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D MATL

CASE STUDY

Life Cycle Assessment and Material Flow analysis of commercial lighting equipment

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1 Introduction

1.1 A brief history of lighting

The presence of reliable and energy efficient lightings has played and continues playing a major role in modern society. The main advancements in lighting technology occurred in sequence more than two centuries ago with the advent and progress of the industrial revolution. Firstly, gas lamps were developed in England in 1790 and different types of gas, as methane, acetylene, butane, hydrogen or natural gas, were used over the years. Afterwards, on the other hand, the invention of electric light bulbs, attributed to Thomas Edison in 1879, entered the market and incandescent bulbs went on to dominate the world of lighting until the first light-source based on gas discharges was introduced commercially by Daniel McFarlan Moore in 1904. The 20th century was the century of high intensity discharge lamps (HID), among the most popular ones were fluorescent, mercury-vapor, high pressure sodium, and metal halide. All of these lamps used a similar type of technology and operated by sending an electrical current between two metal electrodes in a glass tube filled with inert gas that results in the emission of visible light. The lighting technology that significantly revolutionized the market was the one of Light Emitting Diodes (LEDs) that consisted in a solid-state lighting (SSL) that produced light by converting electrical current using a semiconductor material. The first practical LED emerged in 1962, and its invention was attributed to Nick Holonyak. Thenceforward, LEDs have been commercially available in many colors such as green, amber, and red, and this has contributed to their increasing popularity in signage and display applications. Moreover, the discovery of gallium nitride (GaN) LED revolutionized the lighting world making possible to get white light from a semiconductor and, this kind of LEDs established themselves in many fields including architectural lighting, indoor and outdoor lighting, and traffic and railway signaling. The excellent characteristics such as high luminous efficacy, robustness, long lifetime, high color rendering index (CRI), and high reliability, make LEDs good candidates for replacing completely traditional light sources in the short-term [1].

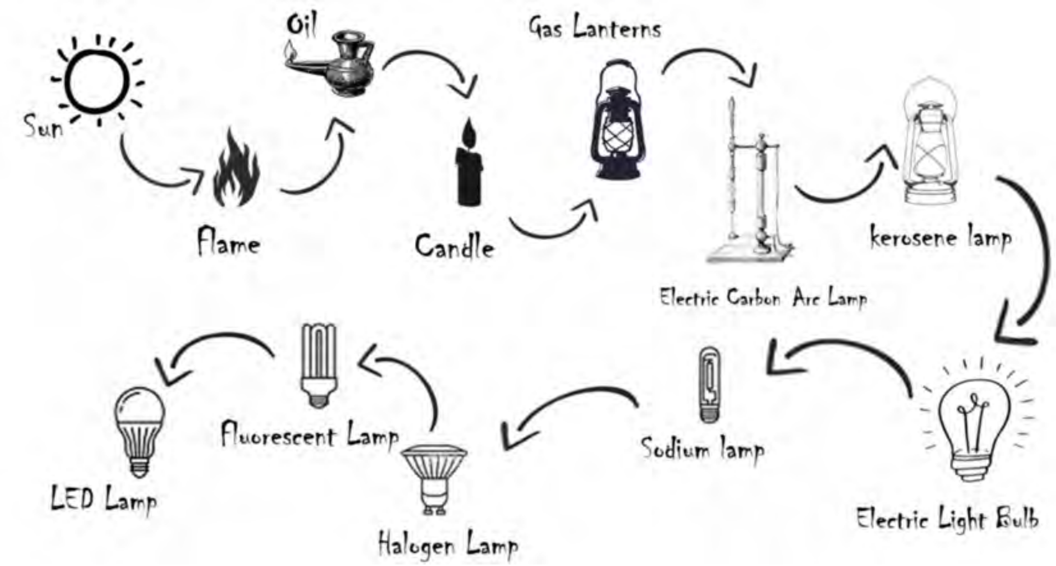


Figure 1: History of lighting [2].

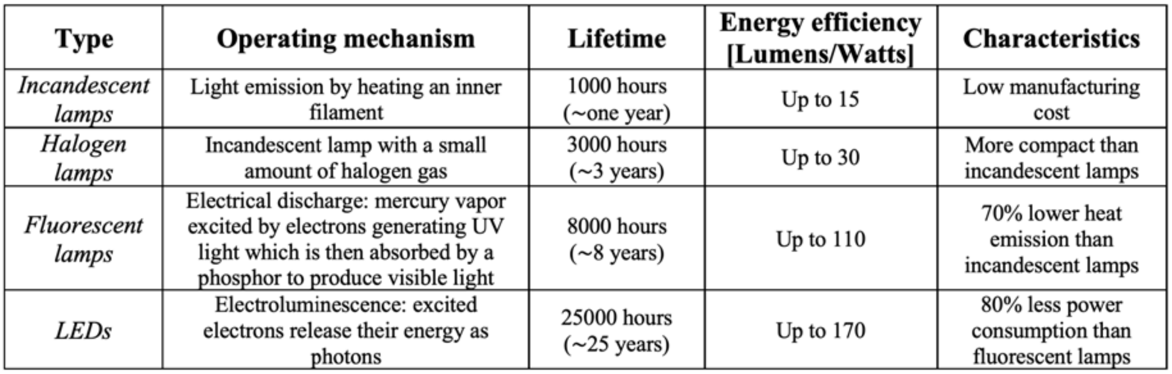
2 The various types of lighting

2.1 Nowadays technologies

In Table 1 it is shown a comparison of the operating systems and properties of the major types of lighting commercially available for everyday use: incandescent lamps, halogen lamps, fluorescent lamps and LEDs.

