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Potential Long-Term Global Environmental Implications of Efficient Light-Source Technologies

Joseph D. Bergesen, Leena Täkkämö, Thomas Gibon, and Sangwon Suh

Summary

Artificial lighting is a major source of electricity demand globally. As the demand for lighting services grows over the next 40 years, especially in developing countries, efficient light-source technologies such as light-emitting diodes (LEDs) can reduce the energy consumed for lighting services and therefore its environmental impacts. LED technologies in both residential and commercial/industrial applications are expected to see dramatic improvements in luminous efficacy over the coming decades, potentially leading to more environmentally benign lighting. A scenario-based, integrated hybrid life cycle assessment quantifies and confirms the environmental benefits of deploying efficient light sources in all global regions through 2050, with electricity generation following the International Energy Agency’s (IEA) BLUE Map scenario for limiting climate change to 2 degrees Celsius. Data used for previous assessments of light sources is updated and harmonized to reflect recent and expected future improvements in luminous efficacy and materials efficiency for LED lamps and luminaires. The aggregate life cycle greenhouse gas (GHG) emissions of global light provision can be reduced by more than a factor of 7 owing to decarbonization of electricity generation, increased adoption of efficient light sources, and future advances in LED technology. Estimates of the technological capability and market penetration of efficient light sources show that by 2050, a 2.5 to 2.9 times growth in the global demand for lighting services can be accommodated while still meeting IEA GHG mitigation goals and increasing metal depletion just 20% above 2010 estimates.

Keywords:
- energy efficiency
- hybrid life cycle assessment
- industrial ecology
- light-emitting diodes (LEDs)
- scenario assessment
- solid-state lighting

Introduction

Mitigating global greenhouse gas (GHG) emissions will require deploying both low-carbon energy generation technologies as well as demand-side technologies that promote energy efficiency at an unprecedented scale (IEA 2012). As such technologies are deployed throughout the economy, it is important to understand their potential environmental and natural resource benefits and trade-offs at an early stage. This article is written in conjunction with a series of reports by the International Resource Panel (IRP) of the United Nations Environment Program (UNEP) that will address this issue. These reports will quantify and compare the environmental and natural resource benefits and trade-offs of a wide array of low-carbon energy technologies and efficient demand-side technologies for GHG mitigation on the basis of consistent methods, system boundary, and background life cycle inventory (LCI) data.

Artificial lighting is essential to a modern lifestyle, enabling numerous tasks from detection to recognition and orientation, contributing to a feeling of safety and comfort, and creating a pleasant atmosphere. Lighting is one of the largest electrical end uses, accounting for 17% of global electricity consumption...
RESEARCH AND ANALYSIS

The demand for lighting has been shown to be highly correlated with gross domestic product (GDP) (Tsao et al. 2010; McKinsey & Company 2012), and GDP is expected to grow fivefold in developing countries such as China and India by 2050 over the course of the GHG mitigation scenarios analyzed in this article (IEA 2012; OECD 2012). Currently, the majority of residential, commercial, and industrial lighting services in the world are provided by incandescent and fluorescent lamps (US DOE 2012). At the same time, many people in developing countries without access to a reliable electricity grid depend on costly and extremely inefficient fuel-based light sources, mainly kerosene lamps (Mills 2005). While only providing a small fraction of total illumination, fuel-based lighting still accounts for 7% of the global energy consumption for lighting services (IEA 2013), while emitting particulate pollution and black carbon that exacerbate climate change and impact human health (Lam et al. 2012; Furukawa 2012; Mahapatra et al. 2009).

Solid-state technologies, particularly light-emitting diodes (LEDs), have emerged as a more energy-efficient source of light. LED lamps and luminaires are declining in cost, while continuing to improve in energy efficiency and durability. Additionally, solid-state light-source technologies are the only current light-source technologies expected to improve significantly in luminous efficacy, that is, the amount of light produced (lumens) per power consumed (watts) (US DOE 2012). Further, owing to the rapid decline in the costs of LED lamps and luminaires, McKinsey & Company (2012) predicts that LEDs will make up nearly 70% of the general illumination market by 2020. As these solid-state light sources become more energy efficient, decline in cost, and gain larger market shares, estimates of the energy savings and the potential life cycle environmental burdens of efficient light sources must be updated from time to time. Also, if global electricity generation is decarbonized, the environmental impacts of providing lighting services will also change substantially in comparison with the present day. Thus, to fully understand the global environmental and natural resource impacts of lighting in the long term, it is critical to account for both direct improvements in light-source technologies as well as structural changes in upstream energy generation and material production.

