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1 **Estimating the benefits of increasing the recycling rate of lamps from the** 2 **domestic sector: Methodology, opportunities and case study**

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10 **Abstract**

11 The scope of this paper is to identify the benefits of lamp recycling from the domestic sector.
12 Data related to the recycled lamps was obtained from two recycling companies and were
13 compared to those related to the waste lamps from the domestic sector. This was achieved by
14 a new methodology which uses two alternative approaches. The first one is dependent on
15 previous research data in relation to the number of active lamps while the second one
16 elaborates on electricity consumption and sales data, in order to define the corresponding
17 number of active lamps., The wasted amount of glass, metal and plastic is calculated along
18 with the energy savings, the annual emissions of CO₂-eq, the economic benefit from their sale
19 and the potential reduction of hazardous waste, such as mercury to solid waste landfills under
20 various scenarios. The amount of recovered materials collected by the Hellenic recycling
21 companies contributes to a reduction of CO₂-eq by 1,298tonnes, which falls significantly
22 short of the CO₂-eq that could have been saved 3,108-5,463tonnes if all the lamps were
23 recycled. Furthermore, the recycling companies have an annual economic benefit of €32,251
24 which could be increased by €122,725 if all lamps were recycled together with the proper
25 recycling of 3.4kg of mercury, which was disposed in the environment. Finally, a future

scenario was examined, in which all lamps in the domestic sector were assumed to be LEDs, an issue that can affect the viability of the recycling factories and it was proved that these might be affected.

Keywords: Domestic sector waste; LED; Lighting; Lamps; Lamp recycling; Mercury reduction

1. Introduction

Worldwide, electricity consumption for lighting represents about 17% to 20% of the total electricity production (Zissis, 2016; Welz et al., 2010). In Greece, the share of lighting electricity over total electricity is 21%. In addition to the effort to reduce lighting consumption by using daylight (Mavridou and Doulos, 2019), there is also a concerted effort to increase the use of renewable energy sources (Arabatzis G. et al, 2017; Kyriakopoulos G.L. et al, 2018; Ntanos S. et al, 2018) and design new policies for electricity generation (Kyriakopoulos G.L. and G. Arabatzis, 2016). Due to the rapid evolution of higher efficacy light sources such as Compact Fluorescent Lamps (CFL) and Light-Emitting Diodes (LED) (European Union, 2019; Mc Kinsey and Company, 2019), a reduction of electricity consumption in the domestic sector has been observed (Mills and Schleich, 2014; Tähkämö et al., 2014), representing 6% to 8% of the total electric energy consumption (EURECO, 2019; EL. STAT 2012, 2019). The worldwide market penetration of LED lamps grew from non-existent in 2001 to 9% in 2011 in the European Union (E.U) and in the near future (2020) it is estimated this can be increased to over 70%. However, the research interest for their recycling is small (Mizanur Rahman et al 2017; Kumar A, et al 2019; Richter J.L. et al, 2019). LED lamps have radically changed the lighting industry due to, their high luminous efficiency (Madias et al, 2019) and long lifespan. Due to these advantages, it is expected that millions of domestic fluorescent luminaires (Leopoldino C.C.L., et al 2019) will be replaced

by LED lamps and eventually will become waste. Consequently, decision makers (Manolis et al, 2019) should take into consideration circular economy aspects, like the possibility of future retrofit solutions (Doulos et al, 2019a, 2019b, 2019c) and of course recycling. Recycling could be an alternative source of raw materials that can be recovered and reused (Gaitanelis et al., 2018; Beu et al., 2018; Novais et al., 2016; Tunsu et al., 2014, Yufeng et al., 2014). Sheng Fang et al (Fang et al., 2018) showed that significant quantities of metal can be recovered from LED lamps that are at the end of their life. This is evident by the fact that the rapid rise in the use of LED lamps has increased the global demand for Rare Earth Elements (REEs) at a rate of 3.7–8.6% annually (Tan et al., 2014).