Lighting efficiency has improved considerably since 2000. Incandescent bulbs have been recently banned in most countries and their phase-out prompted global technology shifts towards more efficient technologies such as fluorescent lamps or LEDs. In 2018, LEDs reached a critical milestone, achieving the same share of global residential sales as less-efficient fluorescent lamps (40%), and now appear to have overtaken fluorescent lamps with their sales that are expected to further increase in the next years. Even if many markets are still dominated by halogen and fluorescent lamps, LEDs need to become the global norm to remain in line with a Sustainable Development Scenario (SDS) in the global energy system. Current trends suggest that the market is on track to follow the SDS trajectory by 2030; however, to raise the share of LED sales to more than 65% of the residential market by 2025, countries need to update their regulatory policies, for instance extending the phase-out regulation also to halogen lamps, which are only slightly more efficient than incandescent ones.

LEDs are now massively produced in many markets, and competition among manufacturers is driving further innovation, wider product choices and lower prices. In particular, China has taken the lead in manufacturing, benefiting from strong financial subsidies and incentives from the government, and prices of LED lamps have fallen substantially to 3-5 $, making them more and more affordable [3].



Type	**Operating mechanism**	**Lifetime**	**Energy efficiency [Lumens/Watts]**	**Characteristics**
Incandescent lamps	Light emission by heating an inner filament	1000 hours (~one year)	Up to 15	Low manufacturing cost
Halogen lamps	Incandescent lamp with a small amount of halogen gas	3000 hours (~3 years)	Up to 30	More compact than incandescent lamps
Fluorescent lamps	Electrical discharge: mercury vapor excited by electrons generating UV light which is then absorbed by a phosphor to produce visible light	8000 hours (~8 years)	Up to 110	70% lower heat emission than incandescent lamps
LEDs	Electroluminescence: excited electrons release their energy as photons	25000 hours (~25 years)	Up to 170	80% less power consumption than fluorescent lamps

Table 1: Comparison of lighting systems.

3 Life Cycle Assessment

A question arises: LEDs are the most efficient lighting technology, but what about their life cycle impact? Are they sustainable? To answer this question the following Life Cycle Assessment, where LEDs were compared with incandescent lamps (IND) and compact fluorescent lamps (CFL), was performed.

For each luminaire system, the impacts were separately calculated for the production of four raw material components (fixture, ballast, lamp and lens), the packaging, the transport (by road and by sea), the power consumed during use, and the end of life (recycling and disposal). Examples of the impact categories include resource depletion, land use and landfill, ecotoxicity (terrestrial and aquatic), and global warming. Fig 2 shows the flow diagram of an LCA evaluation of a generic lamp, including the component parts involved in the raw material phase, the manufacturing, transport, the in- use service and the end of life disposal [4].

Of all the possible LCA variations, this analysis used a "cradle-to-grave" approach: it examined the entire life cycle, from the extraction of the raw material (the "cradle") to the end of life ("grave"). The time period of analysis was calibrated on the longest-lived component to guarantee that the maximum life service is taken into account and the impacts associated with manufacturing are amortized over that time range.

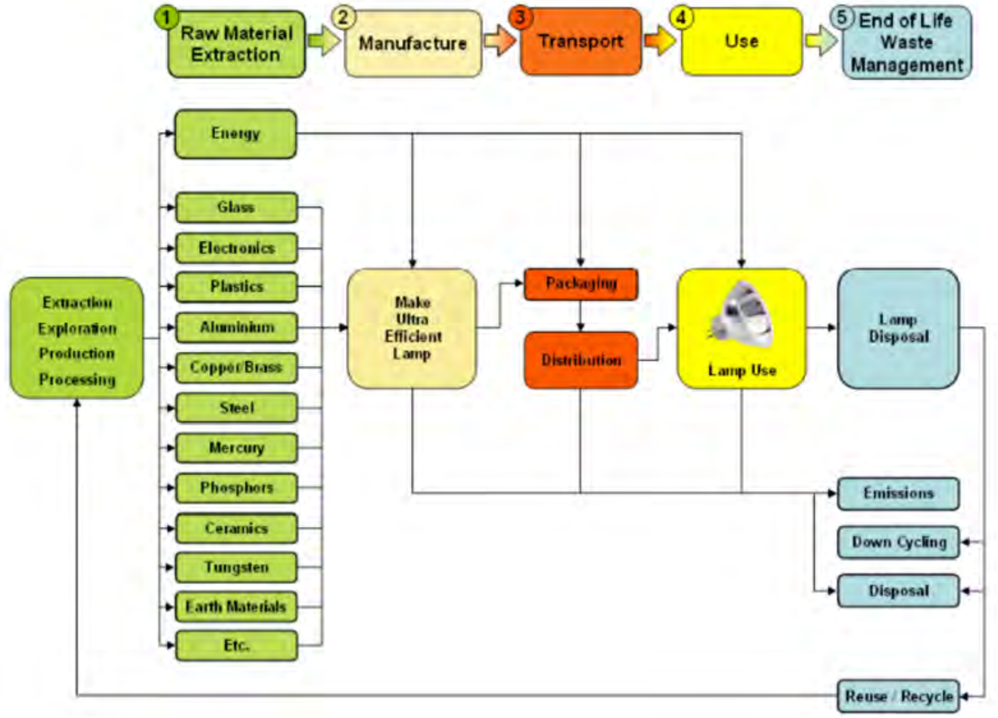
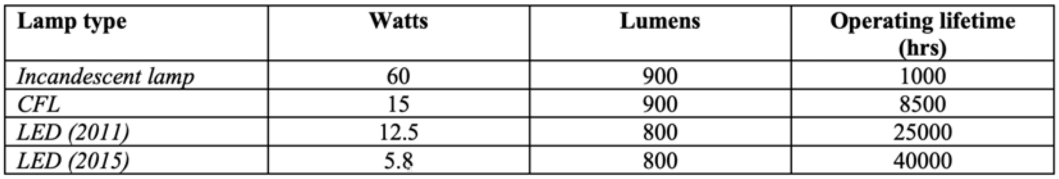


Figure 2: Life Cycle Assessment Flow Diagram for a Generic Lamp [4].

