**Technical assessment for**

**COMMERCIAL LED LIGHTING**

Sector: Buildings

Agency Level: Building Owners

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Version 1

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# Acronyms and Symbols Used

**CFL** – Compact Fluorescent Lamp

**DC** – Direct Current

**FL** – Fluorescent Lamp

**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

**LOR** – Light Output Ratio

**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

# Executive Summary

LED lighting offers a great possibility to reduce the GHG emissions in commercial lighting, and it has advanced to the point where it is the best option for almost every lighting application (Morgan Pattison, Hansen, & Tsao, 2018). This due to the high luminous efficacy of LED lighting and also due to the size of the lighting sector in commercial buildings. Traditionally, there have been four types of light source technologies used in commercial lighting: linear fluorescent lamp (LFL), compact fluorescent lamp (CFL), incandescent lamp (including halogen lamp), and high-intensity discharge (HID) lamp. Globally, the LFLs have traditionally been the most widely used, approximately 75 % of installed lighting. However, this is expected to change, as LED lighting products (lamps and luminaires) penetrate the market. In 2014, the LED adoption was estimated to be 4.3%.

LED lighting products offer high luminous efficacy and thus high energy efficiency, emission reductions, and reduced costs during operation. LED luminaires are potentially more energy efficient compared to conventional technologies.

In addition, LED lighting enables advanced lighting controls including dimmable lighting, various colors of light and color tuning. The purchase price of LED products may still hamper the wider penetration of the technology, but the price is decreasing. Despite the high purchase price, the total life cycle costs of LED commercial lighting are typically somewhat lower than those of conventional technologies due to the low operating costs. 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 energy in commercial buildings. According to the calculations in the model, the LED lighting solution consumed annually approximately 14.9 TWh per Plmh, whereas the conventional technologies consumed almost 20 TWh per Plmh. The drawdown commercial LED scenario would result in a CO2 reduction of 8.2 Gt CO2e by 2050. The Project Drawdown LED commercial and residential model combined would result in a CO2 reduction of 20.3 Gt by 2050.

# 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 Commercial LED’s

### 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 commercial 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 recombination of electron–hole pairs in semiconductor p–n junctions (Weisbuch, 2018). When the electrons and holes recombine in the junction, a quantum of energy (a photon) is emitted. Semiconductors are solid state materials characterized by a small band gap (the energy difference between isolated and conducting states) (Franz & Wenzl, 2017). The color of the light is determined by the wavelength of the photon, which depends on the characteristics of the semiconductor material. LED solid-state lighting offers great versatility and meets the need for a wide variety of lighting requirements 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 for LEDs from 2012 onwards, when eﬃciency and cost made them competitive with the 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 but 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. Yet similar approach can also be used in commercial lighting. In commercial buildings, the lamps are occasionally replaced by another (more energy efficient) lamp in the same luminaire but it’s also likely that the entire luminaires are changed when the lighting needs refurbishing.

### LED Components, Materials, Rare Earths and Metals

Typically, a luminaire consists of three components (parts): a light source, controlgear, and the outer envelope (housing, cover) (see Table 1.1). The LFL and HID luminaires include all these three parts. CFL may contain an integrated (as in the “energy saving” lamp frequently used in households) or a non-integrated ballast. In addition to the CFL (and ballast), a luminaire housing is needed for the entity in question. As incandescent and halogen lamps do not need a controlgear to operate, the entity contains only the lamp and the luminaire cover. When it comes to LED lighting products, defining the entity in the study is more complex, as there are LED lamps, modules and luminaires in the market. The LED luminaire may be an integrated LED luminaire, meaning that it includes all three parts together (module, controlgear, cover). This is a typical LED luminaire type in commercial lighting. The LED luminaire may also contain a replaceable LED lamp that includes the controlgear. This kind of luminaire may be equipped with LED lamp or any conventional lamp type (mainly incandescent, halogen, CFL and LFL) depending on the cap type. The model includes all the parts of the commercial luminaires. Typically, a LED-lamp consists of (a) the LED-array, (b) the electronic ballast, (c) the heat sink, (d) an optical element, and (e) the housing (Franz & Wenzl, 2017). Commercial lighting has traditionally been provided by fluorescent technology (see Table 1.4).

Table 1.1. Components of Lighting Products Typically Used in Commercial Lighting

| **Technology** | **Light source** | **Controlgear** | **Luminaire cover** |
| --- | --- | --- | --- |
| Linear fluorescent (LFL) | Lamp | Ballast | Housing |
| Compact fluorescent (CFL) | Lamp | Ballast (may be integrated to light source) | Housing |
| Incandescent and halogen (INC&HAL) | Lamp | - | Housing |
| High intensity discharge (HID) | Lamp | Ballast | Housing |
| LED | Lamp or module | Power supply and control unit (may be integrated to light source or luminaire) | Housing or as integrated luminaire (all components integrated) |

Lighting controls is not included in the current study but it is strongly recommended to add it in the future. Offices and other commercial applications were estimated as the greatest application for lighting controls, as currently, the lighting system control component market was mainly (90 %) in these applications. Offices were estimated to be the single largest market for lighting control components accounting for approximately 43 % of the market (in euros) in 2020(McKinsey, 2012).

### 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.

LEDs have a luminaire efficacy more than four times higher than fluorescent lamps and offer new opportunities for modern control systems (Beu, Ciugudeanu, & Buzdugan, 2018). LEDs can deliver substantial energy savings (they save up to 50% of the energy used by fluorescent lamps), they may also last longer (20-50 times incandescent light bulbs and 2-5 times longer than compact fluorescent lamps (CFLs)) (Cirrincione, Macaluso, Mosca, Scaccianoce, & Costanzo, 2018). 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 lighting products used traditionally in commercial buildings, such as the most efficient linear fluorescent lamps (LFLs) (including ballast losses) have the efficacy of 108 lm/W(US DOE SSL, 2017a).