Recycling is a significant part of Life Cycle Analysis (LCA), where the environmental, economic and social impacts of a lamp's life cycle are estimated. The environmental impacts, especially during their production stage, are difficult to be estimated accurately (Berkeley University, 2019) since this stage involves raw material acquisition and manufacturing, processes that are different for each manufacturer. Only a few manufactures reveal the materials used together with the production methods (OSRAM Berlin Germany, 2019). In contrast to the incandescent lamp, which had a standard production procedure, LED lamp manufacturers use materials with a composition that is not exactly known in every case and this affects the accurate estimation of the environmental impact during an LCA analysis (Zissis, 2016; Tähkämö, 2013). Indeed, there is a lack of information in the public domain about the extent to which materials used in the manufacturing of LEDs are either reused or acquired from recycling (Scholand and Dillon, 2012; Tuenge et al, 2013). Its therefore evident that all data concerning these materials can be retrieved more easily during recycling than during manufacturing (Tahkamo 2013; Dzombak et al, 2017, 2019). In many cases, in addition to materials, the energy needed for recycling has to be calculated. This information usually comes from literature (Dillon et al, 2019; Scholand and Dillon, 2012).

75 The total life cycle of a lamp involves various stages including raw material acquisition,
76 manufacturing, packaging and distribution, use and end of life. The stages involving the raw
77 materials acquisition, manufacturing, transport and end of life represent less than 30% of the
78 total environmental impact of the lamp during its life (Tähkämö, 2013). CFL and LED lamps
79 during the production can pollute the environment with toxic materials (Rhee et al., 2014;
80 Jang et al., 2005), which are associated with the ballasts from CFLs and LEDs drivers
81 (Tähkämö et al., 2012, 2013; Tähkämö and Dillon, 2014;). At the end of the life of a lamp,
82 which is the last stage of the LCA, the lamp must be recycled and not disposed to a solid
83 waste landfill. With the recycling process, materials such as Rare Earth Elements (REEs) can
84 be recovered and reused at the production stage of LED lamps. The REEs are obtained from
85 fluorescent lamps (Hasegawa et al., 2018; Innocenzi et al., 2013) with two methods, by
86 taking advantage of the differences in resistance of the different lamp phosphors to chemical
87 attacks by inorganic acids / bases (Anibal et al., 2013; Binnemans and Jones, 2013) or by
88 using a new hydrometallurgical route from the green phosphor (Tan et al., 2014; Machacek et
89 al., 2015; Loy et al., 2017). Similarly, glass and metal from the incandescent lamps, can be
90 recovered, while from fluorescent lamps aluminum and REEs are recoverable (Tähkämö,
91 2013; Rhee, 2017; Zimmermann et al., 2014). It is estimated that fluorescent lamps will still
92 be available for the next 20-30 years for recycling and thus the recovery of REEs will be
93 possible (Machacek et al., 2015). Another important issue of the recycling process of CFLs is
94 mercury, which is toxic for the environment and humans, and must be collected with
95 specialized techniques (Zimmermann et al., 2014, Lecler et al., 2018, Mukherjee et al., 2004).
96 Case studies in Japan and China (Asari, 2008; Hobohm, 2016; Zhang, 2016; Xi et al 2016)
97 have demonstrated that every year tons of mercury can be potentially released in the
98 environment if fluorescent lamps at the end of their life are not recycled properly. Tahkamo
99 (2013) analyzed the types of materials and their amount that can be retrieved from various

types of lamps. Gu et al (2018) in a case study in China presented the recycling potential of lamp waste together with the crucial factors that affect recycling promotion.

The scope of this paper is to calculate the number of waste lamps from the domestic sector in Greece, their environmental impact and the lost benefit from the non-recycled lamps. The main problem in the domestic sector is that not every lamp installed in household is used, thus a new methodology was introduced capable to calculate the number of both active and waste lamps. The number of the active lamps was calculated using the electric consumption for lighting. The results were compared with the retrieved material data collected from the two lamp recycling factories in Greece. The number of lamps that were not recycled and were disposed to the environment was estimated and the corresponding benefits from the potential sale of the waste materials, the reduction of the consumed energy and CO₂ emissions were calculated. Furthermore, a future scenario of using only LED lamps in the domestic sector in Greece was examined, as their usage time is higher than any other lamp technology. The viability of the two Hellenic recycling factories was examined using this future scenario.