3.1 Lamp Performance and Functional Unit

As seen in the previous chapter, incandescent lamps, compact fluorescent bulbs and LED lamps have different performance characteristics. A functional unit of "20 million lumens-hour" was chosen to ensure the uniformity required for the energy life cycle analysis (see Table 2). This functional unit represents the lighting service provided by a single 12.5 W LED lamp over its lifetime (Fig. 3) [5].



Lamp type	Watts	Lumens	Operating lifetime (hrs)
Incandescent lamp	60	900	1000
CFL	15	900	8500
LED (2011)	12.5	800	25000
LED (2015)	5.8	800	40000

Table 2: Performance of conventional and LED lighting technologies [5].

Figure 3: Number of lamps needed to supply 20 million Lumen-Hours [5].

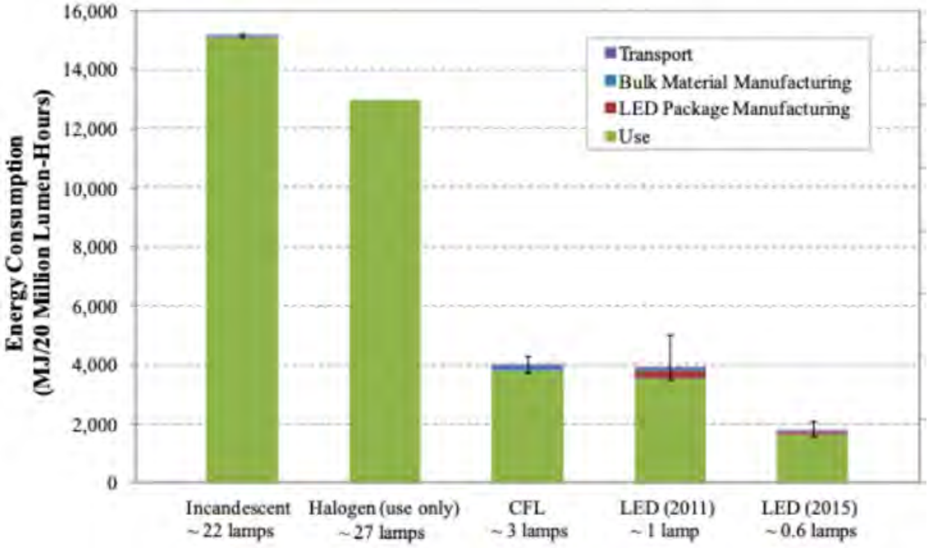
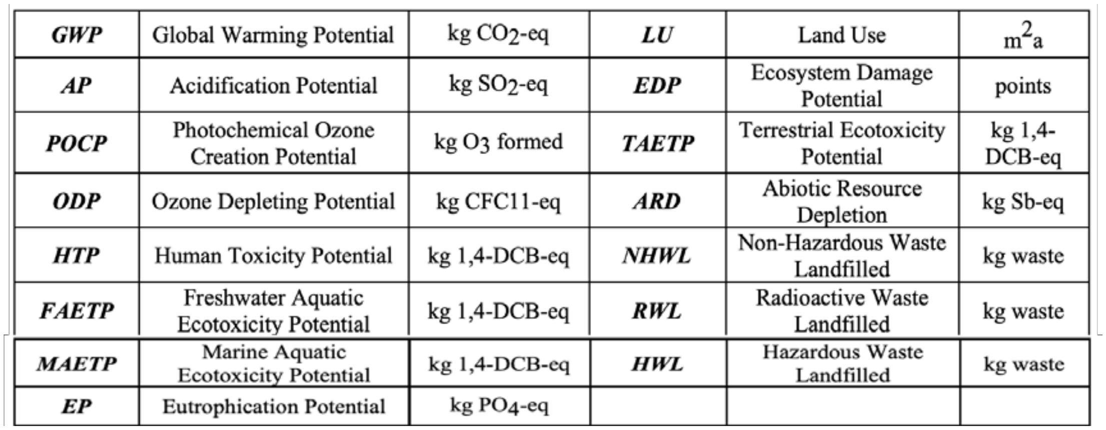


Figure 4: Life-Cycle Energy of incandescent lamps, CFLs and LED lamps [5].

The following discussion in based on a research made in 2012, so the data for 2015 are estimations that, however, are not far from the actual values [5,6]. Since incandescent lamps and CFLs have a lower efficiency than LEDs, the functional unit can be used to indicate how many incandescent lamps and compact fluorescent bulbs are required to achieve performance equivalence. Fig. 4 shows that the energy consumption of LEDs (2011) and compact fluorescent lamps during their life cycle is approximately the same: 3900 MJ per 20 million lumens per hour. This corresponds to approximately a quarter of the energy consumption of an incandescent lamp (15100 MJ per functional unit). The "use phase" contributes the most to the consumption of energy (approx. 90% of total energy consumption over a life cycle), followed by lamp production and finally transportation (less than 1% of the total). It is finally worth remembering that one pivotal issue that can be easily identified in literature is the high uncertainty of manufacturing-related energy consumption data, which range from 0.1% to 27% of the total life cycle [5,7].

3.2 LCA – Results

The first step is to identify which stages of the LCA are ecologically relevant and which are not. For each lamp type, the LCA impacts are calculated separately for the raw materials, the manufacturing, the transport (by sea and by road), the power consumed during the lamp's operating life and finally the end of life. The following series of tables and bar charts (Fig 5) present the LCA results for each lamp type, broken down by these LCA stages. These results clearly show that the factor that dominates the majority of the environmental indicators considered (Table 3) is "energy-in-use" which is depicted in each figure with yellow shading, followed by "raw materials" and "manufacturing". The remaining two LCA steps – disposal and transport – are almost insignificant although the packaged lamps have traveled over 10000 km from factory to home [6].