A number of studies have used life cycle assessment (LCA) to show that LED light sources offer environmental benefits in comparison to incandescent and fluorescent light sources (Tähkämö et al. 2013a; Scholand and Dillon 2012; Tähkämö et al. 2013b; Dale et al. 2011; Weiz et al. 2011; Lim et al. 2011, 2012; Principi and Fioretti 2014), but those studies have been limited to specific geographical regions and near-term time scales. This article expands the scope of the assessment of efficient light sources to the global scale and estimates the long-term, aggregate environmental and resource impacts of efficient light sources by accounting for technological improvements to solid-state light sources and potential future changes in global electricity supply in nine global regions. This article is the first to compare LCI data from previous LCAs of fluorescent and LED luminaires in commercial applications, as well as incandescent, compact fluorescent (CFL), and LED lamps in residential applications, using a common background model and methods. By providing an overview of efficient light-source technologies, their technological capabilities and potential market shares, and by analyzing the aggregate life cycle environmental and resource impacts of production and use of efficient light sources in all world regions from 2010 to 2050, this article allows for a more comprehensive discussion of the global long-term environmental implications of efficient light sources.

The main contributions of this article are to: (1) update and harmonize the estimated impacts of efficient light-source technologies for all global regions; (2) provide first-ever long-term estimations of the environmental impacts from light sources as LEDs reach their full technological potential and electricity is decarbonized; (3) assess the aggregate trends in environmental impacts of light provision given a transition toward efficient solid-state light-source technologies; and (4) estimate the growth in demand for illumination that can be accommodated by LEDs while still meeting IEA energy and GHG reduction targets.

Light-Emitting Diode Technologies and Their Environmental Impacts: An Overview

In developed countries, light-source technologies in use today range from inefficient incandescent lamps to more efficient discharge and increasingly efficient LED technologies. In developing nations, kerosene lamps and other fuel-based light sources are still common in rural areas that do not have reliable access to electricity. The energy efficiency of light sources is generally expressed in luminous efficacy (lumens per watt; lm/W), dividing the luminous flux of the light source by the electrical power it consumes. High luminous efficacy is characteristic of fluorescent, LED, and high-intensity discharge (HID) technologies, whereas incandescent lamps are the most inefficient electrical light sources. Fuel-based light sources are, by far, the least efficient, with efficacies far below those of incandescent lamps. LED and solid-state technologies are promising, given that their luminous efficacies have rapidly improved in recent years.

The properties of the most common light source technologies are described in table 1 of supporting information S1 on the Journal’s website.

Light-Emitting Diode Technology

LED technology is based on a semiconductor (diode) junction that emits photons when an electric field is applied to the material. The electric field produces the electrons and holes in the material, the recombination of which creates the photons. The wavelength of the light depends on the band gap energy of the electron-hole recombination. By choosing the materials correctly and modifying the wavelength of the light by coating the LED package or bulb with a phosphor, an LED lamp is able to produce white light. White light can also be produced by color mixing, which involves the combination of different
proportions of colored LEDs (usually red, green, and blue). In the most widely used application, blue light from an indium-gallium nitride (InGaN) LED is absorbed by an yttrium aluminum garnet phosphor, thereby producing white light. LEDs of all colors usually include small amounts of by-product metals, particularly gallium (Ga), indium (In), and arsenic (As) (Wilburn 2012).

LED lamps and luminaires are increasingly used in households, offices, and industrial and commercial buildings in place of incandescent and fluorescent lamps and luminaires. A luminaire is defined as a complete light fixture, containing one or more lamps, their housing, and any necessary drivers or ballasts. Fluorescent technology needs a ballast to control the operation of the lamp, and LED technology requires a control gear and a driver that are integrated into the base. LED lamps are available in various colors, shapes, luminous intensity distributions, and luminous fluxes. Dimmable LED lamps are also becoming widely available.

Although LED luminaires are expected to have longer life expectancies than other light sources, and usually consume less power, the up-front costs of LED lamps and luminaires are relatively high, compared to incandescent and fluorescent lamps and luminaires, but the prices of the LED products are expected to decrease with the improvement of manufacturing processes, yield, and economies of scale (McKinsey & Company 2012). In developing nations, solar powered LEDs are increasingly being considered as a replacement to fuel-based lighting (Furukawa 2012). Replacing such inefficient and costly light sources presents an opportunity for such countries to decrease local air pollution, improve human health, and mitigate climate change while developing economically (Jones et al. 2005; Bhusal et al. 2007).

