**Technical assessment for**

**Residential LED Lighting**

Sector: Buildings

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Version 1

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# Acronyms and Symbols Used

**CFL** – Compact Fluorescent Lamp

**DC** – Direct Current

**GBPN** – Global Building Performance Network

**GHG** – Greenhouse Gas

**HID** – High Intensity Discharge Lamp

**IEA** – International Energy Agency

**klm** – Kilolumen

**LCA** – Life-Cycle Assessment

**LED** – Light Emitting Diode

**LFL** – Linear Fluorescent Lamp

**Lm/W** – Lumen per Watt

**Lmh** – Lumen hour

**MT** – Million metric tonnes

**nm** – nanometer (= 1 billionth of a meter)

**OECD** – Organisation for Economic Cooperation and Development

**OLED** – Organic LED

**PDS** – Project Drawdown Scenario

**Plm** – Petalumen (1 *million* billion lumens)

**Plmh** – Petalumen-Hour (1 *million* billion lumen-hours)

**REF** – Reference Scenario (of Project Drawdown)

**SSL** – Solid State Lighting

**TAM** – Total Addressable Market

**TCO** – Total Cost of Ownership

# Executive Summary

LED lighting offers a great possibility to reduce the GHG emissions in residential lighting. Traditionally, there have been four types of lamps used in residential lighting: incandescent lamp, halogen lamp, compact fluorescent lamp (CFL) and linear fluorescent lamp (LFL). Globally, the lamps of the lowest luminous efficacy, i.e., incandescent and halogen lamps, have been the most widely used, but the trend is currently changing: in 2014, the market share of incandescent and halogen lamps accounted for approximately 51% of global residential lighting, but in the 2020’s, their market share is expected to be decreased to 10%. In some areas, incandescent lamps are replaced by halogen lamps that are a bit more energy efficient: the luminous efficacy of incandescent lamp is around 14 lm/W whereas that of halogen lamp is around 22 lm/W. If the challenges are overcome in the product quality, reducing the purchase price and increasing the luminous efficacy even further, the LED lighting is expected to take over the residential sector nearly entirely by 2050.

LED lighting products offer high luminous efficacy and thus high energy efficiency, emission reductions, and reduced costs during operation. Despite the high purchase price, the total life cycle costs of LED residential lighting are typically lower than those of conventional technologies due to the low operating costs. The high energy efficiency reduced operating costs and reduced amount of GHG emissions are considered to be the main benefits of LED lighting. Also, LED lighting products have much longer service life, usually 50 000 hours, which reduces the need for replacement.

The LED technology is expected to save a significant amount of energy in residential buildings. According to the calculations in the model developed, the LED lighting solution consume approximately 14 TWh per Plmh, whereas the conventional technologies (incandescent lamp, halogen lamp, CFL, and LFL) consume 42 TWh per Plmh. This is also seen in the average luminous efficacies of the various technologies: LED lamp is estimated to have a luminous efficacy of 73 lm/W, whereas the conventional technologies have generally lower efficacies (incandescent lamp approximately 14 lm/W, halogen lamp 22 lm/W, CFL 61 lm/W, and LFL 80 lm/W).

With the expected high adoption rate of LED lighting in residential buildings in 2050, the GHG emission reduction is estimated to be approximately 631 MMt CO2-eq. globally in 2050. As a cumulative emission reduction for 2020-2050, the LED residential lighting is estimated to result in a reduction of approximately 12.1 Gt CO2 globally. When combined with commercial LED adoption, total reduction over this period should be around 20.3 Gt CO2e.

# Literature Review

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. Including building construction increases this to 36%. These two together account for 39% of energy-related CO2 emissions (UN Environment & IEA, 2017). Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. Breaking down the building sector by energy end-use gives us an idea of where the potentials lie. Space heating consumed 32% of final building energy in 2014. The other top uses are cooking energy (22%), water heating (19%), appliances and equipment (16%), and lighting (6%) (IEA, 2017). Clearly there are many opportunities across the building sector for energy efficiency. Space and water heating energy is affected by windows, walls and heat source, cooking energy is affected by source and cooking technology, appliance energy by appliance efficiency and use, and lighting is affected by light technology and use.

## State of Residential LED

### Light-Emitting Diode Basics

The light emitting diode (LED) technology, also known as “Solid State Lighting” (US DOE SSL, 2017b), is used to convert electrical energy into visible radiation, i.e., light. In buildings, the LED lighting products provide illumination especially for visual performance but also for visibility, safety and atmosphere. The LED technology is especially suitable for decorative lighting as there are LEDs of various colors in the market and the size of the LED is small so that it can be attached or integrated, for example, into furniture. The LED lighting products can also be easily controlled, which enables further energy savings without decreasing the user satisfaction or even improving the alertness and comfort of the user by modifying the intensity and the color of the light.

LEDs are the latest of many lighting revolutions, albeit still relying on electricity. LED technology directly converts electricity into light, by radiative electron and hole recombination in semiconductor junctions (Weisbuch, 2018). When the electrons and holes recombine in the junction, a quantum of energy (a photon) is emitted. Semiconductors are materials characterized by a small band gap (the energy difference between isolated and conducting states) (Franz & Wenzl, 2017).The wavelength of the photon released determines the color of the light emitted. This wavelength depends on the characteristics of the semiconductor material. LED solid-state lighting offers great versatility and fulfils a broad range of lighting needs considering its quality, ease of use, reliability, and its very high efficiency (Weisbuch, 2018).

The phenomenon of a semiconductor junction to produce light was first reported by H. J. Round in 1907 in England. The phenomenon was also investigated by O. Losev in Russia in the 1920’s, but it was only in the 1962 when an American engineer N. Holonyak Jr developed the first practical LED of visible spectrum, succeeding in observing laser emission at 710 nm wavelength (red light) (Weisbuch, 2018). Since then, colored LEDs were used as indicator lights in electronic devices. In the 1990’s, after the development of blue LED by S. Nakamura, which was crucial for the production of white light, the use of LED products spread from indicator and decorative lighting to various lighting applications, such as general and task lighting in buildings and road and park lighting in outdoor areas. LED lighting only developed into the major market from 2012 onwards, when eﬃciency and cost made them cost competitive with alternatives (Weisbuch, 2018). In 2014 the Nobel Prize in Physics was awarded to Akasaki, Amano, and Nakamura for “the invention of eﬃcient blue light-emitting diodes which has enabled bright and energy-saving white light sources” (Gayral, 2017).

White light, which is especially needed for general lighting applications, may be produced by LED technology in two basic methods: 1. mixing monochromatic LEDs (such as red + blue + green)) or 2. converting blue or UV light using a phosphor layer (phosphor-conversion) (Franz & Wenzl, 2017). In phosphor conversion, the radiation from a blue or ultra violet (UV) LED is converted into white light by using phosphors, however the color mixing method makes is possible to tune the color of the light, for example, if a colored or cooler or warmer white light is needed.