2. Materials and Methods

2.1 Overview

In order to calculate the missing benefit from the lamps that are not recycled in Greece, not only is the actual number of recycled lamps needed, but also the number of waste (burn-out) lamps. Their difference consists the missing benefit for the country. The overall methodology and the corresponding data needed in order to calculate the potential benefit for the Hellenic domestic sector is presented in Fig. 1a. The number of waste (burn-out) lamps for each year can be estimated using the number of the corresponding active lamps and their useful life time, which of course depends on their technology (CFL, LED). As the number of the active lamps in the Hellenic households is not officially known, data from various sources

(REMODECE, 2008; EL. STAT 2011, 2012, 2016; Eurostat Energy balance sheets, 2006, 2012, 2016) were used and combined for 2016 (Supplementary material, Table S.1) which was considered as a reference year (using the latest Eurostat's data concerning Hellenic households). The number of the active lamps is not always known, because it is different from the number of installed lamps. As not all installed lamps are in simultaneous use in households the estimation of the active lamps is vague.

Fig. 1. Methodology used for the estimation of waste (burnt-out) lamps' materials that can be retrieved in

domestic sector in Greece (a) and diagram of the methodology used for the calculation of the active lamps used in domestic sector in Greece (b). Orange color is used for the part of the methodology which is based on data collection, green for the calculation part and blue color for the corresponding results

Because all the necessary data were incomplete, two sub-methods (A and B), which can be considered as alternative approaches, were used for the calculation of the active lamps (Fig. 1b). At this point, it has to be mentioned that Method A estimates the number for active

lamps from the REMODECE (2008) research project, while Method B, calculates the active lamps by using the energy consumption for lighting per household (REMODECE, 2008; EL. STAT 2012,) together with the corresponding number of households. Both sub-methods use lamp sales data from Greece, in order to define the type of lamps (incandescent, CFL or LED) installed in Hellenic households from 2005 to 2016. Furthermore, two scenarios with different power per lamp were examined. A range of values for the active lamps were calculated (year 2016) and thus the waste lamps were estimated. The corresponding average values of the two sub-methods were compared with the data of the recycling factories and in this way the number of lamps that were not recycled was defined.

2.2 Collected data

2.2.1 Materials recovered from recycling in the Hellenic domestic sector

Information concerning the quantity of materials recovered from the recycled lamps (Supplementary material, Table S.2) were collected from two government-certified lamp recycling companies: a) Oiko-Kiklios S.A (Oiko-Kyklios S.A, 2019) (Recovered Materials, Glass: 154 tonnes, Metal: 28.2 tonnes and Plastic: 37 tonnes) and b) Appliance Recycling S.A (Appliance Recycling S.A, 2019), (European Commission 2012, 2019) (Recovered Materials, Glass: 152.6 tonnes, Metal: 21.7 tonnes and Plastic: 9 tonnes). Both companies collect different types of lamps and through the recycling process recover materials such as glass, metal and plastics. In 2012, Oiko-kyklios S.A had distributed over 4,000 collection boxes for lamps while Appliance Recycling S.A had placed 2,788 collection boxes (Zarzulas and Apostolidis, 2019) all over Greece.

2.2.2 Sales data of lamps for the domestic sector

Lamp sales data was collected from three companies (KAFKAS S.A., 2019; LEDVANCE A.E., 2019; Super market chain, 2019). with more than 50% of selling share at a national

level. The absolute number of lamps sold, was not provided due to commercial restriction policies of each company. Instead the market share of different lamp technologies used in domestic sector was used. The dynamic entrance of LED lamps in the Hellenic domestic sector was recorded in 2016 (the average value of market share for LED lamps from all three manufacturers was 35%, Fig. 2). Furthermore, REMODECE (2008) conducted a survey using 500 questionnaires, recording the lamp type and the average annual usage time of lighting in Hellenic domestic sector for 2006. The project results show that 73% of the total number of lamps were either incandescent or halogen and 27% CFLs. The results were in accordance with the market share of that year (2006).