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 (that is, the fraction of light that actual shines out of the luminaire). 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 commercial sector, since its operation may be more energy efficient compared to most other lighting technologies used in commercial buildings. 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

In 2014, lighting was estimated to account for 10 % of global electricity consumption and in 2006, it was estimated to produce 1900 Mt of CO2 annually (IEA, 2017; IEA, 2006). The commercial lighting was estimated to account for 59.5 Plmh in 2005 and to increase to 96 Plmh in 2030.

The share of LED lighting was so low in 2005 that it is undetectable in the charts in IEA source(IEA, 2006). The lighting industry is enthusiastic about the LED technology and expects it to take over the clear majority of the lighting business in near future.

In commercial buildings, the share of lighting in electricity consumption varies by region, but it has been estimated that, for example, in USA, lighting accounts for 21 %(IEA, 2006), and in China for about 14% of total power consumption (Ding et al., 2018). In 2010, lighting was estimated to account for 16 % of the commercial building energy consumption globally(Urge-Vorsatz et al., 2015).

Lighting has sometimes been found to be the greatest single end-use of electricity in commercial buildings, but typically in hot climates, air condition causes the greatest share of electricity. This may, however, be related to lighting electricity consumption: Especially the conventional lighting technologies add the heat load in commercial buildings. Changing to energy efficient lighting reduced also the need for air conditioning.

Table 1.2 Performance and characteristics of various lighting sources

(US DOE SSL, 2017a) (Weisbuch, 2018)

| **Technology** | **Physical Phenomenon** | **Luminous efficacy of lamp (lm/W)** | **Power (W)** | **Remarks** |
| --- | --- | --- | --- | --- |
| Incandescent (INC) | Blackbody by resistive heating; low-IR emissivity tungsten filament | 10-15 | 3-500 | Warm color temperature. High electricity costs |
| Halogen (HAL) | Blackbody by resistive heating with filament regeneration | 15-20 | 5-500 | Warm color temperature. High electricity costs |
| Fluorescent tube or Linear fluorescent (LFL) | Electrical gas discharges creates UV; phosphor-coating conversion | 60-100 | 4-200 | Needs high-voltage power supply. Contains Hg |
| Compact fluorescent lamp (CFL) | Electrical gas discharge creates UV; phosphor- coating version | 50-75 | 3-120 | Need high-voltage power supply. Needs warm up. Delay for restrike. Contains Hg |
| High intensity discharge metal halide (HID) | Electrical arc leading to gas discharge | 60-115 | 30-2000 | Need high-voltage power supply. Needs warm up. Dim with aging. Delay for restrike. |
| Low-pressure sodium | A gas discharge excites Na in states emitting at 589 nm | 100-200 | 10-180 | Need high-voltage power supply. Needs warm up. Delay for restrike. |
| High-pressure sodium | High-pressure Na emits broader, whiter light than low-pressure Na | 100-150 | 35-1000 | Need high-voltage power supply. Needs warm up. Delay for restrike. |
| LED luminaire with LED lamp | Direct electricity-to-light conversion | 80-200 | 2-20 | None |

Table 1.3 Luminous Efficacies Of Lamps and Luminaires and Assumed Light Output Ratio

| **Technology** | **Luminous efficacy of lamp (lm/W)** | **Light output ratio (LOR) (%)** | **Luminous efficacy of luminaire (lm/W)** |
| --- | --- | --- | --- |
| Linear fluorescent (LFL) | 87 | 70 % | 61 |
| Compact fluorescent (CFL) | 59 | 70 % | 42 |
| Incandescent and halogen (INC&HAL) | 17 | 70 % | 12 |
| High intensity discharge (HID) | 90 | 70 % | 63 |
| LED luminaire with LED lamp | 80 | 70 % | 56 |
| Integrated LED luminaire | - | - | 94 |

## 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).

For many years, LEDs were confined to specialty uses, from light indicators, car lights and projectors, and only developed into the major market from 2012 on, when efficiency and cost made them competitive with the mainstream lighting solutions (Weisbuch, 2018).

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 but is used as a proxy for commercial lighting due to the lack of more sector-specific data. 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. In Europe, the Collaborative Labeling and Appliance Standards Program (CLASP) predicts non-residential LED penetration to be 66% by 2030 and in South Korea in 2011, there was a policy aiming for 60% LED penetration of all buildings by 2020 (Ahn et al., 2016).

In 2014, the majority of commercial lighting (75 %) was estimated to be provided by LFL, while CFL and HID technologies both accounted for 10 % while the share of LED lighting was estimated to be 3 % (US DOE SSL, 2015) . However, in 2017 these figures changed dramatically, according to a recent version of the same study.

Table 1.4. Shares of Technologies of the Production of Lighting Globally (US DOE SSL, 2015)

|  |  |
| --- | --- |
| **Technology** | **Share of Commercial Lighting Service** |
| Linear fluorescent (LFL) | 75 % |
| Compact fluorescent (CFL) | 10 % |
| Incandescent and halogen (INC&HAL) | 2 % |
| High intensity discharge (HID) | 10 % |
| LED | 3 % |

### Trends to Accelerate Adoption

LED has advanced to the point where it is the best option for almost every lighting application. The eﬃcacies of cool white LED packages have improved over six-fold to over 160 lm/W in 15 years, which is higher than many alternatives. The installation costs of LED’s have decreased significantly so that they are price competitive with conventional lighting, and they offer signiﬁcantly lower cost of ownership (initial cost plus cost of electricity cost) (Morgan Pattison et al., 2018). The major adoption trend is this drastic drop in price, high savings potential, and the increasing interest in energy efficiency in buildings. However Morgan Pattison et al., also identify the following trends:

**Realization of new Applications and Use Cases**

The technology transition from conventional technologies to LED, has opened a broad myriad of new applications that could not be realized before with conventional lighting. LED also known as “smart lighting”, includes many other capabilities such as color change, dimming functionalities, speaker integration and WLAN repeaters.