A LED component is rarely used in lighting alone as it needs auxiliary components to operate properly, such as optical, thermal, mechanical and electrical interfaces. The light from the LED chip may need to be controlled by adding lens(es) on it. The LED package, i.e., the LED component with possible additional interfaces, is attached on a printed circuit board, which forms a single or multichip (array) LED module(Franz & Wenzl, 2017). One or several LED modules may form a LED lamp with an integrated control gear and a cap for easy installation. LED module(s) may also form a LED luminaire with a separate control gear. Control gear, consisting the power supply and control unit, serves to supply the rated voltage or current for the LED package and may enable the dimming, power-factor correcting and other control functions. LED luminaires are the LED lighting products typically used in commercial buildings, whereas residential lighting is assumed to be based on LED lamps. LED lamps and LED tubes are may also be used in commercial lighting to replace conventional light sources, such as a linear fluorescent lamp (FL) or an incandescent lamp. Lamp design has a large influence on lamp performance. For instance, retrofit lamps may have less favorable thermal management and lifetime performance, but they can fit into existing luminaires and sockets (Franz & Wenzl, 2017).

A LED lamp can directly replace any lamp of the same cap type. For example, a LED lamp with an E27 cap can directly replace a compact fluorescent lamp (CFL) or a halogen lamp of the same cap type. This kind of direct replacement is typical in residential lighting where the luminaire usually remains the same and only the light source inside is replaced. LED luminaires are less frequently used in residential lighting, whereas the LED lamps are assumed to be the solution for households. An LED luminaire may replace a luminaire of some other lighting technology, e.g., a fluorescent lamp (FL) luminaire or a high-intensity discharge (HID) luminaire. Control gear, consisting the power supply and control unit, serves to supply the rated voltage or current for the LED package and may enable the dimming, power-factor correcting and other control functions.

### Energy Efficiency of LED Technology

LED products are currently one of the most energy efficient light sources on the market. The energy efficiency of lighting products is measured in luminous efficacy. 1 lumen is the amount of *visible* light emitted from a source per unit time, and the unit of luminous efficiency is lumens per watt i.e., the ratio of luminous flux (unit lumen, lm) produced by the light source and respective electrical power (unit watt, W) required for the operation. Since introduction, the luminous efficacy of LED lighting products has improved from around 25 lm/W to over 160 lm/W, depending on color quality and drive conditions (Morgan Pattison, Hansen, & Tsao, 2018) and is increasing more rapidly than any other light source technology. The luminous efficacy of a top performing LED lamp or luminaire has been reported to range between 86 and 149 lm/W in 2017 while the long-term future goal for LED package luminous efficacy is set at 255 lm/W and luminaire luminous efficacy at 218 lm/W(US DOE SSL, 2017a). In contrast, conventional lighting products are *not* expected to be developed as drastically.

The efficiency of a luminaire is determined as the light output ratio (LOR). LOR is defined as the ratio of the total luminous flux of the luminaire to the sum of the individual luminous fluxes of the light sources (lamps) when operated outside the luminaire with the same control gear needed. The LOR value depends on the shape and materials of the luminaire and varies a lot. Generally, the LOR ranges around 50-80%.

The LED lighting has good potential to reduce the GHG emissions from residential sector, since its operation may be more energy efficient compared to most other lighting technologies There is a great potential to further develop the luminous efficacy of LED products, as the ultimate goal is set at 255 lm/W for a LED luminaire (US DOE SSL, 2017a). In contrast, the efficacy of other light source technologies is not expected to have such a development potential. For instance, kerosene lamps account for 3% of total lighting, yet are responsible for 20% of CO2e emissions due to lighting(Gayral, 2017). However, daylighting, as a non-electric type of lighting, could be another clearly sustainable lighting technology, but it’s not sufficient as the *only* type of lighting due to its limitations, such as the restrictions of availability.

### Lighting Service and Energy Consumption

The residential lighting was estimated to account for 19.2 Plmh in 2005 and to increase to 49 Plmh in 2030. In 2005, average households in International Energy Agency (IEA) member countries were estimated to have 27.5 lamps, including 19.9 incandescent lamps, 5.2 linear fluorescent lamps (LFL), 0.8 halogen lamps and 1.7 compact fluorescent lamps (CFL) globally but regional differences were estimated to be significant (IEA, 2006).

## Adoption Path

### Current Adoption

Since LEDs are more expensive than traditional technologies, the market share if based on sales will be greater than if based on units. LED penetration of the unit installations will grow more slowly than of sales or revenue, as LEDs become the majority of sales and replace existing installations (US DOE SSL, 2017a).

The US DOE estimated that LED technology accounted for approximately 3% of global installed base in 2014, 11% at the end of 2016, and forecasts that the penetration of the global installed lamp base will reach 50% around 2022 and 74% by 2030 (US DOE SSL, 2017b). This covers all lighting sectors. The global estimates for LED adoption vary significantly, and some sources double the estimate for the lamp sales (from 3% to 6%)(US DOE SSL, 2014), but it’s generally agreed that the revenue from and the market penetration of LED technology are increasing.

The penetration rate of LED technology has been largest in the residential lighting sector. In the U.S. it was estimated to be the greatest in terms of number of lamp and luminaire installations. In 2015, residences accounted for 71 percent of all lighting installations nationwide, at 6.2 billion (US DOE SSL, 2014). Although the annual installation of residential LED bulbs increased six-fold to 78 million between 2012 and 2014 (there were fewer than 400,000 installations in 2009), LED bulbs accounted for only 3 percent of the installed base of indoor lighting and 14 percent of outdoor in 2014 (National Academies of Sciences, Engineering, and Medicine, 2017).This is also in line with the McKinsey estimates of linear fluorescent lamps (LFL) still remaining approximately at 16% of value-based market share in all general lighting in 2020. The reason for LED technology to replace LFL technology more slowly compared to other conventional lighting technologies is the robustness, maturity, energy efficiency (approx. 100 lm/W) and cost efficiency of LFL. Residential lighting uses few LFLs (Table 1.1) and the uptake for compact fluorescent lighting (CFL) in residences was relatively slow until the 1990s, led by Western European markets (Luth, 2012).

LED lighting is already in use in households. On the basis of McKinsey data for 2012 and 2016 (Table 1.1), the market share of LED lighting is estimated to be approximately 31% in 2014 (linear interpolation), but it is noted that this is the market share of *sales,* not that of the installed base, so this value cannot be used for the share of LED products in installed base. Installed base refers to the light sources in use, while market refers to the sales of light sources in a year. It turned out to be rather difficult to collect LED adoption data globally and regionally. US DOE estimated that in 2014 the penetration rate of LED lighting of the installed base was 2.4% in replacing A19 general service lamps (US DOE, 2015). These lamps and this share are used as a proxy for residential lighting penetration rate in the U.S.