Fig. 2. Market share of different lamp technology used in domestic sector. Incandescent-Halogen: Blue color, CFL: Green color and LED lamps: Orange color. Dash line: Osram S.A., Round dot line: Kafkas S.A., Solid line: Private label. Other types of lamps are not included.

2.2.3 Energy consumption data and households in use

The total electricity consumption in the Hellenic domestic sector was obtained from Eurostat (Eurostat Energy balance sheets, 2006, 2012, 2016). The number of households in use, for

years 2006 and 2012, were collected from the Hellenic Statistical Authority (EL. STAT 2006, 2012). The number of households for 2016 was calculated using data concerning new building permits (EL. STAT 2016) from 2013 to 2016. The corresponding yearly electricity consumption per household in Greece is presented in Table 1. REMODECE results showed that the peak lighting load in the Hellenic domestic sector occurred between 20:00 and 22:00 LST.

Table 1. Yearly electricity consumption per household, total number of households in use in Greece corresponding average electric energy consumption of active lamps and calculation of the average power of active lamps per household and corresponding share of various light source technology using the sale data (Fig.

2)

Parameter	Year		
	2006	2012	2016
Electricity consumption in the domestic sector (GWh)	17,956	18,468	19,991
Households in use in Greece (Houses)	3,926,000	4,134,000	4,204,000
Electricity consumption per household (kWh)	4,570	4,463	4,755
Percentage of energy consumed for lighting (%)	8	6.40	5.40
Average Electric energy consumption of active lamps per household (kWh/year)	366	286	257
Average Power of active lamps per household in use (W)	223	174	156
Incandescent (%)	70	65	45
CFL (%)	30	25	18
LED (%)	0	10	37

3. Calculations

3.1 Power used for lighting per household

EURECO project (2002) used data from 88 households and concluded that there were 7 active lamps per household. REMODECO project (2008) results showed that, while there were 27 installed lamps per household, only 10 were taken into account as active lamps.

Using the value of 1642.5 hours (CRES, 2019) as a reference value of the annual operating hours of lamps in the Hellenic domestic sector and 10 active lamps per household, the corresponding average power values for lighting were calculated (Table 1).

3.2 Number of waste (burnt-out) lamps

The waste (burnt-out) lamps for both methods A and B were calculated using Eq. 1.

$$ANW = AL * RAW \quad \text{Eq.1}$$

Where: ANW is the annual number of waste (burnt-out) lamps, AL (Active lamps) is the average number of the lamps that are in use in a household during a year (which is always smaller than the number of the installed lamps) and RAW (Ratio of annual waste lamps) is the ratio of the useful lifetime of each lamp type to its annual operation time.

Since the number of the active lamps is different than the number of the installed lamps, methods A and B use different approaches for their necessary calculations. Method A, uses as input 10 active lamps per household (REMODECE, 2008) while Method B uses a parametric analysis in order to calculate the corresponding number.

3.2.1 Ratio of annual waste (burnt-out) lamps

The ratio of waste (burnt-out) lamps in a year per household per lamp type was calculated (Supplementary material, Table S.3) by dividing the useful lifetime of each lamp type (European Commission, 2012, KAFKAS S.A., 2019; LEDVANCE A.E., 2019; Super market chain, 2019) with its annual operation time (CRES, 2019). The useful lifetime was used in an effort for the results to be comparable among various lamp technologies. While the useful time of the incandescent and fluorescent lamps was defined as 70% of their half-life time (half-life time is defined when 50% of the lamps from the examined sample have been burnt-out, IEC 60357, 2002; IEC 60969, 2016), the useful life for LEDs was defined as the time at

which the luminous flux of the lamp reaches 70% (L70) of its initial value (IES TM-21-11, 2011; European Commission, 2012; ANSI/IES LM-80-15, 2015; ISO/CIE TS 22012, 2019). In general, the useful life of LED lamps can have larger variations than the useful life of the other type of lamps. In the current study, the useful life time of lamp was taken from the lamp manufacturers' data. When examining a different case study, this should be taken into account.