GWP	Global Warming Potential	kg CO_2-eq	***LU***	Land Use	m^2a
AP	Acidification Potential	kg SO_2-eq	***EDP***	Ecosystem Damage Potential	points
POCP	Photochemical Ozone Creation Potential	kg O_3 formed	***TAETP***	Terrestrial Ecotoxicity Potential	kg 1,4-DCB-eq
ODP	Ozone Depleting Potential	kg CFC11-eq	***ARD***	Abiotic Resource Depletion	kg Sb-eq
HTP	Human Toxicity Potential	kg 1,4-DCB-eq	***NHWL***	Non-Hazardous Waste Landfilled	kg waste
FAETP	Freshwater Aquatic Ecotoxicity Potential	kg 1,4-DCB-eq	***RWL***	Radioactive Waste Landfilled	kg waste
MAETP	Marine Aquatic Ecotoxicity Potential	kg 1,4-DCB-eq	***HWL***	Hazardous Waste Landfilled	kg waste
EP	Eutrophication Potential	kg PO_4-eq			

Table 3: Environmental impacts considered in the LCA with their units of measurement [6].

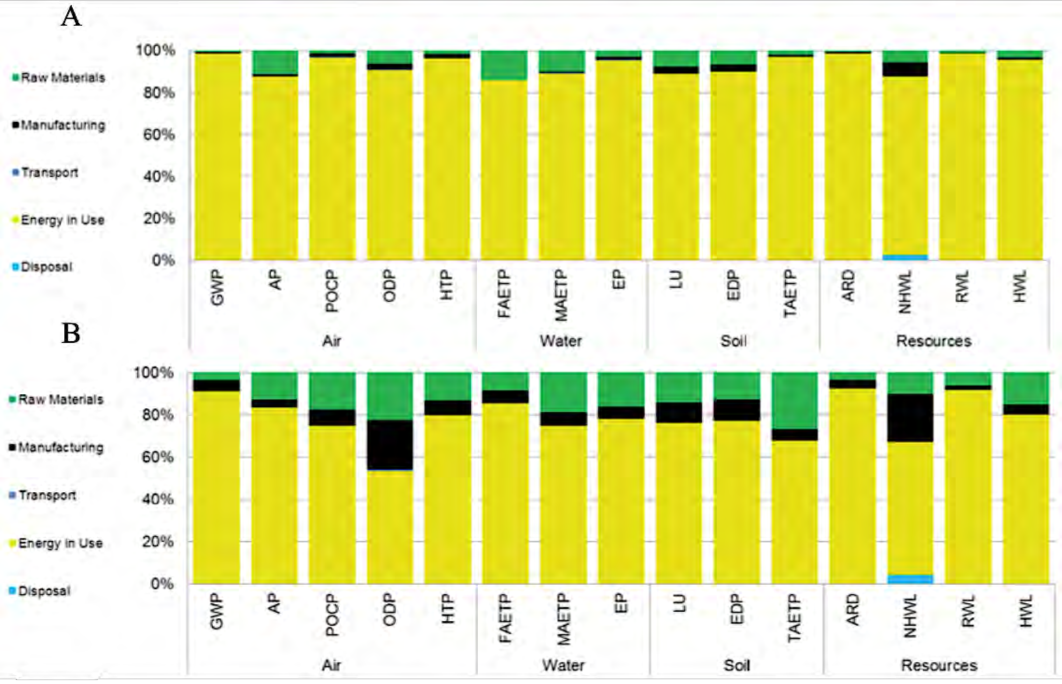


Figure 5: Proportions of the Life Cycle Impact of (A) 60 W incandescent lamp, (B) Compact Fluorescent Lamp, (C) 2012 LED lamp, and (D) 2017 LED lamp [6].

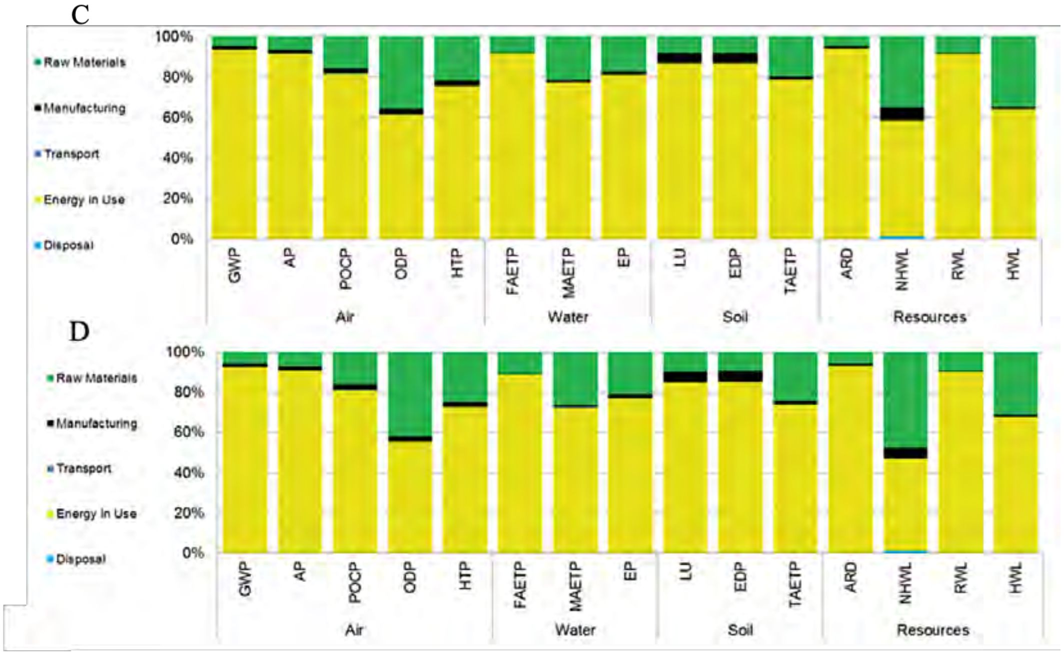


Figure 5: Proportions of the Life Cycle Impact of (A) 60 W incandescent lamp, (B) Compact Fluorescent Lamp, (C) 2012 LED lamp, and (D) 2017 LED lamp [6](*cont.*).

