting replacement products to obtain the range of life cycle costs expected for each replacement product type. These results provide a richer description of the expected outcomes. However, to fully account for the different system conditions seen in real life, a stochastic model is needed. Stochastic models take random samples from the distributions of parameter values to arrive at a distribution of possible responses. Each iteration in a stochastic model can be thought of as a deterministic model. In this way, stochastic models support more robust decision-making and larger-scale planning by quantifying the uncertainty bounds on the model outcome and examining the range of conditions seen in a population, respectively.

6.3 Recommendations for future research

The followings highlight some of the research areas in which this dissertation can be extended and that I plan to explore in my research career:

- **Energy efficiency adoption**

Energy efficiency remains a pivotal goal for buildings in the U.S. To examine the temporal effects of energy efficiency measures or optimize the deployment schedule of these technologies, equipment replacement can be integrated with large scale building stock energy model, such as ResStock (developed by NREL), to obtain the roadmap for how the region-specific energy efficiency technology portfolio should be carried out to minimize costs and maximize energy savings. ResStock conducts random sampling from distributions of building characteristics (e.g. fuel type, square footage), occupancy, and energy use behaviors (e.g. HVAC setpoints, window opening) to capture the variability in the building stock and energy use pattern. Hence, similar to Monte Carlos simulations, ResStock simulations are stochastic and capable of quantifying model uncertainty by providing a distribution of all possible outcomes based on the parameters. These portfolios and roadmaps will be useful for institutions, municipalities, and states in developing and executing sustainable urban planning policies and carbon neutrality plans.

- **Low-income housing**

Low-income housing, particular those that are not public or government-subsidized, have traditionally been marginalized. While low-income buildings tend to be lower energy users to due smaller building footprint, their energy use intensity or energy use per square footage tends to be high (Bednar et al. 2017, Drehobl and Castro-Alvarez 2017, Hernandez and Bird 2010). The energy burden for low-income tenants relative to their income is also greater. While programs such as the federal Weatherization Assistance Program and Low-Income Home Energy Assistance Program are available to assist homeowners or renters lacking the financial resources to improve their homes or pay high energy bills, these programs have finite funding and resources and simply cannot reach the entire eligible population. Additionally, the cost of these programs per unit electricity saved is four times higher than average, as low-income housing tends to in poorer conditions and require repair and more weatherization needs (Hoffman et al. 2018). Energy efficiency is undoubtedly the long-term solution for relieving low-income of the high energy burden and improving their living environment in terms of comfort, health, and safety. Coordinated top-down efforts from home assistance policies and programs are the best mechanism for providing the necessary groundwork to implement such solution (Hernandez and Bird 2010). Cost optimization for building energy efficiency portfolios is thus necessary to lower the cost of these programs and to maximize their reach and longevity. To this end, large scale building stock model, such as ResStock can be calibrated to look at low-income housing stock region by region and provide evidence-based cost-effective energy efficiency recommendations and roadmaps with high spatial granularity for programs to implement in their communities.

- **Grid interactive efficient buildings (GEB)**

GEB are new concept buildings that synthesize energy efficiency with renewable integration, energy storage, and smart technologies to provide demand flexibility to the grid. By enabling two-way communication between buildings and the electric grid, buildings could serve as a site for distributed renewables as well as a demand side resource to balance other grid-connected renewable supplies, thus enabling higher renewable penetration and deferring the construction of new powerplants. The result is an electric grid that is more reliable, lower cost, lower carbon, and ultimately cost savings to consumers. Chapter 5 touches upon this research by investigating the demand response available from a subset of the current housing stock in the Midwest, most of which do not have onsite renewables, energy storage, or smart sensors. As buildings converge towards GEB, their demand flexibility will depend on the synthesis of different low-carbon building technologies.

There are many exciting research opportunities concerning GEB and their role in grid modernization and decarbonization. Many of the low-carbon building technologies have synergies and tradeoffs with one another that require more holistic optimization at the consumer, building, and regional level. For example, high energy consumers are good candidates for demand response programs as well as for weatherization and energy efficiency improvement. But as the building energy efficiency increases, its demand response capability decreases. How should homeowners choose between these programs? What criteria should utilities consider when designing and recruiting for these programs? Energy storage helps store and balance renewable energy supply as well as provides load shifting and energy arbitrage (which circumvents high energy prices by charging during low-priced hours and discharging during high-priced hours) in Time of Use rate schemes. How should battery charging and discharging schedule be optimized to maximize these benefits? What is the optimal mix of energy efficiency, energy storage, renewable energy integration, and demand response in terms of cost? Reliability? How will climate factors, electric grid characteristics, and spatial granularity (e.g. scaling between building and region levels) affect these technology portfolios? These are just some research questions around this area and much research is still needed to bring GEB to full scale.

Appendices

Appendix A Chapter 2 Supplemental Information

A.1 Model functions

This section provides a list of functions used in the life cycle optimization model in several subsections – A.1.1 Objective functions, A.1.2 Meta functions, A.1.3 Life cycle cost functions.

A.1.1 Objective functions

The objective function f is defined as:

$$\begin{aligned} f(M, U, W, \boldsymbol{l}, \boldsymbol{x}, n, m) &= \{U(l_1, 0, x_1) + W(l_1, x_1)\} \\ &+ \sum_{i=1}^{n} \{M(l_2, x_i) + U(l_2, x_i, x_{i+1}) + W(l_2, x_{i+1})\} \\ &+ \sum_{i=n+1}^{n+m-1} \{M(l_3, x_i) + U(l_3, x_i, x_{i+1}) + W(l_3, x_{i+1})\} \\ &+ \{M(l_3, x_{n+m}) + U(l_3, x_{n+m}, 35) + W(l_3, 35)\} \\ &- \{M(l_3, x_{n+m}) + W(l_3, 35)\} \left(1 - \frac{35 - x_{n+m}}{LT(l_3, x_{n+m})}\right) \end{aligned} \tag{0.1}$$

where *impact functions* M, U, W represent the impacts before, during, and after the use-phase, respectively, of a lamp of type l purchased in year x_i and replaced in year x_{i+1}. $LT(l, x)$ is the rated lifetime (in yrs) of the lamp, defined as:

$$LT(l,x) = \begin{cases} logistic(0.00, 8.22E4, 0.127, 2022, x)/(365\cdot HOU) & \text{if } l = LED \\ exponential(1.20E4, 6.40E-3, x)/(365\cdot HOU) & \text{if } l = CFL \\ 8.40E3/(365\cdot HOU) & \text{if } l = HL \\ 1.00E3/(365\cdot HOU) & \text{if } l = IL \end{cases} \tag{0.2}$$

where HOU is the average daily hours of use. The 2015 rated lifetime of all lamps are provided by US DOE (2016b). $LT(LED,x)$ is curve-fitted based on the projection that it would reach 50,000 hrs by 2025[3] and 80,000 hrs by 2050 (Bergesen 2015). Due to the maturity of incumbent technologies, $LT(CFL,x)$ assumes that by 2050, it would reach 15,000 hrs, the longest rated lifetime available for CFL today. $LT(HL,x)$ and $LT(IL,x)$ assume no change over time. A graphical comparison of rated lifetime [hrs] is provided by Figure A.1.

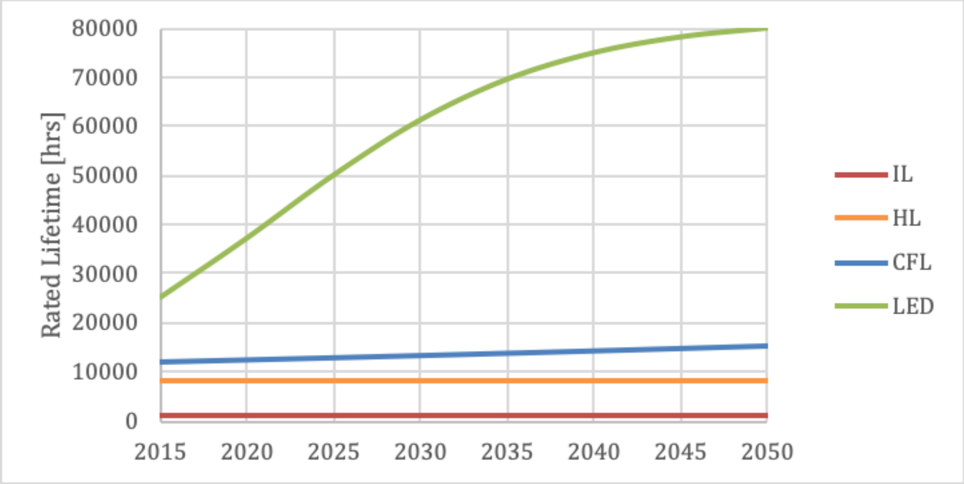


Figure A.1: Comparison of projected rated lifetime of lamp by type.

The first term of the objective function f ((0.1)) is the impacts of the initial lamp (of type l_1) during and after the use-phase, the 2nd and 3rd terms are the life cycle impacts of the incumbent technology lamps (of type l_2) and the replacement technology lamps (of type l_3) except for the last lamp, respectively. The 4th term is the life cycle impacts of the last lamp (of type l_3) until the end of the time horizon (35 years), and the last term is the terminal value for the last lamp, proportional to its remaining usability.

Depending on the quantity chosen as the objective of optimization, *impact functions* M, U, W can take the forms of: 1) Cost to Consumer (abbr. as Cost), 2) Primary Energy (abbr. as Energy), 3) GHG Emissions (abbr. as Emissions), or 4) Life Cycle Cost (LCC), which is defined as the sum of Cost to Consumer and Social Cost of Carbon ($SCCost$), as shown in Table A.1.

Table A.1: Definitions of impact functions per optimization objective.

Impact functions	**Cost to Consumer [$]**	**Primary Energy [MJ]**	**GHG Emissions [kg CO2e]**	**Life Cycle Cost [$]**
Pre-use impact $M(l,x)$	$Cost_{purchase}(l,x)$ $+ Cost_{install}(x)$	$E_{prod}(l,x)$ $+ E_{trpt}(l,x)$	$GHG_{prod}(l,x)$ $+ GHG_{trpt}(l,x)$	$Cost_{purchase}(l,x)$ $+ Cost_{install}(x)$ $+ SCCost_{prod}(l,x)$ $+ SCCost_{trpt}(l,x)$
Use phase impact $U(l,x_{start},x_{end})$	$Cost_{ele}(l,x_{start},x_{end})$	$E_{ele}(l,x_{start},x_{end})$	$GHG_{ele}(l,x_{start},x_{end})$	$Cost_{ele}(l,x_{start},x_{end})$ $+ SCCost_{ele}(l,x_{start},x_{end})$
Post-use impact $W(l,x)$	$Cost_{EOL}(l,x)$	$E_{EOL}(l,x)$	$GHG_{EOL}(l,x)$	$Cost_{EOL}(l,x)$ $+ SCCost_{EOL}(l,x)$

The definition of each term in Table A.1 appears in Appendix 0–0.

A.1.2 Meta functions

This section provides the generalized form of functions which are used to estimate the life cycle costs and impacts of lamps.

- **Logistic**

The logistic functions used in the model can be generalized as:

$$logistic(a,b,k,t,x) = a + \frac{b-a}{1+e^{-k(x+2015-t)}} \tag{0.3}$$

where a and b represent the lower and upper asymptotes of the curve, respectively, k is the growth rate, with negative values representing growth, t is the inflection point at which the maximum growth occurs.

- **Exponential**

The exponential functions used in the model can be generalized as:

$$exponetial(p, r, x) = p(1 + r)^x \tag{0.4}$$

where p is the initial value of the exponential curve at $x = 0$ (i.e., 2015) and r is the annual growth rate.

- **Average exponential**

When averaged over the time horizon, (0.4) becomes:

$$\begin{aligned} &\overline{exponetial}(p, r, x_{start}, x_{end}) \\ &= \frac{1}{x_{end} - x_{start}} \int_{x_{start}}^{x_{end}} exponetial(p, r, x) dx \\ &= \left(\frac{p}{x_{end} - x_{start}}\right) \left\{\frac{(1 + r)^{x_{end}} - (1 + r)^{x_{start}}}{\ln(1 + r)}\right\} \end{aligned} \tag{0.5}$$

where p is the initial value of the exponential curve at $x = 0$ (i.e., 2015) and r is the annual growth rate. With an annual discount rate of 0.03, (0.5) becomes:

$$
\begin{aligned}
&\overline{exponetialD}(p, r, x_{start}, x_{end}) \\
&\qquad = \frac{1}{x_{end} - x_{start}} \int_{x_{start}}^{x_{end}} exponetial(p, r, x) \left(\frac{1}{1.03}\right)^{x} dx \\
&\qquad = \left(\frac{p}{x_{end} - x_{start}}\right) \left\{ \frac{\left(\frac{1+r}{1.03}\right)^{x_{end}} - \left(\frac{1+r}{1.03}\right)^{x_{start}}}{\ln\left(\frac{1+r}{1.03}\right)} \right\}
\end{aligned}
\tag{0.6}
$$

A.1.3 Life cycle cost functions

This section provides the functions for estimating the life cycle cost at a given life cycle process or stage.

- **Purchase cost**

(0.7)–(0.10) describe the purchase cost trajectory of various lamps over time.

$$
\begin{aligned}
&Cost_{purchase}(LED, x) \\
&\qquad = logistic(2.00, 52.7, -0.256, 2008, x) \left(\frac{LP}{9}\right) \left(\frac{1}{1.03}\right)^{x}
\end{aligned}
\tag{0.7}
$$

$$
Cost_{purchase}(CFL, x) = exponential(1.80, -0.0132, x) \left(\frac{1}{1.03}\right)^{x} \tag{0.8}
$$

$$
Cost_{purchase}(HL, x) = 2.25 \left(\frac{1}{1.03}\right)^{x} \tag{0.9}
$$

$$
Cost_{purchase}(IL, x) = 0.567 \left(\frac{1}{1.03}\right)^{x} \tag{0.10}
$$

The $logistic$ function is curve-fitted for a 900 lm dimmable lamp at $10/klm in 2015 (DOE 2016b) and reaching a price of $2/lamp by 2030 (US EIA 2014). The function is then adjusted for a non-dimmable lamp by the factor, $LP/9$, where 9 is the 2015 price of the dimmable lamp and LP is the 2015 price of the non-dimmable lamp ($5.09). Based on a US DOE report (2016b), LED package at $1/klm accounts for 23% of the manufacturing cost of LED A19 lamps in 2015 and a 30% markup is added to the manufacturing cost to estimate the lamp cost. The price of CFL in 2015 is $2/klm and assumed to be the same as that of LED by 2050. The price of HL and IL are $2.50/klm and $0.63/klm, respectively, assuming no change over time. A graphical comparison of lamp purchase cost (undiscounted) is provided by Figure A.2.

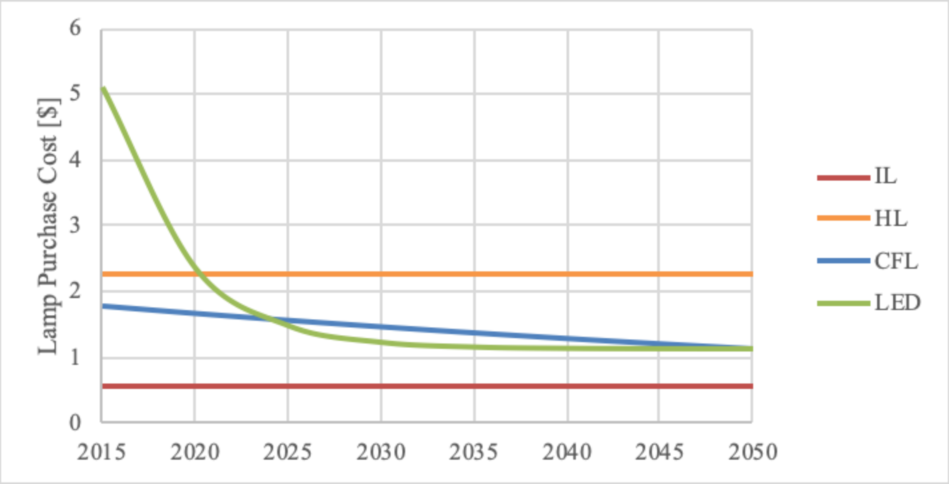


Figure A.2: Comparison of projected purchase cost of lamp by type.

- **Installation cost**

The cost of installation is calculated as an opportunity cost (Goldschmidt-Clermont 1993) that is equivalent to one third of the US median wage of $17.40/hour (US DOL 2016) applied to an estimated 9-minute labor time (which includes purchase and installation of the new lamp, and disposal of the old lamp).

$$Cost_{install}(x) = 0.542\left(\frac{1}{1.03}\right)^{x} \tag{0.11}$$

- **Electricity cost**

Electricity cost is given as:

$$\begin{aligned} &Cost_{ele}(l, x_{start}, x_{end}) \\ &\quad = \overline{Price_{ele}}(x_{start}, x_{end}) \cdot Consum_{ele}(l, x_{start}, x_{end}) \end{aligned} \tag{0.12}$$

where $\overline{Price_{ele}}$ is the average use-phase electricity price [$/kWh], defined as:

$$\overline{Price_{ele}}(x_{start}, x_{end}) = \overline{exponetialD}(p, r, x_{start}, x_{end}) \tag{0.13}$$

with the values of parameters p (electricity price in 2015) and r (annual growth rate) depend on the location, given as:

Table A.2: 2015 electricity price [$/kWh] and annual growth rate to 2050 of selected state.

Location	***p***	***r***
US avg	0.127	2.30%
DC	0.132	2.73%
Ill.	0.126	2.59%
KS	0.124	1.82%
TX	0.117	2.69%
WY	0.110	2.20%
CA	0.169	1.80%
HI	0.298	2.30%

(Source: US EIA 2016)

The annual growth of the electric rates are interpolated using data between 2015 and 2040 and assumed valid for extrapolation until 2050. The electricity price for HI is taken as the average of the Electric Power Monthly[5] data from January to December 2015. Its growth rate is assumed the same as that of US average due to lack of forecast data for the state.

$Consum_{ele}(l, x_{start}, x_{end})$ is the electricity consumption of the lamp [kWh], defined as:

$$Consum_{ele}(l, x_{start}, x_{end}) = \frac{365 \cdot HOU \cdot (x_{end} - x_{star}) \cdot LMR}{Eff(l, x_{start}) \cdot 1{,}000} \tag{0.14}$$

where HOU is the average daily hours of use and LMR is the lumen requirement at 900 lm, and Eff is the lamp efficacy [lm/W] given as:

$$Eff(l,x) = \begin{cases} logistic(0.00, 300, 0.174, 2021, x) & \text{if } l = LED \\ exponential(70.0, 5.00E-3, x) & \text{if } l = CFL \\ 20.0 & \text{if } l = HL \\ 15.0 & \text{if } l = IL \end{cases} \tag{0.15}$$

The 2015 efficacy of all lamps are provided by US DOE (2016b). $Eff(LED,x)$ is curve-fitted based on the projection that it would reach 300 lm/W by 2050 (Bergesen et al. 2015). Due to the maturity of incumbent technologies, $Eff(CFL,x)$ is not expected to change significantly over time, improving at less than 1% annually (US DOE 2014). $Eff(HL,x)$ and $Eff(IL,x)$ assume no change over time. A graphical comparison of lamp efficacy is provided by Figure 0.3.

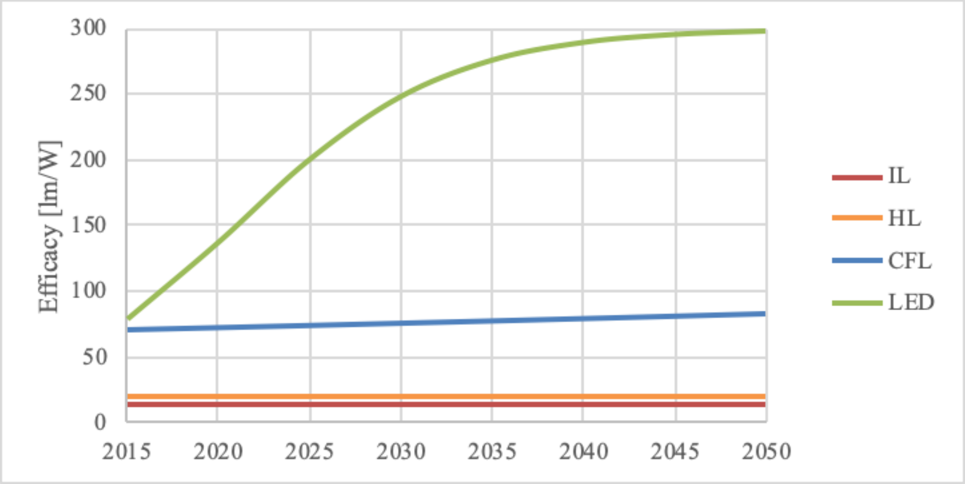


Figure 0.3: Comparison of projected efficacy of lamp by type.

- **EOL processing cost**

The cost to process a lamp at end of life is given as:

$$Cost_{EOL}(l,x) = \begin{cases} exponential(0.0589, -1.32E-3, x)\left(\frac{1}{1.03}\right)^x & \text{if } l = LED \\ 0.0601\left(\frac{1}{1.03}\right)^x & \text{if } l = CFL \\ 0.0287\left(\frac{1}{1.03}\right)^x & \text{if } l = HL \text{ or } IL \end{cases} \tag{0.16}$$

10% recycling is assumed for IL and HL, 20% for CFL and LED, and 30% for all lamp packaging (US DOE 2012b, 2012c). 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. Landfill cost is estimated at \$45/ton (US EPA 2014, 2015a) and the same rate is applied to recycling packaging.

A.1.4 Primary energy functions

This section provides the functions for estimating the primary energy (PE) at a given life cycle process or stage.

- **Production**

The PE of lamp production is given as:

$$E_{prod}(l,x) = \begin{cases} logistic(172, 400, -0.296, 2015, x) & \text{if } l = LED \\ 65.0 & \text{if } l = CFL \\ 1.90 & \text{if } l = HL \text{ or } IL \end{cases} \tag{0.17}$$

All $E_{prod}(l,x)$ are based on US DOE (2012b), which also provides an estimate for an improved LED model with an expected efficacy of 134 lm/W by 2017. This projected improvement has been adjusted to 2020 based on $Eff(LED,x)$ in this study.

- **Transportation**

The PE of transporting a lamp from gate to consumers is estimated as:

$$E_{trpt}(l, x) = exponential(p, r, x) \tag{0.18}$$

where the values of parameters p (primary energy from lamp transport in 2015) and r (annual growth rate) depend on lamp type l and the location, given as:

Table A.3: 2015 average per lamp transportation primary energy [MJ] and annual growth rate to 2050 for selected states.

	LED		**CFL**		**HL / IL**	
Location	***p***	***r***	***p***	***r***	***p***	***r***
US avg	1.88	-3.48%	2.03	-2.44%	0.679	-2.44%
DC	3.11	-3.48%	1.45	-2.45%	1.13	-2.45%
Ill.	2.36	-3.48%	1.10	-2.45%	0.854	-2.45%
KS	1.75	-3.48%	0.812	-2.44%	0.632	-2.44%
TX	1.63	-3.48%	0.758	-2.44%	0.589	-2.44%
WY	1.36	-3.47%	0.632	-2.44%	0.492	-2.44%
CA	0.499	-3.45%	0.228	-2.42%	0.177	-2.42%
HI	0.178	-3.42%	0.0801	-2.38%	0.0623	-2.38%

(Sources: Nahlik et al. 2015, US DOE 2016b, 2012b, 2012c)

Manufacturers are assumed in Taiwan for LED and Shanghai for all other lamps. The lamps are received from cargo ship at the port of Los Angeles and then transported to the geographical centroid of each region via diesel trucks. The calculations account for LED weight reduction by 33% in electronics and proportionally to wattage demand in heat sink between 2015 and 2020 (US DOE 2016b). The calculations also account for improved vehicle technology and lower-carbon fuels, which together would decrease the life cycle energy factor by 57% for ships and 58% for trucks by 2050 (Nahlik et al. 2015).

- **Use phase electricity**

The PE of use phase electricity consumption is given as:

$$E_{ele}(l, x_{start}, x_{end}) = 3.6 \cdot \overline{EF_{ele}}(x_{start}, x_{end}) \cdot Consum_{ele}(l, x_{start}, x_{end}) \tag{0.19}$$

where $Consum_{ele}$ is defined in Appendix 0 and $\overline{EF_{ele}}$ is the average use-phase primary energy factor for electricity production [kWh/kWh] defined as:

$$\overline{EF_{ele}}(x_{start}, x_{end}) = \overline{exponetial}(p, r, x_{start}, x_{end}) \tag{0.20}$$

with the values of parameters p (electricity primary energy factor in 2015) and r (annual growth rate) depend on the location, given as:

Table A.4: 2015 average per lamp use phase primary energy [MJ] and annual growth rate to 2050 for selected states.

Location	***p***	***r***
US avg	2.95	-0.385%
DC (RFCE)	3.18	-0.139%
Ill. (RFCW)	3.23	-0.220%
KS (SPNO)	2.94	-0.797%
TX (ERCT)	2.84	-0.508%
WY (RMPA)	2.87	-0.884%
CA (CAMX)	2.61	-0.185%
HI (HICC)	3.26	-1.10%

(Sources: US EIA 2016, US DOE 2007, 2012a, US EPA 2015b)

The electricity primary energy factors are calculated using EIA's electricity market module forecast fuel mixes (US EIA 2016, US DOE 2012a) and fuel-specific primary energy factors (US DOE 2007), which account for both combustion and upstream. Transmission and distribution losses (US EPA 2015b) are included in the estimates. All growth rates are interpolated using data between 2015 and 2040 and assumed valid for extrapolation until 2050.

- **EOL processing**

The average PE associated with processing a lamp at end of life is given as:

$$E_{EOL}(l,x) = \begin{cases} exponential(0.0372, -0.0170, x) & \text{if } l = LED \\ 0.0219 & \text{if } l = CFL \\ 0.00265 & \text{if } l = HL \text{ or } IL \end{cases} \tag{0.21}$$

where 10% recycling is assumed for IL and HL, 20% for CFL and LED, and 30% for all lamp packaging (US DOE 2012b, 2012c). The calculations use the US EPA Waste Reduction Model (2015b) 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.

A.1.5 Greenhouse gas emission functions

This section provides the functions for estimating the greenhouse gas (GHG) emission at a given life cycle process or stage.

- **Production**

The GHG emission of lamp production is given as:

$$GHG_{prod}(l,x) = \begin{cases} logistic(8.10, 20.0, -0.424, 2014, x) & \text{if } l = LED \\ 8.99 & \text{if } l = CFL \\ 0.948 & \text{if } l = HL \text{ or } IL \end{cases} \tag{0.22}$$

All $E_{prod}(l,x)$ are based on US DOE (2012b), which also provides an estimate for an improved LED model with an expected efficacy of 134 lm/W by 2017. This projected improvement has been adjusted to 2020 based on $Eff(LED,x)$ in this study.

- **Transportation**

The GHG emission of transporting a lamp from gate to consumers is estimated as:

$$GHG_{trpt}(l,) = exponential(p, r, x) \tag{0.23}$$

where the values of parameters p (GHG emissions from lamp transport in 2015) and r (annual growth rate) depend on lamp type l and the location, given as:

Table A.5: 2015 average per lamp transportation GHG emission [kg CO_2e] and annual growth rate to 2050 for selected states.

	LED		**CFL**		**HL / IL**	
location	**p**	**r**	**p**	**r**	**p**	**r**
US avg	0.212	-4.59%	0.226	-3.53%	0.0754	-3.53%
DC	0.299	-4.18%	0.321	-3.12%	0.107	-3.12%
Ill.	0.246	-4.39%	0.263	-3.33%	0.0878	-3.33%
KS	0.202	-4.66%	0.215	-3.60%	0.0720	-3.60%
TX	0.194	-4.73%	0.207	-3.67%	0.0690	-3.67%
WY	0.175	-4.93%	0.186	-3.86%	0.0621	-3.86%
CA	0.114	-6.35%	0.119	-5.30%	0.0398	-5.30%
HI	0.0713	-7.64%	0.0746	-6.65%	0.0249	-6.65%

(Sources: Nahlik et al. 2015, US DOE 2016b, 2012b, 2012c)

Manufacturers are assumed in Taiwan for LED and Shanghai for all other lamps. The lamps are received from cargo ship at the port of Los Angeles and then transported to the geographical centroid of each region via diesel trucks. The calculations account for LED weight reduction by 33% in electronics and proportionally to wattage demand in heat sink between 2015 and 2020 (US DOE 2016b). The calculations also account for improved vehicle technology and lower-carbon fuels, which together would decrease the GHG emission factor by 91% for ships and 56% for trucks by 2050 (Nahlik et al. 2015).

- **Use phase electricity**

The GHG emission of use phase electricity consumption is given as:

$$GHG_{ele}(x_{start}, x_{end}) = \overline{GHGF_{ele}}(x_{start}, x_{end}) \cdot Consum_{ele}(l, x_{start}, x_{end}) \quad (0.24)$$

where $Consum_{ele}$ is defined in Appendix 0 and $\overline{GHGF_{ele}}$ is the average use-phase GHG emission factor for electricity production [kg CO_2e/kWh] defined as:

$$\overline{GHGF_{ele}}(x_{start}, x_{end}) = \overline{exponential}(p, r, x_{start}, x_{end}) \quad (0.25)$$

with the values of parameters p (electricity GHG emission factor in 2015) and r (annual growth rate) depend on the location, given as:

Table A.6: 2015 average per lamp use phase GHG emission [kg CO_2e] and annual growth rate to 2050 for selected states.

Location	*p*	*r*
US avg	0.647	-1.31%
DC (RFCE)	0.507	-0.558%
Ill. (RFCW)	0.819	-1.27%
KS (SPNO)	0.891	-1.54%
TX (ERCT)	0.658	-1.23%
WY (RMPA)	0.971	-1.94%
CA (CAMX)	0.384	-2.38%
HI (HICC)	0.995	-3.50%

(Sources: US EIA 2016, US DOE 2012, 2013c, 2015b, US EPA 2015b)

The electricity GHG emission factors are calculated using EIA's electricity market module forecast fuel mixes (US EIA 2016, US DOE 2012a). The emission factors account for combustion emissions and upstream emissions (by multiplying the percent contribution from fuels by their specific upstream emission factors) (US DOE 2013c, 2015b). Transmission and distribution losses (US EPA 2015b) are included in the estimates. All growth rates are interpolated using data between 2015 and 2040 and assumed valid for extrapolation until 2050.

- **EOL processing**

The average GHG emission associated with processing a lamp at end of life is given as:

$$GHG_{EOL}(l,x)=\begin{cases} exponential(0.0150,-0.0106,x) & \text{if } l=LED \\ 0.0284 & \text{if } l=CFL \\ 0.0128 & \text{if } l=HL \text{ or } IL \end{cases} \tag{0.26}$$

where 10% recycling is assumed for IL and HL, 20% for CFL and LED, and 30% for all lamp packaging (US DOE 2012b, 2012c).