Table 1.1 Shares of Lighting Technologies in Residential Market in Europe and US

(Excluding Lighting Control Market) percent in Euros (US DOE SSL, 2014)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Year** | **Incandescent lamp** | **Halogen lamp** | **HID lamp** | **LFL** | **CFL** | **LED** |
| 2011 | 26% | 27% | 0% | 11% | 28% | 7% |
| 2012 | 22% | 26% | 0% | 11% | 27% | 13% |
| 2016 | 5% | 19% | 0% | 9% | 18% | 49% |
| 2020 | 2% | 8% | 0% | 6% | 11% | 73% |

The US DOE estimated that LED technology accounted for approximately 3% of the *global* installed base in 2014 (US DOE SSL, 2014). This is a value for all lighting sectors, but it’s used as a proxy for residential lighting. A similar estimate was provided by a model used in UNEP Enlighten Initiative, where 2% of the Plmh/a of lighting consumption was produced by LED technology in residential lighting in 2014 (UN Environment, 2017). The global lamp sales estimates vary significantly, and some estimates are double the Strategies Unlimited estimate (3%), resulting in 6% of unit sales(US DOE SSL, 2014). What is generally agreed in all references is the increase in the revenue from and the market penetration of LED lighting products. In contrast to the market shares (sales) of LED lighting, only very few data sources were found for global or regional LED lighting shares of the installed base.

In 2014, it has been estimated that LED products have penetrated approximately 3% of the installed base of lighting, or 2%(US DOE SSL, 2015). It is assumed that the installed base is expressed in lumen-hours. In addition, the 3% share of the installed base refers to all lighting, and the specific share in residential lighting may differ. The UNEP data provides also regional LED adoption rates based on annual lmh consumption: 1.8% global, 2.2% in China, 0.5% in India, 2.0% in EU, and 1.2% in the US. These adoption rates are used to calculate average LED adoption in 2014.

There is clearly a lack of global and regional data for the adoption rate for and near the base year. Most data on residential lighting focus on the sales and market value, not the lighting demand expressed in lumen-hours. The base year adoption uses year 2010 estimates with the respective estimated growth from 2010 to 2014 and all adoption data directly available for 2014. Globally, LED technology accounts for approximately 3% of the TAM. The adoptions are admittedly somewhat exaggerated in certain areas, such as Eastern Europe and Middle East & Africa, compared to other areas of few more datapoints available, such as EU and USA.

### Trends to Accelerate Adoption

Increase in National Programs for LED-based residential: The number one trend fueling the increasing adoption of LED in the residential sector is the **increasing number of energy efficiency programs from utility companies**. In the US, the boom in LED A-lamp stock is due to residential utility energy efficiency programs (Navigant Consulting, 2017). According to the report prepared for US DOE SSL, many utilities have efficiency programs that provide incentives (typically rebates) that lower the cost of LED A-lamps. For instance, replacement LED A-lamps became available to consumers between 2007 and 2009 at a typical cost of over $50 per lamp and by 2016, for only $5 or 90% less, consumers could obtain a dimmable A19 60 Watt-equivalent LED replacement lamp partly due to rebates and incentives (Navigant Consulting, 2017).

A global trend in lighting in general is the increase of the need for artificial light. Modern and modernizing societies use increasing amounts of light. No saturation has been found in the empirical evidence of per-capita consumption of light(Tsao & Waide, 2010), and with the growing population, the light consumption is expected to increase globally for the duration of Project Drawdown’s analysis period (2050).

### Barriers to Adoption

There are several issues that need to be solved before LED lighting can reach its full market potential in residential lighting.

#### First Cost

The primary barrier of adoption in the residential sector has been the first cost of LED. According to the US DOE SSL program, “The adoption of LED-based products in many commercial and industrial applications has accelerated as the payback period reaches the one to two year level, but lighting sold at the consumer level will tend to depend less on total cost of ownership (TCO) considerations and more on first cost. Part of the reason for this is that the average residential consumer uses lighting for shorter periods of time and does not factor in maintenance costs to install or replace lights. So, while falling prices have helped drive LED adoption, first costs have been a significant barrier (US DOE SSL, 2014). LEDs were still about five times that of halogen ($2/klm) and non-dimmable CFL replacements ($2.50/klm) around 2014 (Navigant Consulting, 2017), but today LEDs likely have dropped in price helping reduce this price barrier.

Higher prices hamper the wider use of LEDs, unless the life cycle costs are taken into account in purchase decision making. The TCO or life cycle costs of an LED lighting product may well be lower compared to other technologies, due to the greater luminous efficiency and possibly improved performance (e.g., need for fewer luminaires).

#### Reliability Across The Lifetime of a LED Luminaire

A key advantage of LED luminaire is its lifetime, however it requires better development (and cost) of electronic drivers. Individual LED products may not meet a user’s reliability expectations due to the use of low cost materials, designs or manufacturing processes (US DOE SSL, 2017b). There are still technical problems of reliability, thermal overload, irreversible color shift, decrease of efficacy, and other material fatigue problems (Franz & Wenzl, 2017). According to Gayral, the lifetime of the LED’s semiconductor chip itself is very large, (over 50,000 h, or 6 years of continuous operation). But other LED components or metallic contacts may fail before this, for instance electrical drivers that convert the AC 220 V (or 110 V) into continuous low voltage (around 3 V), which is suitable for the LED. Lifetime is a consequence of the care (and cost) that the manufacturer has put in the packaging and in the electronic drivers (Gayral, 2017). The quality of products needs to be ensured also with regard to the light sources it may replace. For example, in Europe, there have been problems in the equivalence of the light distribution from the LED lamp compared to conventional technologies. Replacement lamps that are not equivalent to the technology to be replaced tend to annoy the consumers.

According to Ding et al., while China is the world’s largest producer, consumer, and exporter of efficient lighting products, the U.S. is the world’s largest producer of LED chip technology. Therefore, it’s important for these two industries to work together for uniform policy/regulations, products, and systems (Ding et al., 2018).

#### Development Progress

LED lighting products are still developing, and this may affect compatibility and result to difference in timescales for the building industry and the timescale of progress for LEDs. If a LED module or a luminaire needs to be replaced, the replacement need may occur years after the initial installation. Given the fast development of the technology, the same (looking) luminaires may not be available in the market anymore. This long-term maintenance issue may be solved by using certain typical luminaire design types. According to Gayral, this is one of the most important paradoxes: the LEDs bought today will be outdated by new products long before they fail, so their actual lifetime may be much shorter than it should be due to better technology replacements. This will improve the customer experience, but at a larger cost due to premature bulb replacement.

### Adoption Potential

The LED is expected to account for half of lamps worldwide in 2020 (De Almeida, Santos, Paolo, & Quicheron, 2014) and is expected to replace traditional types of lighting, such as fluorescent and hydrogen lamps, because of its superior characteristics (Ahn et al., 2016). In the residential sector, however, even when the market penetration has been dramatic, there remains a large opportunity for SSL products worldwide. In 2010 4 billion incandescent and halogen lamps were installed in residential buildings (National Academies of Sciences, Engineering, and Medicine, 2017).