3.3 LCA – Environmental impact

To simplify the interpretation of the results for the four lamps and the 15 environmental indicators (Table 3), the results are also displayed in the form of two "spider graphs" (Fig.6-7). The 15 impacts are also here divided into four categories: soil (green), resources (yellow), air (orange) and water (blue). The radial lines in the diagram identify the different environmental indicators, and, for each of these, the technology with the greatest impact value is put to the outer circle while the remaining ones are then normalized respect to that value. In other words, those lamps with many impacts plotted close to the spider-graph center are the best environmental-friendly performers [6]. Fig. 6 clearly shows that, of all the sources considered, it is the incandescent lamp that has the greatest impact per lighting unit; this result is intuitive since it has the lowest efficiency (i.e. the highest energy consumption per lighting unit) among the four lamps. The next worst performer is the CFL ("hazardous waste landfill" indicator excluded), followed by the 2012 LED lamp and finally by the 2017 LEDs. It has been demonstrated that 2012 LEDs showed a slightly higher "hazardous waste landfill" indicator (0.4 grams) than that of CFLs because of one of their components - the aluminum heat sink - which counts for the 20% of this indicator. From a quantitative point of view, the impact of 2017 LED lamps is considerably lower than that of incandescent lamps, about 70% lower than that of compact fluorescent bulbs and about 50% lower than that of LEDs in 2012. Fig. 7 presents the same results of Fig. 6, but the graph has been adjusted to remove the incandescent lamp and provide the impacts relative mainly to the CFL. Therefore, out of these graphs, it can be noticed the remarkable reduction (up from 3 to 10 times) in environmental impacts that would result from replacing incandescent lamps and CFL with the new generation LEDs [7].

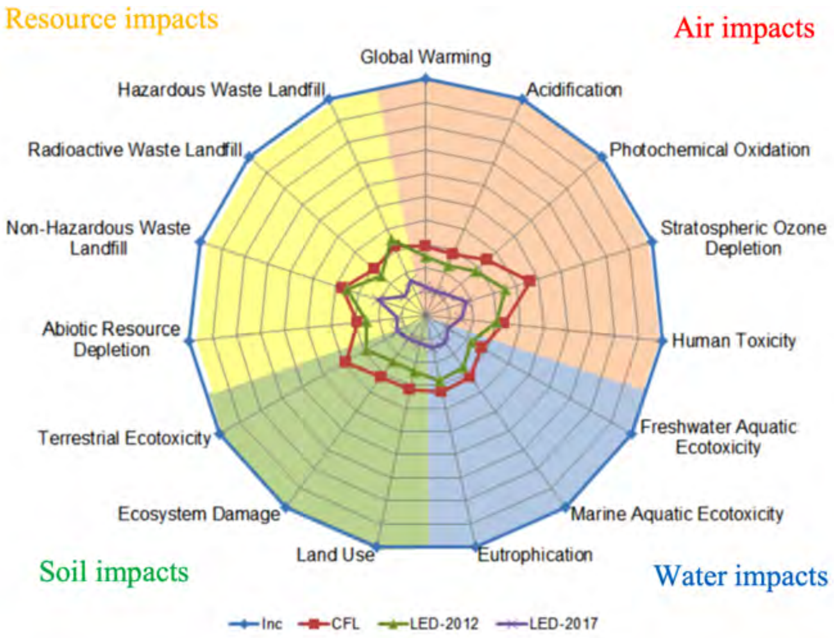


Figure 6: Life-Cycle Assessment Impacts of the lamps analysed relative to incandescent lamps [6].

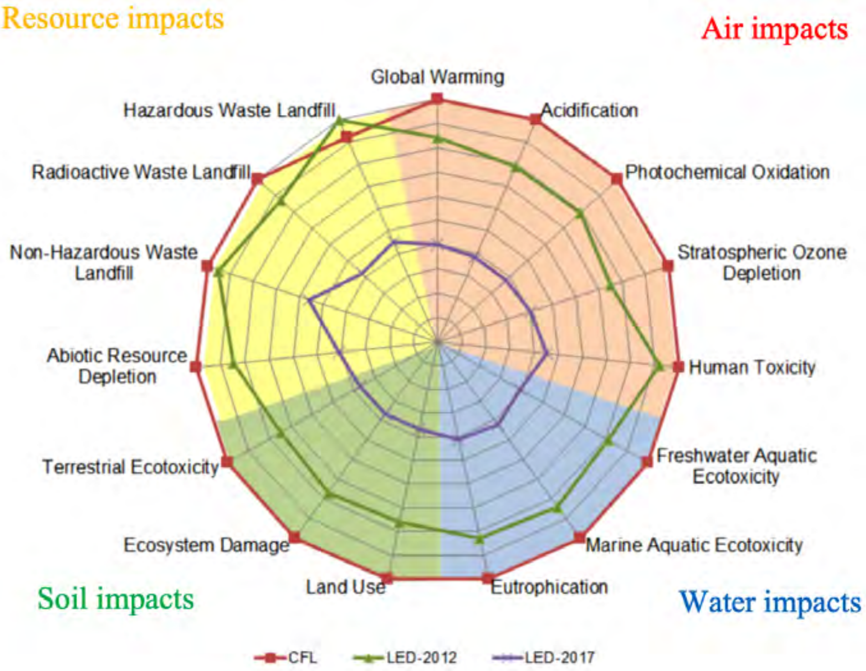


Figure 7: Life-Cycle Assessment Impacts of the lamps analysed relative mainly to CFLs [6].

Finally, it can be concluded that LEDs are the best technology on the market both concerning the performances and the sustainability of their life cycle. This is the reason why, following the Sustainable Development Scenario (SDS), LEDs will occupy up to the 80% of the market share of lighting equipment by 2030 (Fig. 8).

