Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies

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Abstract: Compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) produce illumination four times more efficiently than standard incandescent light bulbs during their use-phase. When the large amounts of energy needed to produce these newer technologies are included in the comparison, however, their life-cycle energy efficiencies decrease by 10-30%. The current policy framework ignores this energy used for production, so any subsidies employed to foster the adoption of energy efficient lighting will over-count the resulting CO2 emissions reductions by about 5%. Lighting constitutes 22% of US electricity demand. Therefore, a small error in this calculation could easily negate the effects of very expensive emission reduction efforts in sectors such as transportation or land use. Two previous life-cycle assessments have compared CFLs to incandescents, but this is the first study to include LEDs, estimate environmental impacts of the CFL recycling industry, and put the results within the context of global warming policy. To simulate global conditions, four locations with unique electricity mixes were modeled: China, the US average, California, and a hypothetical grid with 33% renewable energy. In all locations, the manufacturing of incandescents represented less than 1% of life-cycle carbon emissions. However, depending on the electricity mix used to power CFLs and LEDs, 10-30% of life-cycle emissions were associated with manufacturing. For all bulbs, less than 1% of energy use and CO2 emissions were due to recycling or disposal. Finally, though currently very similar in performance, LEDs are likely to significantly improve in the future, while CFLs have already reached their theoretical limit.

Introduction

The purpose of this research was to evaluate the full life-cycle costs and benefits of using government subsidies to encourage a transition away from inefficient incandescent lighting. While some life-cycle analysis of compact fluorescent lamps (CFLs) has been done, this is the first such examination of light emitting diodes (LEDs), and the first study to consider the disposal costs for either technology (Parson 2006, and Ramroth 2008). The analysis suggests that adopting LEDs could yield higher reductions in energy use and CO2 emissions compared with CFLs. The analysis also shows that an understanding of all life-cycle impacts is critical in the development of cost-effective climate change mitigation policy.

Improvements in energy efficiency (EE) have been championed as the "cheapest, cleanest and fastest" way to reduce anthropogenic CO2 emissions and conserve non-renewable fossil fuel resources (NRDC 2008). Lighting, currently 22% of US electricity demand, has been identified as the sector with the greatest potential for cost-effective efficiency improvements (DOE 2008).

To foster the adoption of more efficient lighting devices, governments and electricity providers have created subsidies for appliances that are proven to save energy (NRDC 2008, CPUC 2008). Most notably, nearly 80% of all EE subsidies have gone to CFLs, representing over 20 billion dollars in investment since 1970 (Friedman 2008). LEDs, an emerging and unsubsidized technology, have the potential to save more energy than CFLs, produce better light and be less damaging to the environment (Taub 2009). However, it is not clear if LEDs will ever make it to the mainstream without subsidies similar to what CFLs have received over the last 30 years (Kammen 2008).

Currently, the benefits of subsidizing EE light bulbs are measured using only the amount of energy each technology saves while in actual use, without any adjustment for the energy needed to make or dispose of them (CPUC 2008). However, this has been shown to be an unreasonable approach for several reasons (McCullough *et al.* 2008, and Peters and Hertwich 2008). First, CFLs require nearly 30 times as much energy to manufacture as standard incandescent light bulbs (Ramroth 2008). Second, CFLs contain mercury, a toxic heavy metal that must be properly recycled to prevent environmental contamination (Eckelman 2008). Legislation has already been passed in California and Europe to promote CFL recycling, but the carbon and energy impacts of creating and maintaining the necessary infrastructure is currently unknown (AB-1109 2008 and Bohman 2008). LEDs do not contain mercury, but they do contain semiconductors which are extremely energy intensive to produce and require a completely sterile environment (Matthews *et al.* 2009).

Failing to account for the embedded energy of production on the macro-scale has been widely cited as a reason that the Kyoto Protocol was not able to reduce global green house gas (GHG) emissions (Babiker 2000, Matthews *et al.* 2008, Peters and Hertwich 2008). Countries with clean electricity mixes simply moved their production facilities to developing countries and continued to buy the same products, effectively doubling the carbon footprint for these same products (Babiker 2004). For example, about 20% of US emissions are due to imports, but these emissions are not included in domestic emission inventories because they happen outside the country (Weber 2007). Thus, some of the benefits from increasing domestic EE or renewable electricity generation may be offset by the continued outsourcing of goods production to countries with carbon intensive electricity mixes.