**LEDs are better for human health and productivity**

In recent years, there has been an important focus on the role of buildings in increasing occupant comfort and productivity. Currently, LED is considered the best light source for the human eye, since they contain all the wavelengths in the visible spectrum, and because our eyes can naturally adapt to them (Cirrincione et al., 2018). LED lamps energy consumption is influenced by the lamp SPD, which, one of the basic parameters that affect the human circadian rhythms in terms of light (the others being timing of exposure, duration of exposure, intensity of the stimulus, and exposure pattern to light) (Cirrincione et al., 2018).

**Versatility in Areas with Low Infrastructure**

LED lighting is expected to be implemented throughout the world. According to Gayral, LEDs are particularly well suited to serve the 1.3 billion people living off-grid, with no access to the electrical distribution network, since they work on DC low voltage, as do solar panels and batteries, and they consume little energy (OECD, 2014; Gentile et al., 2016). A key application of LEDs is to equip off-grid populations with LED’s connected to solar panels and batteries: these are cheap equipment requiring little maintenance and with negligible running costs allow one to secure lighting for large populations (Gayral, 2017). Yet, in slower developing areas, such as many countries in Africa, the rate of penetration is expected to be lower compared to faster developing areas, such as China. The policy decisions and rebate policies may impact the penetration of LED lighting into the commercial sector. Cultural reasons are not expected to significantly slow down the market penetration of LED lighting. Cultural differences exist in what kind of lighting (color, intensity) is preferred in certain regions or countries but due to the versatility of LED lighting products, it is expected that LED lighting can be widely used in any type of commercial building throughout the world.

### Barriers to Adoption

A few years ago, first cost used to be the primary barrier to adoption of LED technology. However, prices have dropped rapidly. LED products remain more expensive than incandescent light sources, but may be as cheap as $2 to $3 per lamp for standard replacement products (US DOE SSL, 2017b). There are several issues that need to be solved before LED lighting can reach its full market potential in commercial lighting:

#### 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 if they were made with cheap materials, poor designs, or inadequate 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, meaning that useful lifetime may be much shorter than it should be due to better technology. This will improve the customer experience, but at a larger cost due to premature bulb replacement(Gayral, 2017).

#### Technology Understanding And Uncertainty

According to the US DOE SSL program, many concerns have been raised about environmental, aesthetics or physiological impacts of LED lighting, and these may have caused delays or cancellation of SSL lighting installations (US DOE SSL, 2017b).

### Adoption Potential

The LED is expected to account for half of lamps worldwide in 2020 (De Almeida, Santos, Paolo, & Quicheron, 2014) and should replace traditional types of lighting, such as fluorescent and hydrogen lamps, due to all the benefits previously mentioned (Ahn et al., 2016).

The LED technology adoption is estimated to be slower in commercial buildings than in residential sector. In commercial buildings, the modern FL lighting systems have good luminous efficacy (over 80 lm/W with luminaire losses), which slows down the rate at which LED lighting products may actually penetrate the sector. The LED adoption in commercial buildings in the U.S. was estimated at 2 % in 2010 and projected to be 30 % in 2030, while in residential buildings, the LED adoption is projected to increase from 0% in 2010 to 70 % in 2030 (US DOE SSL, 2014). This is also in line with the estimates by McKinsey(*Lighting the way: Perspectives on the global lighting market*, n.d.) where LFL still has a value-based market share of 16% in 2020 in general lighting. The fluorescent lamp technology persists on the market, since it is a mature, energy efficient and cost-efficient technology. In some applications, such as in fridges and refrigerators in shops, LED lighting has a high adoption due to its small size and low heat radiation.

## Advantages and disadvantages of Commercial LED’s

### 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 junction, but otherwise a 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 the 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 unclear that laser diodes could provide improved lighting compared to LED technology.

### Arguments for Adoption

LED lighting offers many advantages in the lighting of commercial buildings. Compared to the conventional technologies, LED lighting products typically have high lifespans (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)), they operate well with lighting control systems, and there is a lot of freedom in luminaire design and illumination design due to the small size of the LED chips and the choice of color and intensity (Table 1.5).

### Additional Benefits and Burdens

Currently, the main burdens discussed in the literature are the environmental impacts and cost after disposal or end of life.The increasing rate of disposal caused by the continuing improvement of LED technology described in Section 1.2.3, causes waste due to the incorrect disposal and environmental impacts at the end of life of the LED luminaire.

At the end-of life, LED-lamps become electronic waste which is generally classified as hazardous waste in the European Union (Franz & Wenzl, 2017). In 2002, the EU launched the first Waste of Electrical and Electronic Equipment (WEEE) directive to control the collection, recycling and general treatment of of e-waste. The directive includes strict requirements for some technologies like gas discharge lamps, which include fluorescent, compact fluorescent (CFLs), high-pressure mercury and sodium lamps, and metal halide lamps. These are required to be collected separately, due to their hazardous mercury content (EU, 2003).

LED lighting products need also to be recycled appropriately. As commercial buildings are typically professionally maintained, it is assumed that the lighting products are disposed as they should be. The problem of disposal at the end of life, has seen different solutions in different countries. The European e-waste directive requires a recycling quota of 80% for the category ‘lamps’ as of 2018 (Franz & Wenzl, 2017).