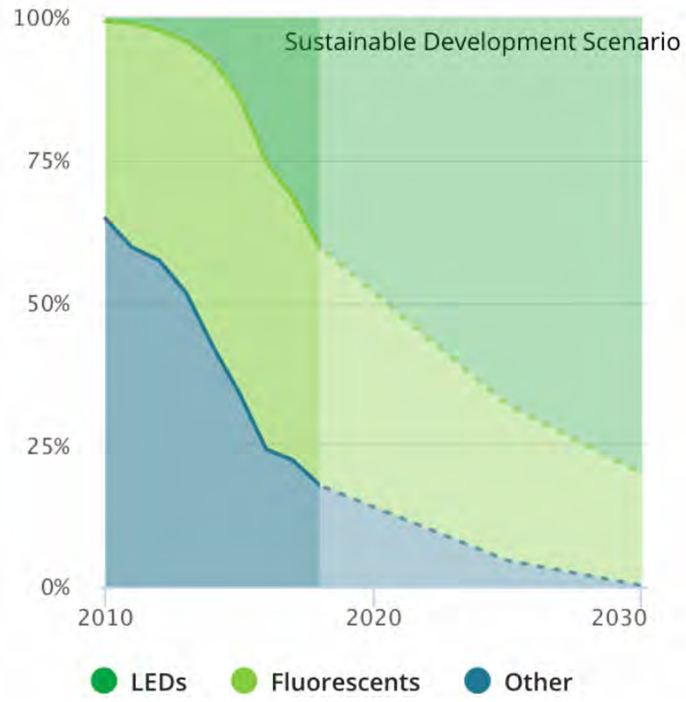


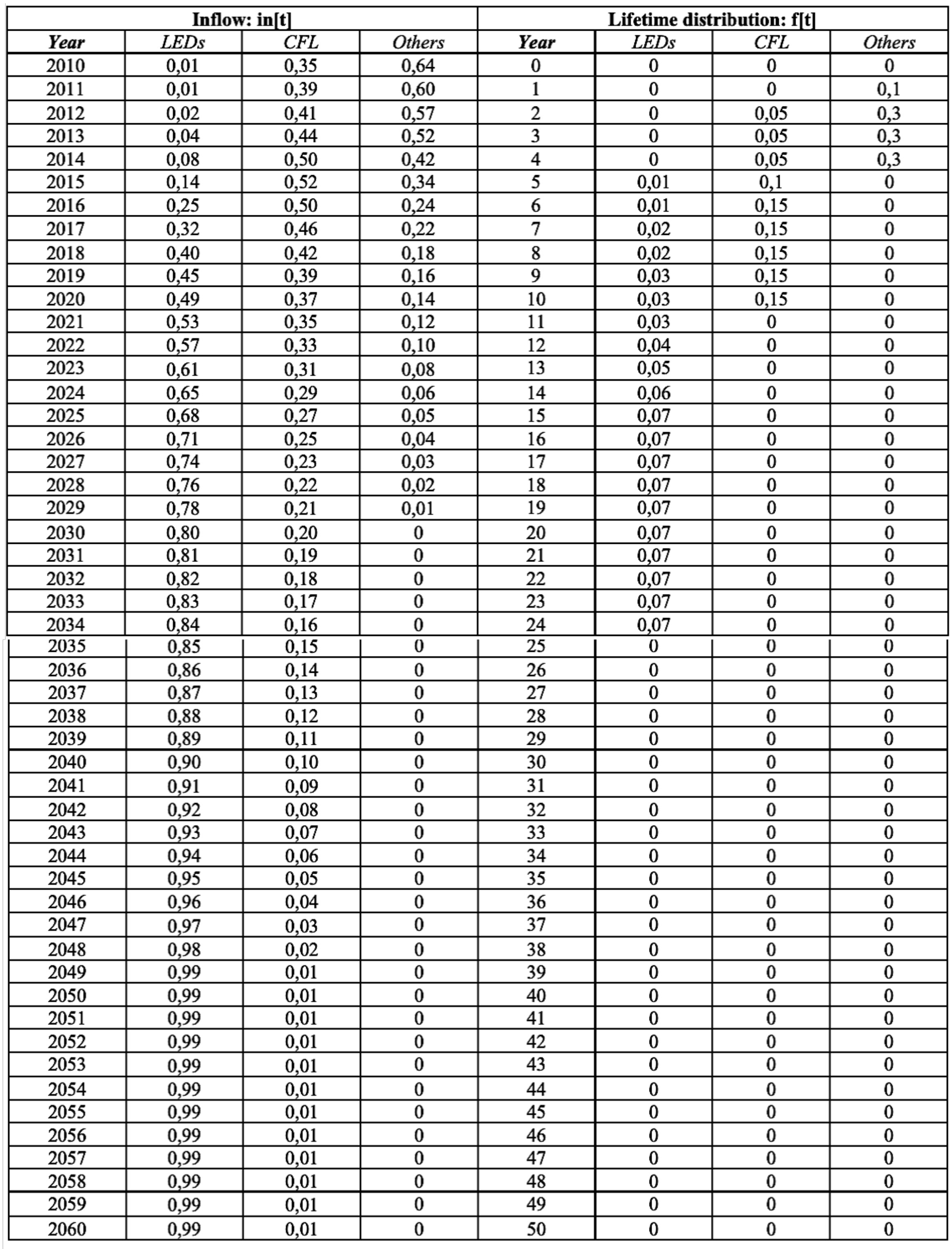
Figure 8: Lighting sales by type according to Sustainable Development Scenario [3].

4 Material flow analysis

According to the graph in Fig. 8, a simplified material flow analysis (MFA) was carried out to understand what kind of output the recycling system of lighting equipment will face in the next years.