While analysis of the Kyoto Protocol has demonstrated the importance of embedded energy on the macro-scale, virtually no research has been conducted to investigate how discounting for embedded energy might affect the perceived benefits of specific energy efficient appliances (McMahon 2009). Two life-cycle assessments have been conducted comparing CFLs and incandescents, but neither study included LEDs (Parson 2006, and Ramroth 2008). Also, neither of the previous two studies attempted to model the effects of a CFL or LED recycling industry or to put the results within the context of energy efficiency or global warming policy.

This study first presents a life-cycle assessment (LCA) of CFLs, LEDs, and incandescents. It then quantifies the extent to which life-cycle analysis changes the overall energy efficiency and perceived benefits of adopting each technology.

The study also shows how the importance of discounting for production energy changes depending on where each technology is actually used. To demonstrate this effect, four country-specific scenarios were investigated, each with a different mix of electrical generation sources. The scenarios ranged from conditions in China, where 80% of electricity comes from coal and 20% from hydro-electric sources to California's ambitious goal of generating 33% of its electricity from renewable sources by 2020; California will then have a combined carbon intensity roughly 75% below China's (Nunez 2006). This analysis is meant to inform future energy efficiency policy and help ensure that countries do not negate their efforts to reduce global CO2 emissions by simply moving them elsewhere.

Methods

Overview The life-cycle assessment (LCA) model was constructed using Gabi 4.2 software by PE Americas. The life-cycle was broken into three stages: production and transport, use, and end of life (Figure 1). Input data was gathered through interviews, physical disassembly of light bulbs, and the software's internal databases. Relevant outputs were considered to be primary fossil energy use in kilowatt hours (kWh) and global warming emissions in kilograms (kg) of carbon dioxide (CO2) equivalent over a 100 year time horizon.

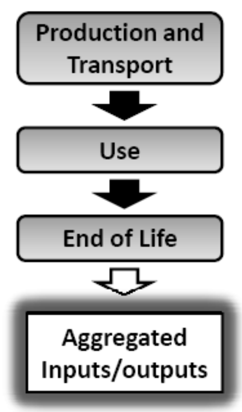

Figure 1: Generic LCA model summary

The bulbs compared included a 60 watt incandescent made by GE ($0.50), a 13 watt CFL made by Philips ($3.00 before subsidy, $1.00 after), and a 6 watt LED made by EarthLed ($30.00). These bulbs were chosen because of their similarities in light output. However, they differed greatly in lifetime, so the per-bulb results were adjusted to represent the energy needed to produce one million lumen hours of useful light. As is the case today, all bulbs were assumed to be made in China, but various use-phase scenarios were evaluated to determine the importance of the use-phase energy mix in the life-cycle analysis (Fox 2008).

Production and Transport This phase, commonly known as the "cradle-to-gate" impacts, represents all of the energy consumed and green house gasses released in order to bring the bulb to market (Matthews 2002). All bulbs and packaging were disassembled and the individual components massed. This mass data was then entered into Gabi 4.2 to calculate the energy needed to manufacture each constituent part (Figure 2). The only component not present in Gabi was the LED semiconductor. Energy needed to make this component was taken from the literature (Matthews *et al.* 2009). Finally, 10% was added to the production energy to account for electricity used in final assembly, an assumption common in life-cycle assessments of consumer electronics (Matthews 2002). Following the literature, impacts of transportation were estimated using Ramroth's assumptions that all bulbs were shipped 8,000 miles by an ocean-going freighter and 4,000 miles by a light duty truck for distribution within the US (Ramroth 2008).