There are various adoption scenarios for global and regional LED lighting markets. In 2012, McKinsey estimated the penetration of the LED lighting to be the greatest in Asia (12% of value-based market share in China, 11% in “*Other Asia*”) in 2011(McKinsey, 2012). It was estimated that the greatest penetration in 2020 will be in Europe and North America (73% and 72%, respectively). The penetration of LED lighting measured in value-based market share was estimated to remain the lowest in Middle East and Africa (56% in 2020) and in Latin America (61% in 2020). Yet, it is acknowledged that government industry policy may have a significant impact on the LED penetration rate.

In developing countries, especially where there is no electric grid available, off-grid lighting solutions are needed. LED lighting may well be combined with solar panels (both DC solutions) for efficient off-grid lighting, or, as a high-efficacy light source technology powered by the sun. These kind of solutions have a significant social impact on the entire community enabling working hours after dark, improving schooling conditions, reducing accidents related to candle or paraffin use and improving the indoor air quality. Non-electric and off-grid lighting solutions though, are excluded from the scope of the current study.

countries but due to the versatility of LED lighting products, it is expected that LED lighting can be widely used throughout the world.

## Advantages and Disadvantages of Residential LED Lighting

### Similar Solutions

LED lighting is by far the most promising lighting solution in a large scale at the moment. A related technology is organic LED (OLED), based also on semiconductor junctions but otherwise very different light source technology in practice. OLEDs are illuminating surfaces rather than lamps and they are not expected to replace the existing lighting technologies directly but offering a new kind of lighting, for example when integrated into walls, ceilings or windows. The price of OLED systems per kilolumen is very high and their functionality is not fully developed yet. Rigorous product development is needed for OLED technology to become more widely used. In the future, it may offer new possibilities if integrated into construction materials. In the far future, laser diodes may be developed to be used in general lighting, as they are already penetrating car headlight market. Laser diodes are not likely to penetrate the general lighting market in the near future. It is possible by 2050 but it is very unsure that laser diodes could provide radically better and more energy efficient lighting compared to LED technology in residential buildings.

### Arguments for Adoption

LED lighting offers many advantages in residential lighting compared to conventional light sources (Table 1.2). LED technology can be more energy efficient compared to conventional technologies especially in residential lighting, without compromising the lighting quality. Compared to the conventional technologies, LED lighting products typically have high life (typically 50 000h, higher estimates exist for LED luminaires, e.g., 84 000 h in 2015 and 100 000 h in 2030 (US DOE SSL, 2015). With greater energy efficiency, LED lighting may offer savings in life cycle costs due to the reduced energy costs. Depending on the purchase price and the price of electricity, and considering the total cost of ownership, LED lighting may be a more economic solution compared to traditional lighting, especially in residential lighting. LED products have significantly longer operating life compared to all other light sources used in residential lighting.

### Additional Benefits and Burdens

It is possible to develop LED lamps and luminaires of different colors. LED technology enables the use of advanced lighting controls, including dimming and tuning the color of the light, which help to create atmosphere. LED products can be dimmed also to very low light levels. In addition, LED lighting may benefit the environment not only by reducing the greenhouse gas emissions but also being free from mercury – an element necessary for the operation of fluorescent lamps – and being a solution to reduce the light pollution. However, light pollution is more of a concern in outdoor lighting, not in the (indoor) residential lighting in the scope of this Project Drawdown solution.

There are also few disadvantages in LED lighting (Table 1.2). Most notably, the high purchase price prevents the greater penetration rate of LED lighting in residential buildings. Yet, the purchase price is decreasing as the technology itself and manufacturing technologies develop, but the purchase price can still be considered as a hurdle. There have also been some challenges in the equivalence of the LED lamp compared to conventional technologies with regard to the light distribution, physical size, color and color rendering. This is especially a problem in Europe, whereas the light distribution and size issues are handled well in the U.S. The replacement lamps that produce light with a different distribution and that are not equivalent with the technology to be replaced tend to annoy the consumers. Another disadvantage is that the LED technology is not a mature technology, which may make it difficult to find the same or similar replacement products in the future, although this is not a major issue in residential lighting. The disposal of LED products needs special attention, as they need to be disposed as waste electrical and electronic equipment (WEEE), in contrast to halogen and incandescent lamps, which do not need a separate collection.

Table 1.2 List of the main advantages and disadvantages of LED lighting in residential buildings.

| **Advantages** | **Disadvantages** |
| --- | --- |
| Energy efficiency | High purchase price |
| Long life | Equivalence to lighting products it replaces |
| Potentially low life cycle costs | Not mature technology |
| Color choices | Disposal needs attention |
| Dimmability | Possibly glary |
| Small chip size |  |
| No mercury |  |

Despite the great potential in GHG emission reduction provided by the LED lighting, other environmental concerns may arise. Most importantly, the adverse impacts of artificial light are increasingly of concern. Artificial light, especially during natural darkness, is suspected to have harmful impacts on human health, fauna, flora and the ecosystem balance. Excessive artificial light hampers also the star gazing and astronomical observations in general. These impacts are called light pollution and it is not only caused by LED products but all artificial lighting. However, LED lighting may be more harmful to the environment depending on the species in question due to the blue wavelength content of the light, but LED lighting products may also be designed so that the most harmful part of the spectrum is avoided. A well-designed and controlled LED lighting may actually cause *less* light pollution (here considered as all adverse impacts of artificial light) compared to conventional artificial light sources. Currently, there is no clear scientific consensus on the direct cause-effect relationships of ecological impacts of light pollution. Means and measures have been proposed to reduce the light pollution, including advanced lighting controls to provide artificial light at a minimum level of intensity only when and where it is needed. Such measures seem to be in line with energy savings and reduction of operating costs.

The increase in the consumption of light very likely increases light pollution, i.e., the adverse impacts caused by artificial light on humans, fauna, flora and ecosystems. LED lighting may be specifically causing light pollution especially due to the blue wavelength content of the light, as the radiation at the blue wavelength region is often found to be problematic for the environment including humans. However, LED technology enables various wavelength compositions, lighting controls (dimming, switching on and off, color tuning) and accurate optical design of the lighting products, so that the impacts of light pollution may be minimized without compromising the safety and visual performance of humans. Appropriately-designed LED lighting is expected to reduce the light pollution but also providing the needed lighting service for humans. LED lighting may also be included in the Internet of Things (IoT) systems, which may, in turn, provide new services for modern societies.

Table 1.3 Technology Comparison of various lighting sources (Weisbuch, 2018)

| **Technology** | **Luminous efficacy of lamp (lm/W)** | **Power (W)** | **Lamp cost** | **Operating Costs** | **Average lifetime** |
| --- | --- | --- | --- | --- | --- |
| Incandescent (INC) | 10 | 3-500 | low | high | 1000 |
| Halogen (HAL) | 15-20 | 5-500 | medium | high | 3000 |
| Fluorescent tube or Linear fluorescent (LFL) | 60-100 | 4-200 | medium | medium | 5000 |
| Compact fluorescent lamp (CFL) | 50-75 | 3-120 | medium | medium | 10,000 |
| High intensity discharge metal halide (HID) | 60-115 | 30-2000 | high | low | 15,000 |
| Low-pressure sodium | 100-200 | 10-180 | medium | low | 15,000 |
| High-pressure sodium | 100-150 | 35-1000 | high | low | 15,000 |
| LED luminaire with LED lamp | 80-200 | 2-20 | medium | low | 50,000 |

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[[1]](#footnote-1)) is what constituted the results.