A.1.6 Social cost of carbon functions

This section provides the functions for estimating the Social Cost of Carbon (SCC) at a given life cycle process or stage. SCC is simply a product of emissions and the social cost per metric ton of carbon, which is projected to increase annually (US EPA 2015c).

- **Production**

$$SCCost_{prod}(l,x)=SCPrice(x)\cdot GHG_{prod}(l,x) \tag{0.27}$$

where GHG_{prod} is defined in Appendix 0 and $SCPrice$ is the social cost per kg CO_2-eq of carbon defined using the pricing trajectory from US EPA (2015c) as:

$$SCPrice(x)=exponential(0.0478,0.0486,x)\left(\frac{1}{1.03}\right)^{x} \tag{0.28}$$

- **Transportation**

$$SCCost_{trpt}(l,x)=SCPrice(x)\cdot GHG_{trpt}(l,x) \tag{0.29}$$

where GHG_{trpt} is defined in Appendix 0.

- **Use phase electricity**

$$SCCost_{ele}(l, x_{start}, x_{end}) = \overline{SCPrice}(x_{start}, x_{end}) \cdot GHG_{ele}(l, x_{start}, x_{end}) \tag{0.30}$$

where GHG_{ele} is defined in Appendix 0 and $\overline{SCPrice}$ is the average use-phase social cost of carbon per kg CO_2e, defined using the pricing trajectory from US EPA (2015c) as:

$$\overline{SCPrice}(x_{start}, x_{end}) = \overline{exponetialD}(0.0478, 0.0486, x_{start}, x_{end}) \tag{0.31}$$

- **EOL processing**

$$SCCost_{EOL}(l, x) = SCPrice(x) \cdot GHG_{EOL}(l, x) \tag{0.32}$$

where GHG_{EOL} is defined in Appendix 0.

A.2 Supplemental information on sensitivity analysis

A.2.1 Parametric assessment

For the higher value of the *CFL & LED Base Price* (which represent dimmable lamp prices), $Cost_{purchase}$[\$] is illustrated in Figure A.4 and given as:

$$Cost_{purchase}(LED, x) = logistic(2.00, 52.7, -0.256, 2008, x)\left(\frac{1}{1.03}\right)^{x} \tag{0.33}$$

$$Cost_{purchase}(CFL, x) = logistic(2.00, 52.7, -0.256, 2008, x)\left(\frac{CP}{9}\right)\left(\frac{1}{1.03}\right)^{x} \tag{0.34}$$

where the $logistic$ function is curve-fitted for a 900 lm dimmable lamp at \$10/klm in 2015 (US DOE 2016b) and reaching a price of \$2/lamp by 2030 (US EIA 2014). CP is the price of dimmable

CFL lamp in 2015 (assumed \$7). Note the reduction in CFL price over time is assumed proportional to that in LED price. Dimmable halogen and incandescent lamps are assumed not available.

For the lower value of *LED Net Price Reduction (2015-2050)*, $Cost_{purchase}$[\$] is illustrated in Fig. B1-1 and given as:

$$Cost_{purchase}(LED, x) = logistic(5.36, 9.34E9, -0.455, 1968, x)\left(\frac{LP}{9}\right)\left(\frac{LMR}{1{,}000}\right)\left(\frac{1}{1.03}\right)^{x} \quad (0.35)$$

where the $logistic$ function is in [\$/klm] and curve-fitted based on the historic values reported in DOE's SSL R&D Multi-Year Program Plans from 2008 to 2015 (US DOE 2016b). LP is the 2015 price of non-dimmable LED lamp (\$5.09) LMR is the lumen requirement (900 lm). Figure A.4 compares the lamp purchase price per change in *CFL & LED Base Price* and *LED Net Price Reduction (2015-2050)*.

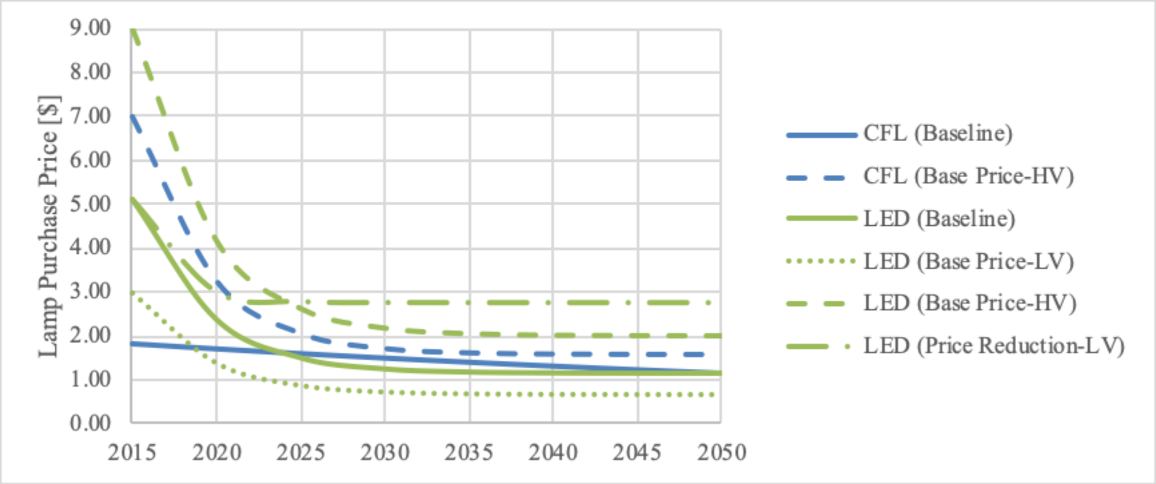


Figure A.4: Comparison of lamp purchase price per change in CFL & LED Base Price and LED Net Price Reduction (2015-2050).

For the lower value of *LED Net Efficacy Gain (2015-2050)*, Eff [lm/W] is based on US EIA (2014) and illustrated in Figure A.5 below:

$$Eff(LED, x) = logistic(0.00, 201, 0.301, 2017, x) \qquad (0.36)$$

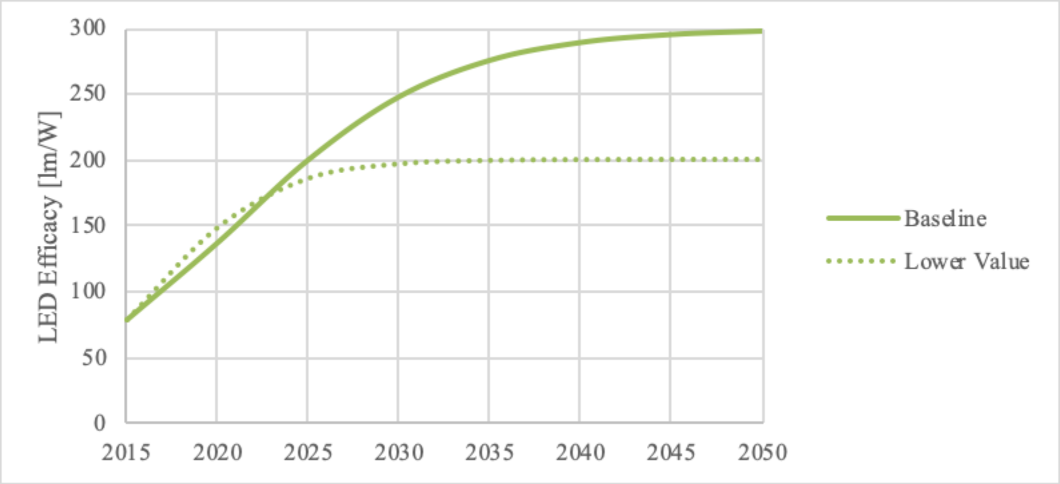


Figure A.5: Comparison of LED efficacy per change in LED Net Efficacy Gain (2015-2050).

For the lower value of *LED Net Lifetime Gain (2015-2050)*, LT [yrs] is curve-fitted based on the projection that it would reach 50,000 hrs by 2025 (US DOE 2016b) with an upper limit of 55,000 hrs (assumed). LT is defined below and illustrated in Figure A.6.

$$LT(LED, x) = logistic(0.00, 5.50E4, 0.248, 2016, x)/(365 \cdot HOU) \qquad (0.37)$$

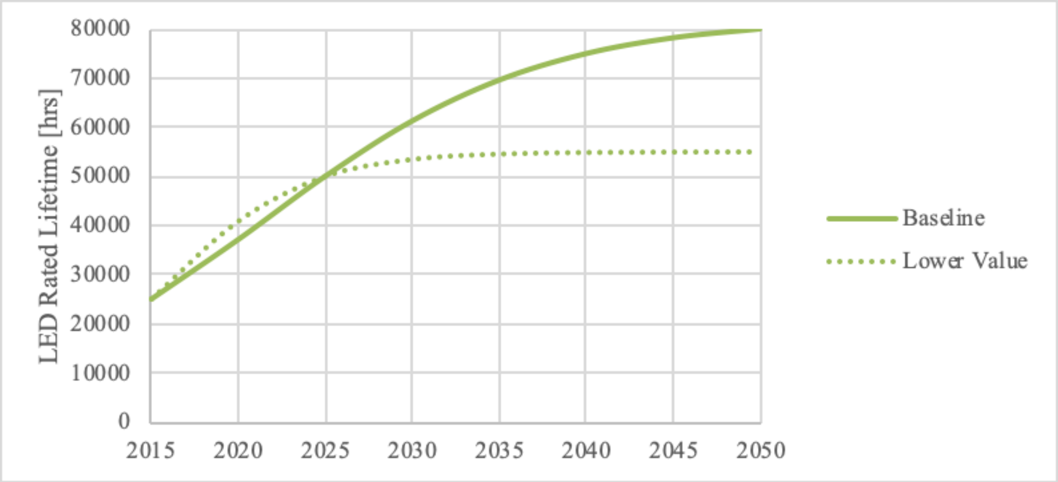


Figure A.6: Comparison of LED rated lifetime per change in LED Net Lifetime Gain (2015-2050).

A.2.2 Results from parametric assessment

Table A.7: Percent value change in parameters compared to their baseline values.

ID	Parameters	Units	Lower Value	Higher Value
1	Ele. GHG Emission Factor (2015)	kg CO2e/kWh	-50%	+50%
2	Electricity Base Price (2015)	$/kWh	-50%	+50%
3	Discount Rate	%	-50%	+100%
4	Eletricity Price Annual Growth	%	-100%	+100%
5	CFL & LED Base Price (2015)	$	0% & -41%	+289% & +77%
6	LED Net Efficacy Growth (2015-50)	lm/W	-45%	N/A
7	Installation Cost	$	-100%	+122%
8	Ele. GHG Emiss. Annual Reduction	%	-100%	+100%
9	LED Net Price Reduction (2015-50)	$	-40%	N/A
10	LED Net Lifetime Growth (2015-50)	hrs	-45%	N/A

Table A.8: Summary of LCC-optimized policies per parameter value change (listed in Table A.7) compared to Case 1 baseline scenario.

Parameter/ Scenario	Cost to Consumer [$]	Electricity [kWh]	Primary Energy [MJ]	GHG Emissions [kg CO2e]	Carbon Cost [$]	Replacement Schedule (2015-2050) [Purchase Year]
Baseline	**31.70**	**222.7**	**2586**	**143.8**	**8.45**	**CFL in 2015; LED in 2020 and 2030**
1-LV	18.63	224.9	2599	144.9	8.50	CFL in 2015; LED in 2021 and 2031
1-HV	31.89	208.1	2611	201.1	11.82	CFL in 2015; LED in 2019, 2025, and 2034
2-LV	31.69	222.9	2587	82.4	4.77	CFL in 2015; LED in 2020 and 2030
2-HV	44.00	206.9	2607	143.1	8.37	CFL in 2015; LED in 2019, 2025, and 2033
3-LV	37.49	208.4	2613	143.8	10.15	CFL in 2015; LED in 2019, 2025, and 2034
3-HV	24.19	222.1	2586	143.5	6.14	CFL in 2015; LED in 2020 and 2029
4-LV	25.92	222.3	2584	143.6	8.44	CFL in 2015; LED in 2020 and 2029
4-HV	40.13	208.9	2615	144.0	8.42	CFL in 2015; LED in 2019, 2026, and 2034
5-LV	30.51	206.6	2605	143.0	8.36	CFL in 2015; LED in 2019, 2025, and 2033
5-HV	39.11	216.9	2725	143.4	8.41	LED in 2015, 2022, and 2031
6-LV	33.25	233.4	2707	148.4	8.91	CFL in 2015; LED in 2019 and 2027
7-LV	29.37	207.7	2611	143.5	8.39	CFL in 2015; LED in 2019, 2025, and 2033
7-HV	33.89	223.2	2588	144.0	8.46	CFL in 2015; LED in 2020 and 2030
8-LV	31.69	222.8	2586	165.1	9.91	CFL in 2015; LED in 2020 and 2030
8-HV	31.70	222.6	2585	127.1	7.32	CFL in 2015; LED in 2020 and 2030
9-LV	32.67	222.3	2583	143.5	8.44	CFL in 2015; LED in 2020 and 2030
10-LV	31.77	222.6	2595	144.2	8.48	CFL in 2015; LED in 2020 and 2030

Note: Parameter number corresponds to parameter ID in Table 4. LV and HV stand for Lower Value and Higher Value, respectively.

A.3 Tradeoff between objectives

Figure A.7 displays the Pareto curves weighing the tradeoff between Cost and Energy and between Cost and Emissions for the Case 1 baseline scenario, determined using the constrained method (i.e. by constraining one objective to an upper bound while minimizing the other).

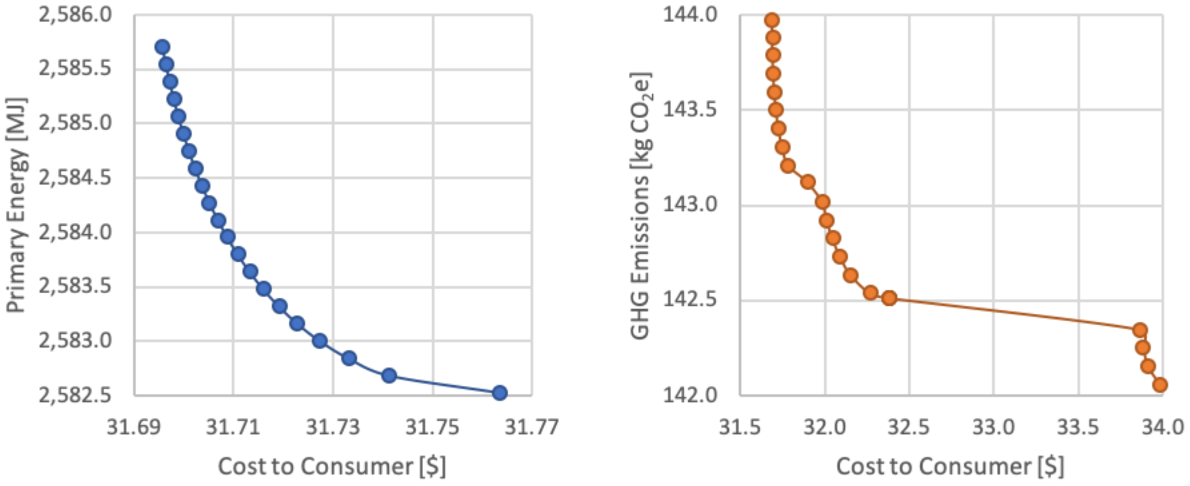


Figure A.7: Pareto curve of Cost-Energy (left) and Cost-Emissions (right) for Case 1 baseline scenario.

Figure A.7 shows that the tradeoff between Cost and Emissions is greater and less predictable than that between Cost and Energy. The concavity (where Cost is between $31.7-$32) and the large gap (where Cost is between $32.4-$33.8) on the Cost-Emissions Pareto curve come from the policy shifting in terms of the total number of replacement and the type of replacement lamps recommended. The large gap shows where the tradeoff between Cost and Emissions is highest - $1.4 more for the reduction of less than ¼ kg of CO_2e. In general, as both Pareto curves move to the left (with increasing emphasis on Cost), utilization increases for each lamp and replacement is delayed subsequently.

In general, the life cycle impact tradeoffs among the four objectives – Cost, Energy, Emissions, and LCC – are only a few percent or less. This is because Cost, Energy, and Emissions (which determines the Social Cost of Carbon) are coupled through electricity consumption. Since electricity usage generally dominates the life cycle impacts of lighting, the minimization of one objective would impose a partial minimization on the other objectives, thus leading to small tradeoffs in objective value. However, as the use phase impacts increase with higher HOU or as the non-use phase impacts vary across regions (e.g. from different transportation distance), the replacement policy may change with respect to changes in the ratio between the use-phase and non-use phase impacts.

A.4 Regional differences in replacement policy

This section investigates the differences in replacement policy between the District of Columbia (DC), Illinois (Ill.), Kansas (KS), Texas (TX), Wyoming (WY), California (CA), and Hawaii (HI). Due to differences in the regional grid electricity in terms of cost, primary energy intensity, and carbon intensity (US EIA 2016, US DOE 2007, 2012, 2013c, 2015b, 2016a, US EPA 2015b), as shown in Figure A.8, the optimal replacement policies are expected to vary by region.

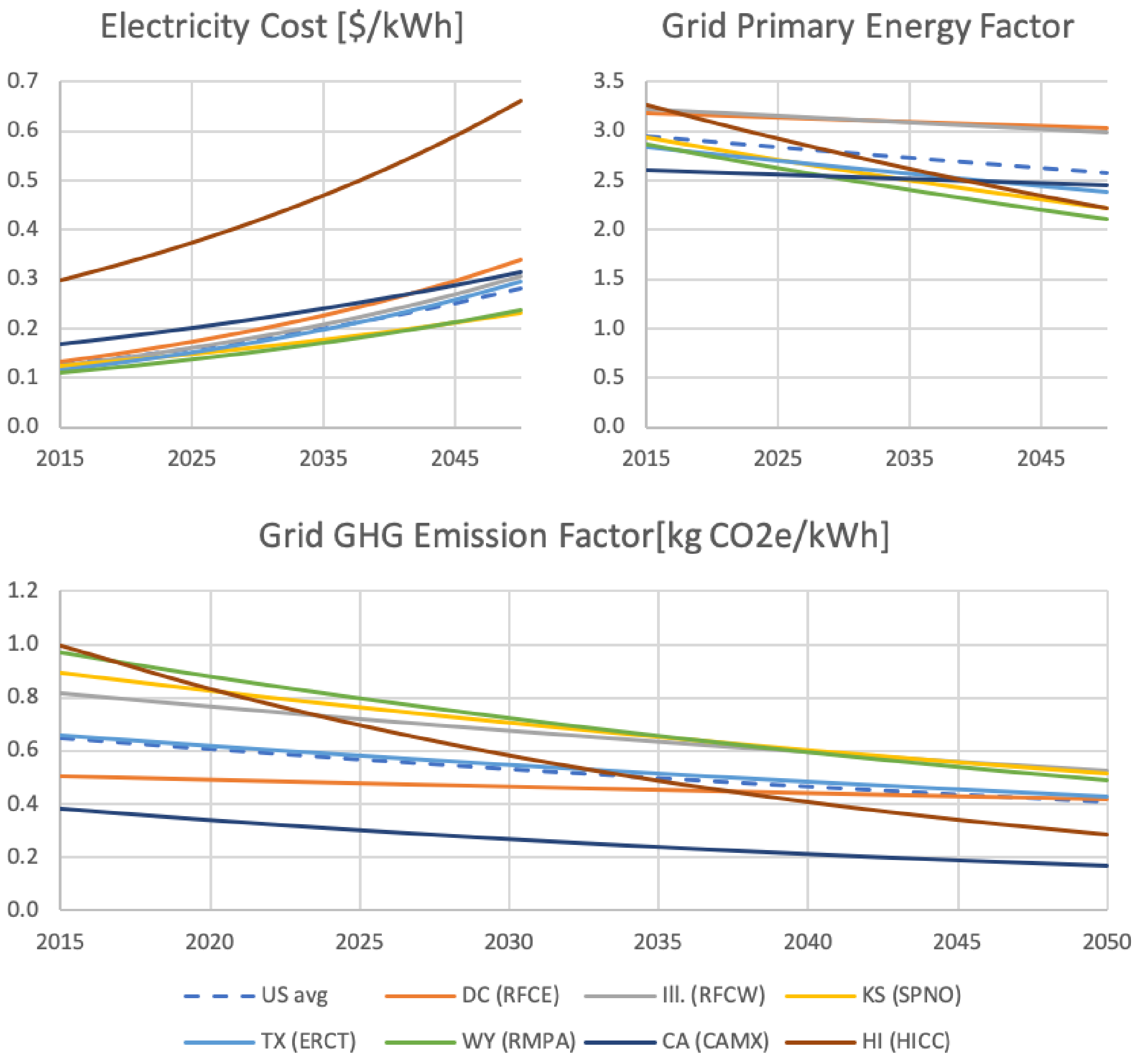


Figure A.8: Trends in average electricity cost, grid primary energy factor, and GHG emission factor for selected regions.

Table A.9, Table A.10, and Table A.11 show the regional baseline results at 3 HOU that are optimized for Cost, Energy, and Emissions, respectively. Overall, the replacement policies vary the least for Energy and the most for Emissions. In terms of Emissions only, the policies show that LEDs should be adopted in 2015 in Case 1 except for CA, where the carbon intensity of the grid is lower. In terms of Cost only, LEDs are adopted earlier and replaced more frequently for DC, CA, and HI, where the electricity costs are higher. Results for 1/7, 1.5, and 12 HOU can be found in Appendix 0.

Table A.9: Summary of regional Cost-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.)

Region	**Cost to Consumer [$]**	**Electricity [kWh]**	**Primary Energy [MJ]**	**GHG Emissions [kg CO2e]**	**Carbon Cost [$]**	**Replacement Policy (2015-2050) [Purchase Year]**
Case 1						
US avg	31.69	223.1	2588	144.0	8.46	CFL in 2015; LED in 2020 and 2030
DC (RFCE)	34.30	209.5	2861	128.0	7.53	CFL in 2015; LED in 2020, 2026, and 2035
Ill. (RFCW)	32.38	223.2	2852	177.4	10.46	CFL in 2015; LED in 2020 and 2030
KS (SPNO)	29.65	223.0	2470	185.8	10.93	CFL in 2015; LED in 2020 and 2030
TX (ERCT)	30.78	223.5	2475	147.4	8.67	CFL in 2015; LED in 2021 and 2030
WY (RMPA)	28.09	223.6	2399	193.0	11.28	CFL in 2015; LED in 2021 and 2030
CA (CAMX)	38.18	207.9	2414	89.0	5.07	CFL in 2015; LED in 2019, 2025, and 2034
HI (HICC)	64.21	198.4	2729	169.7	9.66	CFL in 2015; LED in 2018, 2022, 2028, and 2036
Case 2 with $l_1 = IL$						
US avg	31.72	223.1	2588	144.0	8.46	Discard IL; CFL in 2015; LED in 2020 and 2030
DC (RFCE)	34.33	209.5	2861	128.0	7.53	Discard IL; CFL in 2015; LED in 2020, 26, and 35
Ill. (RFCW)	32.40	223.2	2852	177.4	10.46	Discard IL; CFL in 2015; LED in 2020 and 2030
KS (SPNO)	29.68	223.0	2470	185.8	10.93	Discard IL; CFL in 2015; LED in 2020 and 2030
TX (ERCT)	30.81	223.5	2475	147.4	8.67	Discard IL; CFL in 2015; LED in 2021 and 2030
WY (RMPA)	28.12	223.6	2399	193.1	11.29	Discard IL; CFL in 2015; LED in 2021 and 2030
CA (CAMX)	38.20	207.9	2414	89.0	5.07	Discard IL; CFL in 2015; LED in 2019, 25, and 34
HI (HICC)	64.25	197.9	2728	169.4	9.63	Discard IL; CFL in 2015; LED in 2018, 22, 28, and 35
Case 2 with $l_1 = HL$						
US avg	31.72	223.1	2588	144.0	8.46	Discard HL; CFL in 2015; LED in 2020 and 2030
DC (RFCE)	34.33	209.5	2861	128.0	7.53	Discard HL; CFL in 2015; LED in 2020, 26, and 35
Ill. (RFCW)	32.40	223.2	2852	177.4	10.46	Discard HL; CFL in 2015; LED in 2020, and 2030
KS (SPNO)	29.68	223.0	2470	185.8	10.93	Discard HL; CFL in 2015; LED in 2020 and 2030
TX (ERCT)	30.81	223.5	2475	147.4	8.67	Discard HL; CFL in 2015; LED in 2021 and 2030
WY (RMPA)	28.12	223.6	2399	193.1	11.29	Discard HL; CFL in 2015; LED in 2021 and 2030
CA (CAMX)	38.20	207.9	2414	89.0	5.07	Discard HL; CFL in 2015; LED in 2019, 25 and 34
HI (HICC)	64.25	197.9	2728	169.4	9.63	Discard HL; CFL in 2015; LED in 2018, 22, 28, and 35
Case 2 with $l_1 = CFL$						
US avg	29.02	223.1	2521	134.8	8.02	Keep CFL; LED in 2020 and 2030
DC (RFCE)	31.63	209.5	2795	118.6	7.09	Keep CFL; LED in 2020, 2026, and 2035
Ill. (RFCW)	29.71	223.2	2785	168.1	10.02	Keep CFL; LED in 2020 and 2030
KS (SPNO)	26.98	223.0	2404	176.6	10.49	Keep CFL; LED in 2020 and 2030
TX (ERCT)	28.11	223.5	2410	138.2	8.23	Keep CFL; LED in 2021 and 2030
WY (RMPA)	25.42	223.6	2333	183.9	10.85	Keep CFL; LED in 2021 and 2030
CA (CAMX)	35.51	207.9	2349	79.9	4.64	Keep CFL; LED in 2019, 2025 and 2034
HI (HICC)	61.54	198.4	2664	160.7	9.22	Keep CFL; LED in 2018, 2022, 2028, and 2036
Case 2 with $l_1 = LED$						
US avg	27.89	215.7	2435	130.0	7.77	Keep LED; LED in 2021 and 2030
DC (RFCE)	30.45	215.7	2686	113.4	6.84	Keep LED; LED in 2021 and 2030
Ill. (RFCW)	28.57	215.8	2692	162.2	9.71	Keep LED; LED in 2021 and 2030
KS (SPNO)	25.90	215.6	2321	170.3	10.15	Keep LED; LED in 2021 and 2030
TX (ERCT)	27.03	216.0	2327	133.3	7.97	Keep LED; LED in 2021 and 2031
WY (RMPA)	24.41	216.1	2251	177.0	10.49	Keep LED; LED in 2021 and 2031
CA (CAMX)	34.32	214.9	2233	73.4	4.31	Keep LED; LED in 2021 and 2030
HI (HICC)	59.90	201.0	2496	152.8	8.82	Keep LED; LED in 2019, 2025, and 2033

Table A.10: Summary of regional Energy-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.)

Region	Cost to Consumer [$]	Electricity [kWh]	Primary Energy [MJ]	GHG Emissions [kg CO2e]	Carbon Cost [$]	Replacement Policy (2015-2050) [Purchase Year]
Case 1						
US avg	31.76	221.8	2583	143.3	8.43	CFL in 2015; LED in 2020 and 2029
DC (RFCE)	34.39	221.8	2840	126.2	7.48	CFL in 2015; LED in 2020 and 2029
Ill. (RFCW)	32.46	221.7	2845	176.3	10.43	CFL in 2015; LED in 2020 and 2029
KS (SPNO)	29.73	221.6	2464	184.6	10.89	CFL in 2015; LED in 2020 and 2029
TX (ERCT)	30.88	221.8	2468	146.5	8.64	CFL in 2015; LED in 2020 and 2029
WY (RMPA)	28.20	221.6	2390	191.2	11.22	CFL in 2015; LED in 2020 and 2029
CA (CAMX)	38.41	222.0	2374	85.2	4.88	CFL in 2015; LED in 2020 and 2029
HI (HICC)	66.53	221.4	2607	168.3	9.66	CFL in 2015; LED in 2019 and 2029
Case 2 with $l_1 = IL$						
US avg	31.79	221.8	2583	143.3	8.43	Discard IL; CFL in 2015; LED in 2020 and 2029
DC (RFCE)	34.42	221.8	2840	126.2	7.48	Discard IL; CFL in 2015; LED in 2020 and 2029
Ill. (RFCW)	32.49	221.7	2845	176.3	10.43	Discard IL; CFL in 2015; LED in 2020 and 2029
KS (SPNO)	29.76	221.6	2464	184.7	10.89	Discard IL; CFL in 2015; LED in 2020 and 2029
TX (ERCT)	30.90	221.8	2468	146.5	8.64	Discard IL; CFL in 2015; LED in 2020 and 2029
WY (RMPA)	28.23	221.6	2390	191.2	11.22	Discard IL; CFL in 2015; LED in 2020 and 2029
CA (CAMX)	38.44	222.0	2374	85.2	4.88	Discard IL; CFL in 2015; LED in 2020 and 2029
HI (HICC)	66.56	221.4	2607	168.3	9.66	Discard IL; CFL in 2015; LED in 2019 and 2029
Case 2 with $l_1 = HL$						
US avg	31.79	221.8	2583	143.3	8.43	Discard HL; CFL in 2015; LED in 2020 and 2029
DC (RFCE)	34.42	221.8	2840	126.2	7.48	Discard HL; CFL in 2015; LED in 2020 and 2029
Ill. (RFCW)	32.49	221.7	2845	176.3	10.43	Discard HL; CFL in 2015; LED in 2020 and 2029
KS (SPNO)	29.76	221.6	2464	184.7	10.89	Discard HL; CFL in 2015; LED in 2020 and 2029
TX (ERCT)	30.90	221.8	2468	146.5	8.64	Discard HL; CFL in 2015; LED in 2020 and 2029
WY (RMPA)	28.23	221.6	2390	191.2	11.22	Discard HL; CFL in 2015; LED in 2020 and 2029
CA (CAMX)	38.44	222.0	2374	85.2	4.88	Discard HL; CFL in 2015; LED in 2020 and 2029
HI (HICC)	66.56	221.4	2607	168.3	9.66	Discard HL; CFL in 2015; LED in 2019 and 2029
Case 2 with $l_1 = CFL$						
US avg	29.09	221.8	2515	134.1	7.99	Keep CFL; LED in 2020 and 2029
DC (RFCE)	31.72	221.8	2773	116.9	7.04	Keep CFL; LED in 2020 and 2029
Ill. (RFCW)	29.79	221.7	2778	167.1	9.98	Keep CFL; LED in 2020 and 2029
KS (SPNO)	27.06	221.6	2398	175.4	10.45	Keep CFL; LED in 2020 and 2029
TX (ERCT)	28.21	221.8	2402	137.3	8.20	Keep CFL; LED in 2020 and 2029
WY (RMPA)	25.53	221.6	2324	182.0	10.78	Keep CFL; LED in 2020 and 2029
CA (CAMX)	35.74	222.0	2309	76.1	4.44	Keep CFL; LED in 2020 and 2029
HI (HICC)	63.86	221.4	2542	159.2	9.22	Keep CFL; LED in 2019 and 2029
Case 2 with $l_1 = LED$						
US avg	27.95	214.6	2431	129.4	7.75	Keep LED; LED in 2020 and 2030
DC (RFCE)	30.51	214.6	2681	113.0	6.83	Keep LED; LED in 2020 and 2030
Ill. (RFCW)	28.64	214.5	2686	161.3	9.67	Keep LED; LED in 2020 and 2030
KS (SPNO)	25.96	214.5	2316	169.3	10.12	Keep LED; LED in 2020 and 2030
TX (ERCT)	27.11	214.6	2321	132.6	7.94	Keep LED; LED in 2020 and 2030
WY (RMPA)	24.50	214.5	2244	175.5	10.43	Keep LED; LED in 2020 and 2030
CA (CAMX)	34.34	214.8	2232	73.3	4.30	Keep LED; LED in 2021 and 2030
HI (HICC)	61.55	214.3	2454	153.1	8.90	Keep LED; LED in 2020 and 2029

Table A.11: Summary of regional Emissions-optimized replacement policies at 3 HOU. (Label in parenthesis represents NERC regions.)