Over the years, a large number of life cycle assessment (LCA) studies have been developed to inform the impact of LED lighting products across their lifespan. Many of these studies used different lighting technologies, such as HID or CFL in order to know which one had less environmental impact (Elijošiutė, Balciukevičiūtė, & Denafas, 2012) and to which life cycle stage the impact was allocated (*Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products*, n.d.). Casamayor et al. recently compared the environmental impact of a new LED eco-lighting product with an existing LED product using a cradle to grave LCA that revealed that the new ecolighting product has about 60% less environmental impact than the existing one under 3 life scenarios (1,000, 15,000 and 40,000 hours) (Casamayor, Su, & Ren, 2018). Dulout et al. performed a comparative LCA and revealed that LED lights exhibit better performance than CFL, halogen, and incandescent lamps in terms of energy consumption and overall LCA (Dulout et al., 2018).

Beu et al. indicate that the light industry will have a paradigm shift and move towards a circular economy, using artificial intelligence, new sensors, and new services. For instance, under services such as the “LED lighting leasing model”, instead of selling luminaires and control systems, customers lease lighting systems or quality of lighting at a “pay-per-lux” model (Beu et al., 2018).

Environmental impacts due to outdoor light pollution; A special concern in evaluating the environmental impacts of lighting products is the negative impacts of artificial light on humans, fauna, flora and the ecosystem balance. Davies et al. argue that while LEDs are often advocated for their potential to reduce global CO2e, environmental scientists and human health experts have raised concerns about the broad-spectrum light and prominent short wavelength peak that the commonly used white models emit (Davies & Smyth, 2018). According to the authors the impact of LED is summarized in: Firstly, LED’s reproduce day-like light at night that may change organism behavior; Secondly, some biological responses of species may be sensitive to the short wavelength peak emitted by white LEDs; Thirdly, these wavelengths cover a broad spectrum and therefore may affect many different sensitive species; Fourthly, LED’s high efficiency may lead to a large rebound in artificial lighting demand; and finally this extensive demand growth (when coupled with say, solar power) may apply to rural areas that were previously insulated from excessive artificial light (Davies & Smyth, 2018).

Compared to the most efficient LFL luminaires, the efficacy gain in LED lighting is not necessary very notable but it depends on the type of LED luminaire. As the luminous efficacy of a LFL luminaire (including LOR 70 %) is approximately 61 lm/W, 42 lm/W for CFL and 63 lm/W for HID luminaires, only the integrated LED luminaire surpasses the luminous efficacy (94 lm/W). If the LED luminaire is a kind of luminaire where one or several LED lamps are installed, the luminous efficacy is approximately 56 lm/W (LOR 70%). In addition, the LFL luminaires typically have lower purchase price compared to LED luminaires. Compared to LFL, CFL and HID light sources, LED products do not contain mercury, which is an element essential for the operation of FL and HID lamps. Yet, the amount of mercury is currently only few milligrams per lamp at best.

Table 1.5. List of the Main Advantages and Disadvantages of LED Lighting in Commercial Buildings.

| **Advantages** | **Disadvantages** |
| --- | --- |
| Long lifetime | High purchase price |
| High luminous efficacy and Energy efficiency | Not mature technology |
| Potentially low life cycle costs | LED heat affect indoor thermal comfort and increase cooling load in Summer |
| Flexible Design Color choices (Ahn et al., 2016) | Environmental Concerns: Disposal needs attention |
| Dimmability (Ahn et al., 2016) is fully controllable and could offer many innovative functionalities, such as connected lighting applications and visible light communication (Dulout et al., 2018) | Environmental Concerns: Outdoor Light pollution |
| No mercury (Gentile et al., 2016) |  |

An important disadvantage of LED Technology is that heat from LED lights affect indoor thermal conditions in buildings and increases the indoor cooling load in summer (Ahn et al., 2016).

Table 1.6 Technology Comparison as per Performance and characteristics 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 | 1,000 |
| Halogen (HAL) | 15-20 | 5-500 | medium | high | 3,000 |
| Fluorescent tube or Linear fluorescent (LFL) | 60-100 | 4-200 | medium | medium | 5,000 |
| Compact fluorescent lamp (CFL) | 50-75 | 3-120 | medium | medium | 10,000 |
| High intensity discharge metal halide (HID) | 60-115 | 30-2,000 | high | low | 15,000 |
| Low-pressure sodium | 100-200 | 10-180 | medium | low | 15,000 |
| High-pressure sodium | 100-150 | 35-1,000 | 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 lighting in commercial buildings is compared to conventional lighting technologies. The level of comparison is done on the basis of luminaires, not only lamps or other types of light sources (LED module). The luminaire comparison affects primarily the luminous efficacy data and purchase price data. Non-electric and off-grid lighting solutions are excluded from the scope of the current study.

The functional unit of the study is petalumen-hours (Plmh), i.e., 10^15 lumen-hours (1 million billion lumen-hours), where the installed luminous flux of all electric light sources and the estimated annual operating time in commercial buildings are taken into account. The implementation unit is Plm corresponding to the luminous flux of installed base of all lighting technologies in commercial buildings.

## Data Sources

The energy consumption data is available for commercial buildings as a whole or for lighting in commercial buildings. In case of commercial building energy consumption as a whole, there are only a few estimates available for the share of lighting in the commercial building energy or electricity consumption. Some of these data sources are: “Energy efficiency status report 2012 electricity” (Bertoldi et al., 2012); the latest “Commercial Building Energy Consumption Survey (CBECS) 2012 microdata” (Deng, Fannon, & Eckelman, 2018); “Light’s Labour Lost” (IEA, 2006) and (Urge-Vorsatz et al., 2012). The floor area data is available from as many sources as possible (U.S. EIA, 2012); (Hong, Zhou, Fridley, Feng, & Khanna, 2014); and the U.S Department of Energy Solid State Lighting Program (US DOE SSL, 2017a) (US DOE SSL, 2014).

The qualities of the lighting technologies; such as the annual operating time, luminaire life, and luminous efficacy; are based on a data collection of the U.S Department of Energy Solid State Lighting Program (US DOE SSL, 2017a) (US DOE SSL, 2014), published peer reviewed sources and author estimates.