The LED residential lighting, as a solution, is compared to conventional lighting technologies. The conventional lighting technologies include incandescent lamp, halogen lamp, CFL and LFL. Other lighting technologies may exist, but their share of the total global residential lighting is considered to be very low. Only artificial electric grid-based lighting is included in the study. Luminaires (housing) are excluded from the scope of the study. An aggregated conventional technology is generated on the basis of the average luminous and electrical qualities of the conventional technologies and weighted on the basis of their market share.

The functional unit of the study is Petalumen-hours (Plmh), i.e., 1 million billion or 1015 lumen-hours, where the installed luminous flux of all electric light sources and the annual operating time in residential buildings are taken into account. The implementation unit is Plm corresponding to the luminous flux of installed base of all lighting technologies in residential buildings.

## Data Sources

One of the main data sources is the Light’s Labour’s Lost book by IEA published in 2006[[2]](#footnote-2). In the course of the data collection, it became very clear that it is the book to which most of the scientific articles as well as the gray literature on lighting refer. It is acknowledged that the data is over 10 years old and that it does not consider LED lighting to have great penetration rates. In 2006, LED lighting products were very expensive and poor-performing. Hence, the IEA book from 2006 is used as a source of data for the TAM data only for 2005 and the regional light consumption data for 2005. These data are used as the basis for the regional and global TAM, while the growth rate of TAM is estimated on the basis of GDP per capita from the year 2005 level. The IEA book provides also an estimate for the Plmh global consumption assuming a current policy scenario in 2030 but this is not used in the calculations.

The adoption scenarios were found for OECD and non-OECD regions in Bergesen et al., as well as the adoption data for US[[3]](#footnote-3) and EU[[4]](#footnote-4). The OECD and non-OECD adoption scenarios are estimated on the basis of percentage shares of TAM. The OECD and non-OECD estimates are same for residential lighting, except for 2010 estimate (1% and 0% adoption, respectively). These are combined, and OECD data is used also in non-OECD regions[[5]](#footnote-5). Both likely (conservative) and high-LED adoption scenarios are included. It is estimated that currently, the high-LED penetration scenario is actually more likely considering the forecasts of LED market shares. Bergesen et al. presented also a no change scenario but due to the promising price and efficacy development, the conservative and high LED penetration scenarios are chosen for the study. The conservative scenario may be excluded. The lamp data is gathered from several sources both gray literature and scientific literature for the lamp characteristics, such as luminous efficacy and life[[6]](#footnote-6). A handbook by S. Kitsinelis[[7]](#footnote-7) was used as a reference.

## Total Addressable Market

The Total Addressable Market (TAM) for LED’s is assumed to be the global building lighting demand. The TAM chosen utilizes Project Drawdown’s Integrated Buildings Sector TAM Model which combines estimates of global floor area and lighting intensity across the world. Floor area data come from the International Energy Agency (IEA) and Global Building Performance Network (GBPN) (GBPN & Central European University, 2012; IEA, 2013b). Lighting intensity data come from several sources including the IEA (2006) (Lights Labour Lost). Figure 2.1 represents the growth in the global TAM between 2015 and 2060. The residential TAM is the current focus of this Solution.

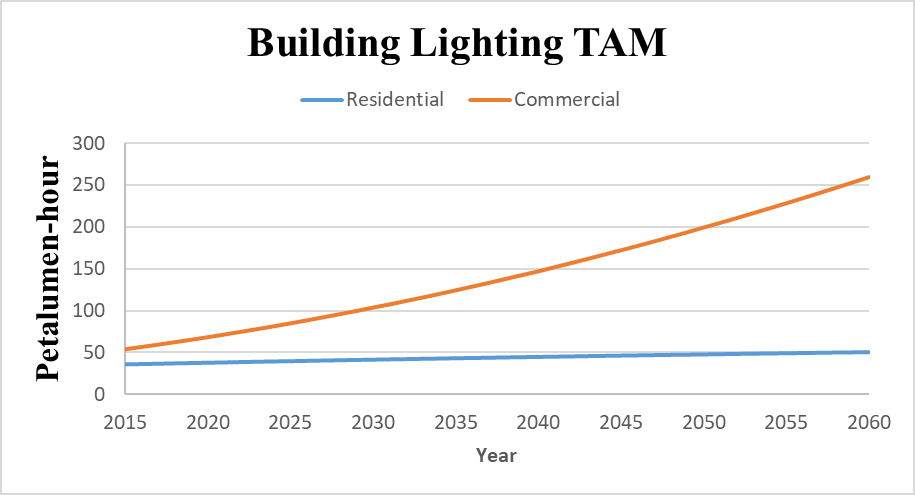


Figure 2.1 Lighting TAM for Global Building Stock

## Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline. The PDS scenarios are in case of LED lighting actually the most likely scenario, while REF is more like a “no change” scenario.

The potential adoption of LED lighting is estimated to be high (90%) in 2050, while in 2014 the global adoption was only approximately 3% of the demand[[8]](#footnote-8). It was difficult to gather data on LED lighting adoption in residential buildings. There were only very few data sources and only one that was expressed directly in lumen-hours, but that data point was 0 lmh for 2010[[9]](#footnote-9). All other adoption data was converted as a share (%) from the total (residential) lighting market.

### Reference Case / Current Adoption

In the reference case (REF), the LED adoption share in percent remains the same.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

#### Plausible Scenario

Uses the average of published adoption projections from several sources and use the average energy efficiency and a linear growth adoption to 90% of the TAM.

#### Drawdown Scenario

Used the average Energy Efficiency. Assumes a linear growth in adoption to 95% of the TAM

#### Optimum Scenario

Uses the average energy efficiency. Assumes a linear growth in adoption to 100% of the TAM.

## Inputs

### Climate Inputs

The GHG emissions are reduced by using LED lighting in residential buildings instead of conventional lighting technologies of lower luminous efficacy. The savings in the energy consumption directly reduces the GHG emissions. Yet, some level of rebound effect can be expected, as the amount of light and the number of light sources are on the increase, but the rebound effect is excluded from the current study. In addition to reducing GHG emissions, LED lighting reduces a number of environmental impacts related to energy consumption (Tähkämö, 2013).

#### Direct Emissions

The reduction in direct emissions are calculated by comparing the annual energy consumption (TWh) per functional unit (Plmh) of conventional (aggregated) lighting to the LED lighting solution. Energy consumption variables are described in the Technical Inputs section. To calculate key model results, the model uses reported emissions factors for the electric grid. Emissions factors for electricity generation are derived from the projected global energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA’s ETP 6DS scenario.