**Literature Review of Life Cycle Assessments of Light Sources**

The life cycle environmental impacts of light sources have been studied in a number of LCA articles and reports (Takahmō et al. 2013a; Scholand and Dillon 2012; Takahmō et al. 2013b; Dale et al. 2011; Welz et al. 2011; Lim et al. 2011, 2012). Studies have shown clearly that the environmental impacts of light sources, that is, lamps and luminaires, are predominantly caused by electricity consumption during use, suggesting that, in general, more energy-efficient light sources will have lower environmental impacts. Lim and colleagues (2012) have discussed that the production of an LED lamp requires a greater quantity of metals than an incandescent, some of which could be potentially hazardous if not disposed of or recycled properly. When comparing LEDs, CFLs, and incandescent lamps based on functionality (i.e., lumen output), LEDs were shown by Scholand and Dillon (2012) to perform better than incandescent lamps in terms of resource depletion and potential toxic impacts owing to their longer product life and lower power consumption. Because of the importance of the use phase, it stands to reason that the environmental impacts of light sources in general could change drastically as the global electricity mix incorporates more renewable or low-carbon energy supply technologies, even without the adoption of new efficient light-source technologies such as LEDs—an issue not fully addressed in the scope of previous studies.

Additionally, efficient LED light-source technologies are expected to more than double in luminous efficacy over the coming decades (US DOE 2012), lowering the amount of energy needed to provide the same lighting services. Scholand and Dillon’s study for the US DOE (2012) began to explore the potential changes in environmental impacts from near-term technological improvements in LED devices, finding that even near-term (5-year) improvements in luminous efficacy and LED production yield could lead to approximately 50% reductions in environmental impacts compared to today’s technology. Takahmō and colleagues (2013a) do not calculate near- or long-term changes to the environmental impacts of LED luminaires, but the same methods developed by Scholand and Dillon (2012) can be used to model the possible technological development of LED luminaires in the near and long term as well, allowing for a harmonized comparison of LED lamps and luminaires.

| Market type | Light source | Commercial and industrial (%) | Residential (%) | References |
|-------------|--------------|------------------------------|----------------|------------|
|             |              | 2010 | 2030 | 2050 | 2010 | 2030 | 2050 |
| OECD        | Incandescent lamps | 7   | 0   | 0   | 85  | 0   | 0   |
|             | CFLs         | 4   | 0   | 0   | 9   | 40  | 25  |
|             | LED lamps    | <1  | 0   | 0   | <1  | 40  | 55  |
|             | FL luminaires | 88  | 50  | 30  | 6   | 10  | 5   |
|             | LED luminaires | <1  | 50  | 70  | <1  | 10  | 15  |
| Non-OECD    | Incandescent lamps | 20  | 0   | 0   | 61  | 0   | 0   |
|             | CFLs         | 3   | 0   | 0   | 9   | 40  | 25  |
|             | LED lamps    | 0   | 0   | 0   | 0   | 40  | 55  |
|             | FL luminaires | 77  | 50  | 30  | 2   | 10  | 5   |
|             | LED luminaires | 0   | 50  | 70  | 0   | 10  | 15  |
|             | Kerosene lamps | 0   | 0   | 0   | 28  | 0   | 0   |

Note: OECD = Organization for Economic Cooperation and Development; CFL = compact fluorescent; LED = light-emitting diode; FL = fluorescent.

Table 1 Shares of energy consumption for likely (conservative) scenario of solid-state lighting market penetration.
Further, previously published LCAs have a limited geographical scope, having analyzed the environmental impacts of light sources as used in only individual regions, mainly Europe (Tahkamo et al. 2013a, 2013b) or the United States (Scholand and Dillon 2012), while not representing other regions, particularly the developing world. Because the environmental profile of electricity generation varies from region to region, the published results of these studies may not be directly comparable. Thus, a recalculation of life cycle impact results is needed for a harmonized comparison of lamps and luminaires.

Last, a number of articles have investigated the so-called rebound effect (Berkhout et al. 2000) from energy efficiency in regard to lighting. In the context of efficient lighting, the monetary savings from decreased energy consumption could result in both increased use of lighting (direct rebound) as well as an increased demand for other goods and services owing to income effects (indirect rebound) (Borenstein 2013; Hertwich 2005). Several studies have examined the possible range and magnitude of rebound from lighting, including Hicks and Theis (2014) and Saunders and Tsao (2012), finding that the rebound effect for lighting could, in some cases, erode all energy savings.

This article addresses gaps in previous literature by highlighting the importance of accounting for both long-term technological improvements to light-source technologies, as well as the changing electricity grid mix over the course of different long-term energy scenarios developed by the IEA. Further, this article compares efficient light-source technologies using a common method and background database, allowing for a greater degree of comparability among the technologies analyzed in previous studies.