A typical LOR value of 70 % was assumed for luminaires of LFL, CFL, HID and incandescent or halogen light sources, meaning that 70% of the flux of the lamps can be utilized in lighting while the 30% remains trapped inside the luminaire.

The same 70% LOR was used for luminaires equipped with LED lamps but not for the LED luminaires in which the LED light source is integrated. The LOR ranges between 50 % and 100 % depending on the luminaire design and materials. It has been estimated that a LOR approximately 75% and beyond are possible with diffusers and developed reflector materials (Hanselaer, Lootens, Ryckaert, Deconinck, & Rombauts, 2007) .

## 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 commercial TAM is the current focus of this Solution.

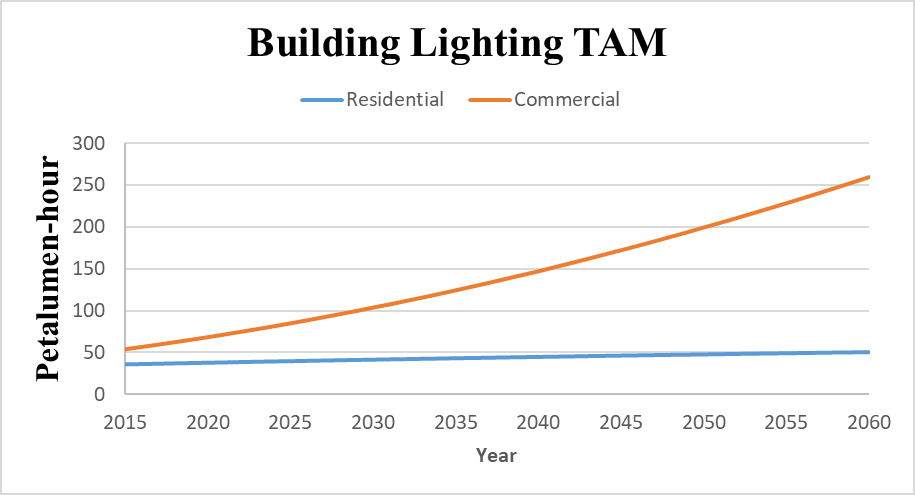


Figure 2.1 Lighting TAM for Global Building Stock

## 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 potential adoption of LED lighting is estimated to be high (90%) in 2050, while in 2014 the global adoption was only approximately 3% (US DOE SSL, 2015). It was difficult to gather data on commercial LED lighting adoption. There were only very few data sources. Typically, the adoption data was given as a share (%) from the total (commercial) lighting market or installed base. This 3 % current adoption share of the installed base refers to *all* lighting. Due to the limited adoption data available, this 3 % share of TAM is used as a global estimate for commercial lighting in all regions.

There is clearly a lack of global and regional data for the adoption rate for and near the base year. Most data on commercial lighting focus on the sales and market value, not the lighting demand expressed in lumen-hours. The base year adoption scenario is based on the 3 % of TAM estimate. It is admitted that the adoptions may be somewhat exaggerated in certain areas, such as Eastern Europe and Middle East & Africa.

### Reference Case / Current Adoption

The current adoption scenario is based on the US DOE estimation that LED technology accounted for approximately 3% of global installed base in 2014 (US DOE SSL, 2017b). However, when adoption estimates were combined with data from the TAM model, the adoption was estimated at 4.3%. The reference scenario assumes that this percent remains constant in the future, that is, that adoption only grows with the total lighting market (TAM) to maintain a 4.3% adoption.

### 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

Used the average Energy Efficiency. Assumes a linear growth in adoption to 80% of the TAM.

#### Drawdown Scenario

Used the average Energy Efficiency. Assumes a linear growth in adoption to 90% of the TAM.

#### Optimum Scenario

Uses the average energy efficiency. Assumes a linear growth in adoption to 95% of the TAM.

## Inputs

### Climate Inputs

The GHG emissions are reduced by using LED lighting in commercial buildings instead of conventional lighting technologies of lower luminous efficacy. Depending on the type of LED luminaire (integrated or not), the luminous efficacy may be greater than that of the conventional luminaires. Thus, the LED lighting is an electricity reduction solution. The savings in the energy consumption directly reduce the GHG emissions. Yet, some level of rebound effect can be expected, as the amount of light and the number of light sources are expected to be constantly increased, 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. It has been estimated that approximately 90 % of the environmental impacts of lighting products in general are caused by the energy consumption during operation of the product, so improving the luminous efficacy is very effective (Tähkämö, 2013).

#### Direct Emissions

The reduction in GHG emissions are calculated by comparing the annual electricity 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 Emission

Indirect CO2 emissions were estimated on the basis of life cycle assessment (LCA) case studies of lighting products found in the literature (generally 2009-2016). The indirect CO2 emissions of conventional technologies are weighted on the basis of their shares. Explanations and detailed calculations and conversions are provided in the model.

The indirect CO2 emissions are calculated as ton of CO2eq. per functional unit (Plmh), as most of the data is provided in a unit of kg CO2 per lmh. The LCAs of both lamps and luminaires were used, as it was found that the lamp CO2 were not always smaller than that of a luminaire, suggesting that the differences in LCA methodologies are more notable than the product level (lamp or luminaire). The aggregated amount of indirect CO2 for conventional and LED lighting products is shown in Table 2.1.

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* | 104.00 - 924,660 | 196,462 | 18 | 10 |
| Solution Indirect Emissions | *T CO2eq/ Plm* | 257,801-674,813 | 466,307 | 5 | 4 |

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[[2]](#footnote-2).