The assumptions made are the following:

- the period under observation is from 2010 to 2060;
- the market stock in 2010 was considered equal to zero. This assumption introduces an error only in the first years, but not from the 2019 onwards;
- the value of output is normalized respect to the total amount of lighting system introduced every year in the market, that was assumed constant over all the period;
- as a simplification, only three different categories of lighting equipment were considered: LEDs, CFL and “other technologies”;
- it was considered the model according to which the outflow is the inflow delayed and dispersed by a lifetime distribution function F(t);
- most of the data concerning the input were taken according to the graph in Fig. 8, while the others that are not displayed were assumed;
- regarding the lifetime, it was considered of 15-24 years for LEDs, 6-10 for CFL and 2-4 for “other technologies”. Therefore, the failure probability was assumed higher in those years, but with a smaller percentage of failure also in the years before (Table 4).



Inflow: in[t]				**Lifetime distribution: f[t]**			
Year	*LEDs*	*CFL*	*Others*	***Year***	*LEDs*	*CFL*	*Others*
2010	0,01	0,35	0,64	0	0	0	0
2011	0,01	0,39	0,60	1	0	0	0,1
2012	0,02	0,41	0,57	2	0	0,05	0,3
2013	0,04	0,44	0,52	3	0	0,05	0,3
2014	0,08	0,50	0,42	4	0	0,05	0,3
2015	0,14	0,52	0,34	5	0,01	0,1	0
2016	0,25	0,50	0,24	6	0,01	0,15	0
2017	0,32	0,46	0,22	7	0,02	0,15	0
2018	0,40	0,42	0,18	8	0,02	0,15	0
2019	0,45	0,39	0,16	9	0,03	0,15	0
2020	0,49	0,37	0,14	10	0,03	0,15	0
2021	0,53	0,35	0,12	11	0,03	0	0
2022	0,57	0,33	0,10	12	0,04	0	0
2023	0,61	0,31	0,08	13	0,05	0	0
2024	0,65	0,29	0,06	14	0,06	0	0
2025	0,68	0,27	0,05	15	0,07	0	0
2026	0,71	0,25	0,04	16	0,07	0	0
2027	0,74	0,23	0,03	17	0,07	0	0
2028	0,76	0,22	0,02	18	0,07	0	0
2029	0,78	0,21	0,01	19	0,07	0	0
2030	0,80	0,20	0	20	0,07	0	0
2031	0,81	0,19	0	21	0,07	0	0
2032	0,82	0,18	0	22	0,07	0	0
2033	0,83	0,17	0	23	0,07	0	0
2034	0,84	0,16	0	24	0,07	0	0
2035	0,85	0,15	0	25	0	0	0
2036	0,86	0,14	0	26	0	0	0
2037	0,87	0,13	0	27	0	0	0
2038	0,88	0,12	0	28	0	0	0
2039	0,89	0,11	0	29	0	0	0
2040	0,90	0,10	0	30	0	0	0
2041	0,91	0,09	0	31	0	0	0
2042	0,92	0,08	0	32	0	0	0
2043	0,93	0,07	0	33	0	0	0
2044	0,94	0,06	0	34	0	0	0
2045	0,95	0,05	0	35	0	0	0
2046	0,96	0,04	0	36	0	0	0
2047	0,97	0,03	0	37	0	0	0
2048	0,98	0,02	0	38	0	0	0
2049	0,99	0,01	0	39	0	0	0
2050	0,99	0,01	0	40	0	0	0
2051	0,99	0,01	0	41	0	0	0
2052	0,99	0,01	0	42	0	0	0
2053	0,99	0,01	0	43	0	0	0
2054	0,99	0,01	0	44	0	0	0
2055	0,99	0,01	0	45	0	0	0
2056	0,99	0,01	0	46	0	0	0
2057	0,99	0,01	0	47	0	0	0
2058	0,99	0,01	0	48	0	0	0
2059	0,99	0,01	0	49	0	0	0
2060	0,99	0,01	0	50	0	0	0

Table 4: Inflow and lifetime distribution used for plotting the graph in Fig.9.

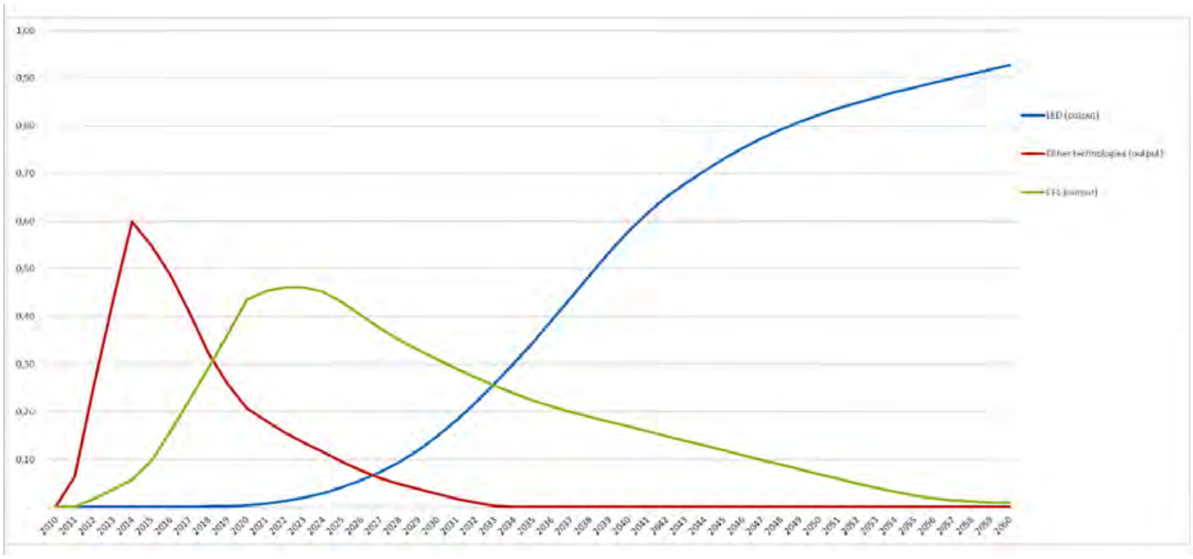


Figure 9: Material flow analysis.