Region	Total Cost [$]	Electricity [kWh]	Primary Energy [MJ]	GHG Emissions [kg CO2e]	Carbon Cost [$]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1						
US avg	34.02	214.1	2717	142.0	8.36	LED in 2015, 2020 and 2029
DC (RFCE)	36.51	214.4	2966	125.9	7.45	LED in 2015, 2020 and 2030
Ill. (RFCW)	35.34	200.1	3001	172.4	10.14	LED in 2015, 2018, 2024, and 2032
KS (SPNO)	32.87	200.0	2655	179.8	10.55	LED in 2015, 2018, 2023, and 2032
TX (ERCT)	33.20	214.1	2606	145.1	8.56	LED in 2015, 2020, and 2030

WY (RMPA)	31.59	200.0	2590	185.5	10.83	LED in 2015, 2018, 2023, and 2032
CA (CAMX)	38.46	221.4	2377	85.1	4.88	CFL in 2015; LED in 2019 and 2029
HI (HICC)	66.29	200.0	2789	164.4	9.39	LED in 2015, 2018, 2023, and 2031
Case 2 with $l_1 = IL$						
US avg	34.05	214.1	2717	142.1	8.36	Discard IL; LED in 2015, 2020, and 2029
DC (RFCE)	36.54	214.4	2966	125.9	7.45	Discard IL; LED in 2015, 2020, and 2029
Ill. (RFCW)	35.36	200.1	3001	172.5	10.14	Discard IL; LED in 2015, 2018, 2024, and 2032
KS (SPNO)	32.90	200.0	2655	179.8	10.55	Discard IL; LED in 2015, 2018, 2023, and 2032
TX (ERCT)	33.22	214.1	2606	145.2	8.56	Discard IL; LED in 2015, 2020, and 2029
WY (RMPA)	31.62	200.0	2590	185.5	10.83	Discard IL; LED in 2015, 2018, 2023, and 2032
CA (CAMX)	38.49	221.4	2377	85.2	4.88	Discard IL; CFL in 2015; LED in 2019 and 2029
HI (HICC)	66.31	200.0	2789	164.4	9.39	Discard IL; LED in 2015, 18, 23, and 31
Case 2 with $l_1 = HL$						
US avg	34.05	214.1	2717	142.1	8.36	Discard HL; LED in 2015, 2020 and 2029
DC (RFCE)	36.54	214.4	2966	125.9	7.45	Discard HL; LED in 2015, 2020, and 2030
Ill. (RFCW)	35.36	200.1	3001	172.5	10.14	Discard HL; LED in 2015, 2018, 2024, and 2032
KS (SPNO)	32.90	200.0	2655	179.8	10.55	Discard HL; LED in 2015, 2018, 2023, and 2032
TX (ERCT)	33.22	214.1	2606	145.2	8.56	Discard HL; LED in 2015, 2020, and 2029
WY (RMPA)	31.62	200.0	2590	185.5	10.83	Discard HL; LED in 2015, 2018, 2023, and 2032
CA (CAMX)	38.49	221.4	2377	85.2	4.88	Discard HL; CFL in 2015; LED in 2019 and 2029
HI (HICC)	66.31	200.0	2789	164.4	9.39	Discard HL; CFL in 2015; LED in 2018, 23, and 31
Case 2 with $l_1 = CFL$						
US avg	29.72	205.0	2540	133.3	7.90	Keep CFL; LED in 2018, 2023 and 2032
DC (RFCE)	31.77	221.5	2774	116.9	7.04	Keep CFL; LED in 2020 and 2029
Ill. (RFCW)	30.46	204.8	2787	163.8	9.74	Keep CFL; LED in 2018, 2023, and 2031
KS (SPNO)	27.97	204.7	2435	171.5	10.16	Keep CFL; LED in 2018, 2023, and 2031
TX (ERCT)	28.91	204.9	2436	136.3	8.08	Keep CFL; LED in 2018, 2023, and 2032
WY (RMPA)	26.66	204.7	2369	177.4	10.46	Keep CFL; LED in 2018, 2023, and 2031
CA (CAMX)	35.79	221.4	2311	76.0	4.45	Keep CFL; LED in 2019 and 2029
HI (HICC)	62.24	204.8	2576	156.2	9.01	Keep CFL; LED in 2017, 2022, and 2030
Case 2 with $l_1 = LED$						
US avg	28.07	214.1	2434	129.3	7.75	Keep LED; LED in 2020 and 2029
DC (RFCE)	30.55	214.4	2682	113.0	6.84	Keep LED; LED in 2020 and 2030
Ill. (RFCW)	29.38	200.1	2717	159.7	9.53	Keep LED; LED in 2018, 2024, and 2032
KS (SPNO)	26.92	200.0	2373	167.1	9.94	Keep LED; LED in 2018, 2023, and 2032
TX (ERCT)	27.24	214.1	2324	132.4	7.95	Keep LED; LED in 2020 and 2029
WY (RMPA)	25.64	200.0	2307	172.8	10.22	Keep LED; LED in 2018, 2023, and 2032
CA (CAMX)	34.39	214.3	2234	73.3	4.30	Keep LED; LED in 2020 and 2029
HI (HICC)	60.33	200.0	2507	151.8	8.78	Keep LED; LED in 2018, 2023, and 2031

A.5 Alternative generation from coal and natural gas

This section compares the baseline replacement policies under 5 hypothetical fuel mixes: coal, natural gas (NG), 75%coal+25%NG, 50%coal+50%NG, and 25%coal+75%NG. For future improvement, all coal generation is assumed to become integrated gasification combined cycles and all NG generation becomes combined cycles by 2050. Note that both factors account for the upstream impacts of generation. Using data from the GREET model (US DOE 2016a), the alternative generation profiles are summarized in Table A.12.

Table A.12: Fuel cycle primary energy factor, and GHG emission factor for alternative fuel mixes. Exponential growth is assumed between 2015 and 2050.

Fuel Mix	Primary Energy Factor		GHG Emission Factor [kg CO_2e/kWh]	
	2015	2050	2015	2050
Coal (average)	3.03	2.73	1.08	0.973
75% Coal + 25% NG	2.86	2.58	0.943	0.851
50% Coal + 50% NG	2.69	2.43	0.806	0.729
25% Coal + 75% NG	2.51	2.28	0.669	0.607
NG (average)	2.34	2.13	0.532	0.485

Table A.13 and Table A.14 present the Energy-optimized and Emission-optimized baseline results at 3 HOU, respectively. Table A.13 shows essentially no change in policy across the marginal fuel mixes, indicating that the difference in primary energy intensity between coal and NG is not large enough to be significant. Note the Energy-optimized results are also similar to that for the US average fuel mix. Table A.14 shows that lamps are replaced more frequently under coal than NG, indicating that higher carbon fuels benefits more from use-phase GHG emission reduction through rapid replacement to energy-efficient lamps than lower carbon fuels. In general, there is little variation between the policies under natural gas and those under the US average fuel mix.

Table A.13: Summary of Life Cycle Energy-optimized replacement policies at 3 HOU under alternative fuel mixes.

Fuel Mix	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						
Coal (average)	$31.76	221.8	2674	251.9	$15.19	CFL in 2015; LED in 2020 and 2029
75% coal + 25% NG	$31.76	221.8	2542	222.8	$13.41	CFL in 2015; LED in 2020 and 2029
50% coal + 50% NG	$31.75	221.9	2411	193.7	$11.63	CFL in 2015; LED in 2020 and 2029
25% coal + 75% NG	$31.74	222.0	2279	164.6	$9.85	CFL in 2015; LED in 2020 and 2029
NG (average)	$31.73	222.2	2147	135.4	$8.07	CFL in 2015; LED in 2020 and 2030
Case 2 with $l_1 = IL$						
Coal (average)	$31.79	221.8	2674	251.9	$15.19	Discard IL; CFL in 2015; LED in 2020 and 2029
75% coal + 25% NG	$31.79	221.8	2542	222.8	$13.41	Discard IL; CFL in 2015; LED in 2020 and 2029

50% coal + 50% NG	$31.78	221.9	2411	193.7	$11.63	Discard IL; CFL in 2015; LED in 2020 and 2029
25% coal + 75% NG	$31.77	222.0	2279	164.6	$9.85	Discard IL; CFL in 2015; LED in 2020 and 2029
NG (average)	$31.76	222.2	2147	135.4	$8.07	Discard IL; CFL in 2015; LED in 2020 and 2030
Case 2 with $l_1 = HL$						
Coal (average)	$31.79	221.8	2674	251.9	$15.19	Discard HL; CFL in 2015; LED in 2020 and 2029
75% coal + 25% NG	$31.79	221.8	2542	222.8	$13.41	Discard HL; CFL in 2015; LED in 2020 and 2029
50% coal + 50% NG	$31.78	221.9	2411	193.7	$11.63	Discard HL; CFL in 2015; LED in 2020 and 2029
25% coal + 75% NG	$31.77	222.0	2279	164.6	$9.85	Discard HL; CFL in 2015; LED in 2020 and 2029
NG (average)	$31.76	222.2	2147	135.4	$8.07	Discard HL; CFL in 2015; LED in 2020 and 2030
Case 2 with $l_1 = CFL$						
Coal (average)	$29.09	221.8	2607	242.7	$14.75	Keep CFL; LED in 2020 and 2029
75% coal + 25% NG	$29.09	221.8	2475	213.6	$12.97	Keep CFL; LED in 2020 and 2029
50% coal + 50% NG	$29.08	221.9	2343	184.5	$11.19	Keep CFL; LED in 2020 and 2029
25% coal + 75% NG	$29.07	222.0	2212	155.4	$9.41	Keep CFL; LED in 2020 and 2029
NG (average)	$29.06	222.2	2080	126.2	$7.63	Keep CFL; LED in 2020 and 2030
Case 2 with $l_1 = LED$						
Coal (average)	$27.95	214.6	2519	234.7	$14.32	Keep LED; LED in 2020 and 2030
75% coal + 25% NG	$27.94	214.6	2392	206.6	$12.59	Keep LED; LED in 2021 and 2030
50% coal + 50% NG	$27.94	214.7	2265	178.4	$10.86	Keep LED; LED in 2021 and 2030
25% coal + 75% NG	$27.93	214.8	2138	150.3	$9.14	Keep LED; LED in 2021 and 2030
NG (average)	$27.92	215.0	2010	122.1	$7.41	Keep LED; LED in 2021 and 2030

Table A.14: Summary of GHG Emission-optimized replacement policies at 3 HOU under alternative fuel mixes.

Fuel Mix	**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						
Coal (average)	$34.68	200.1	2844	240.9	$14.49	LED in 2015, 2018, 2024, and 2032
75% coal + 25% NG	$34.64	200.2	2725	214.6	$12.87	LED in 2015, 2019, 2024, and 2032
50% coal + 50% NG	$34.60	200.2	2605	188.3	$11.26	LED in 2015, 2019, 2024, and 2033
25% coal + 75% NG	$34.55	200.4	2485	162.1	$9.65	LED in 2015, 2019, 2024, and 2033
NG (average)	$33.94	214.4	2294	134.8	$8.03	LED in 2015, 2020, and 2030
Case 2 with $l_1 = IL$						
Coal (average)	$34.70	200.1	2844	240.9	$14.49	Discard IL; LED in 2015, 2018, 2024, and 2032
75% coal + 25% NG	$34.67	200.2	2725	214.6	$12.87	Discard IL; LED in 2015, 2019, 2024, and 2032
50% coal + 50% NG	$34.63	200.2	2605	188.4	$11.26	Discard IL; LED in 2015, 2019, 2024, and 2033
25% coal + 75% NG	$34.58	200.4	2485	162.1	$9.65	Discard IL; LED in 2015, 2019, 2024, and 2033
NG (average)	$33.97	214.4	2294	134.8	$8.03	Discard IL; LED in 2015, 2020, and 2030
Case 2 with $l_1 = HL$						
Coal (average)	$34.70	200.1	2844	240.9	$14.49	Discard HL; LED in 2015, 2018, 2024, and 2032

75% coal + 25% NG	$34.67	200.2	2725	214.6	$12.87	Discard HL; LED in 2015, 2019, 2024, and 2032
50% coal + 50% NG	$34.63	200.2	2605	188.4	$11.26	Discard HL; LED in 2015, 2019, 2024, and 2033
25% coal + 75% NG	$34.58	200.4	2485	162.1	$9.65	Discard HL; LED in 2015, 2019, 2024, and 2033
NG (average)	$33.97	214.4	2294	134.8	$8.03	Discard HL; LED in 2015, 2020, and 2030
Case 2 with $l_1 = CFL$						
Coal (average)	$31.20	196.2	2729	233.4	$14.10	Keep CFL; LED in 2017, 2021, 2026, and 2034
75% coal + 25% NG	$29.75	204.9	2504	206.8	$12.52	Keep CFL; LED in 2018, 2023, and 2032
50% coal + 50% NG	$29.70	205.0	2381	179.9	$10.87	Keep CFL; LED in 2018, 2023, and 2032
25% coal + 75% NG	$29.64	205.1	2258	153.0	$9.22	Keep CFL; LED in 2018, 2023, and 2032
NG (average)	$29.56	205.4	2135	126.0	$7.57	Keep CFL; LED in 2018, 2024, and 2033
Case 2 with $l_1 = LED$						
Coal (average)	$28.72	200.1	2561	228.1	$13.88	Keep LED; LED in 2018, 2024, and 2032
75% coal + 25% NG	$28.69	200.2	2442	201.9	$12.26	Keep LED; LED in 2019, 2024, and 2032
50% coal + 50% NG	$28.65	200.2	2322	175.6	$10.65	Keep LED; LED in 2019, 2024, and 2033
25% coal + 75% NG	$28.60	200.4	2202	149.3	$9.04	Keep LED; LED in 2019, 2024, and 2033
NG (average)	$27.98	214.4	2011	122.0	$7.42	Keep LED; LED in 2020 and 2030

A.6 Results by regions and fuel type

This section presents the optimal replacement policy by selected states (or NERC regions in parenthesis). Note: All life cycle impact values are normalized to 1 HOU. LCC is the sum of Cost to Consumer and Social Cost of Carbon. The initial LED lamp in Case 2 assumes an efficacy of 78 lm/W. For region-specific results 0 to 0, see 0 for region-specific generation profiles. For fuel type results 0 and 0, see 0 for fuel-specific primary energy and GHG emission factors and their respective annual improvement rates.

A.6.1 US average

Table A.15: Optimal replacement policy for typical US consumers (using US average grid mix and Kansas (US centroid) as the location).

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO_2e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	20.00	149.8	1634	84.3	5.48	LED in 2015
	Energy	29.71	89.1	1405	115.1	6.15	CFL in 2015; LED in 2024
	Emissions	20.00	149.8	1634	84.3	5.48	LED in 2015
	LCC	20.00	149.8	1634	84.3	5.48	LED in 2015
	Burnout	20.00	149.8	1634	84.3	5.48	LED in 2015
1.5	Cost	12.27	75.4	958	54.5	3.15	CFL in 2015; LED in 2021 and 2031

	Energy	12.35	74.1	953	53.9	3.12	CFL in 2015; LED in 2020 and 2030
	Emissions	12.45	73.8	955	53.8	3.12	CFL in 2015; LED in 2019 and 2029
	LCC	12.27	75.0	956	54.3	3.14	CFL in 2015; LED in 2021 and 2030
	Burnout	15.57	118.1	1248	71.3	4.26	CFL in 2015; LED in 2036
3	Cost	10.56	74.4	863	48.0	2.82	CFL in 2015; LED in 2020 and 2030
	Energy	10.59	73.9	861	47.8	2.81	CFL in 2015; LED in 2020 and 2029
	Emissions	11.34	71.4	906	47.3	2.79	LED in 2015, 2020 and 2029
	LCC	10.57	74.2	862	47.9	2.82	CFL in 2015; LED in 2020 and 2030
	Burnout	11.53	88.9	951	53.5	3.17	CFL in 2015; LED in 2025
12	Cost	8.53	64.4	730	39.5	2.35	CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.56	63.8	728	39.3	2.34	CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.68	62.8	735	38.9	2.32	LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.53	64.1	729	39.4	2.35	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	8.85	69.4	755	41.1	2.45	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	19.75	151.1	1634	86.4	5.38	Keep IL; LED in 2016
	Energy	29.91	89.1	1405	115.2	6.15	Discard IL; CFL in 2015; LED in 2024
	Emissions	20.20	149.8	1634	84.4	5.49	Discard IL; LED in 2015
	LCC	19.75	151.2	1634	86.4	5.38	Keep IL; LED in 2016
	Burnout	52.12	439.1	4493	249.6	14.42	Keep IL; LED in 2034
1.5	Cost	12.29	75.4	958	54.5	3.15	Discard IL; CFL in 2015; LED in 2021 and 2031
	Energy	12.37	74.1	953	53.9	3.12	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	12.47	73.8	955	53.8	3.12	Discard IL; CFL in 2015; LED in 2019 and 2029
	LCC	12.29	75.0	956	54.3	3.14	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	19.38	151.6	1632	87.2	5.32	Keep IL; LED in 2016
3	Cost	10.57	74.4	863	48.0	2.82	Discard IL; CFL in 2015; LED in 2020 and 2030
	Energy	10.60	73.9	861	47.8	2.81	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.35	71.4	906	47.4	2.79	Discard IL; LED in 2015, 2020, and 2029
	LCC	10.57	74.2	862	47.9	2.82	Discard IL; CFL in 2015; LED in 2020 and 2030
	Burnout	13.61	105.8	1127	64.2	3.69	Keep IL; CFL in 2015; LED in 2026
12	Cost	8.54	64.4	730	39.5	2.35	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.57	63.8	728	39.3	2.34	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.68	62.8	735	38.9	2.32	Discard IL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.54	64.1	729	39.4	2.35	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	9.34	73.5	796	43.7	2.57	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	18.47	144.7	1552	83.2	5.06	Keep HL; LED in 2017
	Energy	29.91	89.1	1405	115.2	6.15	Discard HL; CFL in 2015; LED in 2024
	Emissions	18.75	144.1	1557	82.1	5.14	Keep HL; LED in 2016
	LCC	18.47	144.7	1553	83.2	5.06	Keep HL; LED in 2017
	Burnout	64.84	574.9	5707	298.1	19.82	Keep HL
1.5	Cost	12.29	75.4	958	54.5	3.15	Discard HL; CFL in 2015; LED in 2021 and 2031
	Energy	12.37	74.1	953	53.9	3.12	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	12.47	73.8	955	53.8	3.12	Discard HL; CFL in 2015; LED in 2019 and 2029
	LCC	12.29	75.0	956	54.3	3.14	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	33.24	277.8	2865	160.6	9.09	Keep HL; LED in 2030
3	Cost	10.57	74.4	863	48.0	2.82	Discard HL; CFL in 2015; LED in 2020 and 2030
	Energy	10.60	73.9	861	47.8	2.81	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.35	71.4	906	47.4	2.79	Discard HL; LED in 2015, 2020 and 2029
	LCC	10.57	74.2	862	47.9	2.82	Discard HL; CFL in 2015; LED in 2020 and 2030
	Burnout	21.79	178.4	1873	105.2	5.90	Keep HL; LED in 2022
12	Cost	8.54	64.4	730	39.5	2.35	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.57	63.8	728	39.3	2.34	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.68	62.8	735	38.9	2.32	Discard HL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.54	64.1	729	39.4	2.35	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	11.51	91.8	989	54.8	3.12	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	11.02	89.2	936	50.7	3.07	Keep CFL; LED in 2024
	Energy	11.02	89.1	936	50.6	3.07	Keep CFL; LED in 2024
	Emissions	11.04	89.1	937	50.6	3.08	Keep CFL; LED in 2023
	LCC	11.02	89.2	936	50.7	3.07	Keep CFL; LED in 2024
	Burnout	18.54	164.3	1631	85.2	5.66	Keep CFL
1.5	Cost	10.49	75.4	913	48.4	2.86	Keep CFL; LED in 2021 and 2031
	Energy	10.57	74.1	908	47.8	2.83	Keep CFL; LED in 2020 and 2030
	Emissions	10.67	73.8	910	47.7	2.82	Keep CFL; LED in 2019 and 2029
	LCC	10.49	75.0	911	48.2	2.84	Keep CFL; LED in 2021 and 2030
	Burnout	13.79	118.1	1203	65.2	3.96	Keep CFL; LED in 2036
3	Cost	9.67	74.4	840	44.9	2.67	Keep CFL; LED in 2020 and 2030
	Energy	9.70	73.9	838	44.7	2.66	Keep CFL; LED in 2020 and 2029
	Emissions	9.91	68.3	847	44.4	2.63	Keep CFL; LED in 2018, 2023, and 2032
	LCC	9.68	74.2	840	44.9	2.67	Keep CFL; LED in 2020 and 2030
	Burnout	10.64	88.9	929	50.4	3.03	Keep CFL; LED in 2025
12	Cost	8.31	64.2	724	38.7	2.31	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Energy	8.34	63.8	722	38.5	2.30	Keep CFL; LED in 2016, 20, 24, 29, and 38
	Emissions	8.37	63.6	723	38.5	2.30	Keep CFL; LED in 2016, 19, 23, 28, and 37
	LCC	8.31	64.1	724	38.7	2.31	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Burnout	8.62	69.4	749	40.3	2.41	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	10.42	84.6	886	47.8	2.91	Keep LED; LED in 2025
	Energy	10.42	84.6	886	47.8	2.91	Keep LED; LED in 2025
	Emissions	10.44	84.5	887	47.7	2.91	Keep LED; LED in 2024

	LCC	10.42	84.6	886	47.8	2.91	Keep LED; LED in 2025
	Burnout	16.63	147.4	1463	76.4	5.08	Keep LED
1.5	Cost	9.98	83.2	872	46.9	2.85	Keep LED; LED in 2025
	Energy	9.98	83.2	872	46.9	2.85	Keep LED; LED in 2025
	Emissions	9.99	83.2	873	46.9	2.86	Keep LED; LED in 2024
	LCC	9.98	83.2	872	46.9	2.85	Keep LED; LED in 2025
	Burnout	16.63	147.4	1463	76.4	5.08	Keep LED
3	Cost	9.30	71.9	812	43.3	2.59	Keep LED; LED in 2021 and 2030
	Energy	9.32	71.5	810	43.1	2.58	Keep LED; LED in 2020 and 2030
	Emissions	9.36	71.4	811	43.1	2.58	Keep LED; LED in 2020 and 2029
	LCC	9.30	71.8	811	43.3	2.59	Keep LED; LED in 2021 and 2030
	Burnout	12.82	110.2	1121	60.5	3.71	Keep LED; LED in 2037
12	Cost	8.13	63.3	713	38.1	2.28	Keep LED; LED in 2018, 22, 26, 31, and 39
	Energy	8.15	63.0	711	37.9	2.27	Keep LED; LED in 2017, 20, 24, 30, and 39
	Emissions	8.18	62.8	711	37.9	2.27	Keep LED; LED in 2017, 20, 24, 29, and 38
	LCC	8.13	63.2	712	38.0	2.28	Keep LED; LED in 2018, 21, 25, 31, and 39
	Burnout	8.50	69.9	744	40.2	2.41	Keep LED; LED in 2020, 2029, and 2043

A.6.2 DC: District of Columbia (NERC: RFCE)

Table A.16: Optimal replacement policy for consumers in DC (using RFCE grid mix).

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO_2e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	21.72	147.4	1794	74.5	4.83	LED in 2015
	Energy	30.59	87.7	1488	108.3	5.75	CFL in 2015; LED in 2024
	Emissions	21.72	147.4	1794	74.5	4.83	LED in 2015
	LCC	21.72	147.4	1794	74.5	4.83	LED in 2015
	Burnout	21.72	147.4	1794	74.5	4.83	LED in 2015
1.5	Cost	13.15	75.3	1044	48.6	2.82	CFL in 2015; LED in 2021 and 2031
	Energy	13.23	74.1	1039	48.2	2.80	CFL in 2015; LED in 2020 and 2030
	Emissions	13.27	74.0	1039	48.2	2.80	CFL in 2015; LED in 2020 and 2029
	LCC	13.15	75.0	1042	48.5	2.82	CFL in 2015; LED in 2021 and 2030
	Burnout	16.99	118.1	1385	62.5	3.74	CFL in 2015; LED in 2036
3	Cost	11.43	69.8	954	42.7	2.51	CFL in 2015; LED in 2020, 2026, and 2035
	Energy	11.46	73.9	947	42.1	2.49	CFL in 2015; LED in 2020 and 2029
	Emissions	12.17	71.5	989	42.0	2.48	LED in 2015, 2020 and 2030
	LCC	11.44	74.3	948	42.2	2.50	CFL in 2015; LED in 2020 and 2030
	Burnout	12.58	88.9	1054	46.5	2.78	CFL in 2015; LED in 2025
12	Cost	9.29	64.1	804	34.5	2.08	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Energy	9.33	63.7	802	34.4	2.07	CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	9.41	62.9	808	34.2	2.06	LED in 2015, 17, 20, 24, 29, and 38
	LCC	9.29	64.1	804	34.5	2.08	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	9.67	69.4	835	35.7	2.15	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	21.32	149.2	1791	74.9	4.66	Keep IL; LED in 2016
	Energy	30.79	87.7	1488	108.4	5.76	Discard IL; CFL in 2015; LED in 2024
	Emissions	21.53	147.3	1783	74.3	4.74	Discard IL; LED in 2015
	LCC	21.32	149.5	1793	75.0	4.66	Keep IL; LED in 2016
	Burnout	56.84	439.1	4976	211.1	12.22	Keep IL; LED in 2034
1.5	Cost	13.17	75.3	1044	48.6	2.82	Discard IL; CFL in 2015; LED in 2021 and 2031
	Energy	13.24	74.1	1039	48.2	2.80	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	13.29	74.0	1039	48.2	2.80	Discard IL; CFL in 2015; LED in 2020 and 2029
	LCC	13.17	75.0	1042	48.5	2.82	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	21.22	151.6	1810	75.9	4.65	Keep IL; LED in 2016
3	Cost	11.44	69.8	954	42.7	2.51	Discard IL; CFL in 2015; LED in 2020, 2026, and 2035
	Energy	11.47	73.9	947	42.1	2.49	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.18	71.5	989	42.0	2.48	Discard IL; LED in 2015, 2020, and 2029
	LCC	11.45	74.3	948	42.2	2.50	Discard IL; CFL in 2015; LED in 2020 and 2030
	Burnout	14.76	105.8	1244	55.0	3.19	Keep IL; CFL in 2015; LED in 2026
12	Cost	9.30	64.1	804	34.5	2.08	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Energy	9.33	63.7	802	34.4	2.07	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	9.41	62.9	808	34.2	2.06	Discard IL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	9.30	64.1	804	34.5	2.08	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	10.18	73.5	880	37.7	2.25	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	19.89	142.7	1696	71.2	4.34	Keep HL; LED in 2017
	Energy	30.79	87.7	1488	108.4	5.76	Keep HL; CFL in 2015; LED in 2024
	Emissions	20.00	141.6	1693	70.9	4.39	Keep HL; LED in 2017
	LCC	19.89	142.8	1697	71.3	4.34	Keep HL; LED in 2017
	Burnout	72.81	574.9	6431	264.8	17.60	Keep HL

1.5	Cost	13.17	75.3	1044	48.6	2.82	Discard HL; CFL in 2015; LED in 2021 and 2031
	Energy	13.24	74.1	1039	48.2	2.80	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	13.29	74.0	1039	48.2	2.80	Discard HL; CFL in 2015; LED in 2020 and 2029
	LCC	13.17	75.0	1042	48.5	2.82	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	36.09	277.8	3163	134.8	7.65	Keep HL; LED in 2030
3	Cost	11.44	69.8	954	42.7	2.51	Discard HL; CFL in 2015; LED in 2020, 2026, and 2035
	Energy	11.47	73.9	947	42.1	2.49	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.18	71.5	989	42.0	2.48	Discard HL; LED in 2015, 2020, and 2030
	LCC	11.45	74.3	948	42.2	2.50	Discard HL; CFL in 2015; LED in 2020 and 2030
	Burnout	23.58	178.4	2063	88.1	4.98	Keep HL; LED in 2022
12	Cost	9.30	64.1	804	34.5	2.08	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Energy	9.33	63.7	802	34.4	2.07	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	9.41	62.9	808	34.2	2.06	Discard HL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	9.30	64.1	804	34.5	2.08	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	12.48	91.8	1089	46.4	2.67	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	11.90	87.8	1023	43.2	2.64	Keep CFL; LED in 2024
	Energy	11.90	87.7	1023	43.2	2.64	Keep CFL; LED in 2024
	Emissions	11.90	87.7	1023	43.2	2.64	Keep CFL; LED in 2024
	LCC	11.90	87.8	1023	43.2	2.64	Keep CFL; LED in 2024
	Burnout	20.82	164.3	1837	75.7	5.03	Keep CFL
1.5	Cost	11.37	75.3	1000	42.4	2.52	Keep CFL; LED in 2021 and 2031
	Energy	11.45	74.1	994	42.0	2.51	Keep CFL; LED in 2020 and 2030
	Emissions	11.49	74.0	995	42.0	2.51	Keep CFL; LED in 2020 and 2029
	LCC	11.37	75.0	998	42.3	2.52	Keep CFL; LED in 2021 and 2030
	Burnout	15.21	118.1	1340	56.2	3.44	Keep CFL; LED in 2036
3	Cost	10.54	69.8	932	39.5	2.36	Keep CFL; LED in 2020, 2026, and 2035
	Energy	10.57	73.9	924	39.0	2.35	Keep CFL; LED in 2020 and 2029
	Emissions	10.59	73.8	925	39.0	2.35	Keep CFL; LED in 2020 and 2029
	LCC	10.55	74.3	926	39.1	2.35	Keep CFL; LED in 2020 and 2030
	Burnout	11.69	88.9	1031	43.4	2.63	Keep CFL; LED in 2025
12	Cost	9.07	64.2	799	33.7	2.04	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Energy	9.10	63.7	797	33.6	2.04	Keep CFL; LED in 2016, 20, 23, 29, and 38
	Emissions	9.11	63.7	797	33.6	2.04	Keep CFL; LED in 2016, 19, 23, 29, and 38
	LCC	9.07	64.2	799	33.7	2.04	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Burnout	9.45	69.4	829	34.9	2.12	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	11.26	83.3	969	40.8	2.50	Keep LED; LED in 2025
	Energy	11.26	83.2	969	40.8	2.50	Keep LED; LED in 2025
	Emissions	11.27	83.2	969	40.8	2.51	Keep LED; LED in 2024
	LCC	11.26	83.3	970	40.8	2.50	Keep LED; LED in 2025
	Burnout	18.68	147.4	1649	67.9	4.51	Keep LED
1.5	Cost	10.91	72.7	966	41.0	2.45	Keep LED; LED in 2022 and 2031
	Energy	10.97	71.7	962	40.7	2.44	Keep LED; LED in 2021 and 2030
	Emissions	11.02	71.5	962	40.6	2.44	Keep LED; LED in 2021 and 2030
	LCC	10.91	72.5	965	40.9	2.45	Keep LED; LED in 2022 and 2031
	Burnout	18.68	147.4	1649	67.9	4.51	Keep LED
3	Cost	10.15	71.9	895	37.8	2.28	Keep LED; LED in 2021 and 2030
	Energy	10.17	71.5	894	37.7	2.28	Keep LED; LED in 2020 and 2030
	Emissions	10.18	71.5	894	37.7	2.28	Keep LED; LED in 2020 and 2030
	LCC	10.15	71.8	895	37.8	2.28	Keep LED; LED in 2021 and 2030
	Burnout	14.17	110.2	1250	52.3	3.23	Keep LED; LED in 2037
12	Cost	8.88	63.3	786	33.2	2.02	Keep LED; LED in 2018, 22, 26, 31, and 39
	Energy	8.91	62.9	784	33.1	2.01	Keep LED; LED in 2017, 20, 24, 30, and 39
	Emissions	8.92	62.9	784	33.1	2.01	Keep LED; LED in 2017, 20, 24, 30, and 39
	LCC	8.88	63.2	785	33.2	2.01	Keep LED; LED in 2018, 21, 25, 31, and 39
	Burnout	9.32	69.9	825	34.7	2.11	Keep LED; LED in 2020, 2029, and 2043

A.6.3 IL: Illinois (NERC: RFCW)

Table A.17: Optimal replacement policy for consumers in Illinois (using RFCW grid mix).