3.2.2 Method A

Since method A uses a fixed number of active lamps (10), the calculation of the share of each lamp technology was derived from the sales data as these are presented in Fig.2 and Table 1. Using this information three scenarios with different lamp type percentages were considered: Scenario A: 7 incandescent lamps and 3 CFL lamps per household (for year 2006), Scenario B: 6.5 incandescent lamps, 2.5 CFL and 1 LED lamp per household (for year 2012), Scenario C: 4.5 incandescent lamps, 1.8 CFL and 3.7 LED lamps per household (for year 2016).

Using the aforementioned data in Equation (1), the total number of active lamps per type was calculated (Table 2) for scenarios A to C.

3.2.3 Method B

In Method B, a parametric analysis was applied in order to estimate the number of active lamps per household in use. The parameters used for this analysis were the following: a) Two groups of lamps (Group A and B) with different power (CRES, 2019) for each lamp type (Group A: Incandescent 40W, CFL 16W, LED 7W; Group B: Incandescent 60W, CFL 24W, LED 11W), b) two scenarios (I and II) with different amount of lighting electricity consumption share over total household electricity use, Scenario I: 6.4% (EL. STAT 2012) and Scenario II: 8% (REMODECE, 2008) and c) average power of active lamps and share of light source technology (Table 1).

Equations 2-6 were used to calculate the annual waste (burnt-out) lamps per technology type.

$$x * X + y * Y + z * Z = W \quad \text{Eq. 2}$$

Where: x, y, z are the typical power of incandescent (Group A or B), CFL (Group A or B) and LED lamps (Group A or B) correspondingly while X, Y, Z the number of active incandescent, CFL and LED lamps. W is the total power of active lamps per year.

$$R_{RL} = H_h / H_L \quad \text{Eq. 3}$$

Where: R_{RL} is the ratio of the useful time of the lamp to its annual operation time for each lamp technology type, H_h is the annual operation time (1642.5h (CRES, 2019)) and H_L is the useful lifetime of each lamp technology type.

$$X_R = X * R_{RLX} \quad \text{Eq. 4}$$

$$Y_R = Y * R_{RLY} \quad \text{Eq. 5}$$

$$Z_R = Z * R_{RLZ} \quad \text{Eq. 6}$$

Where: X_R , Y_R , Z_R are the annual number of waste (burnt-out) lamps for each technology type (Incandescent, CFL and LED).

The results of the calculation of X, Y, and Z are presented in Table 2, which shows the range of the waste (burnt-out) lamps among Scenario I and II for each lamp technology.

Table 2. Total number of active and waste lamps in the domestic sector in Greece, Method A and B.

Year	Number of Incandescent (Millions)		Number of compact fluorescent (Millions)		Number of LED (Millions)		Total number of lamps (Millions)	
	Active	Waste*	Active	Waste*	Active	Waste*	Active	Waste*
Method A								
2006	27.5	64.6	11.8	4.6	-	-	39.3	69.2
2012	26.9	63.2	10.4	4	4.1	0.45	41.4	67.7
2016	19	44.6	7.5	0.4	15.5	2	42	47

Method B, Scenario I – Group A								
2006	14.5	34.2	6.7	2.7	-	-	21.2	36.9
2012	15.3	36.0	5.8	2.1	2.1	0.2	23.2	38.3
2016	13.2	31.1	5.0	2.1	10.9	1.3	29.1	34.5
Method B, Scenario I - Group B								
2006	9.8	20.1	4.1	1.6	-	-	13.9	21.7
2012	10.1	23.6	3.9	1.7	1.4	0.2	15.4	25.4
2016	8.8	20.6	3.4	1.3	7.1	0.8	19.3	22.7
Method B, Scenario II - Group A								
2006	18.3	42.8	7.7	3.1	-	-	26.0	45.9
2012	19.0	44.6	7.4	2.9	2.9	0.3	29.3	47.8
2016	16.4	38.7	6.7	2.5	13.5	1.5	36.6	42.7
Method B, Scenario II- Group B								
2006	12.2	28.7	5.1	2.0	-	-	17.3	30.6
2012	12.7	29.8	5.0	2.1	2.1	0.2	19.8	32.0
2016	11.0	25.6	4.2	1.7	9.2	1.1	24.4	28.4