**Lighting Demand and Market Penetration Scenarios**

GHG mitigation scenarios, such as those developed by the IEA, highlight the importance of adopting efficient lighting to reduce energy use and GHG emissions by the buildings sector. The IEA BLUE Map scenario has the goal of limiting climate change to 2 degrees Celsius by 2050 by decarbonizing global electricity generation and reducing energy demand through energy efficiency (IEA 2010, 2012). Despite an expected rise in the demand for lighting globally (particularly in non-OECD countries), these scenarios require that an overall reduction in the amount of energy consumed for lighting in 2050. According to the IEA, efficient lighting can save 72 exajoules of energy over the next 40 years relative to baseline (IEA 2013) projections. Using a back-casting approach, this article estimates the deployment of efficient technologies needed to reach the energy and GHG saving goals projected by the IEA scenario and explores the implications of the embodied energy and environmental impacts of deploying efficient light-source technologies 2010–2050 at such a scale.

Knowing the projected electricity consumption for lighting under the IEA scenarios, a scenario analysis can answer two important questions. First, given the expected efficiency improvements in light-source technologies, how much can the demand for lighting services grow while still meeting the energy-saving targets in the IEA scenarios? Second, how will the widespread adoption of efficient light sources affect global trends in the environmental impacts and resource consumption owing to lighting?

**Life Cycle Assessment: Methods and Data**

**Goal and Scope**

The goal of this article is to assess the potential environmental and natural resource benefits, trade-offs, and risks from using efficient light sources as a means of mitigating global GHG emissions in both the near and long term. To accomplish this, the most common light-source technologies are compared over a comprehensive set of environmental indicators using LCA. First, light sources are compared based on the standard functional unit of 1 mega lumen-hour (Mlm-hr) of light. Second, the life cycle impacts of efficient light sources are computed per kilowatt-hour (kWh) of energy saved. This analysis allows the impacts of efficient, energy-saving lighting sources to be compared to those of low-carbon electricity generation and other energy efficiency technologies, such as efficient cooling, photovoltaics (PV), wind power, or more efficient communication technologies. Such an analysis is useful for policy makers to prioritize the most effective, environmentally benign efficiency measures available. Finally, scenario analysis is used to estimate long-term trends in GHG emissions and other key environmental indicators based on the growth in energy demand for lighting from 2010 to 2050, and to estimate the global growth in lighting demand that will be possible while meeting IEA energy and GHG goals.

The ReCiPe 2008 midpoint life cycle impact assessment (LCIA) method is used to characterize the potential impacts of light sources on the following categories: climate change (kilograms [kg] carbon dioxide equivalent [eq]); freshwater eutotoxicity (kg 1,4 dichlorobenzene [DCB]-eq); freshwater eutrophication (kg phosphorus-eq); human toxicity (kg 1,4-DCB-eq); metal depletion (kg iron-eq); particulate matter formation (kg particulate matter 10 micrometers or less in diameter-eq); photochemical oxidant formation (kg nonmethane volatile organic compounds-eq); terrestrial acidification (kg sulfur dioxide-eq); and land occupation (square meters-annum) (Goedkoop et al. 2009).

**Hybrid Life Cycle Assessment Model for Electricity Generation and Materials Production from 2010 to 2050**

This analysis performed for this article employs a common model and method for the calculation of long-term environmental and natural resource impacts following the IEA BLUE Map and Baseline energy scenarios. The THEMIS model (Technology Hybridized Environmental-economic Model with Integrated Scenarios) was constructed as part of efforts for the UNEP IRP research on the environmental implications of low-carbon technologies, details of which are documented in the supporting information of Hertwich and colleagues (2014).
The THEMIS model is an integrated hybrid LCA model (Suh 2004) consisting of nine regionalized versions of the ecoinvent 2.2 database (ecoinvent Center 2010), the EXIOBASE multiregional input-output database (Tukker et al. 2013), and original LCI models for present and future low-carbon electricity generating technologies (Hertwich et al. 2014). Present and future electricity mixes in the model are based on the BLUE Map and Baseline (business as usual) scenarios, which include generation by wind, concentrating solar, PV solar, geothermal, hydropower, and fossil fuels employing carbon capture and sequestration. This model incorporates future technological improvements to energy and materials efficiency of those low-carbon electricity generation technologies, as well as economy-wide technological changes, including improvements to energy consumption, GHG emissions, and pollution control in key sectors (metals production, pulp and paper, and chemicals and cement).