HOU [hr/d]	**Objective/ Scenario**	**Cost to Consumer [$/HOU]**	**Electricity [kWh/HOU]**	**Primary Energy [MJ/HOU]**	**GHG Emissions [kg CO_2e/HOU]**	**Social Cost of Carbon [$/HOU]**	**Replacement Schedule (2015-2050) [Purchase Year]**
Case 1							
1/7	Cost	20.34	147.4	1792	103.8	6.78	LED in 2015
	Energy	29.82	87.7	1488	127.6	6.90	CFL in 2015; LED in 2024
	Emissions	20.34	147.4	1792	103.8	6.78	LED in 2015
	LCC	20.34	147.4	1792	103.8	6.78	LED in 2015
	Burnout	20.34	147.4	1792	103.8	6.78	LED in 2015
1.5	Cost	12.49	75.4	1047	65.9	3.83	CFL in 2015; LED in 2021 and 2031
	Energy	12.58	74.1	1040	65.0	3.78	CFL in 2015; LED in 2020 and 2029

	Emissions	12.72	73.8	1043	64.8	3.78	CFL in 2015; LED in 2019 and 2028
	LCC	12.50	74.9	1043	65.5	3.81	CFL in 2015; LED in 2021 and 2030
	Burnout	15.95	118.1	1387	88.8	5.32	CFL in 2015; LED in 2036
3	Cost	10.79	74.4	951	59.1	3.49	CFL in 2015; LED in 2020 and 2030
	Energy	10.82	73.9	948	58.8	3.48	CFL in 2015; LED in 2020 and 2029
	Emissions	11.78	66.7	1000	57.5	3.38	LED in 2015, 2018, 2024, and 2032
	LCC	10.84	69.4	953	58.3	3.42	CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	11.80	88.9	1056	66.7	3.97	CFL in 2015; LED in 2025
12	Cost	8.74	64.1	805	49.0	2.92	CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Energy	8.77	63.7	804	48.8	2.91	CFL in 2015; LED in 2016, 20, 23, 29, and 38
	Emissions	8.93	62.1	813	48.2	2.89	LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	8.74	64.1	805	49.0	2.92	CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Burnout	9.06	69.4	837	51.4	3.07	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	19.98	149.2	1792	107.2	6.67	Keep IL; LED in 2016
	Energy	30.02	87.7	1488	127.7	6.91	Discard IL; CFL in 2015; LED in 2024
	Emissions	20.54	147.4	1792	103.9	6.78	Discard IL; LED in 2015
	LCC	19.98	149.1	1791	107.0	6.67	Keep IL; LED in 2016
	Burnout	53.17	439.1	4998	316.7	18.30	Keep IL; LED in 2034
1.5	Cost	12.51	75.4	1047	65.9	3.83	Discard IL; CFL in 2015; LED in 2021 and 2031
	Energy	12.60	74.1	1040	65.0	3.78	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.74	73.8	1043	64.8	3.79	Discard IL; CFL in 2015; LED in 2019 and 2028
	LCC	12.52	74.9	1043	65.5	3.81	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	19.88	151.6	1813	109.6	6.70	Keep IL; LED in 2016
3	Cost	10.80	74.4	951	59.1	3.49	Discard IL; CFL in 2015; LED in 2020 and 2030
	Energy	10.83	73.9	948	58.8	3.48	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.79	66.7	1000	57.5	3.38	Discard IL; LED in 2015, 2018, 2024, and 2032
	LCC	10.85	69.4	953	58.3	3.42	Discard IL; CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	13.87	105.8	1249	80.4	4.62	Keep IL; CFL in 2015; LED in 2026
12	Cost	8.74	64.1	805	49.0	2.92	Discard IL; CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Energy	8.77	63.7	804	48.8	2.91	Discard IL; CFL in 2015; LED in 2016, 20, 23, 29, and 38
	Emissions	8.93	62.1	813	48.2	2.89	Discard IL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	8.74	64.1	805	49.0	2.92	Discard IL; CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Burnout	9.55	73.5	882	54.7	3.23	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	18.63	142.6	1699	103.3	6.27	Keep HL; LED in 2017
	Energy	30.02	87.7	1488	127.7	6.91	Discard HL; CFL in 2015; LED in 2024
	Emissions	19.04	141.9	1707	101.3	6.37	Keep HL; LED in 2016
	LCC	18.63	142.6	1699	103.2	6.27	Keep HL; LED in 2017
	Burnout	67.43	574.9	6424	379.3	25.21	Keep HL
1.5	Cost	12.51	75.4	1047	65.9	3.83	Discard HL; CFL in 2015; LED in 2021 and 2031
	Energy	12.60	74.1	1040	65.0	3.78	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.74	73.8	1043	64.8	3.79	Discard HL; CFL in 2015; LED in 2019 and 2028
	LCC	12.52	74.9	1043	65.5	3.81	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	33.81	277.8	3180	203.6	11.52	Keep HL; LED in 2030
3	Cost	10.80	74.4	951	59.1	3.49	Discard HL; CFL in 2015; LED in 2020, and 2030
	Energy	10.83	73.9	948	58.8	3.48	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.79	66.7	1000	57.5	3.38	Discard HL; LED in 2015, 2018, 2024, and 2032
	LCC	10.85	69.4	953	58.3	3.42	Discard HL; CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	22.12	178.4	2074	133.0	7.46	Keep HL; LED in 2022
12	Cost	8.74	64.1	805	49.0	2.92	Discard HL; CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Energy	8.77	63.7	804	48.8	2.91	Discard HL; CFL in 2015; LED in 2016, 20, 23, 29, and 38
	Emissions	8.93	62.1	813	48.2	2.89	Discard HL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	8.74	64.1	805	49.0	2.92	Discard HL; CFL in 2015; LED in 2017, 20, 25, 30, and 38
	Burnout	11.72	91.8	1094	68.9	3.92	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	11.13	87.8	1025	62.9	3.81	Keep CFL; LED in 2024
	Energy	11.13	87.7	1025	62.8	3.81	Keep CFL; LED in 2024
	Emissions	11.16	87.7	1027	62.7	3.82	Keep CFL; LED in 2023
	LCC	11.13	87.8	1025	62.9	3.81	Keep CFL; LED in 2024
	Burnout	19.28	164.3	1835	108.4	7.21	Keep CFL
1.5	Cost	10.71	75.4	1003	59.7	3.53	Keep CFL; LED in 2021 and 2031
	Energy	10.80	74.1	996	58.8	3.49	Keep CFL; LED in 2020 and 2029
	Emissions	10.94	73.8	999	58.7	3.49	Keep CFL; LED in 2019 and 2028
	LCC	10.72	74.9	999	59.4	3.51	Keep CFL; LED in 2021 and 2030
	Burnout	14.17	118.1	1343	82.7	5.03	Keep CFL; LED in 2036
3	Cost	9.90	74.4	928	56.0	3.34	Keep CFL; LED in 2020 and 2030
	Energy	9.93	73.9	926	55.7	3.33	Keep CFL; LED in 2020 and 2029
	Emissions	10.15	68.3	929	54.6	3.25	Keep CFL; LED in 2018, 2023, and 2031
	LCC	9.95	69.4	931	55.2	3.28	Keep CFL; LED in 2019, 2025, and 2034
	Burnout	10.91	88.9	1034	63.6	3.82	Keep CFL; LED in 2025
12	Cost	8.51	64.3	801	48.3	2.89	Keep CFL; LED in 2017, 21, 25, 31, and 39
	Energy	8.55	63.7	798	48.0	2.88	Keep CFL; LED in 2016, 20, 23, 29, and 38
	Emissions	8.72	62.0	806	47.9	2.87	Keep CFL; LED in 2016, 18, 20, 23, 27, 33, and 45
	LCC	8.51	64.1	800	48.2	2.89	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Burnout	8.84	69.4	831	50.7	3.03	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	10.53	83.3	971	59.4	3.61	Keep LED; LED in 2025
	Energy	10.53	83.2	971	59.3	3.61	Keep LED; LED in 2025
	Emissions	10.56	83.2	973	59.2	3.62	Keep LED; LED in 2024
	LCC	10.53	83.3	971	59.4	3.61	Keep LED; LED in 2025

	Burnout	17.30	147.4	1647	97.3	6.47	Keep LED
1.5	Cost	10.26	83.2	971	59.3	3.61	Keep LED; LED in 2025
	Energy	10.35	71.7	963	56.8	3.39	Keep LED; LED in 2021 and 2030
	Emissions	10.47	71.4	965	56.7	3.38	Keep LED; LED in 2020 and 2029
	LCC	10.28	72.4	966	57.3	3.41	Keep LED; LED in 2022 and 2031
	Burnout	17.30	147.4	1647	97.3	6.47	Keep LED
3	Cost	9.52	71.9	897	54.1	3.24	Keep LED; LED in 2021 and 2030
	Energy	9.55	71.5	895	53.8	3.22	Keep LED; LED in 2020 and 2030
	Emissions	9.79	66.7	906	53.2	3.18	Keep LED; LED in 2018, 2024, and 2032
	LCC	9.52	71.8	896	54.0	3.23	Keep LED; LED in 2021 and 2030
	Burnout	13.19	110.2	1252	76.7	4.70	Keep LED; LED in 2037
12	Cost	8.33	63.3	788	47.5	2.85	Keep LED; LED in 2018, 22, 26, 31, and 40
	Energy	8.36	62.9	786	47.2	2.84	Keep LED; LED in 2017, 20, 24, 30, and 39
	Emissions	8.40	62.7	786	47.2	2.83	Keep LED; LED in 2017, 20, 23, 28, and 37
	LCC	8.33	63.1	787	47.4	2.84	Keep LED; LED in 2018, 21, 25, 31, and 39
	Burnout	8.72	69.9	827	50.6	3.03	Keep LED; LED in 2020, 2029, and 2043

A.6.4 KS: Kansas (NERC: SPNO)

Table A.18: Optimal replacement policy for consumers in Kansas (using SPNO grid mix).

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO_2e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	18.03	147.4	1506	107.8	7.05	LED in 2015
	Energy	28.71	87.7	1334	130.4	7.07	CFL in 2015; LED in 2024
	Emissions	18.03	147.4	1506	107.8	7.05	LED in 2015
	LCC	18.03	147.4	1506	107.8	7.05	LED in 2015
	Burnout	18.03	147.4	1506	107.8	7.05	LED in 2015
1.5	Cost	11.51	87.7	916	72.0	4.28	CFL in 2015; LED in 2024
	Energy	11.67	74.1	913	67.8	3.94	CFL in 2015; LED in 2020 and 2029
	Emissions	11.82	73.8	916	67.6	3.94	CFL in 2015; LED in 2019 and 2028
	LCC	11.60	74.9	916	68.4	3.96	CFL in 2015; LED in 2021 and 2030
	Burnout	14.45	118.1	1183	93.1	5.58	CFL in 2015; LED in 2036
3	Cost	9.88	74.3	823	61.9	3.64	CFL in 2015; LED in 2020 and 2030
	Energy	9.91	73.9	821	61.5	3.63	CFL in 2015; LED in 2020 and 2029
	Emissions	10.96	66.7	885	59.9	3.52	LED in 2015, 2018, 2023, and 2032
	LCC	9.89	74.2	822	61.8	3.64	CFL in 2015; LED in 2020 and 2029
	Burnout	10.71	88.9	904	70.1	4.16	CFL in 2015; LED in 2025
12	Cost	7.94	64.3	696	51.6	3.06	CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	7.97	63.8	694	51.2	3.04	CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.16	62.1	705	50.5	3.01	LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.94	64.0	695	51.4	3.05	CFL in 2015; LED in 2017, 20, 24, 30, and 38
	Burnout	8.21	69.4	718	54.1	3.22	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	17.93	148.2	1513	110.8	6.96	Keep IL; LED in 2015
	Energy	28.91	87.7	1334	130.5	7.08	Discard IL; CFL in 2015; LED in 2024
	Emissions	18.23	147.4	1506	107.9	7.05	Discard IL; LED in 2015
	LCC	17.93	148.1	1513	110.8	6.96	Keep IL; LED in 2015
	Burnout	48.48	439.1	4300	335.6	19.38	Keep IL; LED in 2034
1.5	Cost	11.53	87.7	916	72.0	4.28	Discard IL; CFL in 2015; LED in 2024
	Energy	11.69	74.1	913	67.8	3.94	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.84	73.8	916	67.6	3.94	Discard IL; CFL in 2015; LED in 2019 and 2028
	LCC	11.62	74.9	916	68.4	3.96	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	17.94	151.6	1548	115.2	7.02	Keep IL; LED in 2016
3	Cost	9.89	74.3	823	61.9	3.64	Discard IL; CFL in 2015; LED in 2020 and 2030
	Energy	9.92	73.9	821	61.6	3.63	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	10.97	66.7	885	59.9	3.52	Discard IL; LED in 2015, 2018, 2023, and 2032
	LCC	9.90	74.2	822	61.8	3.64	Discard IL; CFL in 2015; LED in 2020 and 2029
	Burnout	12.74	105.8	1080	85.0	4.87	Keep IL; CFL in 2015; LED in 2026
12	Cost	7.94	64.3	696	51.6	3.06	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	7.98	63.8	694	51.2	3.04	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.16	62.1	705	50.5	3.01	Discard IL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.95	64.0	695	51.4	3.05	Discard IL; CFL in 2015; LED in 2017, 20, 24, 30, and 38
	Burnout	8.69	73.5	759	57.6	3.39	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	16.83	142.0	1446	107.7	6.57	Keep HL; LED in 2017
	Energy	28.91	87.7	1334	130.5	7.08	Discard HL; CFL in 2015; LED in 2024
	Emissions	17.15	142.3	1451	105.9	6.69	Keep HL; LED in 2016
	LCC	16.83	142.0	1447	107.7	6.57	Keep HL; LED in 2017
	Burnout	58.43	574.9	5309	395.2	26.27	Keep HL
1.5	Cost	11.53	87.7	916	72.0	4.28	Discard HL; CFL in 2015; LED in 2024

	Energy	11.69	74.1	913	67.8	3.94	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.84	73.8	916	67.6	3.94	Discard HL; CFL in 2015; LED in 2019 and 2028
	LCC	11.62	74.9	916	68.4	3.96	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	31.08	277.8	2755	216.4	12.22	Keep HL; LED in 2030
3	Cost	9.89	74.3	823	61.9	3.64	Discard HL; CFL in 2015; LED in 2020 and 2030
	Energy	9.92	73.9	821	61.6	3.63	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	10.97	66.7	885	59.9	3.52	Discard HL; LED in 2015, 2018, 2023, and 2032
	LCC	9.90	74.2	822	61.8	3.64	Discard HL; CFL in 2015; LED in 2020 and 2029
	Burnout	20.46	178.4	1806	141.5	7.91	Keep HL; LED in 2022
12	Cost	7.94	64.3	696	51.6	3.06	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	7.98	63.8	694	51.2	3.04	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.16	62.1	705	50.5	3.01	Discard HL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.95	64.0	695	51.4	3.05	Discard HL; CFL in 2015; LED in 2017, 20, 24, 30, and 38
	Burnout	10.79	91.8	951	73.1	4.14	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	10.02	87.7	873	66.1	3.99	Keep CFL; LED in 2024
	Energy	10.02	87.7	873	66.0	3.99	Keep CFL; LED in 2024
	Emissions	10.05	87.7	874	65.9	4.01	Keep CFL; LED in 2023
	LCC	10.02	87.7	873	66.1	3.99	Keep CFL; LED in 2024
	Burnout	16.71	164.3	1517	112.9	7.51	Keep CFL
1.5	Cost	9.73	87.7	873	65.8	3.98	Keep CFL; LED in 2024
	Energy	9.89	74.1	869	61.6	3.64	Keep CFL; LED in 2020 and 2029
	Emissions	10.04	73.8	872	61.4	3.64	Keep CFL; LED in 2019 and 2028
	LCC	9.82	74.9	872	62.2	3.67	Keep CFL; LED in 2021 and 2030
	Burnout	12.67	118.1	1139	87.0	5.28	Keep CFL; LED in 2036
3	Cost	8.99	74.3	801	58.9	3.50	Keep CFL; LED in 2020 and 2030
	Energy	9.02	73.9	799	58.5	3.48	Keep CFL; LED in 2020 and 2029
	Emissions	9.32	68.2	812	57.2	3.39	Keep CFL; LED in 2018, 2023, and 2031
	LCC	9.00	74.2	800	58.7	3.49	Keep CFL; LED in 2020 and 2029
	Burnout	9.82	88.9	882	67.0	4.01	Keep CFL; LED in 2025
12	Cost	7.72	64.5	691	50.9	3.03	Keep CFL; LED in 2017, 21, 25, 31, and 41
	Energy	7.75	63.8	688	50.4	3.01	Keep CFL; LED in 2016, 20, 24, 29, and 38
	Emissions	7.95	61.9	699	50.2	2.99	Keep CFL; LED in 2016, 18, 20, 23, 27, 32, and 45
	LCC	7.72	64.0	690	50.6	3.02	Keep CFL; LED in 2017, 20, 24, 30, and 38
	Burnout	7.98	69.4	712	53.3	3.18	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	9.46	83.2	826	62.4	3.78	Keep LED; LED in 2025
	Energy	9.46	83.2	826	62.3	3.78	Keep LED; LED in 2024
	Emissions	9.49	83.2	827	62.2	3.80	Keep LED; LED in 2024
	LCC	9.46	83.2	826	62.4	3.78	Keep LED; LED in 2025
	Burnout	14.99	147.4	1361	101.3	6.74	Keep LED
1.5	Cost	9.19	83.2	826	62.2	3.78	Keep LED; LED in 2024
	Energy	9.19	83.2	826	62.2	3.78	Keep LED; LED in 2024
	Emissions	9.59	71.4	842	59.3	3.53	Keep LED; LED in 2020 and 2029
	LCC	9.40	72.3	842	60.0	3.56	Keep LED; LED in 2022 and 2031
	Burnout	14.99	147.4	1361	101.3	6.74	Keep LED
3	Cost	8.63	71.9	774	56.8	3.38	Keep LED; LED in 2021 and 2030
	Energy	8.65	71.5	772	56.4	3.37	Keep LED; LED in 2020 and 2030
	Emissions	8.97	66.7	791	55.7	3.31	Keep LED; LED in 2018, 2023, and 2032
	LCC	8.63	71.7	773	56.6	3.38	Keep LED; LED in 2021 and 2030
	Burnout	11.76	110.2	1059	80.6	4.94	Keep LED; LED in 2037
12	Cost	7.54	63.4	679	49.9	2.98	Keep LED; LED in 2018, 22, 26, 32, and 40
	Energy	7.57	63.0	677	49.6	2.97	Keep LED; LED in 2017, 20, 24, 30, and 40
	Emissions	7.61	62.7	678	49.5	2.96	Keep LED; LED in 2017, 20, 23, 28, and 36
	LCC	7.54	63.1	678	49.7	2.97	Keep LED; LED in 2018, 21, 25, 31, and 39
	Burnout	7.85	69.9	707	53.3	3.18	Keep LED; LED in 2020, 2029, and 2043

A.6.5 TX: Texas (NERC: ERCT)

Table A.19: Optimal replacement policy for consumers in Texas (using ERCT grid mix).

HOU [hr/d]	**Objective/ Scenario**	**Cost to Consumer [$/HOU]**	**Electricity [kWh/HOU]**	**Primary Energy [MJ/HOU]**	**GHG Emissions [kg CO_2e/HOU]**	**Social Cost of Carbon [$/HOU]**	**Replacement Schedule (2015-2050) [Purchase Year]**
Case 1							
1/7	Cost	19.38	147.4	1526	85.2	5.54	LED in 2015
	Energy	29.20	87.7	1336	115.5	6.17	CFL in 2015; LED in 2024
	Emissions	19.38	147.4	1526	85.2	5.54	LED in 2015
	LCC	19.38	147.4	1526	85.2	5.54	LED in 2015
	Burnout	19.38	147.4	1526	85.2	5.54	LED in 2015
1.5	Cost	11.95	75.6	920	55.7	3.22	CFL in 2015; LED in 2022 and 2031
	Energy	12.04	74.2	914	55.0	3.19	CFL in 2015; LED in 2020 and 2030
	Emissions	12.16	73.8	916	54.9	3.18	CFL in 2015; LED in 2020 and 2029

	LCC	11.96	75.2	918	55.5	3.21	CFL in 2015; LED in 2021 and 2031
	Burnout	15.12	118.1	1186	73.0	4.37	CFL in 2015; LED in 2036
3	Cost	10.26	74.5	825	49.1	2.89	CFL in 2015; LED in 2021 and 2030
	Energy	10.29	73.9	823	48.8	2.88	CFL in 2015; LED in 2020, and 2029
	Emissions	11.07	71.4	869	48.4	2.85	LED in 2015, 2020, and 2030
	LCC	10.26	74.3	824	49.0	2.89	CFL in 2015; LED in 2020, and 2030
	Burnout	11.17	88.9	905	54.7	3.25	CFL in 2015; LED in 2025
12	Cost	8.27	64.4	698	40.5	2.41	CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	8.31	63.8	695	40.2	2.40	CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	8.44	62.7	703	39.8	2.38	LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.28	64.2	697	40.4	2.41	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	8.57	69.4	719	42.1	2.51	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	18.95	149.7	1537	88.0	5.44	Keep IL; LED in 2016
	Energy	29.40	87.7	1336	115.5	6.18	Discard IL; CFL in 2015; LED in 2024
	Emissions	19.58	147.4	1526	85.3	5.55	Discard IL; LED in 2015
	LCC	18.95	149.5	1536	87.9	5.44	Keep IL; LED in 2016
	Burnout	49.88	439.1	4280	255.8	14.78	Keep IL; LED in 2034
1.5	Cost	11.97	75.6	920	55.7	3.22	Discard IL; CFL in 2015; LED in 2022 and 2031
	Energy	12.06	74.2	914	55.0	3.19	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	12.18	73.8	916	54.9	3.19	Discard IL; CFL in 2015; LED in 2020 and 2029
	LCC	11.98	75.2	918	55.5	3.21	Discard IL; CFL in 2015; LED in 2021 and 2031
	Burnout	18.82	151.6	1553	89.4	5.46	Keep IL; LED in 2016
3	Cost	10.27	74.5	825	49.1	2.89	Discard IL; CFL in 2015; LED in 2021 and 2030
	Energy	10.30	73.9	823	48.8	2.88	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.07	71.4	869	48.4	2.85	Discard IL; LED in 2015, 2020, and 2029
	LCC	10.27	74.3	824	49.0	2.89	Discard IL; CFL in 2015; LED in 2020 and 2030
	Burnout	13.08	105.8	1075	65.7	3.78	Keep IL; CFL in 2015; LED in 2026
12	Cost	8.28	64.4	698	40.5	2.41	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	8.32	63.8	695	40.2	2.40	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	8.44	62.7	703	39.8	2.38	Discard IL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.28	64.2	697	40.4	2.41	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	9.02	73.5	759	44.7	2.64	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	17.62	142.9	1458	84.4	5.11	Keep HL; LED in 2017
	Energy	29.40	87.7	1336	115.5	6.18	Keep HL; CFL in 2015; LED in 2024
	Emissions	18.00	141.8	1456	82.9	5.19	Keep HL; LED in 2016
	LCC	17.62	142.9	1458	84.4	5.11	Keep HL; LED in 2017
	Burnout	63.69	574.9	5389	307.1	20.41	Keep HL
1.5	Cost	11.97	75.6	920	55.7	3.22	Discard HL; CFL in 2015; LED in 2022 and 2031
	Energy	12.06	74.2	914	55.0	3.19	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	12.18	73.8	916	54.9	3.19	Discard HL; CFL in 2015; LED in 2020 and 2029
	LCC	11.98	75.2	918	55.5	3.21	Discard HL; CFL in 2015; LED in 2021 and 2031
	Burnout	31.69	277.8	2733	164.5	9.31	Keep HL; LED in 2030
3	Cost	10.27	74.5	825	49.1	2.89	Discard HL; CFL in 2015; LED in 2021 and 2030
	Energy	10.30	73.9	823	48.8	2.88	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.07	71.4	869	48.4	2.85	Discard HL; LED in 2015, 2020, and 2029
	LCC	10.27	74.3	824	49.0	2.89	Discard HL; CFL in 2015; LED in 2020 and 2030
	Burnout	20.75	178.4	1789	107.6	6.04	Keep HL; LED in 2022
12	Cost	8.28	64.4	698	40.5	2.41	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 39
	Energy	8.32	63.8	695	40.2	2.40	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	8.44	62.7	703	39.8	2.38	Discard HL; LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.28	64.2	697	40.4	2.41	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	11.02	91.8	945	56.0	3.19	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	10.50	87.8	876	51.2	3.10	Keep CFL; LED in 2024
	Energy	10.51	87.7	875	51.1	3.10	Keep CFL; LED in 2024
	Emissions	10.54	87.7	876	51.0	3.11	Keep CFL; LED in 2023
	LCC	10.50	87.8	876	51.2	3.10	Keep CFL; LED in 2024
	Burnout	18.22	164.3	1540	87.8	5.83	Keep CFL
1.5	Cost	10.17	75.6	877	49.6	2.93	Keep CFL; LED in 2022 and 2031
	Energy	10.26	74.2	870	48.9	2.89	Keep CFL; LED in 2020 and 2030
	Emissions	10.38	73.8	872	48.8	2.89	Keep CFL; LED in 2020 and 2029
	LCC	10.18	75.2	874	49.3	2.92	Keep CFL; LED in 2021 and 2031
	Burnout	13.34	118.1	1142	66.9	4.07	Keep CFL; LED in 2036
3	Cost	9.37	74.5	803	46.1	2.74	Keep CFL; LED in 2021 and 2030
	Energy	9.40	73.9	801	45.8	2.73	Keep CFL; LED in 2020 and 2029
	Emissions	9.64	68.3	812	45.4	2.69	Keep CFL; LED in 2018, 2023, and 2032
	LCC	9.37	74.3	802	46.0	2.74	Keep CFL; LED in 2020 and 2030
	Burnout	10.28	88.9	884	51.7	3.11	Keep CFL; LED in 2025
12	Cost	8.05	64.4	693	39.7	2.38	Keep CFL; LED in 2017, 21, 25, 31, and 39
	Energy	8.09	63.8	690	39.5	2.36	Keep CFL; LED in 2016, 20, 24, 29, and 39
	Emissions	8.13	63.6	690	39.4	2.36	Keep CFL; LED in 2016, 19, 23, 28, and 37
	LCC	8.05	64.2	691	39.6	2.37	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Burnout	8.35	69.4	714	41.3	2.48	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	9.94	83.3	829	48.3	2.94	Keep LED; LED in 2025
	Energy	9.94	83.2	829	48.2	2.94	Keep LED; LED in 2025
	Emissions	9.97	83.2	830	48.2	2.94	Keep LED; LED in 2024
	LCC	9.94	83.3	829	48.3	2.94	Keep LED; LED in 2025
	Burnout	16.34	147.4	1382	78.7	5.23	Keep LED

1.5	Cost	9.67	83.3	829	48.2	2.93	Keep LED; LED in 2025
	Energy	9.67	83.2	829	48.1	2.93	Keep LED; LED in 2025
	Emissions	9.94	71.4	843	47.1	2.81	Keep LED; LED in 2020 and 2029
	LCC	9.76	72.5	844	47.6	2.83	Keep LED; LED in 2022 and 2031
	Burnout	16.34	147.4	1382	78.7	5.23	Keep LED
3	Cost	9.01	72.0	776	44.4	2.66	Keep LED; LED in 2021 and 2031
	Energy	9.04	71.5	774	44.2	2.65	Keep LED; LED in 2020 and 2030
	Emissions	9.08	71.4	775	44.1	2.65	Keep LED; LED in 2020 and 2029
	LCC	9.01	71.9	775	44.4	2.65	Keep LED; LED in 2021 and 2030
	Burnout	12.42	110.2	1064	62.1	3.81	Keep LED; LED in 2037
12	Cost	7.88	63.4	681	39.0	2.34	Keep LED; LED in 2018, 22, 26, 32, and 40
	Energy	7.91	63.0	678	38.8	2.33	Keep LED; LED in 2017, 20, 25, 30, and 40
	Emissions	7.94	62.7	679	38.8	2.33	Keep LED; LED in 2017, 20, 24, 29, and 38
	LCC	7.88	63.2	680	38.9	2.34	Keep LED; LED in 2018, 21, 26, 31, and 39
	Burnout	8.22	69.9	708	41.2	2.47	Keep LED; LED in 2020, 2029, and 2043

A.6.6 WY: Wyoming (NERC: RMPA)

Table A.20: Optimal replacement policy for consumers in Wyoming (using RMPA grid mix).