* Calculation of waste lamps per year per household: Number of Active lamps * Ratio of change of lamps per year. Incandescent: 2.35 lamp changes per year, CFL: 0.39 lamp changes per year, LED: 0.11 lamp changes per year, Ratio of change of lamps per year: Working hours per year / Useful time. Useful time: Incandescent:700h, CFL: 4,200h, LED: 15,000 for L70 (European Commission, 2012, KAFKAS S.A., 2019; LEDVANCE A.E., 2019; Super market chain, 2019), Working hours per year: 1642.5h (CRES, 2019)

3.2.4 Outcome of waste (burnt-out) lamps for both methods

Using method A (fixed number for the active lamps per house) the total number of the waste (burnt-out) lamps was approximately 47 million for 2016 and all lamp types. Using method B, the number of the waste (burnt-out) lamps ranged from 22.7 to 42.7 million lamps for the same year. Figure 3 presents the corresponding results for all lamp types and both methods. The difference in the number of waste lamps between methods A and B, for each lamp type, will be used as a minimum-maximum range for the subsequent calculations.

Fig 3. Minimum and maximum number of the waste (burnt-out) lamps derived using methods A, and B for the year 2016.

4. Results

The weight of lamps varies depending on the manufacturing process. In this study, data from Tahkamo (2013) was used for all lamp types including LEDs (LED A). However, in a more recent study, Dzombak et al (2019) presented a different value for both LED lamp weight and the amount of its recoverable materials. This was used as well (LED B) with all results presented in Table S.4 (Supplementary material). That made possible the calculation of the lamps' recoverable materials for all the examined scenarios. The minimum, average and maximum quantities of glass, plastic and metal that could be recovered through recycling of the waste lamps are presented in Figs. 4a to 4c. These figures include a) all the examined scenarios (Method A and B: Scenarios I and II for Groups A and B) and b) the amount of the recoverable materials per lamp type (Supplementary material, Table S.4). Fig. 4d presents the minimum, average and maximum values of possible recoverable materials from the waste

(burnt-out) lamps (all types), along with the actual recycled materials from recycling companies, while Table S.5 (Supplementary material) shows analytically the possible recoverable materials for each examined case and scenario.

(d)

Fig. 4. Estimated weight of lamp recoverable materials per year from waste (burnt-out) incandescent lamps (a), fluorescent lamps (b), LED lamps (c) together with actual data from recycling companies in Greece (d).

5. Discussion

5.1 Overall benefit

The results from Method B gave smaller quantities of recoverable materials when compared to those from Method A. The variation of the results is due to the different number of active lamps per household that each method uses. Method A, has the limitation of using the number of active lamps, based on REMODECO project data, (10 active lamps per household in use) while method B calculates the number of active lamps using the parametric analysis as described in 3.2.3. Thus, Method B is more accurate, since it takes into account more realistic and a wider set of parameters than Method A. Despite the deviation of the results between the two proposed methodologies, it is evident there is large potential for material recovery from the waste (burnt-out) lamps. Using Method A the amount of waste lamps varies between 47.7 million (2016) to 69.2 million (2006) and are considered as maximum values, while Method B gives values ranging between 21.7 million (2006) (Scenario I, Group B) and 22.7 million (2016) which are considered as minimum values. It is evident that Method B can be adapted from other countries as well, as long as, the appropriate input data exist (Fig. 5a).