**Computation of Results and Life Cycle Impact Assessment**

LCIs are calculated for fluorescent and LED luminaires (commercial lighting) and incandescent, CFL, and LED lamps (residential lighting) in the years 2010, 2030, and 2050 as manufactured and used in nine global regions defined by the IEA: China, India, OECD Europe, OECD North America, OECD Pacific, Economies in Transition, Latin America, Other Developing Asia, and Africa and the Middle East (IEA 2010). The results section presents the range of LCIA results arising from regional differences in electricity generation, as well as the variation in luminous efficacy of light-source technologies. In each year, the regional LCIs are then weighted by the projected GDP of each region in the IEA scenario to compute global average impacts of each technology. In addition to comparing light-source technologies on the functional unit of 1 Mlm-hr, the life cycle impacts of efficient light-source technologies are quantified based on their ability to save energy, otherwise known as a “negawatt” (Lovins 1976; Steinberger et al. 2009).

In this case, the functional unit would be 1 kWh of energy saved. The LCI of a kWh saved by an efficient light source is the sum of the environmental and resource impacts of efficient light-source production and its end of life needed to save 1 kWh of electricity relative to an incandescent lamp.

**Development of Global Lighting Scenarios**

Finally, given the expected energy demand for lighting in the IEA scenarios and the current and projected future market shares of light-source technologies (US DOE 2012; McKinsey & Company 2012), the demand for lighting services in each region is estimated from 2010 to 2050, and the aggregate environmental impacts are calculated by scaling up the per Mlm-hr LCIs. In addition, by constraining the energy consumption for lighting to IEA projections, this analysis estimates the growth in global demand for lighting services (on a lumen-hour basis) that can be accommodated by a transition to efficient, solid-state lighting while meeting IEA energy reduction targets. The lumen-hour demand for lighting in 2010, 2030, and 2050 is calculated based on the global electricity consumption for lighting in each region of the IEA scenarios (IEA 2012, 2013), current estimates of energy consumption by light-source technologies (Navigant 2012; US DOE 2012; Mills 2005), expected future market shares of lighting technologies (Navigant 2012; US DOE 2012; McKinsey & Company 2012), and the luminous efficiencies of current and future light-source technologies. Shares of technologies not covered in this analysis (HID and halogen) were assigned to fluorescent luminaires because of their similarity in luminous efficacy. Three different LED market penetration scenarios were developed and compared: (1) current market shares of light-source technologies remain the unchanged from 2010 to 2050; (2) likely/conservative scenario of 50% LEDs in 2030 and 70% LEDs in 2050; and (3) high LED penetration of 90% by 2050. By constraining the energy consumption for lighting to the IEA targets, the total possible increase in demand for lighting services under each LED market scenario was calculated. Current and future market shares of light-source technologies in the likely scenario are presented in table 1. A spreadsheet detailing the assumptions and calculations of scenario analysis results is included in supporting information S2 on the Web.

**Inventory Models for Light Sources**

This analysis applies the THEMIS model to data on the manufacturing inputs of light-source technologies known from previously published reports and peer-reviewed journal articles (Tähtikö et al. 2013a, 2013b; Scholand and Dillon 2012). By updating inventory models from those articles to reflect the luminous efficacy and product life expectancy of current and future state-of-the-art LED lamps and luminaires, this analysis is able to recalculate up-to-date and harmonized LCIs for light sources produced and used in all global regions from 2010 to 2050, accounting for a more comprehensive set of economy-wide changes and technological improvements to light sources than previous assessments.

For residential light sources technologies, inventory models were constructed for 60-watt (W) incandescent lamps, 15-W CFLs, and 12.5-W LED lamps using data from the US DOE reports on the environmental impacts of LED lamps (Scholand and Dillon 2012). For commercial and industrial light-source technologies, inventory models were constructed for 83-W linear fluorescent luminaires and 78-W LED luminaires based on Tähtikö and colleagues (2013a, 2013b). Inventory models from aforementioned studies were updated to reflect the luminous efficacy of present-day LED lamps and luminaires, having changed somewhat since publication. For scenario analysis only, an inventory model was also constructed for kerosene lamps, based on the fuel consumption and material requirements estimated in Mahapatra and colleagues (2009) and Jones and colleagues (2005). It must be noted that the residential and commercial lighting sectors in this analysis are represented only by the top five types of light sources (incandescent lamp, CFL, LED lamp, and fluorescent and LED luminaires). Notably HID lamps, widely used in industrial applications and representing 14% of current lighting energy consumption, were excluded from the analysis because of the very low number of
LCAs conducted on these products, and fluorescent luminaires were used to represent these products because of their close similarity in luminous efficacy. Spreadsheets containing inventory models for all light sources used in this analysis are included in supporting information S2 to S5 on the Web.

### Technological Improvements in Efficient Lighting from 2010 to 2050

LED lamps and luminaires are undergoing rapid developments and are likely to see substantial improvements in the long term in terms of efficiency and design (US DOE 2012; Murphy 2012; Pimputkar et al. 2009). Although not all future technological improvements can be predicted and quantified within the scope of an LCA, key parameters, such as luminous efficacy and product life expectancy, can be estimated using projections from industry technology roadmaps and peer-reviewed scientific literature.