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO₂e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	17.30	147.4	1453	110.0	7.19	LED in 2015
	Energy	28.12	87.7	1303	132.7	7.19	CFL in 2015; LED in 2024
	Emissions	17.30	147.4	1453	110.0	7.19	LED in 2015
	LCC	17.30	147.4	1453	110.0	7.19	LED in 2015
	Burnout	17.30	147.4	1453	110.0	7.19	LED in 2015
1.5	Cost	10.92	87.7	887	74.5	4.41	CFL in 2015; LED in 2024
	Energy	10.92	87.7	887	74.4	4.40	CFL in 2015; LED in 2024
	Emissions	11.35	73.8	892	69.7	4.05	CFL in 2015; LED in 2019 and 2028
	LCC	11.06	75.0	891	70.7	4.08	CFL in 2015; LED in 2021 and 2030
	Burnout	13.66	118.1	1143	96.3	5.76	CFL in 2015; LED in 2036
3	Cost	9.36	74.5	800	64.3	3.76	CFL in 2015; LED in 2021 and 2030
	Energy	9.40	73.9	797	63.7	3.74	CFL in 2015; LED in 2020 and 2029
	Emissions	10.53	66.7	863	61.8	3.61	LED in 2015, 2018, 2023, and 2032
	LCC	9.37	74.2	798	64.1	3.75	CFL in 2015; LED in 2020 and 2030
	Burnout	10.09	88.9	874	72.8	4.30	CFL in 2015; LED in 2025
12	Cost	7.49	64.5	675	53.6	3.16	CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	7.54	63.8	672	53.0	3.13	CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	7.75	62.1	684	52.3	3.10	LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.50	64.1	674	53.3	3.15	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	7.73	69.4	695	56.1	3.32	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	17.03	149.1	1471	115.8	7.18	Keep IL; LED in 2016
	Energy	28.32	87.7	1303	132.8	7.20	Discard IL; CFL in 2015; LED in 2024
	Emissions	17.50	147.4	1453	110.1	7.20	Discard IL; LED in 2015
	LCC	17.04	148.6	1466	114.9	7.16	Keep IL; LED in 2016
	Burnout	45.02	439.1	4159	351.5	20.28	Keep IL; LED in 2034
1.5	Cost	10.94	87.7	887	74.6	4.41	Discard IL; CFL in 2015; LED in 2024
	Energy	10.94	87.7	887	74.4	4.41	Discard IL; CFL in 2015; LED in 2024
	Emissions	11.37	73.8	892	69.7	4.05	Discard IL; CFL in 2015; LED in 2019 and 2028
	LCC	11.08	75.0	891	70.7	4.08	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	16.93	151.6	1497	119.5	7.26	Keep IL; LED in 2016
3	Cost	9.37	74.5	800	64.4	3.76	Discard IL; CFL in 2015; LED in 2021 and 2030
	Energy	9.41	73.9	797	63.7	3.74	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	10.54	66.7	863	61.8	3.61	Discard IL; LED in 2015, 2018, 2023, and 2032
	LCC	9.38	74.2	798	64.1	3.75	Discard IL; CFL in 2015; LED in 2020 and 2030
	Burnout	11.90	105.8	1046	88.9	5.07	Keep IL; CFL in 2015; LED in 2026
12	Cost	7.50	64.5	675	53.6	3.16	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	7.54	63.8	672	53.0	3.13	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	7.75	62.1	684	52.3	3.10	Discard IL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.50	64.1	674	53.3	3.15	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	8.15	73.5	735	60.0	3.50	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	15.88	142.5	1404	112.7	6.80	Keep HL; LED in 2017
	Energy	28.32	87.7	1303	132.8	7.20	Keep HL; CFL in 2015; LED in 2024
	Emissions	16.52	143.0	1409	108.9	6.92	Keep HL; LED in 2015
	LCC	15.88	142.3	1401	112.2	6.79	Keep HL; LED in 2017
	Burnout	55.59	574.9	5104	403.8	26.84	Keep HL
1.5	Cost	10.94	87.7	887	74.6	4.41	Discard HL; CFL in 2015; LED in 2024
	Energy	10.94	87.7	887	74.4	4.41	Discard HL; CFL in 2015; LED in 2024

	Emissions	11.37	73.8	892	69.7	4.05	Discard HL; CFL in 2015; LED in 2019 and 2028
	LCC	11.08	75.0	891	70.7	4.08	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	28.75	277.8	2667	227.6	12.84	Keep HL; LED in 2030
3	Cost	9.37	74.5	800	64.4	3.76	Discard HL; CFL in 2015; LED in 2021 and 2030
	Energy	9.41	73.9	797	63.7	3.74	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	10.54	66.7	863	61.8	3.61	Discard HL; LED in 2015, 2018, 2023, and 2032
	LCC	9.38	74.2	798	64.1	3.75	Discard HL; CFL in 2015; LED in 2020 and 2030
	Burnout	18.91	178.4	1750	149.3	8.32	Keep HL; LED in 2022
12	Cost	7.50	64.5	675	53.6	3.16	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	7.54	63.8	672	53.0	3.13	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	7.75	62.1	684	52.3	3.10	Discard HL; LED in 2015, 17, 19, 22, 26, 32, and 44
	LCC	7.50	64.1	674	53.3	3.15	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	10.03	91.8	922	76.8	4.33	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	9.43	87.8	844	68.7	4.12	Keep CFL; LED in 2024
	Energy	9.43	87.7	843	68.5	4.12	Keep CFL; LED in 2024
	Emissions	9.49	87.8	846	68.3	4.14	Keep CFL; LED in 2023
	LCC	9.43	87.7	844	68.6	4.12	Keep CFL; LED in 2024
	Burnout	15.90	164.3	1458	115.4	7.67	Keep CFL
1.5	Cost	9.14	87.7	843	68.4	4.11	Keep CFL; LED in 2024
	Energy	9.14	87.7	843	68.3	4.11	Keep CFL; LED in 2024
	Emissions	9.57	73.8	848	63.6	3.75	Keep CFL; LED in 2019 and 2028
	LCC	9.28	75.0	847	64.6	3.79	Keep CFL; LED in 2021 and 2030
	Burnout	11.88	118.1	1099	90.2	5.47	Keep CFL; LED in 2036
3	Cost	8.47	74.5	778	61.3	3.62	Keep CFL; LED in 2021 and 2030
	Energy	8.51	73.9	775	60.7	3.59	Keep CFL; LED in 2020 and 2029
	Emissions	8.89	68.2	790	59.1	3.49	Keep CFL; LED in 2018, 2023, and 2031
	LCC	8.48	74.2	776	61.0	3.60	Keep CFL; LED in 2020 and 2030
	Burnout	9.20	88.9	853	69.7	4.15	Keep CFL; LED in 2025
12	Cost	7.27	64.5	670	52.8	3.12	Keep CFL; LED in 2017, 21, 25, 31, and 40
	Energy	7.32	63.8	667	52.3	3.10	Keep CFL; LED in 2016, 20, 24, 29, and 39
	Emissions	7.53	62.1	677	51.9	3.08	Keep CFL; LED in 2016, 18, 20, 23, 27, 34, and 47
	LCC	7.27	64.5	670	52.8	3.12	Keep CFL; LED in 2017, 21, 25, 31, and 40
	Burnout	7.50	69.4	689	55.4	3.28	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	8.91	83.3	798	64.8	3.90	Keep LED; LED in 2025
	Energy	8.92	83.2	798	64.6	3.90	Keep LED; LED in 2024
	Emissions	8.96	83.3	800	64.4	3.92	Keep LED; LED in 2024
	LCC	8.91	83.2	798	64.7	3.90	Keep LED; LED in 2025
	Burnout	14.26	147.4	1309	103.5	6.88	Keep LED
1.5	Cost	8.64	83.2	798	64.6	3.90	Keep LED; LED in 2025
	Energy	8.64	83.2	798	64.5	3.90	Keep LED; LED in 2024
	Emissions	9.14	71.4	819	61.3	3.64	Keep LED; LED in 2020 and 2028
	LCC	8.64	83.2	798	64.6	3.90	Keep LED; LED in 2025
	Burnout	14.26	147.4	1309	103.5	6.88	Keep LED
3	Cost	8.14	72.0	750	59.0	3.50	Keep LED; LED in 2021 and 2031
	Energy	8.17	71.5	748	58.5	3.48	Keep LED; LED in 2020 and 2030
	Emissions	8.55	66.7	769	57.6	3.41	Keep LED; LED in 2018, 2023, and 2032
	LCC	8.14	71.8	749	58.8	3.49	Keep LED; LED in 2021 and 2030
	Burnout	11.04	110.2	1022	83.5	5.10	Keep LED; LED in 2037
12	Cost	7.10	63.7	658	51.9	3.08	Keep LED; LED in 2018, 22, 27, 33, and 42
	Energy	7.14	63.0	656	51.4	3.06	Keep LED; LED in 2017, 20, 24, 30, and 40
	Emissions	7.25	62.1	661	51.2	3.05	Keep LED; LED in 2017, 19, 22, 26, 32, and 43
	LCC	7.11	63.2	657	51.6	3.06	Keep LED; LED in 2018, 21, 25, 31, and 39
	Burnout	7.37	69.9	684	55.4	3.28	Keep LED; LED in 2020, 2029, and 2043

A.6.7 CA: California (NERC: CAMX)

Table A.21: Optimal replacement policy for consumers in California (using CAMX grid mix).

HOU [hr/d]	**Objective/ Scenario**	**Cost to Consumer [$/HOU]**	**Electricity [kWh/HOU]**	**Primary Energy [MJ/HOU]**	**GHG Emissions [kg CO₂e/HOU]**	**Social Cost of Carbon [$/HOU]**	**Replacement Schedule (2015-2050) [Purchase Year]**
Case 1							
1/7	Cost	23.50	147.4	1486	44.7	2.85	LED in 2015
	Energy	32.14	87.7	1297	90.7	4.65	CFL in 2015; LED in 2024
	Emissions	23.50	147.4	1486	44.7	2.85	LED in 2015
	LCC	23.50	147.4	1486	44.7	2.85	LED in 2015
	Burnout	23.50	147.4	1486	44.7	2.85	LED in 2015
1.5	Cost	14.54	74.7	883	34.5	1.94	CFL in 2015; LED in 2021 and 2030
	Energy	14.57	74.3	882	34.4	1.93	CFL in 2015; LED in 2020 and 2030
	Emissions	14.93	87.7	886	32.8	1.89	CFL in 2015; LED in 2023
	LCC	14.54	74.6	883	34.5	1.94	CFL in 2015; LED in 2021 and 2030

	Burnout	19.06	118.1	1138	40.3	2.36	CFL in 2015; LED in 2036
3	Cost	12.73	69.3	805	29.7	1.69	CFL in 2015; LED in 2019, 2025, and 2034
	Energy	12.80	74.0	791	28.4	1.63	CFL in 2015; LED in 2020 and 2029
	Emissions	12.82	73.8	792	28.4	1.63	CFL in 2015; LED in 2019 and 2029
	LCC	12.73	69.2	804	29.6	1.69	CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	14.20	88.9	868	30.2	1.75	CFL in 2015; LED in 2025
12	Cost	10.44	63.0	674	23.0	1.34	CFL in 2015; LED in 2017, 20, 23, 27, 33, and 40
	Energy	10.47	63.9	669	22.6	1.32	CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	10.61	64.8	677	22.3	1.30	LED in 2015, 18, 22, 27, and 39
	LCC	10.45	63.9	669	22.6	1.32	CFL in 2015; LED in 2017, 20, 24, 29, and 38
	Burnout	10.93	69.4	690	22.9	1.34	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	23.53	147.5	1474	45.4	2.83	Keep IL; LED in 2015
	Energy	32.34	87.7	1297	90.8	4.66	Discard IL; CFL in 2015; LED in 2024
	Emissions	23.70	147.4	1486	44.8	2.86	Discard IL; LED in 2015
	LCC	23.53	147.5	1474	45.4	2.83	Keep IL; LED in 2015
	Burnout	66.18	439.1	4064	133.8	7.72	Keep IL; LED in 2034
1.5	Cost	14.56	74.7	883	34.6	1.94	Discard IL; CFL in 2015; LED in 2021 and 2030
	Energy	14.59	74.3	882	34.4	1.93	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	14.95	87.7	886	32.8	1.89	Discard IL; CFL in 2015; LED in 2023
	LCC	14.56	74.6	883	34.5	1.94	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	23.84	151.6	1494	47.7	2.86	Keep IL; LED in 2016
3	Cost	12.73	69.3	805	29.7	1.69	Discard IL; CFL in 2015; LED in 2019, 2025, and 2034
	Energy	12.81	74.0	791	28.4	1.63	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.83	73.8	792	28.4	1.63	Discard IL; CFL in 2015; LED in 2019 and 2029
	LCC	12.74	69.2	804	29.6	1.69	Discard IL; CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	16.99	105.8	1024	36.5	2.06	Keep IL; CFL in 2015; LED in 2026
12	Cost	10.45	63.0	674	23.0	1.34	Discard IL; CFL in 2015; LED in 2017, 20, 23, 27, 33, and 40
	Energy	10.47	63.9	669	22.6	1.32	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	10.61	64.8	677	22.3	1.30	Discard IL; LED in 2015, 18, 22, 27, and 39
	LCC	10.46	63.9	669	22.6	1.32	Discard IL; CFL in 2015; LED in 2017, 20, 24, 29, and 38
	Burnout	11.59	73.5	727	24.4	1.41	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	22.32	141.7	1397	44.2	2.67	Keep HL; LED in 2017
	Energy	32.34	87.7	1297	90.8	4.66	Discard HL; CFL in 2015; LED in 2024
	Emissions	22.52	142.2	1414	43.9	2.71	Keep HL; LED in 2016
	LCC	22.32	141.7	1397	44.2	2.67	Keep HL; LED in 2017
	Burnout	79.77	574.9	5233	149.2	9.92	Keep HL
1.5	Cost	14.56	74.7	883	34.6	1.94	Discard HL; CFL in 2015; LED in 2021 and 2030
	Energy	14.59	74.3	882	34.4	1.93	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	14.95	87.7	886	32.8	1.89	Discard HL; CFL in 2015; LED in 2023
	LCC	14.56	74.6	883	34.5	1.94	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	42.43	277.8	2587	87.3	4.92	Keep HL; LED in 2030
3	Cost	12.73	69.3	805	29.7	1.69	Discard HL; CFL in 2015; LED in 2019, 2025 and 2034
	Energy	12.81	74.0	791	28.4	1.63	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	12.83	73.8	792	28.4	1.63	Discard HL; CFL in 2015; LED in 2019 and 2029
	LCC	12.74	69.2	804	29.6	1.69	Discard HL; CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	27.79	178.4	1693	58.3	3.23	Keep HL; LED in 2022
12	Cost	10.45	63.0	674	23.0	1.34	Discard HL; CFL in 2015; LED in 2017, 20, 23, 27, 33, and 40
	Energy	10.47	63.9	669	22.6	1.32	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 39
	Emissions	10.61	64.8	677	22.3	1.30	Discard HL; LED in 2015, 18, 22, 27, and 39
	LCC	10.46	63.9	669	22.6	1.32	Discard HL; CFL in 2015; LED in 2017, 20, 24, 29, and 38
	Burnout	14.52	91.8	898	30.7	1.72	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	13.44	87.6	841	26.9	1.61	Keep CFL; LED in 2024
	Energy	13.45	87.7	840	26.9	1.61	Keep CFL; LED in 2024
	Emissions	13.45	87.7	842	26.9	1.61	Keep CFL; LED in 2023
	LCC	13.44	87.6	841	26.9	1.61	Keep CFL; LED in 2024
	Burnout	22.81	164.3	1495	42.7	2.84	Keep CFL
1.5	Cost	12.76	74.7	840	28.5	1.65	Keep CFL; LED in 2021 and 2030
	Energy	12.79	74.3	839	28.4	1.64	Keep CFL; LED in 2020 and 2030
	Emissions	13.15	87.7	842	26.7	1.60	Keep CFL; LED in 2023
	LCC	12.76	74.6	839	28.4	1.65	Keep CFL; LED in 2021 and 2030
	Burnout	17.28	118.1	1095	34.2	2.07	Keep CFL; LED in 2036
3	Cost	11.84	69.3	783	26.6	1.55	Keep CFL; LED in 2019, 2025 and 2034
	Energy	11.91	74.0	770	25.4	1.48	Keep CFL; LED in 2020 and 2029
	Emissions	11.93	73.8	770	25.3	1.48	Keep CFL; LED in 2019 and 2029
	LCC	11.84	69.2	782	26.6	1.54	Keep CFL; LED in 2019, 2025, and 2034
	Burnout	13.31	88.9	846	27.1	1.61	Keep CFL; LED in 2025
12	Cost	10.24	63.4	667	22.1	1.30	Keep CFL; LED in 2017, 20, 23, 28, 34, and 46
	Energy	10.24	63.9	663	21.8	1.28	Keep CFL; LED in 2016, 20, 24, 29, and 39
	Emissions	10.35	65.7	666	21.7	1.28	Keep CFL; LED in 2017, 21, 26, and 37
	LCC	10.24	63.9	663	21.8	1.28	Keep CFL; LED in 2016, 20, 24, 29, and 39
	Burnout	10.71	69.4	685	22.2	1.30	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	12.70	83.2	796	25.3	1.52	Keep LED; LED in 2024
	Energy	12.71	83.2	796	25.3	1.52	Keep LED; LED in 2025
	Emissions	12.71	83.2	798	25.3	1.52	Keep LED; LED in 2024
	LCC	12.70	83.2	796	25.3	1.52	Keep LED; LED in 2024
	Burnout	20.46	147.4	1342	38.3	2.54	Keep LED
1.5	Cost	12.23	72.2	812	27.5	1.60	Keep LED; LED in 2022 and 2030

	Energy	12.43	83.2	796	25.2	1.51	Keep LED; LED in 2025
	Emissions	12.43	83.2	798	25.2	1.51	Keep LED; LED in 2024
	LCC	12.23	72.1	812	27.4	1.60	Keep LED; LED in 2022 and 2030
	Burnout	20.46	147.4	1342	38.3	2.54	Keep LED
3	Cost	11.44	71.6	744	24.5	1.44	Keep LED; LED in 2021 and 2030
	Energy	11.45	71.6	744	24.4	1.43	Keep LED; LED in 2021 and 2030
	Emissions	11.46	71.4	745	24.4	1.43	Keep LED; LED in 2020 and 2029
	LCC	11.44	71.6	744	24.5	1.44	Keep LED; LED in 2021 and 2030
	Burnout	16.04	110.2	1021	31.6	1.93	Keep LED; LED in 2037
12	Cost	10.01	63.0	653	21.5	1.27	Keep LED; LED in 2018, 21, 25, 30, and 38
	Energy	10.08	64.4	653	21.3	1.25	Keep LED; LED in 2018, 22, 27, and 37
	Emissions	10.12	64.8	654	21.2	1.25	Keep LED; LED in 2018, 22, 27, and 39
	LCC	10.01	63.1	653	21.5	1.26	Keep LED; LED in 2018, 21, 25, 30, and 39
	Burnout	10.60	69.9	679	21.9	1.29	Keep LED; LED in 2020, 2029, and 2043

A.6.8 HI: Hawaii (NERC: HICC)

Table A.22: Optimal replacement policy for consumers in Hawaii (using HICC grid mix).

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO$_2$e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	42.10	147.4	1579	90.3	5.88	LED in 2015
	Energy	43.24	87.6	1384	122.6	6.53	CFL in 2015; LED in 2024
	Emissions	42.10	147.4	1579	90.3	5.88	LED in 2015
	LCC	42.10	147.4	1579	90.3	5.88	LED in 2015
	Burnout	42.10	147.4	1579	90.3	5.88	LED in 2015
1.5	Cost	23.98	69.4	1033	65.0	3.66	CFL in 2015; LED in 2019, 2025, and 2033
	Energy	23.99	74.0	961	62.3	3.53	CFL in 2015; LED in 2020 and 2029
	Emissions	24.20	73.9	967	61.9	3.52	CFL in 2015; LED in 2019 and 2027
	LCC	23.98	74.0	961	62.3	3.53	CFL in 2015; LED in 2020 and 2029
	Burnout	34.05	118.1	1258	83.2	4.93	CFL in 2015; LED in 2036
3	Cost	21.40	66.1	910	56.6	3.22	CFL in 2015; LED in 2018, 2022, 2028, and 2036
	Energy	22.18	73.8	869	56.1	3.22	CFL in 2015; LED in 2019 and 2029
	Emissions	22.10	66.7	930	54.8	3.13	LED in 2015, 2018, 2023, and 2031
	LCC	21.41	66.0	909	56.5	3.21	CFL in 2015; LED in 2018, 2022, 2028, and 2035
	Burnout	25.48	88.9	963	63.7	3.69	CFL in 2015; LED in 2025
12	Cost	18.41	62.1	745	45.9	2.65	LED in 2015, 17, 20, 23, 27, 34, and 43
	Energy	18.56	63.7	735	46.4	2.68	CFL in 2015; LED in 2016, 19, 23, 29, and 38
	Emissions	18.48	62.0	745	45.8	2.64	LED in 2015, 17, 19, 22, 25, 32, and 43
	LCC	18.41	62.1	745	45.9	2.65	LED in 2015, 17, 20, 23, 27, 34, and 43
	Burnout	19.74	69.4	763	49.1	2.83	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	42.14	147.3	1583	93.3	5.92	Keep IL; LED in 2015
	Energy	43.44	87.6	1384	122.7	6.53	Discard IL; CFL in 2015; LED in 2024
	Emissions	42.30	147.4	1579	90.3	5.88	Discard IL; LED in 2015
	LCC	42.15	147.2	1581	92.7	5.91	Keep IL; LED in 2015
	Burnout	122.15	439.1	4625	310.9	17.89	Keep IL; LED in 2034
1.5	Cost	24.00	69.4	1033	65.0	3.66	Discard IL; CFL in 2015; LED in 2019, 2025, and 2033
	Energy	24.00	74.0	961	62.3	3.53	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	24.22	73.9	967	61.9	3.52	Discard IL; CFL in 2015; LED in 2019 and 2027
	LCC	24.00	74.0	961	62.3	3.53	Discard IL; CFL in 2015; LED in 2020 and 2029
	Burnout	43.04	151.6	1644	104.0	6.21	Keep IL; LED in 2016
3	Cost	21.42	66.0	909	56.5	3.21	Discard IL; CFL in 2015; LED in 2018, 22, 28, and 35
	Energy	22.19	73.8	869	56.1	3.22	Discard IL; CFL in 2015; LED in 2019 and 2029
	Emissions	22.10	66.7	930	54.8	3.13	Discard IL; LED in 2015, 18, 23, and 31
	LCC	21.42	66.0	909	56.5	3.21	Discard IL; CFL in 2015; LED in 2018, 22, 28, and 35
	Burnout	30.45	105.8	1158	80.1	4.48	Keep IL; CFL in 2015; LED in 2026
12	Cost	18.41	62.1	745	45.9	2.65	Discard IL; LED in 2015, 17, 20, 23, 27, 34, and 43
	Energy	18.56	63.7	735	46.4	2.68	Discard IL; CFL in 2015; LED in 2016, 19, 23, 29, and 38
	Emissions	18.48	62.0	745	45.8	2.64	Discard IL; LED in 2015, 17, 19, 22, 25, 32, and 43
	LCC	18.41	62.1	745	45.9	2.65	Discard IL; LED in 2015, 17, 20, 23, 27, 34, and 43
	Burnout	20.92	73.5	810	53.0	3.02	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	40.24	141.6	1529	94.9	5.75	Keep HL; LED in 2016
	Energy	43.44	87.6	1384	122.7	6.53	Discard HL; CFL in 2015; LED in 2024
	Emissions	42.30	147.4	1579	90.3	5.88	Discard HL; LED in 2015
	LCC	40.25	141.6	1528	94.6	5.75	Keep HL; LED in 2016
	Burnout	152.29	574.9	5596	326.9	21.73	Keep HL
1.5	Cost	24.00	69.4	1033	65.0	3.66	Discard HL; CFL in 2015; LED in 2019, 2025, and 2033
	Energy	24.00	74.0	961	62.3	3.53	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	24.22	73.9	967	61.9	3.52	Discard HL; CFL in 2015; LED in 2019 and 2027

	LCC	24.00	74.0	961	62.3	3.53	Discard HL; CFL in 2015; LED in 2020 and 2029
	Burnout	77.87	277.8	2972	204.8	11.49	Keep HL; LED in 2030
3	Cost	21.42	66.0	909	56.5	3.21	Discard HL; CFL in 2015; LED in 2018, 22, 28, and 35
	Energy	22.19	73.8	869	56.1	3.22	Discard HL; CFL in 2015; LED in 2019 and 2029
	Emissions	22.10	66.7	930	54.8	3.13	Discard HL; CFL in 2015; LED in 2018, 2023, and 2031
	LCC	21.42	66.0	909	56.5	3.21	Discard HL; CFL in 2015; LED in 2018, 22, 28, and 35
	Burnout	50.53	178.4	1949	136.9	7.51	Keep HL; LED in 2022
12	Cost	18.41	62.1	745	45.9	2.65	Discard HL; LED in 2015, 17, 20, 23, 27, 34, and 43
	Energy	18.56	63.7	735	46.4	2.68	Discard HL; CFL in 2015; LED in 2016, 19, 23, 29, and 38
	Emissions	18.48	62.0	745	45.8	2.64	Discard HL; LED in 2015, 17, 19, 22, 25, 32, and 43
	LCC	18.41	62.1	745	45.9	2.65	Discard HL; LED in 2015, 17, 20, 23, 27, 34, and 43
	Burnout	26.20	91.8	1021	69.9	3.85	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	24.55	87.6	929	59.2	3.50	Keep CFL; LED in 2024
	Energy	24.55	87.6	929	59.2	3.50	Keep CFL; LED in 2024
	Emissions	24.76	88.4	936	58.8	3.51	Keep CFL; LED in 2022
	LCC	24.55	87.6	929	59.2	3.50	Keep CFL; LED in 2023
	Burnout	43.53	164.3	1599	93.4	6.21	Keep CFL
1.5	Cost	22.20	69.4	990	58.9	3.37	Keep CFL; LED in 2019, 2025, and 2033
	Energy	22.21	74.0	917	56.3	3.24	Keep CFL; LED in 2020 and 2029
	Emissions	22.42	73.9	924	55.9	3.23	Keep CFL; LED in 2019 and 2027
	LCC	22.20	74.0	917	56.3	3.24	Keep CFL; LED in 2020 and 2029
	Burnout	32.27	118.1	1214	77.1	4.64	Keep CFL; LED in 2036
3	Cost	20.51	66.1	888	53.6	3.07	Keep CFL; LED in 2018, 2022, 2028, and 2036
	Energy	21.29	73.8	847	53.1	3.07	Keep CFL; LED in 2019 and 2029
	Emissions	20.75	68.3	859	52.1	3.00	Keep CFL; LED in 2017, 2022, and 2030
	LCC	20.52	66.0	888	53.4	3.07	Keep CFL; LED in 2018, 2022, 2028, and 2035
	Burnout	24.59	88.9	941	60.7	3.55	Keep CFL; LED in 2025
12	Cost	18.17	62.2	737	45.7	2.64	Keep CFL; LED in 2016, 19, 22, 25, 29, 35, and 47
	Energy	18.34	63.7	730	45.7	2.64	Keep CFL; LED in 2016, 19, 23, 29, and 38
	Emissions	18.29	62.2	738	45.5	2.63	Keep CFL; LED in 2016, 18, 20, 23, 27, 34, and 48
	LCC	18.17	62.2	737	45.7	2.64	Keep CFL; LED in 2016, 19, 21, 25, 29, 35, and 47
	Burnout	19.52	69.4	758	48.3	2.80	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	23.24	83.1	878	55.7	3.30	Keep LED; LED in 2024
	Energy	23.24	83.1	878	55.7	3.30	Keep LED; LED in 2024
	Emissions	23.40	83.7	885	55.3	3.31	Keep LED; LED in 2023
	LCC	23.24	83.1	878	55.6	3.30	Keep LED; LED in 2024
	Burnout	39.06	147.4	1435	83.8	5.57	Keep LED
1.5	Cost	21.35	71.7	886	54.2	3.13	Keep LED; LED in 2021 and 2030
	Energy	22.96	83.1	878	55.6	3.29	Keep LED; LED in 2024
	Emissions	21.53	71.4	891	53.8	3.12	Keep LED; LED in 2020 and 2028
	LCC	21.35	71.6	886	54.1	3.13	Keep LED; LED in 2021 and 2030
	Burnout	39.06	147.4	1435	83.8	5.57	Keep LED
3	Cost	19.97	67.0	832	50.9	2.94	Keep LED; LED in 2019, 2025, and 2033
	Energy	20.52	71.4	818	51.0	2.97	Keep LED; LED in 2020 and 2029
	Emissions	20.11	66.7	836	50.6	2.93	Keep LED; LED in 2018, 2023, and 2031
	LCC	19.97	66.9	832	50.9	2.94	Keep LED; LED in 2019, 2025, and 2033
	Burnout	30.02	110.2	1128	71.0	4.30	Keep LED; LED in 2037
12	Cost	17.87	61.6	728	45.1	2.62	Keep LED; LED in 2017, 20, 23, 26, 30, 37, and 46
	Energy	18.01	62.9	717	44.8	2.60	Keep LED; LED in 2017, 20, 24, 30, and 39
	Emissions	18.04	62.7	719	44.7	2.60	Keep LED; LED in 2017, 19, 23, 27, and 36
	LCC	17.88	61.5	727	45.0	2.61	Keep LED; LED in 2017, 19, 22, 25, 30, 35, and 47
	Burnout	19.47	69.9	753	48.2	2.80	Keep LED; LED in 2020, 2029, and 2043

A.6.9 All coal scenario

Table A.23: Optimal replacement policy for typical US consumers if the grid mix becomes 100% coal by 2050.