Recovered materials from waste lamps can be sold, reducing the operational costs of the recycling process. According to EUROSTAT (2018), glass costs 53.4 €/t, while plastic 345.9 €/t and metal 180.56€/t (Current Scrap Metal Prices, 2019). Therefore, the total potential income has been calculated for the lamps of the domestic sector (Average value: €154,976, Minimum value: €45,416 for Method B, Scenario I, Group B, LED from Dzombak 2019 data, Maximum value €264,535 for Method A LED from Tahkamo 2013), as well as the actual income of the recycling factories (€32,251). As already mentioned, mercury contained in CFL lamps must to be collected properly. Fluorescent lamps contain 1.5 mg of mercury on

average (Asari et al., 2008; Lecler et al. 2018; Zimmermann et al., 2014;). The waste CFL lamps in the Hellenic domestic sector were 2,307,240 resulting in 3.4 kg of mercury that was possibly released in the environment (Hobohm et al., 2016; Zhang et al., 2016) only for 2016.

The retrieved plastic can be used as fuel in industrial processes, such as cement production. A cement kiln uses coal, petcoke or lignite as main fuels. According to Astrup T. et al (Astrup et al 2009) one (1) tonne of plastic may substitute 1230 to 1640 kg of hard coal. Thus, by taking into account the greenhouse emissions for the provision of this coal, this substitution, leads to savings of 871 to 1467 kg CO₂-eq. per tonne of plastic waste. The metal scrap recovered from waste lamps is mostly aluminum. The corresponding annual reduction of CO₂ through the reuse of 1 tonne of aluminum is between 5 to 19.3 tonnes CO₂-eq. (Damgraad et al 2009). Finally, 1 tonne of glass cullet, that can be used as feedstock in glass production, can save between 445 and 506 kg CO₂-eq. (Larsen et al, 2009). The glass-cullet can also be used by concrete manufacturers, reducing the total amount of sand used. The daily production of concrete in Greece requires about 165 tonnes of sand with the retrieved glass-cullet can replace only 10% of this quantity (Gaitanelis et al 2018).

Using the minimum and maximum values of the aforementioned data (range values of CO₂-eq. per tonne for each material) together with the recovered materials, the calculation of CO₂-eq. emissions is straightforward. Fig. 5b presents the reduction of CO₂-eq. emissions in a hypothetical scenario where all materials recovered from the waste lamps are recycled together with the emissions due to material quantities collected by the recycling companies in Greece. This is an indication that the recycling of lamps should be encouraged in other sectors besides domestic, such as the tertiary (offices, public buildings and lighting) in order to fulfill, the need of the country's decarbonization strategy (European Commission, 2018).

Fig. 5 Number of waste lamps as calculated using Methods A and B (a) and annual reduction of CO₂-eq emissions when all waste lamps of the Hellenic domestic sector have been recycled to actual CO₂-eq reduction using the waste lamps ending up to the recycling factories (b)

5.2 Future scenario using only LED lamps in Hellenic households

Since incandescent lamps have already been banned from the market and assuming that in the next 20 years CFL lamps will not be available for selling, the dominant lamp type left will be

LEDs. Due to their large lifespan the number of waste (burnt-out) lamps will be extremely low compared to the current number of waste lamps, questioning the viability of the recycling companies. However, LED lamps have increased weight compared to the other types of lamps and thus more materials can be recovered. The parameters for this future scenario were the same as used in Methods A and Method B, but using only LED lamps in Hellenic households.

LED lamps have more plastic and metal but less glass than the rest types of lamps. The quantity of the materials that can be recovered is presented in Fig. 6a. The income from the recovered materials (glass, plastic and metal) according to EUROSTAT, (2018) and Current Scrap Metal Prices (2019) prices can be €114,612 as an average value (max value €196,279 with LED type A and min value €32,944 with LED type B), a sum quite lower than the income estimated for the current situation. Fig 6b also presents the annual reduction of CO₂-eq in the future scenario. It is evident that the viability of the recycling factories in the future is not financially secured depending on the amount of recoverable materials per LED lamp type, given that the prices of the materials will not be raised substantially in the future. As shown from the input data (Tahkamo 2013; Dzombak et al 2019, Supplementary material, Table S.4) the recoverable materials are decreasing not only because the initial weight of the LED lamps is reduced together with a reduction in the glass used, but also due to the lower weight of the all other recovered materials (Supplementary material, Table S.4).