Established roadmaps from the US DOE were used to estimate the range of luminous efficacy for all light sources in present day and 2030, and projections from Murphy (2012) were used to show the full potential efficacy of LEDs in the long term (2050). Future LED lamps and luminaires are assumed to be optimized versions of the most typical present-day technology, the blue InGaN LEDs with remote phosphors modeled in Scholand and Dillon (2012) and Tahkimoo and colleagues (2013a). In the future, a larger variety of solid-state lighting technologies could penetrate the market, most notably organic LEDs (OLEDs), laser diodes, and LED light sources utilizing color mixing (US DOE 2012; George et al. 2013; Krames et al. 2007; Pimputkar et al. 2009). Color-mixing LED light sources combine different colored LEDs (e.g., red, green, blue, and amber) with or without phosphor coatings to produce white light. These devices would most likely still rely on many of the same diode materials as the technology considered in this article, given that elements such as In, Ga, and As are commonly used to produce red, blue, green, and amber LEDs (Krames et al. 2007). These facts suggest that the environmental impacts of future LED devices will be affected more by luminous efficacy and life expectancy of the device than by material composition of the LED package. Last, OLED devices are not studied in this article. Although the semiconductor diode of such devices may not require metals such as In and Ga, the same kinds of rare-earth phosphors needed for inorganic LED devices would be needed (Kamtekar et al. 2010).

Table 2 summarizes the projected technological improvements for LED and (to a lesser extent) fluorescent light sources by 2030 and 2050. LED luminous efficacy is assumed to meet DOE program goals by 2030 and achieve maximum efficacy by 2050. Other improvements in LED lamp and luminaire production are modeled similarly to Scholand and Dillon (2012), notably that the mass of metal needed for heat sink decreases proportional to the power consumption of the light source.

### Life Cycle Impact Assessment Results

This section first presents the life cycle GHG emissions for light-source technologies from 2010 to 2050, and then compares the LCIA results of efficient light sources to a reference case of incandescent lamps for the other environmental
and natural resource indicators considered in this article. To visualize the potential c obenefits and trade-offs from efficient light sources, the impacts of 1 Mlm-hr from the efficient (LED and fluorescent) technologies are presented as a proportion of the impacts of the inefficient (incandescent) technology.

**Environmental Impacts of Light Sources from 2010 to 2050**

Figure 1 shows the life cycle GHG emissions for residential and commercial lighting technologies, respectively. Error bars represent the range of the technological variation of each technology (luminous efficacy) and regional differences in electricity mix. Because of the decarbonization of global electricity generation, results for all technologies show a decline in GHG emissions for all three technologies considered. In 2010, LED technologies show a wide range of impacts, owing to the differences in regional electricity mixes, as well as the range of luminous efficacy among commercially available lamps and luminaires. By 2030, however, improvements in luminous efficacy of LED light sources are expected to reduce the impacts at a much faster rate than CFLs.

Because of their close similarity in luminous efficacy, commercial LED and fluorescent luminaires show similar environmental impacts in the present day. Currently available LED luminaires vary greatly in terms of luminous efficacy, with some products on the market having lower efficacies than their comparable fluorescent counterparts. Some LED luminaires have achieved higher efficacies than fluorescent luminaires, with further improvements expected by 2030 and 2050.

Figures 2 and 3 compare a broad set of environmental impacts for efficient light-source technologies to those of incandescent, allowing an exploratory discussion of the possible trade-offs and c obenefits of using efficient light-source technologies to mitigate energy consumption and GHG emissions from 2010 to 2050.

For residential light-source technologies shown in figure 2, CFLs showed greater than 60% reductions in impacts in 13 of 14 impact categories considered. Current LED lamps showed clear reductions in all impacts considered compared to incandescent lamps, and in all impacts except metal depletion compared to CFLs. LED lamps showed 80% or greater reductions in impacts in 13 of 14 categories and a 40% reduction in metal depletion compared to incandescent lamps. By 2030 and 2050, improvements in LED technology allow for even greater reductions in impacts relative to CFLs and incandescent lamps—at least 95% lower than incandescent in 10 of 14 categories, 90% lower terrestrial ecotoxicity, and 75% lower metal depletion.