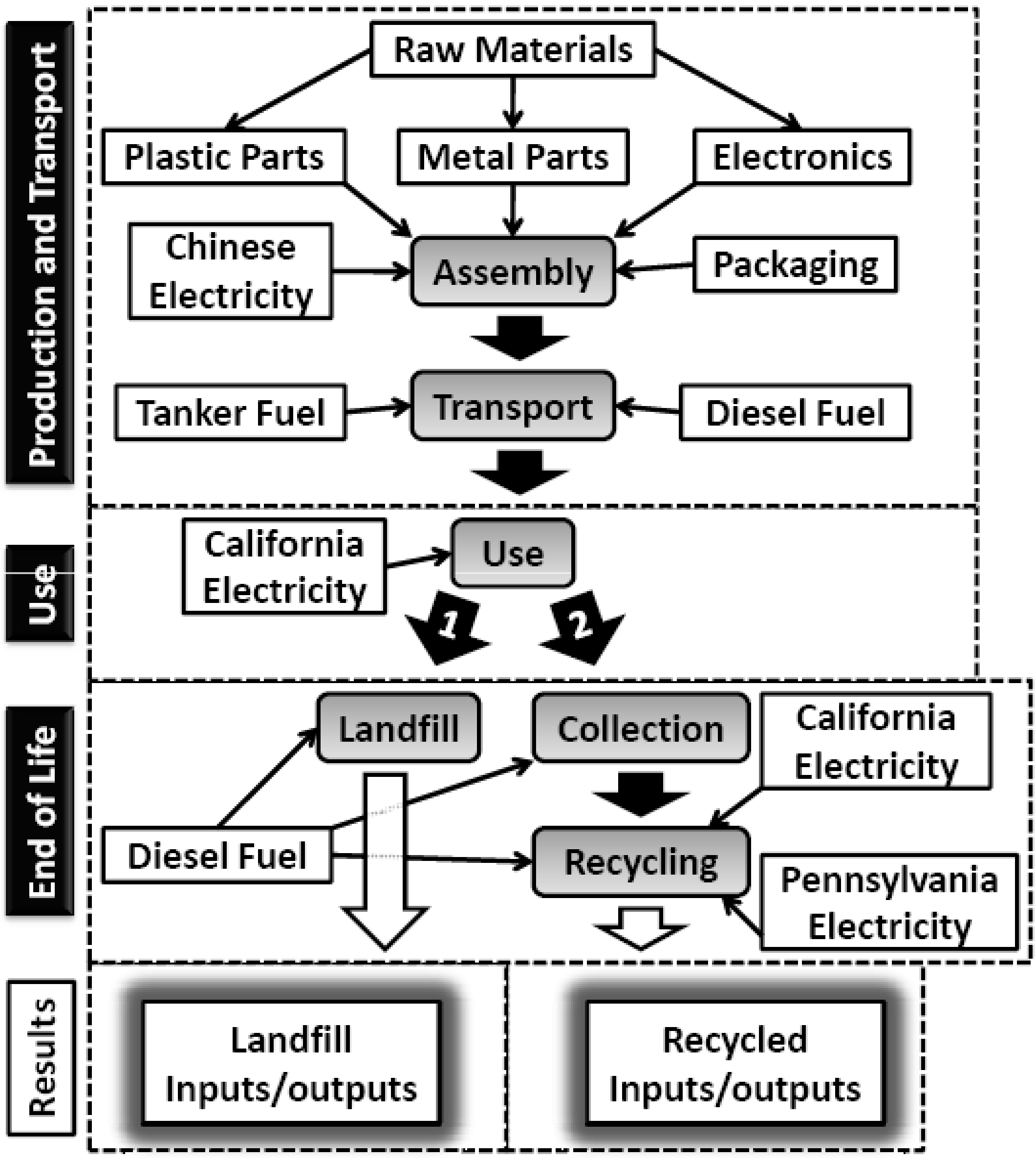

Figure 2: Detailed representation of LCA model for a CFL assuming it is used in California and recycled at the end of its life

Use The use-phase was modeled for four different electricity grids: China, the US Average, California today, and California with 33% renewable electricity generation. Bulb lifetimes were taken from the literature while light output and power consumption were tested in the lab (Table 1). The case of a hypothetical future LED was added because current production models only operate at about 50% of theoretical efficiency, compared to 95% for CFLs (Taub 2008 and Azevedo *et al.* 2009). This future LED was assumed to have the same lifetime, power consumption, and production energy as current LEDs but with a 60% greater light output.

Table 1: Assumptions relevant to use-phase emissions and energy calculations

	Lifetime	Power Consumption	Light Output
Incandescent	1,000 hours	60 watts	800 Lumens
CFL	8,000 hours	13 watts	800 Lumens
LED	40,000 hours	6.7 watts	300 lumens*
Future LED**	40,000 hours	6.7 watts	500 Lumens

*LED light output was claimed by the manufacturer at 350 lumens and 6 watts
**Theoretical LED which is 60% more efficient than current models (80% of theoretical EE)

End of Life Previous lighting LCAs have only investigated the impact of sending these devices to landfills (Ramroth 2008 and Parson 2006). Therefore, this study focused on modeling the creation of a CFL recycling infrastructure similar to what is present in the San Francisco Bay Area, currently the region with the highest landfill diversion rate (AB-1109 2008). After extensive interviews with Northern California's only certified CFL recycler, it was determined that the process could be broken into two phases: collection and final disposal (Lees 2008).