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO_2e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	19.67	147.4	1674	157.8	10.36	LED in 2015
	Energy	29.53	87.7	1426	157.4	8.79	CFL in 2015; LED in 2024
	Emissions	29.54	87.6	1427	157.4	8.81	CFL in 2015; LED in 2024
	LCC	19.67	147.4	1674	157.8	10.36	LED in 2015
	Burnout	19.67	147.4	1674	157.8	10.36	LED in 2015
1.5	Cost	12.27	75.4	989	91.3	5.42	CFL in 2015; LED in 2021 and 2031
	Energy	12.35	74.1	983	90.2	5.37	CFL in 2015; LED in 2020 and 2030
	Emissions	14.19	71.4	1098	89.6	5.34	CFL in 2015; LED in 2020 and 2029

	LCC	12.28	74.8	986	90.8	5.39	CFL in 2015; LED in 2021 and 2030
	Burnout	15.57	118.1	1297	129.4	7.83	CFL in 2015; LED in 2036
3	Cost	10.56	74.4	893	84.3	5.07	CFL in 2015; LED in 2020 and 2030
	Energy	10.59	73.9	891	84.0	5.06	CFL in 2015; LED in 2020 and 2029
	Emissions	11.56	66.7	948	80.3	4.83	LED in 2015, 2018, 2024, and 2032
	LCC	10.63	69.3	899	81.7	4.90	CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	11.53	88.9	988	96.9	5.86	CFL in 2015; LED in 2025
12	Cost	8.53	64.4	757	71.0	4.32	CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.57	63.8	754	70.6	4.30	CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.73	62.0	764	69.5	4.24	LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.54	64.0	755	70.8	4.30	CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	8.85	69.4	783	75.1	4.56	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	19.43	148.7	1671	158.9	10.05	Keep IL; LED in 2016
	Energy	29.73	87.7	1426	157.5	8.80	Discard IL; CFL in 2015; LED in 2024
	Emissions	29.74	87.6	1427	157.5	8.81	Discard IL; CFL in 2015; LED in 2024
	LCC	19.44	149.2	1675	159.4	10.03	Keep IL; LED in 2016
	Burnout	52.12	439.1	4666	460.8	26.68	Keep IL; LED in 2034
1.5	Cost	12.29	75.4	989	91.3	5.42	Discard IL; CFL in 2015; LED in 2021 and 2031
	Energy	12.37	74.1	983	90.2	5.37	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	14.21	71.4	1098	89.6	5.34	Discard IL; CFL in 2015; LED in 2020 and 2029
	LCC	12.30	74.8	986	90.8	5.39	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	19.38	151.6	1695	161.8	10.02	Keep IL; LED in 2016
3	Cost	10.57	74.4	893	84.3	5.07	Discard IL; CFL in 2015; LED in 2020 and 2030
	Energy	10.60	73.9	891	84.0	5.06	Discard IL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.57	66.7	948	80.3	4.83	Discard IL; LED in 2015, 2018, 2024, and 2032
	LCC	10.64	69.3	899	81.7	4.90	Discard IL; CFL in 2015; LED in 2019, 2025, and 2034
	Burnout	13.61	105.8	1169	115.1	6.73	Keep IL; CFL in 2015; LED in 2026
12	Cost	8.54	64.4	757	71.0	4.32	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.57	63.8	754	70.6	4.30	Discard IL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.77	61.7	766	69.3	4.23	Discard IL; LED in 2015, 17, 19, 22, 25, 29, and 38
	LCC	8.54	64.0	755	70.8	4.30	Discard IL; CFL in 2015; LED in 2017, 20, 24, 30, and 38
	Burnout	9.34	73.5	826	79.4	4.77	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	18.17	142.3	1586	151.8	9.37	Keep HL; LED in 2017
	Energy	29.73	87.7	1426	157.5	8.80	Discard HL; CFL in 2015; LED in 2024
	Emissions	18.27	141.6	1585	151.1	9.48	Keep HL; LED in 2016
	LCC	18.18	142.7	1589	152.2	9.36	Keep HL; LED in 2017
	Burnout	64.84	574.9	5963	589.8	39.21	Keep HL
1.5	Cost	12.29	75.4	989	91.3	5.42	Discard HL; CFL in 2015; LED in 2021 and 2031
	Energy	12.37	74.1	983	90.2	5.37	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	14.21	71.4	1098	89.6	5.34	Discard HL; CFL in 2015; LED in 2020 and 2029
	LCC	12.30	74.8	986	90.8	5.39	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	33.24	277.8	2972	292.9	16.64	Keep HL; LED in 2030
3	Cost	10.57	74.4	893	84.3	5.07	Discard HL; CFL in 2015; LED in 2020 and 2030
	Energy	10.60	73.9	891	84.0	5.06	Discard HL; CFL in 2015; LED in 2020 and 2029
	Emissions	11.57	66.7	948	80.3	4.83	Discard HL; LED in 2015, 2018, 2024, and 2032
	LCC	10.64	69.3	899	81.7	4.90	Discard HL; CFL in 2015; LED in 2019, 2025 and 2034
	Burnout	21.79	178.4	1941	189.6	10.76	Keep HL; LED in 2022
12	Cost	8.54	64.4	757	71.0	4.32	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.57	63.8	754	70.6	4.30	Discard HL; CFL in 2015; LED in 2016, 20, 24, 29, and 38
	Emissions	8.77	61.7	766	69.3	4.23	Discard HL; LED in 2015, 17, 19, 22, 25, 29, and 38
	LCC	8.54	64.0	755	70.8	4.30	Discard HL; CFL in 2015; LED in 2017, 20, 24, 30, and 38
	Burnout	11.51	91.8	1025	98.6	5.71	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	10.84	87.7	957	92.9	5.71	Keep CFL; LED in 2024
	Energy	10.84	87.7	957	92.9	5.71	Keep CFL; LED in 2024
	Emissions	10.85	87.6	957	92.9	5.72	Keep CFL; LED in 2024
	LCC	10.84	87.8	957	93.0	5.71	Keep CFL; LED in 2024
	Burnout	18.54	164.3	1704	168.5	11.20	Keep CFL
1.5	Cost	10.49	75.4	944	85.2	5.13	Keep CFL; LED in 2021 and 2031
	Energy	10.57	74.1	939	84.0	5.08	Keep CFL; LED in 2020 and 2030
	Emissions	10.69	73.8	941	83.9	5.08	Keep CFL; LED in 2019 and 2029
	LCC	10.50	74.8	941	84.6	5.10	Keep CFL; LED in 2021 and 2030
	Burnout	13.79	118.1	1252	123.3	7.54	Keep CFL; LED in 2036
3	Cost	9.67	74.4	871	81.3	4.93	Keep CFL; LED in 2020 and 2030
	Energy	9.70	73.9	869	80.9	4.92	Keep CFL; LED in 2020 and 2029
	Emissions	10.40	65.4	910	77.8	4.70	Keep CFL; LED in 2017, 2021, 2026, and 2034
	LCC	9.74	69.3	876	78.7	4.75	Keep CFL; LED in 2019, 2025, and 2034
	Burnout	10.64	88.9	965	93.9	5.72	Keep CFL; LED in 2025
12	Cost	8.31	64.2	750	70.1	4.27	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Energy	8.34	63.8	749	69.8	4.26	Keep CFL; LED in 2016, 20, 24, 29, and 38
	Emissions	8.50	62.0	757	69.1	4.22	Keep CFL; LED in 2016, 18, 20, 24, 28, 34, and 46
	LCC	8.33	63.2	752	69.6	4.25	Keep CFL; LED in 2017, 20, 23, 28, 33, and 43
	Burnout	8.62	69.4	777	74.3	4.53	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	10.25	83.2	906	88.0	5.43	Keep LED; LED in 2025
	Energy	10.25	83.2	906	88.0	5.43	Keep LED; LED in 2025
	Emissions	10.26	83.2	907	87.9	5.44	Keep LED; LED in 2024
	LCC	10.25	83.3	907	88.0	5.42	Keep LED; LED in 2025
	Burnout	16.63	147.4	1529	151.2	10.05	Keep LED

1.5	Cost	9.98	83.2	906	87.9	5.42	Keep LED; LED in 2025
	Energy	9.98	83.2	906	87.9	5.42	Keep LED; LED in 2025
	Emissions	10.22	71.4	909	81.1	4.93	Keep LED; LED in 2020 and 2029
	LCC	10.06	72.3	909	81.8	4.95	Keep LED; LED in 2022 and 2031
	Burnout	16.63	147.4	1529	151.2	10.05	Keep LED
3	Cost	9.30	71.9	841	78.6	4.78	Keep LED; LED in 2021 and 2030
	Energy	9.32	71.5	840	78.2	4.77	Keep LED; LED in 2020 and 2030
	Emissions	9.57	66.7	854	76.0	4.63	Keep LED; LED in 2018, 2024, and 2032
	LCC	9.41	67.6	854	76.7	4.65	Keep LED; LED in 2020, 2026, and 2035
	Burnout	12.82	110.2	1167	114.8	7.08	Keep LED; LED in 2037
12	Cost	8.13	63.3	739	69.1	4.22	Keep LED; LED in 2018, 22, 26, 31, and 39
	Energy	8.15	62.9	737	68.8	4.21	Keep LED; LED in 2017, 20, 24, 30, and 39
	Emissions	8.31	61.4	747	68.3	4.18	Keep LED; LED in 2016, 19, 21, 24, 29, 35, and 47
	LCC	8.13	63.3	739	69.1	4.22	Keep LED; LED in 2018, 22, 26, 31, and 39
	Burnout	8.50	69.9	772	74.4	4.53	Keep LED; LED in 2020, 2029, and 2043

A.6.10 US average in an all-natural gas scenario

Table A.24: Optimal replacement policy for typical US consumers if the grid mix becomes 100% natural gas by 2050.

HOU [hr/d]	Objective/ Scenario	Cost to Consumer [$/HOU]	Electricity [kWh/HOU]	Primary Energy [MJ/HOU]	GHG Emissions [kg CO_2e/HOU]	Social Cost of Carbon [$/HOU]	Replacement Schedule (2015-2050) [Purchase Year]
Case 1							
1/7	Cost	19.67	147.4	1330	81.5	5.29	LED in 2015
	Energy	29.53	87.7	1218	111.4	5.96	CFL in 2015; LED in 2024
	Emissions	19.67	147.4	1330	81.5	5.29	LED in 2015
	LCC	19.67	147.4	1330	81.5	5.29	LED in 2015
	Burnout	19.67	147.4	1330	81.5	5.29	LED in 2015
1.5	Cost	12.27	75.4	810	51.6	3.02	CFL in 2015; LED in 2021 and 2031
	Energy	12.34	87.7	793	52.9	3.16	CFL in 2015; LED in 2024
	Emissions	12.39	74.0	808	51.2	3.00	CFL in 2015; LED in 2020 and 2029
	LCC	12.27	75.1	808	51.5	3.01	CFL in 2015; LED in 2021 and 2030
	Burnout	15.57	118.1	1017	67.4	4.05	CFL in 2015; LED in 2036
3	Cost	10.56	74.4	717	45.3	2.69	CFL in 2015; LED in 2020 and 2030
	Energy	10.58	74.1	716	45.1	2.69	CFL in 2015; LED in 2020 and 2030
	Emissions	11.31	71.5	765	44.9	2.68	LED in 2015, 2020, and 2030
	LCC	10.56	74.3	716	45.2	2.69	CFL in 2015; LED in 2020 and 2030
	Burnout	11.53	88.9	776	50.2	3.02	CFL in 2015; LED in 2025
12	Cost	8.53	64.4	604	37.2	2.25	CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.56	64.1	603	37.1	2.25	CFL in 2015; LED in 2017, 20, 24, 30, and 40
	Emissions	8.66	62.8	611	36.8	2.23	LED in 2015, 17, 20, 24, 29, and 38
	LCC	8.55	64.4	605	37.3	2.26	CFL in 2015; LED in 2017, 21, 24, 31, and 39
	Burnout	8.85	69.4	618	38.6	2.34	CFL in 2015; LED in 2017, 24, and 36
Case 2 with $l_1 = IL$							
1/7	Cost	19.43	148.7	1321	81.3	5.10	Keep IL; LED in 2016
	Energy	29.73	87.7	1218	111.5	5.96	Discard IL; CFL in 2015; LED in 2024
	Emissions	19.51	147.5	1319	81.0	5.16	Keep IL; LED in 2015
	LCC	19.43	149.1	1323	81.4	5.09	Keep IL; LED in 2016
	Burnout	52.12	439.1	3613	228.2	13.22	Keep IL; LED in 2034
1.5	Cost	12.29	75.4	810	51.7	3.02	Discard IL; CFL in 2015; LED in 2021 and 2031
	Energy	12.36	87.7	793	52.9	3.16	Discard IL; CFL in 2015; LED in 2024
	Emissions	12.41	74.0	808	51.2	3.00	Discard IL; CFL in 2015; LED in 2020 and 2029
	LCC	12.29	75.1	808	51.5	3.01	Discard IL; CFL in 2015; LED in 2021 and 2030
	Burnout	19.38	151.6	1336	82.3	5.07	Keep IL; LED in 2016
3	Cost	10.57	74.4	717	45.3	2.70	Discard IL; CFL in 2015; LED in 2020 and 2030
	Energy	10.59	74.1	716	45.1	2.69	Discard IL; CFL in 2015; LED in 2020 and 2030
	Emissions	11.32	71.5	765	44.9	2.68	Discard IL; LED in 2015, 2020, and 2030
	LCC	10.57	74.3	716	45.2	2.69	Discard IL; CFL in 2015; LED in 2020 and 2030
	Burnout	13.61	105.8	916	59.1	3.44	Keep IL; CFL in 2015; LED in 2026
12	Cost	8.54	64.4	604	37.2	2.25	Discard IL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.56	64.1	603	37.1	2.25	Discard IL; CFL in 2015; LED in 2017, 20, 24, 30, and 40
	Emissions	8.67	62.7	612	36.8	2.23	Discard IL; LED in 2015, 17, 20, 24, 29, and 37
	LCC	8.54	64.1	604	37.2	2.25	Discard IL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	9.34	73.5	651	40.7	2.44	Keep IL; CFL in 2015; LED in 2017, 25, and 36
Case 2 with $l_1 = HL$							
1/7	Cost	18.17	142.3	1249	77.1	4.74	Keep HL; LED in 2017
	Energy	29.73	87.7	1218	111.5	5.96	Discard HL; CFL in 2015; LED in 2024
	Emissions	18.20	141.7	1249	77.0	4.77	Keep HL; LED in 2017
	LCC	18.17	142.6	1250	77.2	4.73	Keep HL; LED in 2017
	Burnout	64.84	574.9	4623	292.2	19.42	Keep HL

1.5	Cost	12.29	75.4	810	51.7	3.02	Discard HL; CFL in 2015; LED in 2021 and 2031
	Energy	12.36	87.7	793	52.9	3.16	Discard HL; CFL in 2015; LED in 2024
	Emissions	12.41	74.0	808	51.2	3.00	Discard HL; CFL in 2015; LED in 2020 and 2029
	LCC	12.29	75.1	808	51.5	3.01	Discard HL; CFL in 2015; LED in 2021 and 2030
	Burnout	33.24	277.8	2303	145.2	8.26	Keep HL; LED in 2030
3	Cost	10.57	74.4	717	45.3	2.70	Discard HL; CFL in 2015; LED in 2020 and 2030
	Energy	10.59	74.1	716	45.1	2.69	Discard HL; CFL in 2015; LED in 2020 and 2030
	Emissions	11.32	71.5	765	44.9	2.68	Discard HL; LED in 2015, 2020, and 2030
	LCC	10.57	74.3	716	45.2	2.69	Discard HL; CFL in 2015; LED in 2020 and 2030
	Burnout	21.79	178.4	1511	94.7	5.37	Keep HL; LED in 2022
12	Cost	8.54	64.4	604	37.2	2.25	Discard HL; CFL in 2015; LED in 2017, 21, 25, 31, and 40
	Energy	8.56	64.1	603	37.1	2.25	Discard HL; CFL in 2015; LED in 2017, 20, 24, 30, and 40
	Emissions	8.67	62.7	612	36.8	2.23	Discard HL; LED in 2015, 17, 20, 24, 29, and 37
	LCC	8.54	64.1	604	37.2	2.25	Discard HL; CFL in 2015; LED in 2017, 21, 25, 30, and 39
	Burnout	11.51	91.8	804	49.9	2.89	Keep HL; LED in 2016, 23, 34, and 49
Case 2 with $l_1 = CFL$							
1/7	Cost	10.84	87.7	749	46.9	2.88	Keep CFL; LED in 2024
	Energy	10.84	87.7	749	46.9	2.88	Keep CFL; LED in 2024
	Emissions	10.84	87.7	749	46.9	2.88	Keep CFL; LED in 2024
	LCC	10.84	87.8	749	46.9	2.88	Keep CFL; LED in 2024
	Burnout	18.54	164.3	1321	83.5	5.55	Keep CFL
1.5	Cost	10.49	75.4	765	45.5	2.72	Keep CFL; LED in 2021 and 2031
	Energy	10.56	87.7	749	46.7	2.87	Keep CFL; LED in 2024
	Emissions	10.61	74.0	763	45.1	2.70	Keep CFL; LED in 2020 and 2029
	LCC	10.49	75.1	764	45.4	2.72	Keep CFL; LED in 2021 and 2030
	Burnout	13.79	118.1	972	61.3	3.75	Keep CFL; LED in 2036
3	Cost	9.67	74.4	694	42.2	2.55	Keep CFL; LED in 2020 and 2030
	Energy	9.69	74.1	693	42.1	2.54	Keep CFL; LED in 2020 and 2030
	Emissions	9.85	68.5	712	42.0	2.52	Keep CFL; LED in 2018, 2024, and 2033
	LCC	9.67	74.3	694	42.2	2.55	Keep CFL; LED in 2020 and 2030
	Burnout	10.64	88.9	754	47.1	2.87	Keep CFL; LED in 2025
12	Cost	8.31	64.2	598	36.4	2.21	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Energy	8.33	64.1	597	36.3	2.21	Keep CFL; LED in 2017, 20, 24, 30, and 40
	Emissions	8.35	63.7	598	36.3	2.21	Keep CFL; LED in 2016, 19, 23, 29, and 38
	LCC	8.31	64.2	598	36.4	2.21	Keep CFL; LED in 2017, 21, 25, 30, and 39
	Burnout	8.62	69.4	613	37.8	2.30	Keep CFL; LED in 2017, 2024, and 2036
Case 2 with $l_1 = LED$							
1/7	Cost	10.25	83.2	709	44.3	2.73	Keep LED; LED in 2025
	Energy	10.25	83.2	709	44.3	2.73	Keep LED; LED in 2025
	Emissions	10.25	83.2	710	44.3	2.73	Keep LED; LED in 2025
	LCC	10.25	83.3	709	44.3	2.73	Keep LED; LED in 2025
	Burnout	16.63	147.4	1186	74.9	4.98	Keep LED
1.5	Cost	9.98	83.2	709	44.2	2.73	Keep LED; LED in 2025
	Energy	9.98	83.2	709	44.3	2.73	Keep LED; LED in 2025
	Emissions	10.16	71.5	738	43.6	2.63	Keep LED; LED in 2021 and 2030
	LCC	10.06	72.5	738	43.9	2.64	Keep LED; LED in 2022 and 2031
	Burnout	16.63	147.4	1186	74.9	4.98	Keep LED
3	Cost	9.30	71.9	671	40.8	2.47	Keep LED; LED in 2021 and 2030
	Energy	9.31	71.7	670	40.7	2.47	Keep LED; LED in 2021 and 2030
	Emissions	9.33	71.5	670	40.7	2.47	Keep LED; LED in 2020 and 2030
	LCC	9.30	71.8	670	40.8	2.47	Keep LED; LED in 2021 and 2030
	Burnout	12.82	110.2	906	57.1	3.52	Keep LED; LED in 2037
12	Cost	8.13	63.3	589	35.9	2.19	Keep LED; LED in 2018, 22, 26, 31, and 39
	Energy	8.16	64.5	586	35.9	2.19	Keep LED; LED in 2018, 22, 28, and 37
	Emissions	8.16	62.8	588	35.7	2.18	Keep LED; LED in 2017, 20, 24, 29, and 38
	LCC	8.13	63.2	588	35.8	2.19	Keep LED; LED in 2018, 21, 26, 31, and 39
	Burnout	8.50	69.9	606	37.7	2.30	Keep LED; LED in 2020, 2029, and 2043

Appendix B Chapter 3 Supplemental Information

B.1 Market information on commercial lighting replacement products

Figure B.1 and Figure B.2 compare the material cost and power draw of different lighting replacement products for the 2x4 T8 troffer by lighting type (1000bulbs 2019). Linear curve fits are applied to assess the sensitivity of cost and wattage rating to lumen rating. As shown, material cost has no or mixed relationship with lumen rating whereas power draw increases with the parameter. The slope (W/lm) between power draw and lumen rating is an inverse of lighting efficacy (lm/W), which is a measure of how energy efficient a lighting product is.

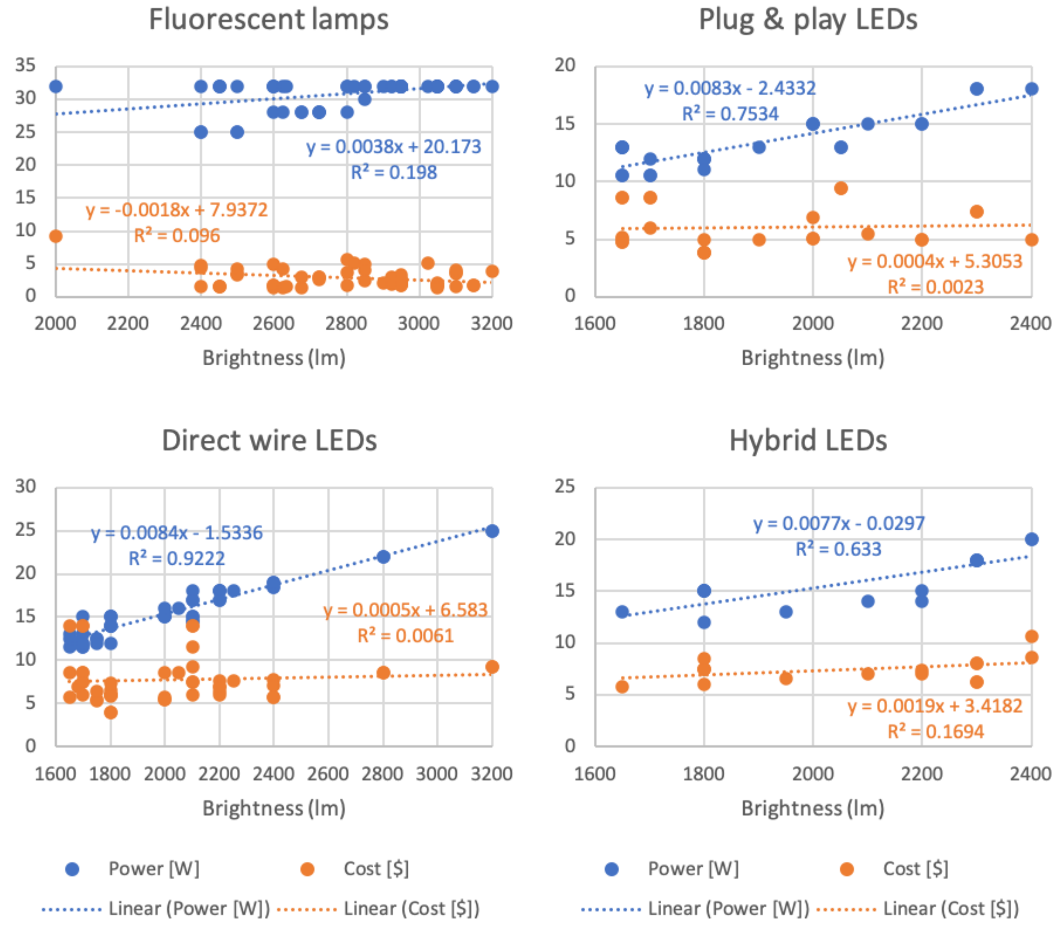


Figure B.1: Lamp power rating and cost of fluorescent, plug & play LED, direct wire LED, and hybrid LED lamps.

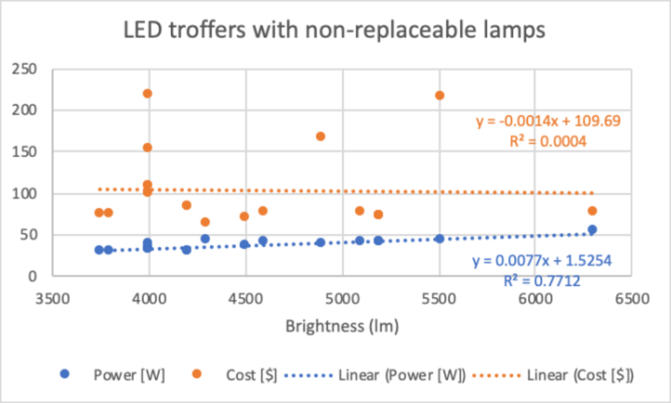


Figure B.2: System power rating and cost of LED troffers with non-replaceable lamps.

Figure B.3 compares the system efficacy of different replacement options for the 2x4 T8 troffer. Note the performance of the hybrid LEDs is taken here by assuming they are used as a ballast-bypass half the time. Depending on the ballast factor of the initial ballast, some retrofit lamps would not make the minimum system brightness requirement. At low to normal ballast factors, the number of performance-equivalent LED options is 89-90%. However, at the high ballast factor, the pool of LED options is down to 45%. Meanwhile, despite having overall lower efficacy than LEDs, all fluorescent replacement lamps surpass the brightness requirement. Since fluorescent lamps generally offer higher lumen level that most LED retrofit options, they may be better contenders for applications requiring high light levels, such as industrial spaces. However, if a reduction in the light level is possible, more LED options would be available as well as greater energy savings could be realized. All lamp options below the brightness requirement are excluded from the LCC analysis.

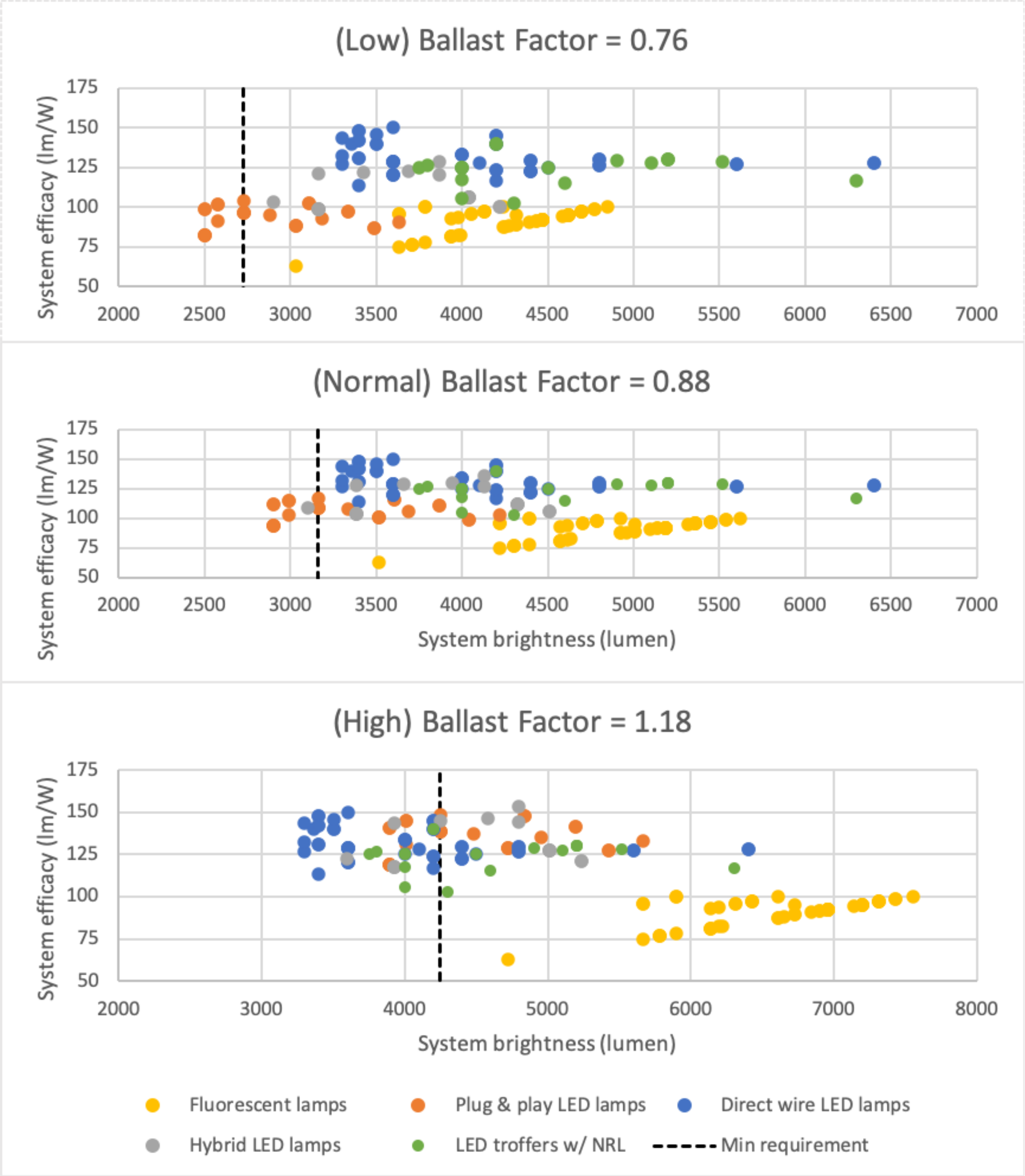


Figure B.3: Comparison of system efficacy and material cost for 6 types of replacement lighting products at three ballast factors. (Note: the system efficacies of LED troffers w/ RL are not plotted as they are the same as those of direct wire LED lamps. Material cost includes ballast for fluorescent lamps and plug & play LEDs.) (RL = with replaceable lamps, NRL = with non-replaceable lamps, Min. reqmt = minimum requirement, BF = ballast factor)

B.2 Life cycle cost analysis – mathematical formulation

The capital recovery factor (CRF) for payment made at the *beginning* of the year is calculated as follows:

$$CRF = \frac{r(1+r)^n}{((1+r)^n - 1)(1+r)} \tag{0.38}$$

where r is the real discount factor and n is the number of years in the time horizon.

The present value (PV) of an annualized cost (AC) over time is calculated as follows:

$$PV = \frac{AC}{CRF(r,n)} \tag{0.39}$$

where $CRF(r,n)$ indicates that the CRF is a function of r and n.

The annualized expected failure rate ($AEFR$) of a product or component i is calculated as follows (US DOE 2014b):

$$AEFR_i = \frac{AO}{LT_i} \tag{0.40}$$

where AO is the annual operation (number of hours operated [hr/yr]) and LT_i is the rated lifetime [hr] of the product or component i.

The annualized maintenance cost ($AC_{mainten.}$) can be generalized as follows:

$$\begin{aligned} AC_{mainten.} &= AC_{mat'l} + AC_{labor} + AC_{eol} \\ &= \sum_{i \in S} (C_{mat'l,i} + C_{labor,i} + C_{recy.,i}) AEFR_i \end{aligned} \tag{0.41}$$

where $AC_{mat'l}$, AC_{labor}, and $AC_{recy.}$ are the annualized material, labor, and recycling cost, respectively. i is the element in a S set of components making up the lighting system. $C_{mat'l,i}$, $C_{labor,i}$, $C_{recy.,i}$ are the material, labor, and recycling cost of component i.