For luminaires in commercial and industrial applications (figure 3), typical current LED luminaires (78 lm/W) showed 10% to 15% higher impacts in most categories, and nearly double the impact of metal depletion compared to the typical linear fluorescent luminaires (88 lm/W) considered in this article. Given that LED technologies are expected to improve dramatically in luminous efficacy by 2030 and 2050 (while fluorescent technology will only improve marginally), the environmental impacts of LED luminaires eventually outpace fluorescent luminaires, leading to at least 40% lower impacts in 11 of 14 categories, compared to fluorescent luminaires in 2030, and even steeper reductions by 2050. In comparison with the current impacts of incandescent lamps, LED luminaires in 2050 show 95% lower impacts in 12 of 14 categories and 90% lower metal depletion and terrestrial ecotoxicity. Results for LED lamps and luminaires are nearly identical in 2050, with the exception that LED luminaires score 60% lower in terms of metal depletion.

**The Impacts of Saving a Kilowatt-Hour of Electricity Using Efficient Light Sources**

Figure 4 compares the environmental impacts generating 1 kWh of grid electricity to those of saving 1 kWh of electricity by replacing incandescent lamps with current, efficient
light sources. For all environmental indicators in 2010, using efficient light sources as a means to save electricity results in net impact reductions by all efficient light-source technologies analyzed. For the natural resource indicator of metal depletion, however, all technologies except fluorescent luminaires require greater impacts to save 1 kWh than to generate 1 kWh of grid electricity. Results suggest that, in the near term, using efficient fluorescent luminaires to save energy (relative to incandescent lamps) is the most environmentally benign strategy at present, owing to the relatively high luminous efficacy and therefore low energy consumption of these devices. Using current, efficient light sources to produce energy savings will likely result in reductions in environmental impacts, but can require somewhat greater metal resources than generating grid electricity.

Analysis of Global Lighting Scenarios

The following section presents the results of the scenario analysis of energy consumption from lighting and its resultant environmental impacts from 2010 to 2050.

Under the likely scenario for LED market penetration (70% of illumination in 2050), more than a twofold increase in the demand for lighting services can be accommodated while still meeting BLUE Map energy consumption goals. Under this scenario, the demand for lighting in OECD countries could increase 1.8 times, and non-OECD countries could increase lighting demand by 3.5 times. Under the high penetration of LEDs scenario, OECD lighting demand could grow by 2.1 times whereas non-OECD lighting demand could increase 4.1 times. With little or no change in the market penetration of efficient light-source technologies, the demand for lighting by 2050 in OECD countries would have to decrease by a factor of 0.7 in order to accommodate a modest increase in lighting demand of 1.1 times in non-OECD countries.

Following the likely/conservative scenario, figure 5 shows selected annual environmental impacts and energy consumption from lighting from 2010 to 2050. The metal depletion indicator was chosen because previous analysis of the IEA scenarios, to which two of the current authors contributed (Hertwich et al. 2014), suggested that a transition to low-carbon electricity supply may significantly increase demand on materials, especially metals. Figure 5 shows an initial increase in metal depletion by 2030, owing to the increase in global demand for lighting services, particularly in the developing world. By 2050, in this scenario, metal depletion increases just 20% above 2010 levels. Although LED lamps and luminaires in 2050 require fewer metals per Mlm-hr than all other light sources, owing to efficiency gains and prolonged product life expectancy, increased demand for lighting services worldwide has the potential to cancel out those savings.

Limitations and Uncertainties

As identified in this article and previous studies, the environmental impacts of light sources depend mostly on the environmental profile of the electricity source used, particularly for GHG emissions (Scholand and Dillon 2012). The results from the Baseline and BLUE Map scenarios can be used.
to provide a range of possible environmental impacts from lighting services in the long term. In addition to the changes in global electricity mixes over time, the most important parameters affecting the assessment of devices (not including the use phase) are luminous efficacy and expected life of a lamp or luminaire, which could greatly affect the assessment of devices on a per kWh saved basis (see also Tahkamö et al. 2013a, 2013b; Scholand and Dillon 2012).

In this article, light sources were considered to be interchangeable, meaning that 1 Mlm-hr of light from an LED lamp is equivalent to 1 Mlm-hr of light from an incandescent lamp or CFL. Although the rebound effect would not influence the assessment of the environmental impacts of light sources on a per lumen-hour basis, and the scenario assessment implicitly assumes growth in the demand for lighting services, rebound would affect the results calculated on a per kWh saved basis (figure 4). Although modeling such an effect in the long term using a scientifically defensible modeling framework is beyond the capability of available models, a sensitivity analysis is used to examine the magnitude of rebound that would cancel out the environmental benefits from efficient lighting (see table 4 of supporting information S1 on the Web). Results of this analysis show that a direct rebound exceeding 97% of energy savings would be needed to cancel out the GHG savings achieved by using CFLs to replace incandescent lamps, and over 99% if using present day LEDs. A much more modest rebound (40% to 80%) could erode the GHG savings from replacing CFLs with present-day LED lamps.