#### Indirect Emissions

Indirect CO2 emissions were estimated on the basis of life cycle assessment (LCA) case studies of lighting products found in the literature (published 2009-2016). CO2e emissions for incandescent lamp, halogen lamp, CFL, LFL and LED lamps were collected from eight LCAs (Elijošiutė, Balciukevičiūtė, & Denafas, 2012). The indirect CO2 emissions of conventional technologies are weighted on the basis of market shares from McKinsey. The indirect CO2 emissions are calculated as ton of CO2eq. per functional unit (Plmh), as most of the data are provided in a unit of kg CO2 per lmh. As the amount of indirect CO2 is expressed per Plmh, it takes into account the life of the lamps, evening out the differences in the indirect CO2 emissions of conventional and LED lamps.

Table 2.1 Climate Inputs

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Global average REF Grid Emissions Factor | *g CO2e/ kWh* | 503-593 | Depends on year. Starts at High Input in 2020 declines to Low Input in 2050 to represent the decarbonization of the grid in the reference. | 12 each year | 4 |
| Conventional Indirect Emissions | *T CO2eq/ Plm* | 391 – 1,751,445 | 633,630 | 17 | 8 |
| Solution Indirect Emissions | *T CO2eq/ Plm* | 256,785 – 671,113 | 463,949 | 5 | 5 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[10]](#footnote-10).

### Financial Inputs

#### First Costs

First cost data are collected from various sources to cover global and regional scope. There are numerous places to purchase the lamps, so it is impossible to get but a glimpse of the prices of different lamps used in residential sector. The prices are frequently expressed as amount of currency per piece of lamp or per klm. Different price data are converted into USD2014/Plm. Default luminous flux is used in conversion from price per piece if no luminous flux of the particular lamp is given.

First cost data is collected from multiple sources: EIA(EIA, 2014), VITO(VITO, 2015), US DOE(US DOE SSL, 2014), and McKinsey(McKinsey, 2012). It is also possible to use a learning rate to estimate the price development, since EIA provides cumulative adoption and respective data for US market for 2005-2050, which could be used as a proxy for global price development. However, since multiple data sources were found, factoring on the basis of them is preferred. Yet, if learning rate data is found or provided later on, the learning rate table in Variable Meta-analysis sheet could be used and developed. Learning rate of first cost development is not used in current calculations but factoring is used instead.

#### Operating Costs

Annual operating costs (Co) in unit of USD/year are calculated on the basis of the equation below:

where

is the lamp power (kW),

is the electricity price of the region (USD/kWh), and

is the annual operating time (h/year).

The operating costs are expressed as USD/functional unit (USD/Plmh), and thus, the operating cost calculated using the equation above needs to be divided by the respective amount of Plmh (aggregated conventional or solution). Disposal costs are not included separately, as they are included in the purchase price in many areas (US, EU). The global electricity price is estimated from a survey of data for multiple years from 55 countries.

Table 2.2 Financial Inputs for Conventional Technologies

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First Cost | *US$2014/klm* | 0.01 – 9.73 | 4.36 | 26 | 6 |
| Variable Operation and Maintenance Costs | *US$2014/klmh* | 0.001-0.009 | 0.005 | (Derived from other inputs) | (Derived from other inputs) |
| Residential Electricity Price (Conventional and Solution) | *US$2014/kWh* | 0.1398 | 0.139 | 509 (for 55 Countries) | 1 |

Table 2.3 Financial Inputs for Solution

| **Variable** | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs | *US$2014/klm* | 0.42 – 33.73 | 17.13 | 34 | 14 |
| Variable Operation and Maintenance Costs | *US$2014/klmh* | 0.002 | 0.002 | (Derived from other inputs) | (Derived from other inputs) |
| Learning Rate Factor | % | 8.31 | 8.31 |  |  |

### Technical Inputs

Besides purely climate and financial inputs, there are some inputs that apply to both climate and financial calculations. These are detailed below.

Table 2.4 Technical Inputs Conventional Technologies

| **Variable** | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity | *Plmh/Plm = hours* | 2,070 – 14,970 | 8,520 | 18 | 4 |
| Average Annual Use | *Plmh/Plm =hours* | 1,964 – 3,756 | 2,860 | 11 | 1 |
| Electricity consumed | *TWh/ Plmh* | 12.94 – 71.74 | 42.34 | 36 | 9 |
| Luminous Efficacy – Incandescent | *lm/W* | 10.3-16.7 | 13.5 | 7 | 7 |
| Luminous Efficacy – Halogen | *lm/W* | 15.3 – 27.7 | 21.5 | 6 | 6 |
| Luminous Efficacy – LFL | *lm/W* | 65.6 – 95.1 | 80.4 | 5 | 5 |
| Luminous Efficacy – CFL | *lm/W* | 54.7 – 67.1 | 60.9 | 8 | 7 |
| Average Luminous Flux - Incandescent | *lm/ unit* | 513 | 513 | 2 | 1 |
| Average Luminous Flux - Halogen | *lm/ unit* | 417.8 - 483 | 450 | 5 | 1 |
| Average Luminous Flux - LFL | *lm/ unit* | 1,568.6 – 2,654.2 | 2.111.4 | 5 | 1 |
| Average Luminous Flux - CFL | *lm/ unit* | 522.5 | 522.5 | 1 | 1 |

Table 2.5 Technical Inputs Solution

| **Variable** | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity | *Plmh/Plm = hours* | 31,058 – 59,208 | 45,133 | 16 | 4 |
| Average Annual Use | *Plmh/Plm = hours* | 1,964 – 3,756 | 2,860 | 11 | 1 |
| Electricity Consumed | *TWh/ Plmh* | 9.65-18.29 | 13.97 | 16 | 7 |
| Luminous Efficacy | *lm/W* | 51.2-95.1 | 73.2 | 12 | 6 |
| Average Luminous Flux | *lm/ unit* | 600 | 600 | 2 | 1 |

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at [www.drawdown.org](http://www.drawdown.org). Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. LED can replace all other major lamp types in a wide variety of applications across the commercial building sector, and replacement is done in proportion to the current market of those conventional lamp types.
2. The luminous efficacy is the ideal metric for estimating the energy consumption (and therefore emissions) of use of lighting technologies, and this is driven by need for a specific amount of light as measured in lumens.
3. Population growth is correlated to lighting demand growth, as the lighting demand tends to increase with the number of people living in the region (for TAM calculation). However, lighting demand in residential buildings may differ from that. Lighting demand (Plmh) may increase due to increasing number of lamps installed, whereas the energy demand for lighting may be reduced due to the increasing luminous efficacy (lm/W) of installed light sources (LED), and with the increasing adoption of lighting controls. Also the floor area per capita in residential buildings may change affecting how much lighting in needed per capita over time, particularly in rapidly industrializing regions.
4. LED adoption can take place worldwide including in places with low lighting demand and low electricity grid penetration.