For collection, all bulbs were assumed to be returned by the customer to the point of purchase when buying new bulbs. Then, light duty trucks transported the bulbs to one regional collection and recycling facility. Rural areas, where extensive infrastructure is not cost-effective, were assumed to ship their used bulbs by UPS Ground in specialized boxes.

Once collected, the process for recycling an LED was assumed to be identical to the recycling of any other electronic device (Lees 2008). However, specialized machinery and very high operating temperatures are required for the safe disposal of CFLs (Lees 2008). Specific energy usage of the required machinery was obtained through interviews and site visits.

Data Standardization and Analysis Because each bulb had a different output and lifetime, per-bulb results were adjusted to represent the life-cycle energy requirements and CO2 emissions generated to produce one million lumen hours of useful light. This standard measure was then used to compare across technologies and evaluate the implications of various policy decisions.

Results

Producing Each Bulb Per-bulb, CFLs require roughly 30 times more primary fossil energy to produce than incandescents, or 38 kWh (Figure 3). Making an LED requires 65 kWh, about twice as much as a CFL. Ninety-five percent of the energy needed to make a CFL is embedded in the integrated circuit board, roughly 25% of total mass. For LEDs, half of the production energy is due to its integrated circuit board (17% of mass); the other half is embedded in the tiny light emitting diode (0.2% of mass). For both LEDs and CFLs, contributions from all other plastic, metal, and glass components are very small (<2% each). Across all three technologies, transportation and distribution to market represents less than one percent of total production energy.

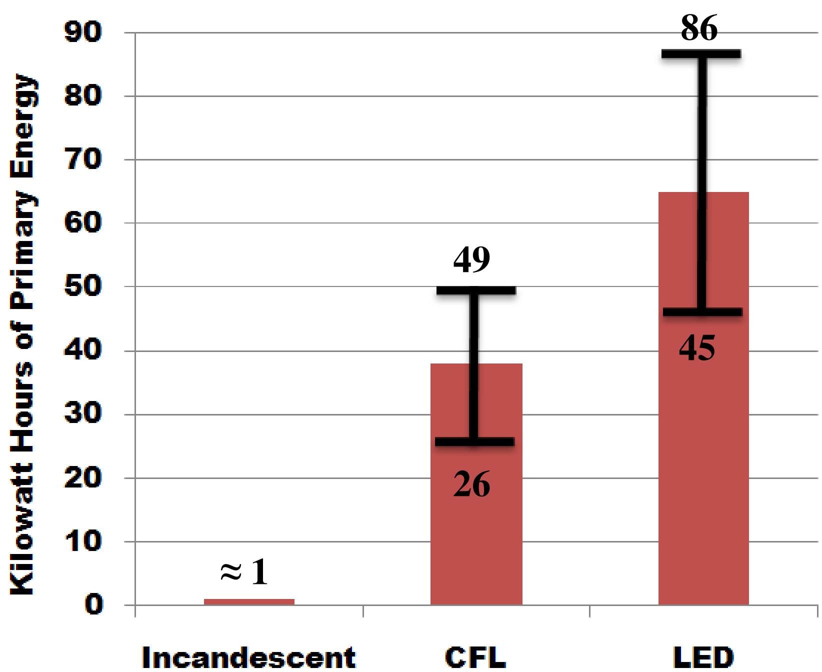

Figure 3: Primary fossil energy required to produce one bulb of each type. The error is due to uncertainty in the exact energy required to manufacture simple electronic components and the active light emitting diode.

Production and Disposal Compared to Life-Cycle CO2 Emissions For incandescents, manufacturing is responsible for less than 1% of total life-cycle CO2 emissions (Figure 4). This is because they are very simple to make and very inefficient in producing light. Consequently, use-phase emissions from producing electricity dominate the life-cycle energy balance. However, for CFLs and LEDs, manufacturing is responsible for 12-29 % of life-cycle CO2 emissions. Ninety percent of this variation is due to where the bulb is used; the other 10% is due to uncertainty regarding the exact amount of energy needed to produce the integrated circuit boards and the light emitting diode. The relative importance of production energy greatly increases as the energy mix used to power the bulb becomes cleaner.