**Discussion**

Lighting is a major contributor to electricity consumption globally, and even considering some growth in the demand for lighting services from now until 2050, overall reductions in energy consumption for lighting are possible. The technological advancement and increasing market penetration of solid-state lighting technologies, together with the possible decarbonization of global electricity generation, have the potential to lead to order of magnitude or greater reductions in almost all of the environmental impacts from light sources on a per lumen basis. Scenario analysis indicates that deployment of solid-state lighting technologies can help meet IEA energy savings goals and stabilize metal depletion at 2010 levels even if the global demand for lighting services increases more than twofold by 2050.

Relative to traditional, incandescent light sources, solid-state LED light sources, CFLs, and fluorescent luminaires examined in this analysis show long-term benefits in all environmental and natural resource categories considered—that is, the life cycle impacts resulting from light sources are expected to decrease over time. The per kWh saved results show that, in the short term, replacing inefficient light sources with efficient ones to produce energy savings may require additional metal resources than generating average grid electricity, owing to the materials requirements of the lamps’ electronics and phosphors. Assessments of the environmental implications of future electricity generation scenarios suggest that because electricity generation emits fewer GHGs, it may require more
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Figure 4 Environmental impacts of saving 1 kilowatt-hour (kWh) of electricity by replacing incandescent lamps compared to the impacts of 1 kWh of global average power generation. BAT is “best available technology.” Electricity represents the environmental impacts of the global, average electricity mix in 2010. Luminaires are represented by solid lines, and lamps are represented by dashed lines.

metals and materials (Hertwich et al. 2014; Bergesen et al. 2014). In that case, technological improvements that improve the materials efficiency of light sources or enable recycling and recovery of metals could become increasingly important.

Scenario assessment of lighting demand shows that an overall decrease or stabilization of key environmental indicators from 2010 to 2050 is possible. Natural resource impacts, particularly the consumption of metals, are of particular concern for lighting, given that scenario results show a slight increase in annual metal depletion by 2050. Results for 2050 for LED lamps, LED luminaires, and fluorescent luminaires show 75-90% lower metal depletion compared to incandescent light sources and 40-75% lower metal depletion than CFLs. If incandescent lamps and CFLs are not phased out in favor of more energy and resource efficient LEDs by 2050, this scenario could result in a larger net increase in metal consumption for lighting than shown in figure 5. This result suggests that an aggressive adoption of solid-state LED lamps and luminaires in both OECD and non-OECD countries is needed to ensure overall reductions in the environmental and natural resources impacts from light-source technologies.

Over the next 20 to 40 years, the life cycle environmental impacts of lighting services will continue to depend heavily on the sources of energy used for electricity generation, as well as the technological advancement of solid-state light-source technologies, particularly LEDs. LED light sources already require approximately 10% of the energy needed by incandescent lamps today and may require only 5% of the energy needed by incandescent lamps when the technology reaches maturity. As solid-state lighting technologies become cheaper to produce, and result in greater energy savings during their lifetimes, the demand for lighting services may increase, and more electricity generation will be needed. In their analysis, Tsao and Waide (2010) show a close empirical relationship historically among illumination, GDP, and the cost of lighting—as GDP has increased and the cost of providing has decreased, the total demand for illumination has increased proportionally. Although it is possible that the demand for lighting may eventually become saturated, the demand for lighting is expected to continue to grow beyond 2030 (Tsao et al. 2010). Under the BLUE Map scenario, more than a threefold increase in global GDP is projected by 2050. The analysis presented in this article estimates that a growth in lighting demand of 2.5 to 2.9 times can be accommodated by a transition to solid-state light-source technologies while meeting GHG emission and energy consumption reduction targets, implying that the demand for lighting would...
need to grow at a slower rate than GDP. To meet the goals of the IEA BLUE Map scenario, and possibly other GHG mitigation scenarios, this result implies that policy measures may be needed to ensure that a growth in demand for lighting does not erode the energy savings required from efficient lighting. On the other hand, this analysis assumes conservative values for luminous efficacy for solid-state lighting by 2030 and 2050, and it is possible that emerging solid-state lighting technologies may exceed these estimations (such as laser light sources), and that other future technological innovations or cultural shifts may drastically change the lighting market, thus improving luminous efficacy or shifting the demand for illumination.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

Supporting Information S1: S1 contains descriptions of the properties of common light-source technologies and their assumed market shares in 2010, 2030 and 2050, details of life cycle inventory methods, contribution analyses and sensitivity analyses.

Supporting Information S2–S5: This supporting information contains workbooks of life-cycle inventory data for light-source technologies in years 2010, 2030, and 2050, consisting of inputs and outputs for each unit process. It also contains underlying data and assumptions for the scenario analysis.