### Financial Inputs

#### First Cost

First cost data are based on purchase prices of the luminaires. The installation costs, such as the wiring and assembly costs, are not included. The purchase price data is collected for light sources (lamps, modules), control gears (magnetic and electronic ballasts, LED controlgears) and luminaires (housing, integrated). The luminaire prices were collected from European and US data sources. The product in question is a bit complex, as it may or may not contain three parts. The luminaire (cover) prices vary by luminaire design and type. The controlgear prices vary by type (electromagnetic or electronic ballast). The price of ignitor, if needed, is included in controlgear price. In the price conversion into USD2014/Plm, the LOR of the luminaire was estimated to be default 70 %, unless luminaire-specific LOR data were available.

The lamp price data needs to be converted into luminaire prices. This is done on the basis of lamp and luminaire price collection in European and US data. From these prices, the shares (%) of light source (lamp), controlgear (electromagnetic or electronic) and the luminaire cover are estimated for the conventional technologies. Both European and US price division data is used to calculate a conversion factor for converting lamp prices into luminaire prices. The conversion factors take into account the additional costs of ballasts and luminaire covers that are needed in commercial lighting in addition to the lamp itself. From these shares (percentages), the luminaire prices of all conventional technologies are formulated, using the lamp prices of various regions as the starting point. Also, the luminaire prices directly collected from the EU and US sources were used to calculate the average first costs of conventional luminaires and LED luminaires. The prices of HID luminaires are estimated directly on the basis of the EU and US price data collection.

#### Operating Cost

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

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 needs to be divided by the respective amount of Plmh (aggregated conventional or solution). Disposal costs are not included in the costs, as there were no data available. The electricity price is estimated specifically for commercial buildings.

Table 2.2 Financial Inputs for Conventional Technologies

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First Cost (Conventional) | *US$2014/klm* | 0.001 – 81.29 | $38.96 | 42 | 8 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/klmh* | 0.0007-0.0028 | $0.0018 | 4 | 1 |
| Commercial Electricity Price (Conventional and Solution) | *US$2014/kWh* | 0.0946 | 0.0946 | 838 (for 55 Countries) | 1 |
| Commercial Discount Rate | *%* | 6.1% - 12.3% | 9.68% | 5 | 4 |

Table 2.3 Financial Inputs for Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Solution) | *US$2014/klm* | 15.23-71.30 | $43.27 | 24 | 4 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/klmh* | 0.0013-0.0013 | 0.0013 | 1 | 1 |
| Commercial Discount Rate | *%* | 6.1% - 12.3% | 9.68% | 5 | 4 |

### 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

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity | *Plmh/Plm = hours* | 12,579 – 23,309 | 17,944 | 26 | 4 |
| Average Annual Use | *Plmh/Plm =hours* | 2,442-4,830 | 3,636 | 10 | 4 |
| Average Energy consumed | *TWh/ Plmh* | 8.22-31.50 | 19.86 | 46 | 6 |
| Luminous Flux –Incandescent | *lm/ unit* | 513 | 513 | 2 | 1 |
| Luminous Flux – Halogen | *lm/ unit* | 418 - 483 | 450 | 5 | 1 |
| Luminous Flux – LF | *lm/ unit* | 1,569 – 2,654 | 2,111 | 5 | 1 |
| Luminous Flux - CFL | *lm/ unit* | 523 | 523 | 1 | 1 |
| Ratio of Lamp Price to Luminaire Price - Incandescent | *%* | 4.4% – 21.3% | 12.8% | 13 | 2 |
| Ratio of Lamp Price to Luminaire Price - HID | *%* | 12.3% – 16.1% | 14.2% | 4 | 2 |
| Ratio of Lamp Price to Luminaire Price - LFL | *%* | 3.2% – 10.0% | 6.6% | 20 | 3 |
| Ratio of Lamp Price to Luminaire Price - CFL | *%* | 5.9% – 17.9% | 11.9% | 8 | 2 |

Table 2.5 Technical Inputs Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity (Solution) | *Plmh/Plm =hours* | 31,313-59,562 | 45,438 | 16 | 4 |
| Average Annual Use (Solution) | *Plmh/Plm =hours* | 2,442-4,830 | 3,636 | 21 | 5 |
| Energy Efficiency (Solution) | *%* | -2.9% - 53.1% | 25.08% | 31 | 14 |
| Luminous Efficacy (Solution) | *lm/W* | 51-107 | 79.4 | 29 | 6 |
| Luminous Efficacy (Forecast 2020) (Solution) | *lm/W* | 71.5 – 114.5 | 93.0 | 5 | 2 |
| Luminous Efficacy (Forecast 2030) (Solution) | *lm/W* | 97 – 155.4 | 126.2 | 5 | 2 |

## 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. LED adoption can take place worldwide including in places with low lighting demand and low electricity grid penetration.
3. The data are collected from multiple sources in the literature for global, EU and US regions. Global average qualities are necessary for the clarity of the model. Yet, regional differences exist.
4. Average efficacy value is necessary for the conversions of lighting energy consumption (Wh) into lumen-hours.
5. A simple adoption projection (linear) provides sufficient data to estimate the emissions and financial impacts of Commercial LED adoption.
6. GDP growth is correlated to lighting demand growth, as the lighting demand tends to increase with the development of the region (for TAM calculation). However, the GDP growth corresponds to the growth of the economic development of the region, and lighting demand in commercial buildings may differ from that. Lighting demand (Plmh) may increase due to increasing number of luminaires 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 required lux level (lx, lm/m2) in commercial buildings may increase, increasing the required lighting demand (Plmh).

## 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[[3]](#footnote-3), 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.

For Commercial LED’s, only the commercial lighting chain was relevant where Commercial LED’s were integrated with Smart Glass and Building Automation Systems. As LED's are assumed to be the highest priority in the Commercial lighting sequence, there are no integration adjustments to its results.

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[[4]](#footnote-4)). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

## Limitations/Further Development

The greatest limitation of the study is the LED adoption data. It was very difficult to gather data for LED adoption in commercial buildings expressed in Plmh share of the installed lighting base. There is market share and per unit sales data available but converting them into Plmh share was considered to require too many assumptions, reducing the quality of the outcome.