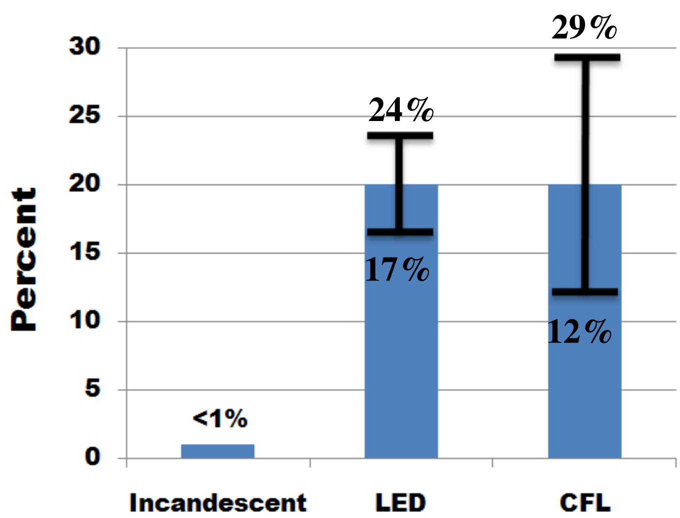

Figure 4: Percent of life-cycle CO2 emissions due to manufacturing. The low bar represents the importance of manufacturing in Chinese conditions. The high bar shows the importance of manufacturing in California with 33% renewables electricity generation.

Another key finding is that the trucks and disposal facilities needed to recycle CFLs and LEDs contributes <1% to life-cycle CO2 emissions. Based on current cost projections, the media campaign and outreach necessary to encourage safe CFL disposal will have a larger carbon footprint than the physical recycling infrastructure (AB 1109 2008).

Use-Phase-Only vs. Life-Cycle Efficiency Finally, the per-bulb results can be modified to calculate the amount of primary fossil energy in kilowatt hours that each technology requires to produce one million lumen hours of useful light (Table 2). This is known as the "name plate efficiency" and is the number used to set multi-year appliance standards. The first column shows the current measure of name plate efficiency, calculated with only use-phase energy consumption. The second column shows the adjusted efficiency of each appliance if production energy is included into the name plate value. Compared to incandescents, CFLs and LEDs are more greatly impacted by this adjustment because of their relatively high production energy inputs. However, LEDs are less affected than CFLs because their production energy is amortized over a much longer lifetime (roughly 4 times as long).

Table 2: Name plate efficiencies calculated using two different methods. Results are presented in kWh of primary fossil energy needed to produce one million lumen hours of useful light. The first measure only includes direct electricity use. The second includes the embedded energy of production and disposal. Different use-phase scenarios are responsible for the ranges presented. The low value is California with 33% renewables. The high value is China.

	Use-Phase Only Energy Efficiency	Life-Cycle Energy Efficiency	Percent Difference Between Measures
Incandescent	60 - 190	61 - 196	2 - 3 %
CFL	14 - 47	18 - 55	17 - 29 %
Current LED	18 - 58	21 - 65	12 - 17 %
Future LED	11 - 34	13-39	15 - 18 %

Finally, the most useful way of looking at these two measures of efficiency is to examine how they affect the perceived benefits of switching from a standard incandescent to any of the more efficient options (Table 3). This is the number used to calculate the actual cost-effectiveness of subsidizing energy efficiency. According to this analysis, current policy overestimates the benefits of CFL subsidies by about 5%. To say it another way, since 1970, roughly 5% of the CO2 emissions reductions attributed to improvements in lighting efficiency have actually just been outsourced to the countries which produce the bulbs.

Table 3: Percent reductions in energy use realized when switching from an incandescent to any of the three technologies listed below. The final column shows the degree to which current policy inflates the benefits of adopting each alternative lighting technology.

	Percent Reduction (Use-Phase Only)	Percent Reduction (Including Production)	Current Policy Over Estimation
CFL	75%	70%	5%
Current LED	69%	66%	3%
Future LED	81%	79%	2%

As with the name plate efficiency, the perceived benefits of LEDs are less severely impacted by the inclusion of production energy because of their longer lifetimes. Moreover, as the performance of LEDs improves and the energy needed to manufacture them decreases, future models will be even less susceptible to the problem of carbon outsourcing.

Discussion

The goal of this study was to build upon two existing lighting LCAs by adding LEDs, and then using the results to evaluate the effectiveness of current energy efficiency policy (Parson 2006 and Ramroth 2008). More broadly, it was constructed to investigate how carbon outsourcing might detract from the perceived benefits of subsidizing specific energy efficient appliances. Understanding the answer to this question is of critical importance if energy efficiency is to be aggressively deployed as a global warming mitigation strategy.