## Integration

The complete Project Drawdown integration documentation (will be available at [www.drawdown.org](http://www.drawdown.org)) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Each solution in the Buildings and Cities Sector was modeled individually, and then integration was performed to ensure consistency across the sector and with the other sectors. These solutions require an integration analysis to avoid double counting, as they primarily relate to either reducing demand for space heating and cooling (for residential and/or commercial buildings), commercial lighting, cooking, or water heating. The integration process therefore was addressed through sequential adjustments to the efficiencies of the solutions in a prioritized sequence for each of space heating and cooling, lighting, cooking, and water heating (performed in four separate sequence chains). The prioritized sequence is fixed for all scenarios and is described in the Drawdown Building Sector Integration documentation.

For each solution in an integration sequence, the estimated impact of previous solutions on the emissions savings of the current solution is estimated and a reduction factor is applied. The factor is only applied to emissions and energy savings attributed to adoptions that overlap with previous solutions[[11]](#footnote-11), and for this adoptions are generally assumed independent. Solutions that start each integration sequence are therefore unaffected (unless they are affected by solutions in other sequences), and solutions that apply to different buildings (say commercial and residential) do not affect each other. The method of estimating overlap is based on the percent adoption of the higher priority solution applied to the area adopted in the lower priority solution. For the efficiency factor of this overlapping area only, the reduction factor is applied, it is scaled and used to update the results in the lower priority solution model.

No other building solution was integrated with Residential LED Lighting since no other modeled solution directly affected residential light (Commercial LED and Building Automation systems were integrated for their shared impact on commercial light energy however).

In addition to building sector integration, there was an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusted for the double counting. Double counting of emissions reduction was a factor of using the reference grid emissions factors for electricity-based solutions. As grid solutions (Utility-scale Solar PV and others) are adopted, the grid gets cleaner and the impact of efficiency solutions is reduced (where they reduce electricity demand) or increased (where they increase electricity demand[[12]](#footnote-12)). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

## Limitations/Further Development

The weakest point of the study is in the LED residential lighting adoption data. There were only a limited number of data sources for LED adoption as Plmh or as a share of Plmh. All these adoption data were used to calculate average LED adoption in 2014.

The current adoption mix of conventional technologies is calculated based on market values provided by McKinsey for years 2012 and 2016, using linear interpolations to calculate 2014 shares. The market shares of conventional technologies are estimated to account for 97% of the TAM (LEDs account for 3% in 2014) with respective shares as in value. It must be noted that these data sources use different units (% of installed base in Plmh; % of market share of sales), and these data are used due to the lack of data.

The average luminous efficacy is calculated based on data on luminous efficacies and market shares of individual lamp technologies in 2014-2015. However, these values are now calculated only for the global case, as no regional data was collected. The luminous efficacy is roughly estimated to be the same in all regions, which is not entirely the case. The luminous efficacy corresponds to the installed lighting technologies of the region in particular.

The base year residential lighting is estimated to be divided into incandescent, halogen, CFL, and LFL as the market share data that McKinsey indicates. However, McKinsey gives estimates for the market shares for 2012 and 2016, and the 2014 shares are calculated using linear interpolation resulting in shares of incandescent lamps (19%), halogen lamps (32%), CFLs (32%), and LFLs (14%) in 2014. This linear interpolation causes some error, so does using the market share as a proxy for the share of technologies in installed base. However, there is no global or regional estimates of the Plmh use in residential lighting literature. This is a weak point in the analysis assumptions and the shares of conventional and solution technologies must be confirmed.

More first price data could be included to make the model more robust and to cover all the regions in more detail.

Operating costs could be made more accurate by taking into account a future estimate of the electricity price fluctuation of each region. Operating cost (PDS) are calculated on the basis of estimated change in 2020-2050 in the luminous efficacy.

Many of the literature used in the LED residential lighting model are not peer-reviewed. This is because of the lack of such scientific, peer-reviewed papers in the area providing the data in the format or unit needed. Yet, many of the non-peer-reviewed reports and books used as references were found to be cited in scientific peer-reviewed literature. This was found when the original references were checked.

# Results

## Adoption

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Table 3.1 World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| LED Residential | *Plmh* | 0.68 | 43 | 45 | 48 |
| *% market* | 1.9% | 90% | 95% | 100% |

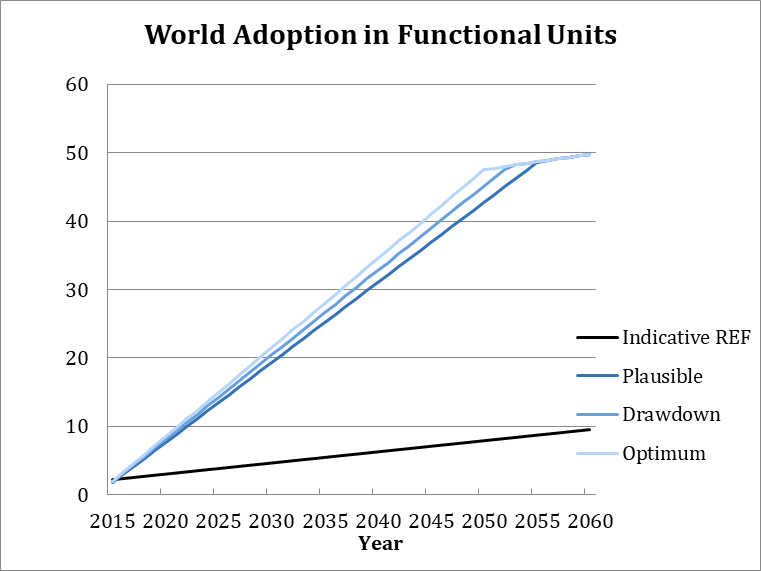


Figure 3.1 World Annual Adoption 2020-2050

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary (Section 6).

Table 3.2 Climate Impacts

| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050** |
| --- | --- | --- | --- | --- |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.60 | 11.48 | 0.30 | 0.60 |
| ***Drawdown*** | 0.63 | 12.14 | 0.31 | 0.63 |
| ***Optimum*** | 0.67 | 12.79 | 0.33 | 0.67 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq

| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| --- | --- | --- |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.95 | 0.04 |
| **Drawdown** | 1.00 | 0.05 |
| **Optimum** | 1.05 | 0.05 |

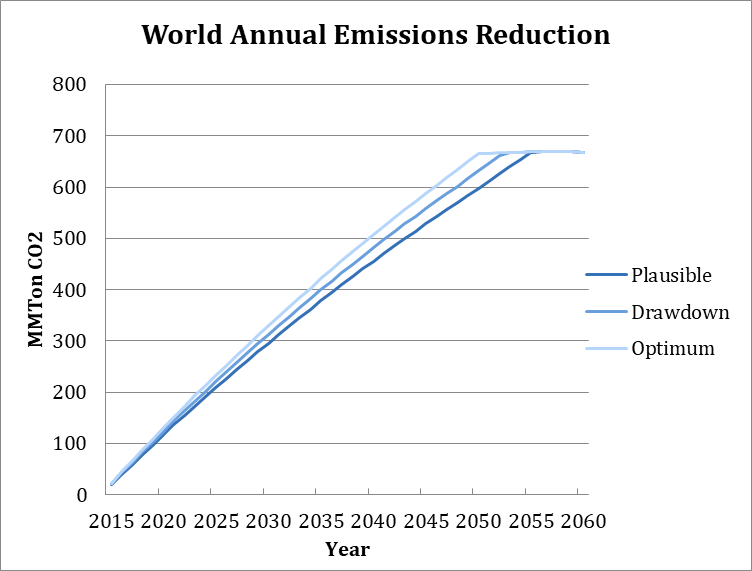


Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 3.4 Financial Impacts

| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Lifetime Operating Cost Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| --- | --- | --- | --- | --- | --- |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 293.70 | -27.62 | 2,450.09 | 3,600.60 | 1,239.31 |
| **Drawdown** | 309.61 | -29.83 | 2,589.17 | 3,804.98 | 1,309.95 |
| **Optimum** | 325.51 | -32.05 | 2,728.25 | 4,009.37 | 1,380.58 |