The annual electricity consumption (AE) [kWh] is as follows:

$$AE = W_{sys}(AO)\left(\frac{1kWh}{1000\,Wh}\right) \tag{0.42}$$

where W_{sys} is the system wattage.

The annualized electricity cost ($AC_{electr.}$) is as follows:

$$AC_{electr.} = AE(ER) \tag{0.43}$$

where ER is the electricity rate. Both $AC_{mainten.}$ and $AC_{electr.}$ are then transformed to $PV_{mainten.}$ and $PV_{electr.}$, respectively, using eq (2).

The social cost of carbon (SCC) per metric ton, obtained from the US EPA, increases linearly each year. The total PV social cost of carbon (PV_{scc}) over the time horizon is calculated as follows:

$$PV_{scc} = AE \cdot CE_{electr} \cdot \sum_{i=0}^{n-1} \frac{SCC_i}{(1+r)^i} \tag{0.44}$$

where CE_{electr} is the carbon emissions per kWh of electricity and SCC_i is the social cost of carbon per metric ton in year i.

With recycling occurring at the end of the time horizon, the PV recycling cost ($PV_{recy.}$):

$$PV_{recy.} = \frac{C_{recy.}}{(1+r)^{n-1}} \tag{0.45}$$

The total PV life cycle cost (PV_{LCC}) is therefore:

$$PV_{LCC} = PV_{mat'l} + PV_{labor} + PV_{mainten.} + PV_{electr.} + PV_{recy.} + PV_{scc} \tag{0.46}$$

where $PV_{mat'l}$ and PV_{labor} are the upfront costs of material and labor incurred at the beginning of the time horizon.

The normalized LCC [\$/klm] is calculated as follows:

$$PV_{NLCC} = \frac{PV_{LCC}}{L_{sys}/1000} \tag{0.47}$$

where PV_{NLCC} is the PV of the LCC normalized per klm, L_{sys} is the lumen output of the lighting system.

Simple payback (SI) is a ratio between the extra investment required for an option and the annual cost savings from that option relative to a benchmark. In terms of the LED options:

$$SI = \frac{(PV_{mat'l,LED} + PV_{labor,LED}) - (PV_{mat'l,FL} + PV_{labor,FL})}{\left(AC_{eletr,LED} + AC_{mainten,LED}\right) - \left(AC_{eletr,FL} + AC_{mainten,FL}\right)} \tag{0.48}$$

where FL denotes fluorescent lamps.

B.3 Influence of ballast factor on life cycle cost

Figure B.4 presents the LCC composition, the NLCC, and the system efficacy compared across three ballast factors – 0.76, 0.88, and 1.18. The operating conditions consist of 2,000 hr/yr for 10 years, electricity price as \$0.12/kWh electricity price, and social cost of carbon at \$52.92/metric ton CO_2.

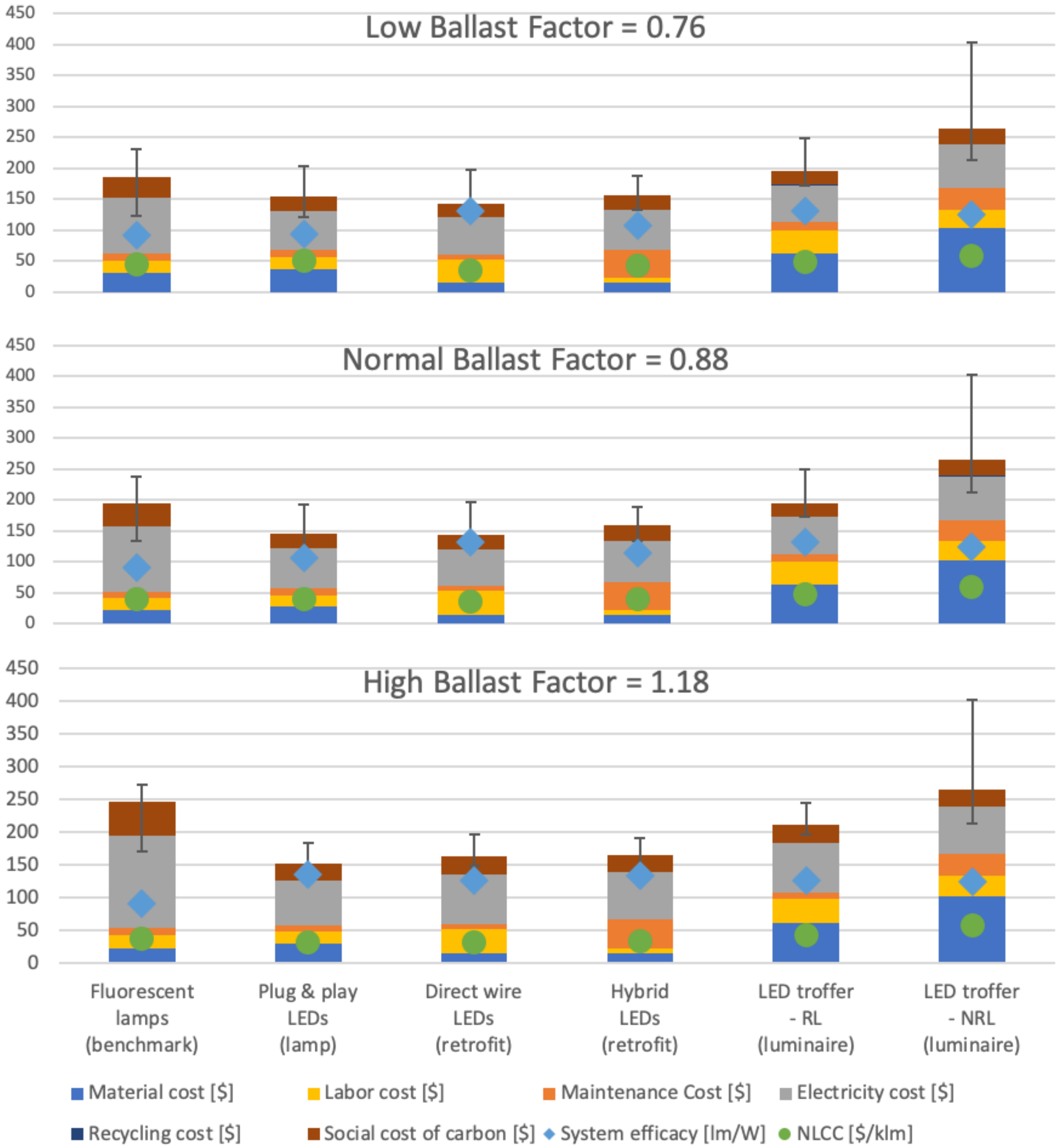
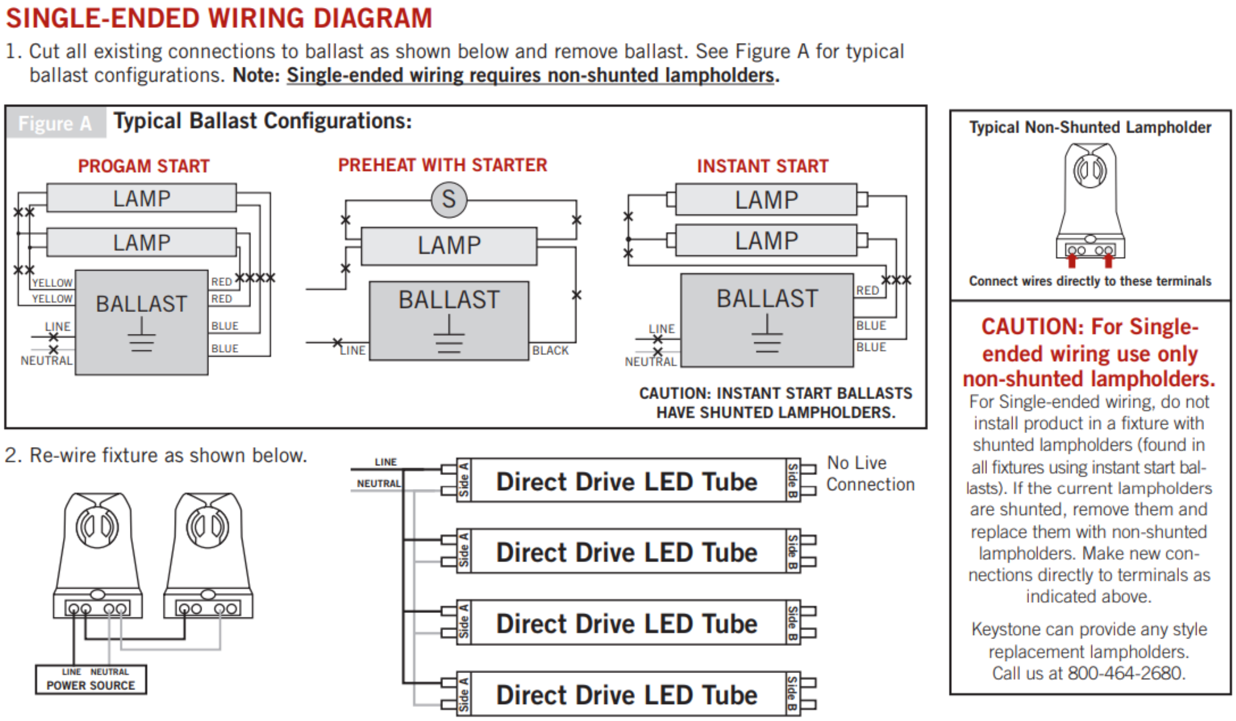


Figure B.4: Life cycle cost (LCC) in present value of six replacement options for a 2x4 2-lamp T8 recessed troffer operating at 2000 hr/yr for 10 years, $0.12/kWh, $52.92/metric ton CO2, and three ballast factors (0.76, 0.88, 1.18). (LCC/klm means LCC normalized per thousand lumens. Bars represent the minimum and maximum of the LCC based on the surveyed retrofit products.)

B.4 LED retrofit rewiring schematics



SINGLE-ENDED WIRING DIAGRAM

1. Cut all existing connections to ballast as shown below and remove ballast. See Figure A for typical ballast configurations. **Note: Single-ended wiring requires non-shunted lampholders.**

Figure A Typical Ballast Configurations:

CAUTION: INSTANT START BALLASTS HAVE SHUNTED LAMPHOLDERS.

2. Re-wire fixture as shown below.

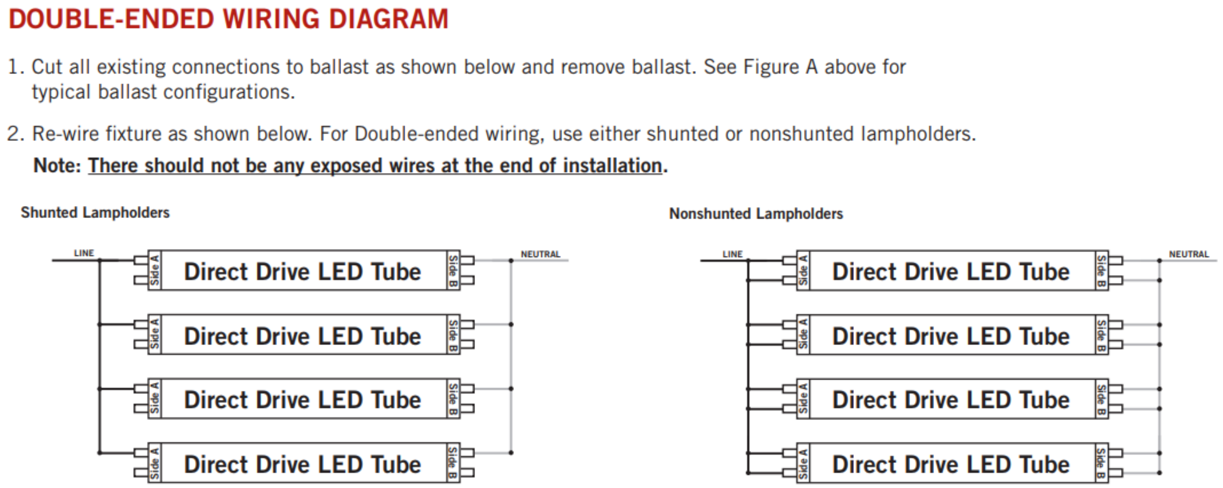
Typical Non-Shunted Lampholder

Connect wires directly to these terminals

CAUTION: For Single-ended wiring use only non-shunted lampholders. For Single-ended wiring, do not install product in a fixture with shunted lampholders (found in all fixtures using instant start ballasts). If the current lampholders are shunted, remove them and replace them with non-shunted lampholders. Make new connections directly to terminals as indicated above.

Keystone can provide any style replacement lampholders. Call us at 800-464-2680.

Figure B.5: Wiring diagrams for single ended direct drive LED lamps. (Image credit: Atlanta Light Bulbs 2020)



DOUBLE-ENDED WIRING DIAGRAM

1. Cut all existing connections to ballast as shown below and remove ballast. See Figure A above for typical ballast configurations.

2. Re-wire fixture as shown below. For Double-ended wiring, use either shunted or nonshunted lampholders. **Note: There should not be any exposed wires at the end of installation.**

Figure B.6: Wiring diagrams for double ended direct drive LED lamps. (Image credit: Atlanta Light Bulbs 2020)

Appendix C Chapter 4 Supplemental Information

C.1 Rare earth element and critical metal recovery process modeling

Rare earth element (REE) recovery from spent fluorescent lighting and Critical metal (CM) recovery from spent LED lighting are modeled per proposed process flow by Tunsu et al. (2016) and Swain et al. (2015), respectively. These methods are developed at the laboratory and describe pilot-scale operating conditions. To simulate more realistic (operating conditions at commercial level in this study, the process flows are scaled up using a framework proposed by Piccinno et al. (2016). Their engineering-based framework, along with expert insights on average industrial process parameters, are designed specifically for LCA modeling purposes and has been used to estimate the environmental impacts of various emerging technologies, including battery materials, geopolymer concrete, recycling methods, and biofuel production. The following sections describe the REE recovery processes in detail, along with a summary of the material/energy inputs and emission/waste outputs estimated for the LCA of recycling an 8ft linear fluorescent fixture and an 8ft linear LED fixture in Appendices B and C, respectively. The LED fixture modeled is a direct replacement of its fluorescent counterpart in real life. A sample calculation for scaling up the inventories to commercial grade is provided in Appendix C on the modeling of the LED fixture recycling.

C.2 Yttrium and europium recovery from linear fluorescent fixture waste

Figure C.1 illustrates a two-stage leaching process proposed by Tunsu et al. (2016) for recovering REE (primarily yttrium (Y) and europium (Eu), which dominate the REE content) from fluorescent waste dust containing phosphors. This process flow sheet was chosen for its high Y and Eu recovery efficiency. The laboratory setup is illustrated in Fig Figure C.2. The process flow offers two ways to remove mercury from the waste dust: 1) by high heat (distillation), or 2) by chemical leaching using a I_2/KI solution. Distillation is modeled in this study since it is the more common practice Binnemans et al. (2013).

After the mercury removal, the residual undergoes a series of leaching and filtration processes. Leaching is done in a 5L reactor mixing at 400 rpm. First it is leached in a 1M HNO_3 solution at a 10% weight-to-volume ratio (w/v) for 10 min and filtered to remove impurity metals (i.e. Ca). The Ca-rich leachate, which can be processed further for recovery, is regarded as wastewater in this study. The residue is leached in a 2M HNO_3 solution at 10% w/v for 24h and then separated into solid (residue) and liquid (leachate). The residue can be processed further to recover the less valuable or concentrated REE (i.e. Ce, Gd, La, and Tb); however, it is regarded as a solid waste in this study.

The aqueous leachate, which is rich in Y and Eu, undergoes solvent extraction by mixing with an organic solvent containing 35% vol Cyanex 923[16] in kerosene, at a 2:1 organic-to-aqueous (O:A) feed ratio. A REE-rich aqueous solution is stripped from the organic phase using 4M HCl in a mixer-settler system at 700rpm and 1:1 O:A ratio. 10 min is assumed for each mixing process. The depleted organic phase is regenerated by washing with water at a 1:1 feed ratio for 1 min (to remove HCl) and reused as a Cyanex solvent. A 90% efficiency is assumed for the organic phase regeneration process. This study includes additional processing of the REE-rich solution to recover

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[16] Cyanex 923 weights 348g/mole and contains 93% trialkylphosphine oxides ($C_{18}H_{39}OP$), which can be produced by the oxidation of tertiary phosphines (Ahmed et al. 2013). The inventory for Cyanex 923 is approximated based on the molar mass distribution of different compounds, i.e. 9.8% phosphine (i.e. phosphane), 4.6% oxygen, and 85.6% organic compounds in SimaPro.

and purify Y and Eu. The solution is treated with oxalic acid, the consumption of which is described by Amato et al. (2019), followed by a thermal treatment for 2 h at 800°C.

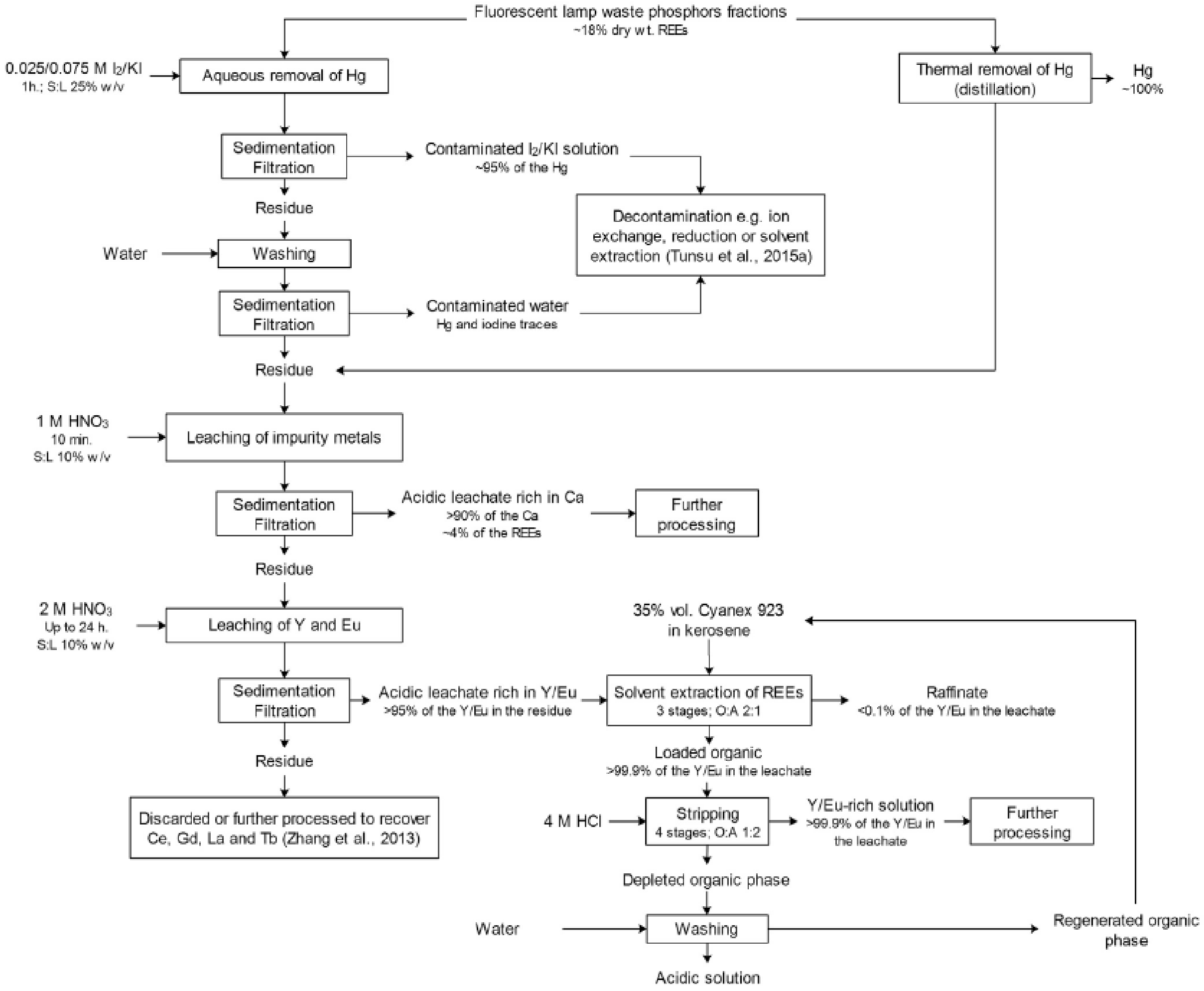

Figure C.1: Proposed flow sheet for REE recovery from fluorescent lamp waste. (Adapted from Tunsu et al. 2016)

The waste dust sieved and collected from crushed florescent lamps in Tunsu et al. (2016)'s study contains approximately 18% REE by dry weight, along with 40-50% glass and non-soluble fractions. The overall recovery efficiency of Y and Eu is approximately 91% and the ratio of Y to Eu in the precipitate is 95:5 w/w. The stripped solution can go back for additional processing if the REE content remains high. In this study, all recoverable REE is assumed to be captured wholly during the second leaching stage, where the remaining solution is considered as wastewater. The material and energy inputs for the processes are calculated based on stoichiometry, assuming negligible losses and commercial operation per Piccinno et al. (2016). Table C.1 provides a summary of the inputs and outputs for the full recycling process of fluorescent linear fixture, starting from collection and disassembly, followed by a cut-and-blow processing of lamp tubes from Apisitpuvakul et al. (2008), whom examined fluorescent tube recycling in Thailand (without REE recovery).

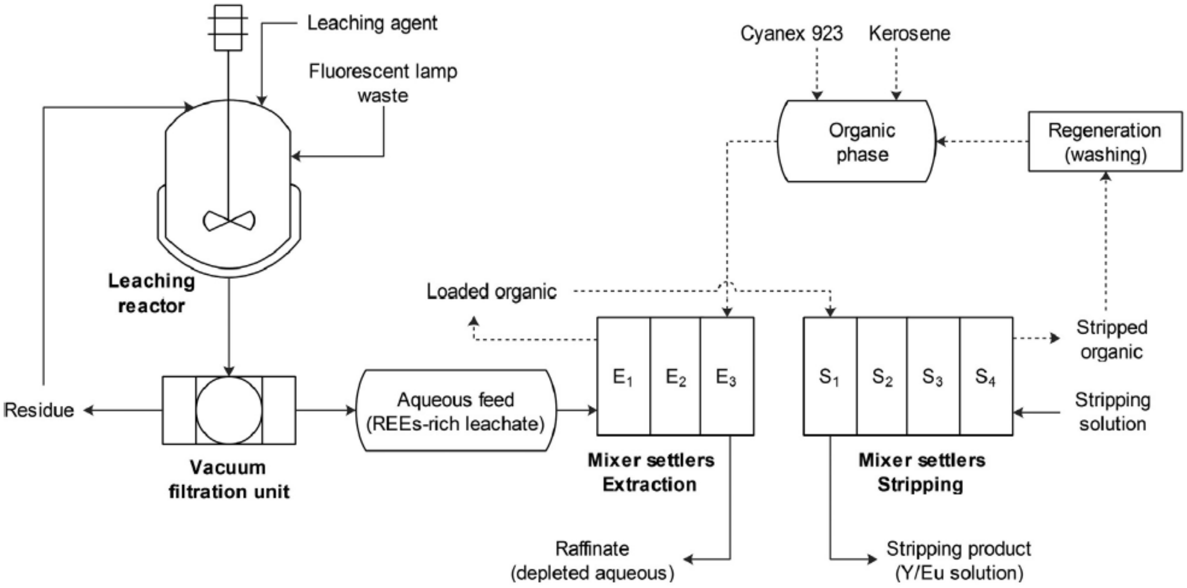

Figure C.2: Laboratory setup for REE recovery from fluorescent lamp waste. (adapted from Tunsu et al. 2016)

Table C.1: Input-output for an 8” fluorescent linear fixture recycling with hydrometallurgical leaching of rare earth elements from its phosphor fraction.

Input	**Unit**	**Qty**	**Output**	**Unit**	**Qty**	**Source/Note**
Spent fluorescent fixture	kg	6.83				
Lorry (21t)	tkm	2.05E-1				
Disassembly of fixture and shredding						

Manual disassembly*	kg	6.83	Steel	Kg	2.42E-1	*An ecoinvent process. Lamp tubes are removed manually from fixture.
Shredding*	kg	6.44	Aluminum	Kg	5.44	
			Copper	Kg	8.00E-3	
			Solid waste	Kg	7.48E-1	
			Lamps	kg	3.93E-1	
Disassembly of tubes via cut & blow						
Lamps	kg	3.93E-1	Hg in air	Kg	8.76E-8	Apisitpuvakul et al. 2008, Tähkämö et al. 2014
Electricity	kWh	5.80E-3	Hg in water	Kg	1.47E-9	
Heat	kWh	8.97E-4	Cullet	Kg	3.38E-1	
Water	kg	3.59E-1	Phosphor fraction	kg	4.52-2	
			Aluminum caps	kg	9.75E-3	
Mercury distillation						
Phosphor fraction	kg	4.52E-2	Hg (recovered)	kg	1.99E-5	Binnemans et al. 2013, Tunsu et al. 2016
Aluminum caps	kg	9.75E-3	Aluminum	kg	9.75E-3	
Heat	kWh	1.37E-2				
REE leaching						
Phosphor fraction	kg	4.52E-2	Yttrium	kg	4.11E-2	Tunsu et al. 2016, Amato et al. 2019
Nitric acid	kg	1.14E-1	Europium	kg	2.16E-3	
Cyanex 923[17]	kg	2.80E-2	Wastewater	kg	2.93	
Kerosene	kg	4.79E-2	Solid waste	kg	2.39E-3	
Hydrochloric acid	kg	6.64E-2				
Oxalic acid[18]	kg	6.48E-2				
Water	kg	2.61				
Heat	kWh	4.89E-3				
Electricity	kWh	6.95E-4				
Infrastructure	unit	1.51E-9				

C.3 Gallium recovery from linear LED fluorescent fixture waste

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[17] Cyanex 923 weights 348g/mole and contains 93% trialkylphosphine oxides ($C_{18}H_{39}OP$), which can be produced by the oxidation of tertiary phosphines (Ahmed et al. 2013). The inventory for Cyanex 923 is approximated based on the molar mass distribution of different compounds, i.e. 9.8% phosphine (i.e. phosphane), 4.6% oxygen, and 85.6% organic compounds in SimaPro.

[18] Oxalic acid is modeled as a product synthesized using sugar and nitric acid, aided by a vanadium pentroxide catalyst, based on the method from prepchem: https://www.prepchem.com/synthesis-of-oxalic-acid/. LCI on vanadium pentroxide is available in Weber et al. (2018)'s supplemental information: https://pubs.acs.org/doi/suppl/10.1021/acs.est.8b02073/suppl_file/es8b02073_si_001.pdf

Swain et al. (2015) recommended a two-stage leaching process for recovering indium (In) and gallium (Ga) from LED waste dust as illustrated in Figure C.3. First the raw waste is leached to recover In at 0.32% weight-to-weight ratio (w/w) by mixing with 4M HCl at 100°C, 100g/L pulp density, and 400 rpm mixing rate for 1 h. Then the residue is separated from the leachate and mixed with Na_2CO_3 at a 1:1 weight ratio. Then the mixture is ball-milled at 150 rpm rotational speed for 24h, dried in an oven at 60°C for 4h, and annealed (heat treated) in a furnace at 1,000°C for 4h. The annealed mixture is leached using the leachate recycled from the first leaching process and under the same conditions as the first leaching process. The lixiviant reuse captures some of the Ga dissolved in the leachate, bringing the overall Ga leaching efficiency to 97%. The leached mixture is separated into solids and a Ga-rich liquor. The solid residue is analyzed and can go back for additional leaching if its Ga content remains high. In this study, all recoverable Ga is assumed to be captured during the second leaching stage.

The Ga-rich liquor obtained after the two-stage acid extraction undergoes a solvent extraction method proposed by Ahmed et al. (2013) to recover the Ga. The liquor (aqueous) is mixed with a Cyanex 923 in kerosene solvent (organic) at a 1:1 O:A feed ratio. The molarity of Cyanex in the solvent is five times the molarity of Ga in the liquor. The organic phase is stripped from the solution using 1M HCl at 1:1 O:A ratio to obtain Ga at a 92% overall solvent extraction efficiency. The depleted organic phase is regenerated by washing with water at a 1:1 feed ratio for 1 min to remove the acid and reused as a Cyanex solvent. A 90% efficiency is assumed for the organic phase regeneration process. The material and energy inputs for Ga recovery from leaching to solvent extraction are calculated based on stoichiometry, assuming negligible losses and commercial operation per Piccinno et al. (2016).