For the production of incandescents and CFLs, the results presented here are within 10% of both previous studies. Based on this similarity, it can be concluded that this analysis of LEDs and public policy is an accurate representation of reality and consistent with the literature.

Key Findings Using any measure of efficiency, CFLs and LEDs are roughly four times more efficient than incandescents, and subsidizing energy efficiency remains an attractive option for reducing anthropogenic CO2 emissions. However, as the policy is currently structured, the benefits of these subsidies are exaggerated by about 5%, and the true costs and benefits of pursuing alternative GHG abatement strategies are distorted as a result.

Generally speaking, LEDs with similar use-phase efficiencies to CFLs look better over their life-cycle because the energy needed to produce them is distributed over their longer lifetimes.

Also, the process of recycling CFLs requires virtually no energy compared with what they use to produce light and what it takes to manufacture them. Lastly, the importance of production energy greatly increases as use-phase countries move towards renewable energy sources.

Policy Implications While a 5% overestimation of energy savings may seem small, scaling up this discrepancy highlights the need to incorporate life-cycle thinking into global warming policy. For example, if every bulb in California were replaced with a CFL (roughly 1 billion bulbs), the state's current models would exaggerate the resulting CO2 emission reductions by 620,000 tons/year. This is on the same order of magnitude as the expected annual CO2 emissions savings from the California High-Speed Rail Project, a multi-billion dollar undertaking (CARB 2009). A simple arithmetic error could effectively negate the projected benefits of this high-profile and very expensive effort to reduce GHG emissions.

Moreover, the tendency to overestimate efficiency benefits is not unique to lighting. Although further research is needed, cursory analysis suggests that the problem of benefit overestimation may be much greater for other energy efficient products. By way of example, a

CFL pays for itself in electricity savings after only 10% of its lifetime, suggesting that the energy and resources needed to produce it are relatively unimportant compared to the use-phase. Conversely, refrigerators routinely have payback times closer to 50% of their useful lives, while some energy efficient air conditioners have negative payback periods in certain climate zones.

It will someday be more cost-effective to optimize international supply chains than to continue pushing for increasingly scarce domestic emission reduction opportunities (Masanet 2009). However, only a climate strategy backed by multi-regional life-cycle thinking will direct us towards addressing these inefficiencies.

In summary, if a comprehensive life-cycle approach is not adopted by policy makers, we are likely to overvalue the benefits of energy efficiency, inadvertently outsource a portion of our emissions to distant countries, and fall short of the ambitious GHG reduction targets necessary to mitigate the effects of climate change.

Technological Considerations Although every effort was taken to ensure that this study was robustly designed and well performed, it represents only a brief snapshot in time. Over the next several years, the components used to make LEDs will become simpler, their efficiencies will increase, and their prices will go down (Dowling 2009). Conversely, CFLs are unlikely to decrease in price or become more efficient (Azevedo *et al.* 2009). This comparison is not meant to predict the future, however. History suggests that the winners will be determined by a variety of factors such as toxicity concerns, consumer acceptance, light quality, economic pay back periods, the availability of government subsidies, and random events (Azevedo *et al* 2009*)*.

Data Uncertainty In this study, two main uncertainties could contribute to error in the results, but neither is large enough to change the overall trends or policy recommendations. First, the CFL recycling model is an extrapolation of programs running in the San Francisco Bay Area. It is possible that more efficient methods of recycling will be developed in the future, but any improvements will only serve to make this negligible contribution to life-cycle energy use (<1%) even smaller. Second, the adoption of efficient lighting technology may not directly translate into the exact emission reduction potentials stated in this paper. The reasons for this are complex and are collectively referred to as the "rebound effect" (Azevedo *et al.* 2009). An example of this "rebound effect" would be if a home owner choose to take longer showers because they knew they were saving money by using more efficient lighting (Sathaye and Murtishaw 2004).

Conclusion

While it remains unclear what mix of technologies will replace the 150-year-old incandescent light bulb, the extinction of this ancient device will necessarily be part of any successful effort to reduce global GHG emissions. Our global supply chains will offer us a variety of alternatives, but with these alternatives come a host of complicating factors such as overseas production and the embedded carbon these new products may contain. This analysis highlights the need to fully consider all energy inputs in determining the value of alternative lighting technologies. However, our societal decision-making process currently lacks a mechanism capable of assessing the myriad potential costs and benefits present in such a decision. Adopting a public policy framework which incorporates life-cycle assessment will help ensure that whatever decision we make both achieves our stated goals and uses global resources efficiently and equitably.

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