The average luminous efficacy of installed commercial lighting is estimated on the basis of one datapoint for 2005 (IEA 2006) and is considered to be the same in all regions, except for in US, for which there is average lm/W data available. From the 2005 data, the growth rate of the average lm/W of all regions is assumed to be that of the US average lm/W data. The luminous efficacy is roughly estimated to be the same in all regions, which is not entirely the case. This causes uncertainty in the TAM values calculated from energy consumption with the help of lm/W.

LED luminaire first cost data is based only on the EU and US data on the purchase price due to the time constraints and that of not being familiar with the commercial lighting places of purchase and not finding literature data for LED luminaire price in other regions. More first price data could be included to make the model more robust and to cover all the regions in more detail. In addition, the installation costs, such as those of the wiring and assembly work, should be included in the model.

The base year commercial lighting is estimated to be divided into incandescent, halogen, CFL, and LFL as the market share data indicates. However, sources give estimates for the market shares for 2010 and 2005, and the 2014 shares are calculated using linear projections resulting in shares of incandescent lamps (2 %), HID lamps (10 %), CFLs (10 %), and LFLs (75 %) in 2014. This linear analysis 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 commercial lighting. This is a weak point in the analysis and the shares of conventional and solution technologies must be confirmed.

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, but the electricity price remains constant.

Many of the literature used in the LED commercial 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.

### Lighting Controls

Lighting controls are excluded from the current study but they are strongly recommended to be added to the model in later phase. Lighting controls may mean controlling the light from the luminaire according to occupancy, daylight availability or other scheme. The lighting system requires light sources that are dimmable, suitable control gears and sensors, such as passive infrared, for detecting the occupancy and light level. Lighting controls may save energy and thus money and CO2 emissions and it may also improve the user satisfaction and increase the lamp life. It must be noted that it also adds the first costs due to purchase of more components and operating costs due to standby power consumption.

The energy savings gained from the use of lighting controls vary significantly. It has been estimated that 75-90 % of lighting energy consumption can be eliminated by combining the following actions: 1. changing the conventional lighting to the most efficient equipment available, 2. using daylighting and lighting controls to adapt to occupancy and daylight, and 3. using ambient and task lighting according to need (*Levine et al., 2007).*

For energy savings from occupancy and dimming, the estimates vary depending the type of space, location of the building and time delay of the system. In a review by Dubois and Blomsterbergthe energy saving potentials of various energy saving strategies were collected (Dubois et al., 2015). Using switch-off occupancy sensors was estimated to result to 20-35% of energy saving potential (Galasiu, Newsham, Suvagau, & Sander, 2007) and using dimming according to daylight availability resulted to 25-60 % savings depending primarily on the climate, shading and the baseline for comparison(*Galasiu et al. 2004 Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls*, n.d.). Williams et al. estimated that daylighting saves approximately 28 % and occupancy controls 24 % of lighting energy consumption (Williams, Atkinson, Garbesi, Page, & Rubinstein, 2012). Dubois et alsummarized that dimming according to daylight availability may result to energy savings of 10-93 % and occupancy control to savings of 20-93 % but strongly depending of space occupancy and time delay of the sensor system (Dubois et al., 2015). Typically occupancy-based lighting control was found to save 25-75 % of energy.

Haq et al.summarized from several previous studies that the occupancy-based lighting controls would save 3-84 % of energy in offices, 11-60% in educational buildings, and 17-78% in infrequently occupied spaces depending on the time delay of the system (Haq et al., 2014). They collected also studies showing that dimming according to daylight would result 9-31 % energy savings in offices, 23-70% in classrooms, and 11-46% in indoor open spaces or atriums. Their collection of studies combining occupancy- and daylight-related lighting controls indicated energy savings of approximately 35-68% (Haq et al., 2014).

Hebert et al. anticipated a 50% energy savings by occupancy sensor in their calculations and concluded an approximate energy savings of 30% for daylight-based dimming (*Hebert et al. 2014 Energy saving via lighting study at US National Laboratories. Facilities, 32 (7/8) 396-410*, n.d.). Depending on the time delay, energy savings of 20-28% was recorded in an office building when occupancy-based lighting controls was used(Labeodan, De Bakker, Rosemann, & Zeiler, 2016). All in all, the energy savings from occupancy and dimming schemes depends much on the time delay of the system and the type of space.

# 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 Commercial | *Plmh* | 2 | 159 | 179 | 189 |
| *% market* | 4.3 | 80 | 90 | 95 |

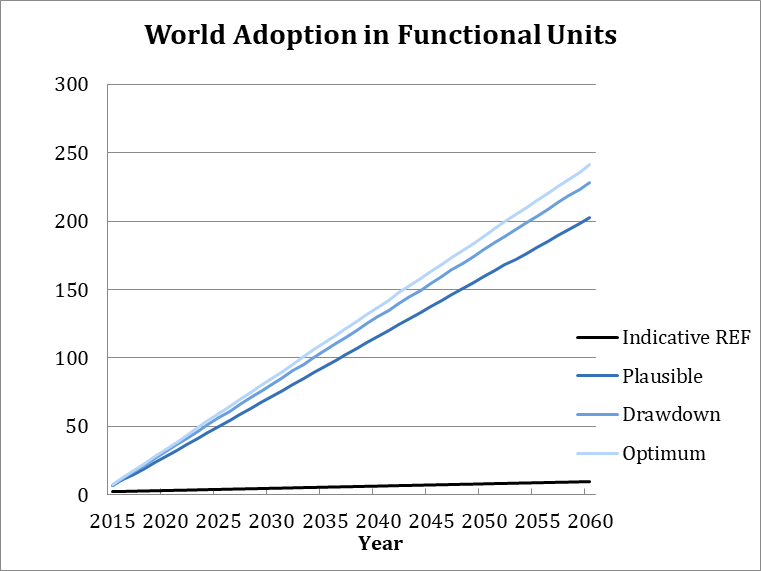


Figure 3.1 World Annual Adoption 2020-2050

## 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*** | 0.38 | 7.29 | 0.19 | 0.38 |
| ***Drawdown*** | 0.43 | 8.24 | 0.21 | 0.43 |
| ***Optimum*** | 0.45 | 8.72 | 0.22 | 0.45 |