Fig. 6. Weight of recoverable materials resulting in from the waste LED lamps for the future scenario (a) and annual reduction of CO₂-eq emissions for 2016 and future scenarios (b).

6. Conclusions

Sustainability is dependent on two key factors: the proper management of natural resources and the protection of the environment. Natural resources are finite and for this reason they should be recycled and re-used to the fullest possible extent for future generations. At the design stage of luminaires, the manufacturer should take into consideration circular economy aspects such as repair, reuse, remanufacturing, retrofitting, recycling and upcycling (Beu et

al., 2018) and not only the energy savings due to luminaire operation (Madias et al, 2019; Manolis et al 2019), adopted lighting controls (Adam et al, 2019; Doulos et al 2008, 2014, 2017; Topalis and Doulos, 2017) and the use of daylight systems (Tsangrassoulis et al 2005; Kontadakis et al 2017, 2018). Luminaires, according to the results of a large number of LCA (Leena Tähkämö, 2013; Dillon et al, 2019; Dzombak et al, 2019) analyses have a substantial environmental impact, particularly at the end of their expected life. Therefore, LCA results should be used to make product selection decisions focused on their financial viability together with their environmental impact. The eco design products have approximately 60% less environmental impact than the non-eco design products (Fang et al., 2018; Apisitpuvakul et al., 2008; Casamayor and Su, 2017; Chen et al., 2017). The dynamic entrance of LED lamps in the domestic market, which was noticed during year 2016 in Greece, reflected in lamps sales with LEDs representing 35% of the total lamp sales.

Using a set of data, the total amount of active lamps was calculated for the Hellenic domestic sector. Using the corresponding recycled data from the recycling companies, the number of waste (burnt-out) lamps were calculated and the missing economic income was estimated equal to €122,725 as an average value. It is obvious that the amount of recovered materials collected by the Hellenic recycling companies (1,298 tonnes CO₂-eq) falls significantly short of the quantities that could have been collected if all the lamps were recycled (5,463 tonnes CO₂-eq, as average value, using LED type A and 3,108 tonnes CO₂-eq using using LED type B) and this is considered as a missed opportunity to further reduce emissions by 1,810 to 4,156 tonnes CO₂-eq contributing to the decarbonization strategy of Greece (European Commission, 2018).

The proposed methodology takes into account not only the domestic electrical energy consumption for lighting, but also the number of the households in use, together with sales data from the lamp manufactures in an effort to reliably estimate the number of the active

lamps per household. Using Greece as a case study, these input data were necessary in order to exclude any uncertainty due to the recent economic recession. The number of newly built houses was reduced by 91%, from 71,936 in 2007 to 4,853 in 2016 (Kathimerini, 2019) while the reduction of electrical consumption was 7% between 2007 and 2017 (Capital, 2019) Due to the fact that there is no substantial increase in the overall housing stock the input data can predict reliably the number of waste lamps.

The underlying purpose of this paper was to highlight the problem of the waste (burnt-out) lamps of the Hellenic domestic sector that are not recycled, to sensitize the government and to motivate citizens to recycle. While the benefit of the recycling lamps is evident, the collection of the waste (burnt-out) lamps is not an easy process in Greece requiring the involvement of all citizens. Therefore, a set of actions than can supported by the Greek government are the following:

- Constantly informing citizens about the dangers of non-recycled lamps and the benefits of the environmental protection and the proper management of natural resources. This action should be focused on the educational institutions with the realization of seminars, emphasizing the fact that all lamps should be recycled.
- A discount as a reward when a lamp (especially for the fluorescent lamps that contain mercury) from the domestic sector is recycled in tandem with the purchase of a new LED lamp.

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None

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