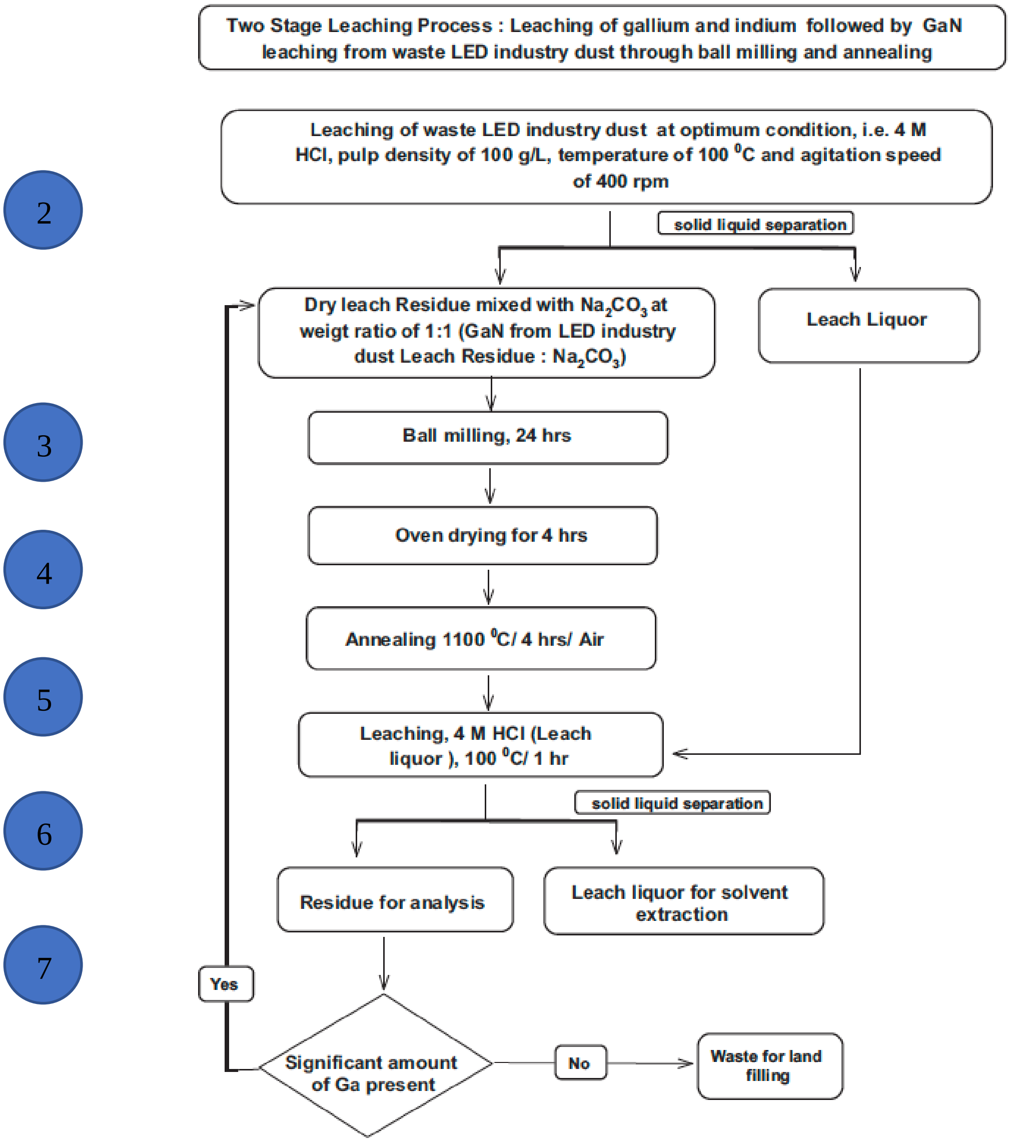

Figure C.3: Proposed process flow for Indium and Gallium recovery from LED waste dust through two-stage leaching and annealing. (Adapted from Swain et al. 2015)

Swain et al. (2015)'s flow sheet is chosen for its high leaching rate for Ga while using "minimum energy" and no hazardous chemicals. The process flow is developed for recovering REE from MOCVD dust, or dust collected from the metal organic vapor deposition process of GaN semiconductor manufacturing. It is applicable also to the treatment of GaN-rich waste streams, such as LED lamp wastes and electronic wastes. To adapt this method for LED lamp recycling, the REE concentration in the waste dust is adjusted from over 97 w/w% to 0.234 w/w%, which is concentration of Ga in the LED chips modelled. In this study, the LED wastes are generated from crushed LED chips after they are separated from the rest of the luminaire or light source (Nagy et al. 2017), and do not contain In. The overall recovery efficiency for Ga from leaching to solvent extraction is 89%.

C.3.1 Lixiviant requirement

The chemical reaction for the leaching process can be approximately described by the equation below:

$$NaGaO_{2(s)} + 4HCl_{(l)} \rightarrow GaCl_3 + NaCl + 2H_2O \tag{0.49}$$

The LED chips are removed from the 8-ft LED fixture and crushed to generate 32.4g of LED waste dust, which contains 0.234 w/w% Ga. The specific heat capacity of waste dust is 0.397kJ/kgK based on the composition of the LED chips. At a pulp density of 100 g/L, 3.24E-4 m3 of 4M HCl solution is needed for the amount of LED modelled per functional unit (FU) in our study, as shown below:

$$3.24 \times 10^{-2} kg\ LED \left(\frac{1m^3}{100kg}\right) = 3.24 \times 10^{-4}\ m^3\ 4M\ HCl$$

This is equivalent to **3.23E-1 kg water and 4.73E-2 kg HCl per functional unit** of waste dust, assuming negligible contribution of the salt to the solution volume:

$$3.24 \times 10^{-4}\ m^3\ H_2O \left(\frac{997kg}{1m^3\ H_2O}\right) = 3.23 \times 10^{-1}\ kg\ H_2O/FU$$

$$3.24 \times 10^{-1}\ L\ H_2O \left(\frac{4\ mol\ HCl}{L\ H_2O}\right)\left(\frac{0.0365\ kg}{mol\ HCl}\right) = 4.73 \times 10^{-2}\ kg\ HCl/FU$$

C.3.2 Stage 1 leaching (Indium leaching)

C.3.2.1 Heat requirement

The heat required for the leaching processes consists of: 1) heating the solution to a target temperature (100°C) from an initial temperature (room temperature, 25°C) (Q_{heat}), and 2) maintaining the target temperature for a certain period of time (1 h) (Q_{loss}), both of which subjected to the efficiency of the heating element (η_{heat}), as shown below. The heat required to maintain the solution's temperature can be approximated as the conductive loss to ambient air via the reactor's insulation layer.

$$Q = \frac{Q_{heat} + Q_{loss}}{\eta_{heat}} = \frac{C_p m \Delta T_{ini-rct} + \frac{k}{s} A \Delta T_{rct-out} \Delta t}{\eta_{heat}} \qquad (0.50)$$

Where C_p is the specific heat capacity of the solution at constant pressure, m is the mass of the solution, $\Delta T_{ini-rct}$ is the change from initial to target reactor temperature, $\Delta T_{rct-out}$ is the difference between reactor interior and exterior temperature, both ΔTs in this case are 75°C, k is the thermal conductivity of the insulation material, s is the insulation thickness. A is the surface area of the reactor, and Δt is the processing time (1h).

The mass of the 4M HCl solution is 3.70E-1 kg, with a specific heat capacity 3.30 KJ/kgK at standard conditions. The specific heat capacity of the solution with the waste dust (mixture) is therefore[19]:

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[19] By convention, Cp of the solution should be calculated at the midpoint of the heating temperature range (i.e. 62.5°C) (and standard pressure). Due to a lack of data at that temperature, Cp is calculated at 20°C. However, we expect the error introduced by this method to be very small, as the solution contains 80 w/w% water and Cp of water at 20°C and 62.5°C are very similar.

$$c_{p,sol} = \frac{0.0324(0.397\ kJ/kgK) + (0.370)(3.30\ kJ/kgK)}{0.0324 + 0.370} = 3.04\ kJ/kgK$$

Assuming an average 1000L reactor suggested per Table C.2 from Piccinno et al. (2016), the rate of heat loss (i.e. $\frac{k}{s}A$) is 3.303 W/K and the heating efficiency is 75%. The mixture density is 1,243 kg/m3, so the reactor is capable of processing 1,243 kg of mixture. The heat requirement per ton of mixture is:

$$Q = \frac{\left(\frac{3.04\ kJ}{kgK}(75K)\left(\frac{1\ kWh}{3{,}600\ kJ}\right) + \frac{3.303W}{K}(75K)(1\ h)\left(\frac{1}{1243\ kg}\right)\left(\frac{1\ kWh}{1{,}000\ Wh}\right)\right)}{75\%}\left(\frac{1{,}000\ kg}{ton}\right)$$

$$= 84.7\ kWh/ton$$

For our functional unit of 4.03E-1 kg of mixture, the heat requirement for the first-stage leaching is **3.41E-2 kWh**.

C.3.2.2 Electricity for stirring

The stirring energy is a function of the impeller type (with power factor N_p), impeller diameter (d), stirring speed (N), density of the solution (ρ), processing time (Δt), and stirring efficiency (η_{stir}), as shown below:

$$E_{stirring} = \frac{N_p \rho N^3 d^5 \Delta t}{\eta_{stir}} \qquad (0.51)$$

Per Swain et al. (2015), the stirring takes place at 400rpm for 1h in a 0.5L flask (with a 30mm dia. stirrer). Assuming an axial impeller for the 1,000L reactor per Table C.2 from Piccinno et al. (2016), N_p is 0.79, d is 0.373m, and η_{stir} is 90%. Converting at equivalent tip speed (i.e. $\pi d N = constant$), the stirring speed for the reactor would be 32 rpm. The electricity requirement for stirring is 9.77E-4 kWh/ton or **3.93E-7 kWh per functional unit** of waste dust for the first stage leaching process.

$E_{stirring}$

$$= \frac{0.79\left(\frac{1{,}243\ kg}{m^3}\right)\left(32\ rpm\left(\frac{60s^{-1}}{rpm}\right)\right)^3(0.373m)^5(3600s)}{90\%}\left(\frac{1}{1243\ kg}\right)\left(\frac{kWh}{3.6\times 10^6\ J}\right)\left(\frac{1{,}000\ kg}{1\ ton}\right)$$

$$= 9.77\times 10^{-4}\ kWh/ton$$

C.3.2.3 Electricity for solid-liquid separation

The energy requirement for solid-liquid separation depends on various factors, including the size of particles to be filtered. Piccinno et al. (2016) estimated the energy use to be 1-10 kWh/ton of dry material separated, with average at 5.5 kWh/ton. 4.03E-2 kg of residual is expected after the first stage leaching, assuming 5% wet fraction. Taking the average energy consumption rate, the energy usage for solid-liquid separation is **1.87E-4 kWh**.

C.3.3 Mixing with Na_2CO_3

Per 1:1 waste dust to Na_2CO_3 ratio, **3.24E-2kg Na_2CO_3** is added and mixed with the residue, resulting in a total mixture weight of 6.64E-2 kg. This is done in the lab manually. At a scaled-up facility, this process may be carried out by hand or by machine at low speed. We expect this energy consumption to be negligible given the low energy consumption for the stirring portion of the leaching process.

C.3.4 Electricity for ball milling

The energy requirement for grinding depends on various factors, including grinding method, final particle size, and material hardness. Piccinno et al. (2016) estimated the energy use to be 8-16 kWh/ton of grinded material. Taking the average value for this process and given 6.64E-2 kg of the materials, the energy usage for ball milling is **7.97E-4 kWh**.

C.3.5 Electricity for drying

The drying process involves heating the residue to the boiling temperature of the liquid along with the enthalpy of vaporization (Piccinno et al. 2016). However, since the desired oven temperature is at 60°C, which is below the boiling temperature of 4M HCl (104°C), the drying process here is more similar to that of the heating process in the leaching stage, with one key difference - heat loss includes both wall loss and loss via exhaust air, as described below:

$$\begin{aligned} Q &= \frac{Q_{heat} + Q_{wall\ loss} + Q_{ventilation}}{\eta_{heat}} \\ &= \frac{C_p m \Delta T_{ini-oven} + \frac{k}{s} A \Delta T_{oven-out} \Delta t + C_{p,air} \dot{V}_{air} \rho_{air} \Delta T_{ini-oven} \Delta t}{\eta_{heat}} \end{aligned} \tag{0.52}$$

where for $Q_{ventilation}$, $C_{p,air}$ is the specific heat capacity of air, $\dot{V}_{air}$ is the ventilation rate, ρ_{air} is the air density, $\Delta T_{ini-oven}$ is the difference between inlet air temperature and oven target temperature, and Δt is the duration of operation. Note the heating energy does not include energy for heating the auxiliary components in the oven (e.g. trays) since steady-state operation with negligible heat loss is assumed.

The oven is modeled after a 24 ft^3 (0.681 m^3) standard oven with interior dimensions 122cm x 61cm x 91.5cm. Typical oven wall thickness ranges from 10-25cm. Assuming 20cm of glass fiber insulation (0.042 W/m°C), which results in an oven outer surface area of 10.2m^2, the rate of oven heat loss is 2.14W/K.

The type of oven appropriate for handling lightweight materials is gravity or forced convection batch oven, which uses natural or forced air convection to attain temperature uniformity. The minimum ventilation requirement per American Society for Testing and Materials (ASTM E145-19) is 10 air changes per hour. This is equivalent to heating up 27.2 m^3 of air (at a density of 1.12 kg/m^3) over the 4h drying period. The drying efficiency is default at 80% per Piccinno et al. (2016). The total heating energy per ton of mixture dried is:

$$Q_{heating} = Q_{heat} + Q_{wall\ loss} + Q_{ventilation} \tag{0.53}$$

$$\begin{aligned} Q_{heating} = & \left[205kg\left(\frac{0.645kJ}{kgK}\right)(45K)\left(\frac{1\ kWh}{3{,}600\ kJ}\right) + \frac{2.14W}{K}(45K)(4h)\left(\frac{1\ kWh}{1{,}000\ Wh}\right)\right. \\ & \left. + \frac{1.01kJ}{kgK}(27.2m^3)\left(\frac{1.12kg}{m^3}\right)(45K)\left(\frac{1\ kWh}{3{,}600\ kJ}\right)\right]\left(\frac{1}{205kg}\right)\left(\frac{1{,}000\ kg}{ton}\right)\left(\frac{1}{80\%}\right) \\ & = (7.83 + 1.83 + 1.83)\frac{kWh}{ton} = 11.5\ kWh/ton \end{aligned}$$

Given 6.64E-2 kg of the material, the energy usage for drying is **7.63E-4 kWh**.

C.3.6 Electricity for annealing

In the annealing process, the mixture is heated to 1,000°C for 4 hours. The energy consumption for this process is calculated the same way as the drying process. Assuming the same physical characteristics for the furnace as the drying oven, the total energy consumption for annealing is 320 kWh/ton of mixture and **2.07E-2 kWh** per functional unit of materials treated.

C.3.7 Stage 2-leaching: heating, stirring, & solid-liquid filtration

In the stage 2 leaching process, the leachate from stage 1 is reused. The energy use intensity in this process will differ slightly from stage 1 since the composition of the residue is now diluted with Na_2CO_3. The resultant electricity use is 80.6 kWh/ton and 9.77E-4 kWh/ton for heating and stirring the mixture, respectively. Per functional unit of waste dust processed, the electricity use is

3.49E-2 kWh and **4.24E-7 kWh** for heating and stirring, respectively. The solid-liquid filtration process consumes **3.56E-4 kWh** of electricity.

If the flow between the two stages is continuous in the scale-up operation, the preheated leachate would theoretically reduce the heat requirement at stage 2. This heat saving however was not considered in the model.

C.3.8 Additional considerations

C.3.8.1 Solvent extraction

The solvent extraction process is modelled after Ahmed et al. (2013)'s proposed process flow, which uses a Cyanex 923 solvent diluted in kerosene to extract Ga, followed by stripping with 1M HCl. Given 0.227 moles Ga in the liquor, 1.14 mole Cyanex 923 is required for extraction. This translates to 1.28E-1kg Cyanex diluted in 1.44E-1 kg kerosene. And given 90% regeneration efficiency of the organic solvent at the end of extraction, **1.28E-2kg Cyanex 923** and **1.44E-2kg kerosene** are consumed. The organic solvent regeneration process consumes **3.23E-1kg water**. For the stripping of the aqueous phase, **1.18E-2 kg HCl** and **3.23E-1 kg water** are consumed. The final outputs are **6.76E-5kg Ga** and **1.05kg wastewater**.

C.3.8.2 Electricity for pumping

Pumping of fluids in this scaled-up operation will likely take place intermittently at the leaching stages. The electricity for pumping is taken after the default value from Piccinno et al. (2016) at 1.53E-2 kWh/ton of pumped material. Given 0.403 kg of pumped materials on average, the total electricity for pumping is **6.15E-6 kWh**.

C.3.8.3 Infrastructural allocation

Per Piccinno et al. (2016), it’s conventional to account for the resource consumption for the infrastructure buildout. Although an average chemical plant from ecoinvent can generate a total output of 2.5 million tons of materials over lifetime (50,000ton/yr for 50 yrs), the scale of this production is not realistic for a plant aimed at REE recovery, considering that less than 0.02% w/w of CM can be recovered from the waste dust due to inpurity. Instead, we assumed a plant capacity of 1,200ton treated waste dusts per year (Qiu & Suh, 2019) for 25 years. To this end, the infrastructure allocation per functional unit of LED waste processed is **1.08E-9 unit**.

C.3.8.4 Transportation

A default of 15km on municipal solid waste collection service lorry is assumed for landfilling scenarios, and 30km for recycling scenarios to reflect that recycling facilities are likely less accessible than landfills. A summary of the inputs and outputs for recovering REE from LED waste dusts is provided in Table C.2 below.

Table C.2: Input-output for an 8” LED linear fixture recycling with hydrometallurgical leaching of rare earth elements from its phosphor fraction.

Input	**Unit**	**Qty**	**Output**	**Unit**	**Qty**	**Source**
Spent LED fixture	kg	7.04				
Lorry (21t)	tkm	2.11E-1				
Disassembly, shredding, and crushing						
Spent LED fixture	kg	7.04	Steel	Kg	1.27	*Based on ecoinvent process, Nagy et al. 2017
Electricity*	kWh	6.74E-1	Aluminum	Kg	2.99	
			Copper	Kg	1.69E-1	
			Solid waste	Kg	2.62	
			LED fraction	kg	3.24E-2	
Ga leaching						
LED fraction	kg	3.24E-2	Gallium	Kg	6.76E-8	Swain et al. 2015, Ahmed et al. 2013
Hydrochloric acid	Kg	5.91E-2	Waste water	Kg	1.05	
Water	Kg	9.68E-1	Solid waste	kg	6.80E-2	
Soda ash	Kg	3.24E-2				
Cyanex 923	kg	1.28E-2				
Kerosene	Kg	1.44E-2				

Electricity	kWh	7.04E-2				
Heat	kWh	2.15E-2				
Infrastructure	unit	1.08E-9				

C.4 Life cycle inventory of linear fixtures from cradle-to-gate

The life cycle inventory (LCI) of the linear fluorescent fixture is obtained via a product tear-down analysis, while the linear LED fixture is modeled based on shared industry information. The luminaires modeled are a direct replacement of each other in real life. The FL and LED luminaire weigh 6.83kg and 8.65kg, respectively. Table C.3 and Table C.4 list the LCI of linear fluorescent fixture and linear LED fixture, respectively from Cradle-to-Gate. Table C.5 presents the lighting attributes (e.g. rated lifetime, efficacy, and wattage at 8,250 lm) used for calculating the electricity consumption in the use phase.

For Table C.3, most of the components from the linear fluorescent fixture are easily separated, weighted, and identified for material. For the modelling of the fluorescent tubes and electronic ballast, Tähkämö et al. (2014)'s LCA study on a T5 fluorescent lamp fixture is used for reference LCI. For Table C.4, the LCI for the LED chips, the LED driver, and the LED light source are compiled based on flow sheets shared by the industry partner. The LCI for the LED housing structure are estimated based on CAD rendering of the luminaire.

Table C.3: Life cycle inventory of Linear fluorescent fixture from Cradle-to-Gate.

	Index	**Qty**	**Unit**	**Process**
Main assembly	*Output - main assembly*			
	1	1	unit	**Linear fluorescent fixture (8ft)**
	Inputs			
	1	2	units	Electronic ballast
	2	4	units	Lamp tube (4 ft) - linear fluorescent
	3	1	unit	Housing structure - fluorescent fixture
	4	2	units	Reflector (4 ft) - fluorescent fixture
	5	3.87E-01	kg	Electrical wiring

	6	1.39E+00	kg	Packaging
	7	8.91E+00	tkm	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market
	8	6.42E+00	tkm	Transport, freight, sea, transoceanic ship {GLO}| market
Component 1	*Output - component 1*			
	1	1	unit	**Electronic ballast**
	Inputs			
	1	1.31E-02	kg	Capacitor, for surface-mounting {GLO}| market
	2	3.93E-02	kg	Transformer, low voltage use {GLO}| market
	3	2.90E-03	kg	Resistor, wirewound, through-hole mounting {GLO}| market
	4	7.30E-04	kg	Transistor, surface-mounted {GLO}| market
	5	1.20E-04	kg	Integrated circuit, logic type {GLO}| market
	6	1.02E-01	kg	Steel, low-alloyed {GLO}| market
	7	4.35E-03	kg	Nylon 6 {GLO}| market
	8	4.35E-03	kg	Nylon 6-6 {GLO}| market
	9	7.65E-03	kg	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market
	10	7.65E-03	kg	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market
	11	1.02E-01	kg	Sheet rolling, steel {GLO}| market
	12	3.00E+00	kWh	Electricity, medium voltage {CN}| market group
	13	7.30E-04	kg	Diode, glass-, for surface-mounting {GLO}| market
Component 2	*Output - component 2*			
	1	1	unit	**Lamp tube (4 ft) - linear fluorescent**
	Inputs			
		9.35E-02	kg	Glass tube, borosilicate {GLO}| market
		2.44E-03	kg	Aluminium, cast alloy {GLO}| market
		5.00E-06	kg	Mercury {GLO}| market
		4.06E-04	kg	Argon, liquid {GLO}| market
		2.03E-03	kg	Rare earth concentrate, 70% REO, from bastnasite {GLO}| market
Component 3	*Output - component 3*			
	1	1	unit	**Housing structure - fluorescent fixture**
	Inputs			
		3.42E+00	kg	Aluminium, cast alloy {GLO}| market
		1.94E-01	kg	Steel, low-alloyed {GLO}| market
		3.21E-01	kg	LED-wiring (GE IS18, 8ft)
		6.10E-02	kg	Nylon 6 {GLO}| market
		6.10E-02	kg	Nylon 6-6 {GLO}| market
		2.94E-02	kg	Copper {GLO}| market
Comp. 4	*Output - component 4*			
	1	1	unit	**Reflector (4 ft) - fluorescent fixture**
	Inputs			
	1	7.00E-01	kg	Aluminium, cast alloy {GLO}| market

Table C.4: Life cycle inventory of Linear LED fixture from Cradle-to-Gate.

	Index	**Qty**	**Unit**	**Process**
Main assembly	***Output - main assembly***			
	1	1	unit	**Linear LED fixture (8ft)**
	Inputs			
	1	1	unit	LED driver
	2	1	Unit	LED light source
	3	1	unit	LED housing structure
	4	3.99E-01	kg	Electrical wiring
	5	1	unit	Assembly - LED fixture
	6	1.44E+00	kg	Packaging
	7	9.19E+00	tkm	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market
	8	6.62E+00	tkm	Transport, freight, sea, transoceanic ship {GLO}| market
Component 1	*Output - component 1*			
	1	1	unit	**LED driver**
	Inputs			
	1	9.59E-01	kg	Steel, low-alloyed {GLO}| market
	2	2.78E-03	kg	Capacitor, electrolyte type, > 2cm height {GLO}| market
	3	2.68E-03	kg	Capacitor, tantalum-, for through-hole mounting {GLO}| market
	4	3.05E-03	kg	Copper {GLO}| market
	5	2.14E-04	kg	Electronic component, active, unspecified {GLO}| market
	6	2.25E-03	kg	Electronic component, passive, unspecified {GLO}| market
	7	3.84E-04	kg	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market
	8	1.29E-03	kg	Inductor, low value multilayer chip {GLO}| market
	9	1.86E-04	kg	Nylon 6 {GLO}| market
	10	1.86E-04	kg	Nylon 6-6 {GLO}| market
	11	3.39E-03	kg	Polyester resin, unsaturated {GLO}| market
	12	9.30E-02	kg	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market
	13	9.30E-02	kg	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market
	14	7.82E-03	kg	Resistor, surface-mounted {GLO}| market
	15	2.15E-01	kg	Silicone product {GLO}| market
	16	7.62E-04	kg	Tin {GLO}| market
	17	5.35E-04	kg	Transformer, low voltage use {GLO}| market
	18	1.90E-03	kg	Polycarbonate {GLO}| market
	19	3.11E-03	kg	Diode, glass-, for surface-mounting {GLO}| production
Component 2	*Output - component 2*			
	1	1	unit	**LED light source**
	Inputs			
	1	3.24E-02	kg	LED chips
	2	1.37E-02	kg	Glass fibre {GLO}| market

	3	1.52E-02	kg	Copper {GLO}| market
	4	7.38E-03	kg	Paper, woodfree, coated {RER}| market U
	5	1.24E-01	kg	Polycarbonate {GLO}| market
	6	1.37E+00	kg	Aluminium, cast alloy {GLO}| market
Component 2.1	*Output - subcomponent 2.1*			
	1	3.24E-02	kg	**LED chips**
	Inputs			
	1	1.82E-02	kg	Sodium aluminate, powder {GLO}| market
	2	7.58E-05	kg	Aluminium, cast alloy {GLO}| market
	3	1.89E-05	kg	Cadmium chloride, semiconductor-grade {GLO}| market
	4	2.54E-03	kg	Copper {GLO}| market
	5	7.58E-05	kg	Gallium, semiconductor-grade {GLO}| market
	6	1.89E-04	kg	Gold {GLO}| market
	7	2.27E-04	kg	Rare earth concentrate, 70% REO, from bastnasite {GLO}| market
	8	3.41E-04	kg	Magnesium oxide {GLO}| market
	9	1.52E-04	kg	Molybdenum {GLO}| market
	10	9.47E-05	kg	Nickel, 99.5% {GLO}| market
	11	1.89E-05	kg	Nitrogen, liquid {RoW}| market
	12	1.33E-04	kg	Oxygen, liquid {RoW}| market
	13	1.89E-05	kg	Palladium {GLO}| market
	14	3.98E-04	kg	Phosphorus, white, liquid {GLO}| market
	15	3.22E-04	kg	Silicon, electronics grade {GLO}| market
	16	8.00E-03	kg	Silicone product {GLO}| market
	17	3.79E-05	kg	Titanium, primary {GLO}| market
	18	1.33E-04	kg	Titanium dioxide {RoW}| market
	19	1.48E-03	kg	Tungsten
Component 3	*Output - component 3*			
	1	1	unit	**LED housing structure**
	Inputs			
	1	1.62E+00	kg	Aluminium, cast alloy {GLO}| market
	2	1.73E+00	kg	Polycarbonate {GLO}| market
	3	3.37E-01	kg	Steel, low-alloyed {GLO}| market
	4	2.38E-02	kg	Acrylic binder, without water, in 34% solution state {GLO}| market
Component 4	*Output - component 4*			
	1	3.99E-01	kg	**Electrical wiring**
	Inputs			
	1	1.66E-01	kg	Copper {GLO}| market
	2	4.35E-02	kg	Tin {GLO}| market
	3	1.40E-01	kg	Silicone product {GLO}| market
	4	3.31E-02	kg	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market
	5	1.59E-02	kg	Polycarbonate {GLO}| market

Component 5	*Output - component 5*			
	1	1	unit	**Assembly - LED fixture**
	Inputs			
	1	4.37E-03	kg	Propane {GLO}| market
	2	6.31E+00	kg	Tap water {GLO}| market group
	3	8.47E-01	kg	Electricity, medium voltage {MX}| market
	Other outputs			
	1	9.66E-04	kg	Carbon dioxide
	2	1.10E-01	kg	Inert waste, for final disposal {RoW}| market for inert waste, for final disposal
	3	5.39E-03	kg	Hazardous waste, for underground deposit {GLO}| market
	4	4.06E-03	kg	Wastewater from PV cell production {GLO}| market
	5	7.56E-01	kg	Wastewater, average {RoW}| treatment of, capacity 1E9l/year
Component 6	*Output - component 6*			
	1	1.44E+00	kg	**Packaging**
	Inputs			
	1	1.36E+00	kg	Corrugated board box {GLO}| market for corrugated board box
	2	5.41E-03	kg	Polypropylene, granulate {GLO}| market
	3	2.32E-03	kg	Acrylic binder, without water, in 34% solution state {GLO}| market
	4	4.00E-02	kg	Packaging film, low density polyethylene {GLO}| market
	5	2.50E-02	kg	Printed paper {GLO}| market

Table C.5: Lighting system attributes.

Lighting system	**Lifetime (kh)**	**Efficacy (lm/W)**	**Watt (at 8250 lm)**
Incumbent fluorescent fixture (for extended use)	30	104.6	78.9
Incumbent LED fixture (for extended use)	50	127.3	64.8
Fluorescent fixture replaced with fluorescent components	30	104.6	78.9
Fluorescent fixture replaced with LED components (retrofit)	59.375	128.5	64.2
LED fixture replaced with LED components	62.5	135.2	61.0
New fluorescent fixture	30	104.6	78.9
New LED fixture	62.5	159.1	51.9

C.5 Equations for calculating the life cycle impacts per functional unit

The LCA explores three replacement pathways – extended use, modular replacement, and full replacement. Each incumbent or replacement lighting is assumed to produce 8250 lumen (lm) over the entirety of its rated lifetime. For lighting products with a different brightness rating, the product wattage is adjusted according to their luminous efficacy. The functional unit of the LCA is 1 million lumen-hour (Mlmh) of lighting service. To arrive at the final LCIA results, the life cycle impacts are aggregated across the system boundary (as defined in Figure 4.1 in Chapter 4) and then normalized to the functional unit based on the total lifetime embodied by the product life cycle(s).

For the *extended use* pathway, the life of the incumbent luminaire is extended by 25%. The total life cycle impact per 1Mlmh is therefore:

$$\begin{aligned} I_{Extended\ Use} &= \frac{CG1_{L1} + D1_{L1} + 1.25U1_{L1} + EOL1_{L1}}{1.25LT_{L1}(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)} \\ &= \frac{(CG1 + D1 + 1.25U1 + EOL1)_{L1}}{1.25LT_{L1}(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)} \end{aligned} \tag{0.54}$$

where:

- $CG1_{L1}$: cradle-to-gate impacts of luminaire 1 – a luminaire of technology 1 ($L1$)
- $D1_{L1}$: distribution phase impacts of luminaire 1 – $L1$
- $U1_{L1}$: use phase impacts of luminaire 1 – $L1$
- $EOL1_{L1}$: end of life phase impacts of luminaire 1 – $L1$
- LT_{L1}: rated lifetime of luminaire 1 – $L1$

For the *modular replacement* pathway, the lamp and electronic components of the incumbent luminaire is replaced, thus two life cycles exist. The total life cycle impact per 1Mlmh is:

$$
\begin{aligned}
I_{Modular\ Rep} \\
&= \frac{CG1_{L1} + D1_{L1} + U1_{L1} + EOL1_{(l+e)1} + CG2_{(l+e)2} + D2_{(l+e)2} + U2_{(l+e)2} + EOL2}{\left(LT_{L1} + LT_{(l+e)2}\right)(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)} \qquad (0.55) \\
&= \frac{(CG1 + D1 + U1 + EOL1)_{L1} + (CG2 + D2 + U2 + EOL2)_{(l+e)2}}{\left(LT_{L1} + LT_{(l+e)2}\right)(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)}
\end{aligned}
$$

Note: a luminaire (L) consists of two lamps (l), an electronic component (e), and a fixture (f) or housing structure, i.e.:

$$L_{*} = l_{*} + e_{*} + f_{*} \qquad (0.56)$$

For the *full replacement* system, the incumbent luminaire is replaced in full with a new counterpart, thus two life cycles exist. The total life cycle impact per 1Mlmh is:

$$
\begin{aligned}
I_{Full\ Rep} \\
&= \frac{CG1_{L1} + D1_{L1} + U1_{L1} + EOL1_{L1} + CG2_{L2} + D2_{L2} + U2_{L2} + EOL2_{L2}}{(LT_{L1} + LT_{L2})(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)} \qquad (0.57) \\
&= \frac{(CG1 + D1 + U1 + EOL1)_{L1} + (CG2 + D2 + U2 + EOL2)_{L2}}{(LT_{L1} + LT_{L2})(8250)\left(\frac{Mlmh}{1E6\ lmh}\right)}
\end{aligned}
$$

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Chapter 2

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Chapter 6

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