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** | 0.60 | 0.03 |
| **Drawdown** | 0.63 | 0.03 |
| **Optimum** | 0.72 | 0.03 |

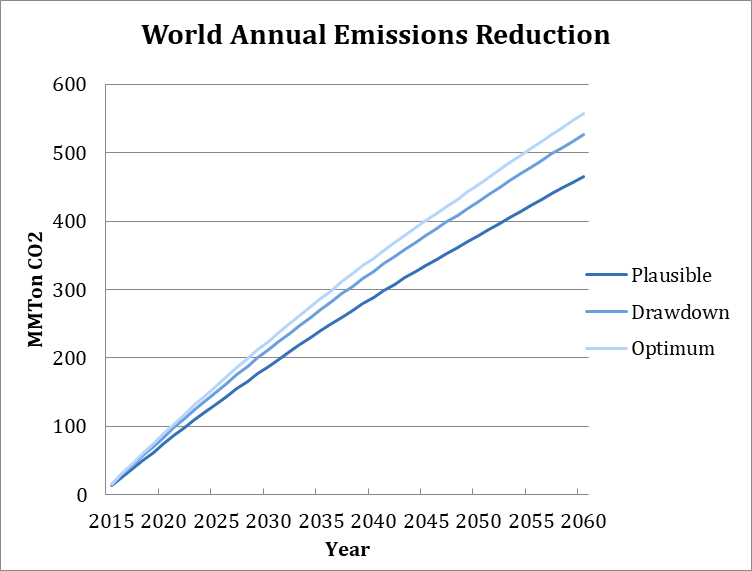


Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the Glossary. The graph (Figure 3.3) of annual operating saving shows the savings until 2060 but only for implementation units adopted until 2050, hence the reduction after 2050.

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)** |
| --- | --- | --- | --- | --- | --- |
| *2020-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 3,585.68 | -2,224.18 | 1,239.60 | 1,682.56 | 491.95 |
| **Drawdown** | 4,039.75 | -2,516.81 | 1,402.70 | 1,903.94 | 556.68 |
| **Optimum** | 4,266.78 | -2,663.13 | 1,484.24 | 2,014.63 | 589.04 |

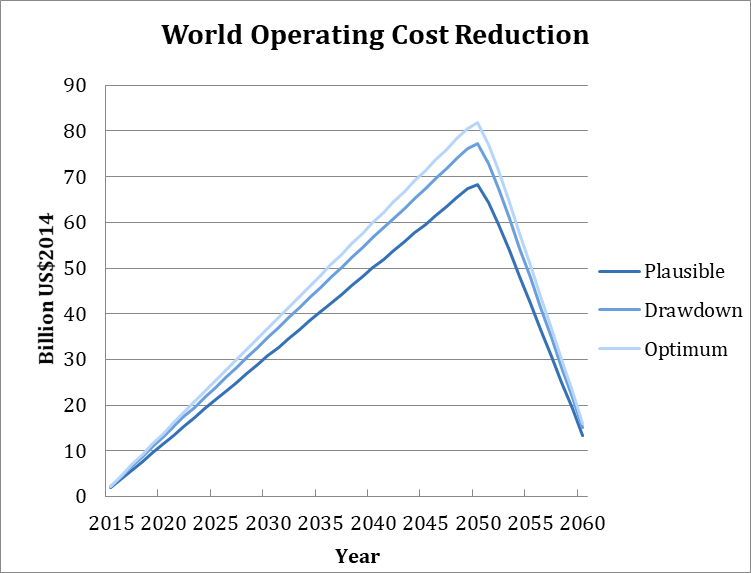


Figure 3.3 Operating Costs Over Time

# Discussion

LED lighting offers great emission reductions in commercial buildings. The light sources traditionally used in commercial buildings, LFLs, have typically rather good luminous efficacy and at best, they have high luminous efficacy (over 100 lm/W from luminaire). This limits the energy savings gained from LED lighting. Yet, it is noted that in the future, the luminous efficacies of the conventional technologies are not expected to be developed as dramatically as that of the LED lighting products is. It is estimated that the luminous efficacy of LED luminaire may well exceed 200 lm/W (US DOE SSL, 2017).

The *drawdown* commercial LED scenario would result in CO2 reduction of 8.2 Gt CO2e by 2050 .The Project Drawdown LED commercial and residential model combined would result in a CO2 reduction of 20.3 Gt CO2e by 2050 in the *drawdown* Scenario.

## 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.

There are therefore several areas in the model needing improvement. First, more LED adoption data should be added and if not available in Plmh’s, conversions may be necessary. Second, the first costs of conventional and LED luminaires could be improved including more global and regional purchase price data. In addition, installation costs could be estimated and added to first costs. Third, the data and respective estimates of lighting qualities could be developed so that regional differences are included and that year by year development is taken into account. Fourth, the model can be improved by including the benefits (and burdens) of lighting controls and advanced BAS technology. Controlling the lighting according to occupancy and dimming according to daylight availability could save significant amount of energy. The energy savings from lighting controls depend strongly on the type of space, building location and the details of the control system (e.g., time delay).

## 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. 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-2)
3. This can be interpreted as a single building with multiple efficiency technologies. [↑](#footnote-ref-3)
4. Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel. [↑](#footnote-ref-4)