From the graph it is possible to see the output trends for the different lighting sources. In the next 10 years the recycling system will mainly deal with fluorescent lamps (green line) and with the last amount of other technologies (red line). On the other hand, from 2025 onwards, the output of LEDs (blue line) will increase significantly and it will continue growing, first reaching the CFL output in approximately 2033, and then becoming almost the only one to take into account. For this reason, the importance to have a good recycling for LEDs is clear, since they will be, undoubtedly, the major technology employed in the following years.

5 Current recycling system and possible improvements

For the moment, the main unsolved challenge for LEDs and CFL recycling are rare earth elements, which are the materials thanks to which they can emit light. Recycling rare earth materials is not easy as glass or plastic, both because they are present in small amounts and because to separate these materials is often necessary to use aggressive solvents or very high temperatures during the process. Indeed, because of the nasty materials and large amount of energy needed, in some cases recycling would create greater environmental harm than mining them. When small amounts of rare earth are part of complex mixtures, separation can be too expansive to justify it for these elements [8].

However, in addition to the technical challenges of recycling rare earths elements, another issue is caused by the little incentives given to try to get these materials back. In fact, their price has remained almost constant over the last years and there are no laws that subsidy their recycle. For this reason, as of 2011, less than 1% of rare earths elements was recovered [8].

The existing recycling infrastructure for fluorescent bulbs makes them good candidates for rare earth recycling. Even if LEDs are getting popularity, there are plenty of fluorescent and compact fluorescent bulbs that will be disposed in next years and they remain the main target for short-term recycling. Fluorescent light bulbs, in fact, make use of a large quantity of rare earth elements to fill out the color spectrum: the red and green phosphors in the powder that lines the inside of the lights are the rare earth elements europium (Eu) and terbium (Tb). Recyclers collect the mercury, the glass and the metal parts of the bulbs, but they have traditionally dumped the rare-earth-containing white powder that lines the tubes. Some companies are now starting to recover it, but much effort should be put on that in order to have an efficient recycling system for rare earth elements. Also LEDs contain REE used as phosphors in them, but their smaller amount compared to CFL makes a possible economical recycle even more difficult [8].

In Switzerland, an example of company that recycles lighting equipment is SOVAG-VEOLIA which uses the so-called BLUBOX technology. Thanks to this technology, 95% of the supplied material is returned either as recycling metal and recycling glass back into the recycle cycle or, in case of plastics, it is used in the thermal utilization of fuel.

The BLUBOX enables to process of almost all kind of lamps (CFLs, LEDs, halogen, incandescent) in one machine. Concerning fluorescent tubes, that usually must be treated differently due to the amount of toxic mercury contained, they are broken down, crushed in smaller particles and the powder containing mercury is captured by the exhaust gas system and collected separately. The whole system is built-in a 40ft HC container, which is constantly working under negative pressure to ensure a clean environment and output products are free from mercury and can be sold on the market. The recycling capacity of lamps is up to 500 kg/h, which results in 1000 tonnes a year based on an 8-hour working shift. BLUBOX system is efficient, fast, and it reduces to minimum manual operations, but, unfortunately, it can only divide materials as metals, glass or plastics without separating completely rare earth elements that are collected in a powder that is sold as well because it contains almost 15% of these species. All the output powder with Hg inside goes lost and, for this reason, the first possible improvement that could be done to this process is to enhance the removal of mercury from the powder, in order to sell a higher percentage of products and result in an increased revenue for the recyclers [9,10]. The separation of mercury from the powdered mixture of elements can be done using iron nanoparticles. However, often mercury remains trapped in the white powder coating in the bulb's glass tubing and, in this case, it would be required additional heat to extract Hg and the operating costs for the recyclers might increase considerably [11].

Figure 10: Process flow of lamp recycling by BLUBOX [10].

Concerning REE, if losing them is such a concern, one solution could be to use phosphors that are free of these elements. Nitrides, such as BCNO materials, have recently emerged as promising environmentally friendly phosphor candidates that are REE free. They are environmentally friendly, but still more expensive than the phosphors containing rare earth elements and their quantum efficiency is slightly lower. For these reasons, further studies and improvements must be done in order to consider them as a valid alternative for the market of lighting equipment [12,13].

If the composition is kept the conventional one, an entirely different recycling approach is necessary to efficiently separate and recycle all the components of a LED or CFL lamp. In fact, if the entire device is shredded, it becomes much more difficult to divide the materials. A process called "electrohydraulic comminution" could be used to break the lamps into their different parts without destroying them. It consists in using shock waves created by electrical impulses in a water bath to separate the components at their predetermined break points. The only question mark is whether this process can be repeated until the desired materials have been separated. For this reason, maybe also a design innovation and a better predisposition of the devices to recycle can help to pursuit the goal [14].

However, all these methods are still at the research stage and their applicability on an industrial level is difficult because they remain quite expansive and they are not worthwhile for the energy effort. Therefore, first more incentives should be given to companies to improve the separate collection of REE in lighting equipment and the development of a more efficient recycling system in terms of energy consumption, and second laws and regulations should be adjusted and updated for the newest technologies such as LEDs. In Switzerland, in fact, the disposal of all kinds of illuminants is part of the 1998 decree VREG (*Verordnung über die Rückgabe, die Rücknahme und die Entsorgung elektrischer und elektronischer Geräte*), whose purpose is to prevent electric and electronic devices to get into normal waste or the environment and to ensure that they are disposed in an environmental-friendly way and according to the technical state of the art. This decree works quite well according to the take-back number of illuminants, but it does not include for the moment LEDs, and this is a serious lack especially since these devices are predicted to be the dominant technology in the close future and for many years to come [15].

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