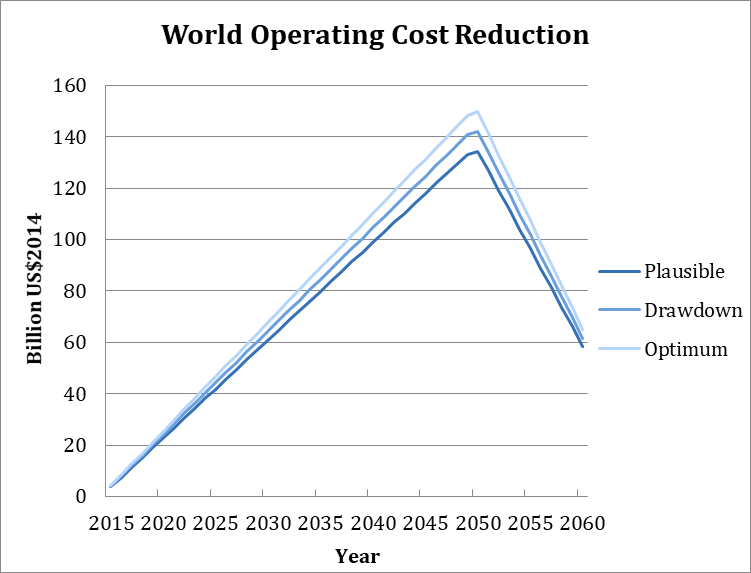


Figure 3.3 Operating Costs Over Time

# Discussion

LED lighting offers especially great emission reductions in residential buildings. The light sources traditionally used in households usually have low luminous efficacy (incandescent and halogen lamps), approximately in the range of 10-20 lm/W, whereas LED lamps that can directly replace the lamps installing them in the same luminaires currently have a luminous efficacy in the range of 50-100 lm/W. Such an increase in energy efficiency will not be reached in other lighting sectors, where the residential lighting technologies are more energy efficient than incandescent lamps (e.g. LFL and CFL lamps that are current close to LED in efficiency).

Several sources of data were found for the market share of LED products either in general or in residential lighting, but they were either as monetary value or as percentage of unit sales. No relevant LED adoption data was found expressed in lumen-hours of the installed base at or after the base year. Relevant conversions have had to be made in order to get as many data points as possible. Several approaches were used to estimate TAM and adoption data: from % of installed base, from energy consumption in residential lighting, from residential building floor space and from market shares. The Project Drawdown residential LED projections (in the *Drawdown Scenario*) would result in CO2 reduction of 12.14 GT CO2e by 2050. The Project Drawdown LED commercial and residential model combined would result to CO2 reduction of 20.3 Gt by 2050.

## Limitations

This analysis is framed within several limitations. The first limitation is the lack of data in relation to incipient trends that may influence the increasing adoption of technologies such as the increasing growth of the IoT. The second limitation is the lack of data in relation to the emergent environmental impact of the rapid turnover of LED lamps as the LED technology continues to evolve. Future studies are needed to understand the impact and costs of LED at the time of disposal or EoL.

## Benchmarks

The most relevant benchmark studies come from the U.S Department of Energy (DOE) Solid State Lighting Program (DOE SSL) used throughout this report. In 2014 the program studied a 2030 scenario ‘proposing a high LED penetration’ that would enable energy savings up to 60% compared to one without LEDs. This annual savings would represent up to 395 TWh (4.5 quads), which is nearly twice the projected wind power electricity generation and 20 times that of solar in 2030. It’s also equivalent to the annual electricity consumption of 36 million U.S homes (Dulout et al., 2018; US DOE SSL, 2015).

The 2013 report Assessment of Advanced Solid-State Lighting (NRC, 2013) estimated the US savings in electricity consumption from LED use. Two estimates were published: 1. based on the lamp efficacy standards in the Energy Independence and Security Act (EISA) of 2007, residential lighting electricity consumption could be reduced by 514 TWh and commercial lighting by 60 TWh (cumulatively from 2012 to 2020). Secondly, using more aggressive assumptions about LED luminaire efficiency, the cumulative residential savings over the same time period could be 939 TWh and for the commercial, 771 TWh (National Academies of Sciences, Engineering, and Medicine, 2017).**…**

A global transition to efficient LED lamps was estimated to result in a reduction of 801 Mt of CO2 (CEM, 2018), though this assumes very aggressive adoptions (all lighting sectors with 100 % adoption). THE UN estimated that replacing inefficient on-grid lighting globally would reduce the annual CO2 emissions by over 530 Mt (UN Environment, 2017). IEA estimated that energy efficient lighting may reduce 449 MMT CO2 in 2030(IEA, 2006).

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# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

**Approximate PPM Equivalent** – the reduction in atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for adoption of the solution

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** are considered till better technologies and less impactful are more cost effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours

1. For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050. [↑](#footnote-ref-1)
2. IEA 2006 Light's Labour's Lost. [↑](#footnote-ref-2)
3. [↑](#footnote-ref-3)
4. [↑](#footnote-ref-4)
5. [↑](#footnote-ref-5)
6. (“Homedepot Lighting Facts - Bulb Comparison Chart,” n.d.; *IEA 2006 Light’s labour’s lost - Policies for energy-efficient lighting*, n.d.; *McKinsey 2012 Lighting\_the\_way\_Perspectives\_on\_global\_lighting\_market\_2012.pdf*, n.d.; “PremiumLight - Different bulb types,” n.d.; *US DOE 2014 Multi-Year Program Plan (Updated May 2014)*, n.d.) [↑](#footnote-ref-6)
7. Kitsinelis S. (2011) Light Sources. [↑](#footnote-ref-7)
8. (*US DOE 2015 Solid-state lighting R&D Plan*, n.d.), original source P. Smallwood, “How big is the LED lighting market going to get?”, in Strategies in Light Conference, Las Vegas, February 25, 2015. [↑](#footnote-ref-8)
9. (*US DOE / Navigant Consulting 2012 2010 US Lighting Market Characterization*, n.d.) [↑](#footnote-ref-9)
10. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-10)
11. This can be interpreted as a single building with multiple efficiency technologies. [↑](#footnote-ref-11)
12. Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel. [↑](#footnote-ref-12)