1. Introduction

Light emitting diode (LED) has several advantages when compared to conventional lighting technologies, especially in terms of power usage, lifetime, and multi-functionality. Nowadays, white LED bulbs and LED tubes are the main products being used for general lighting. There are reports which indicate that the LED lightning market is constantly increasing. For example, in 2014, Smallwood forecasted that the commercial, industrial, outdoor and architectural applications will rise the demand for LED lamps with 21% by 2018. He also suggested that global revenues from the LED lighting market will grow at 30% per annum, accounting to approximately 60% of the overall lighting market by 2020. The current market’s trends of several lighting products indicate the advantage of using LEDs for general lightings. This trend might be due to the fact that the LED bulb is designed to be fitted or mounted into the light bulb socket as a replacement of the incandescent lamp, whereas the LED tube is designed for replacing the fluorescent lamp. Several authors have studied the life-cycle of LED products and reported the advantages of using LED lighting, in order to lower the environmental burden and the energy consumption. For example, Camañes analyzed the materials inventory for manufacturing of LEDs and then conducted a life cycle assessment (LCA) study. He suggested that several types of plastics, stainless steel, and aluminium can be effectively recycled from spent LED lamps. Nevertheless, there are only a few studies that have quantified the environmental burden caused by the treatment of spent LED products, and investigated the ways...
on how to dispose of the spent LED lamps\textsuperscript{11}. It is also important to note that most of these studies have often considered the recycling as out of their scope. Even though the environmental burden caused by the treatment of the spent LEDs (i.e. the final phase of the LED products’ life cycle) might not be dominant when compared with the burden caused by other phases of life-cycle, a comprehensive LCA study should include the recycling of these products. Since there are several recycling options, depending on the type of the material to be recycled and the method to be employed, there is a need to better assess the treatment of spent LED products for recycling. The objective of this study is therefore to develop an environmentally-friendly and cost-effective flow-sheet for recovering various valuable materials from spent LED bulbs, and carry out a combined assessment in the context of LCA and cost-benefit analysis.

2. Experimental and Assessment Methodology

2.1. Qualitative analysis of LED light bulbs

In this study, the commercially available white LED bulbs, which are one of the main LED lighting products consumed in Japan, were used as a sample. Generally speaking a LED light bulb consists of a LED module in which several LED chips are mounted. In addition, the LED bulb has also an Edison screw, an electric driver, a heat sink, and an optical lens. The LED tube, on the other hand, has similar components with the LED bulb, although their sizes and shapes are different. Figure 1 shows the photograph of a LED bulb “Toshiba E-core LDA6L 30W” (Fig. 1a), and their components (Fig. 1b), including a round-shaped LED module (about 30 mm in size) in which several square-shaped LED chips (each of 5 mm in size and 1–2 mm in thickness) are mounted. Figure 2a shows the cross-sectional diagram of a white LED chip\textsuperscript{12}, whereas Figure 2b shows the elemental maps of cross-sectional area of a LED chip, analyzed by using a field emission scanning electron microscope (FE-SEM; JSM-7000F, JEOL Ltd), equipped with energy dispersive spectroscopy (EDS). The results of SEM-EDS analysis indicated the presence of silver (Ag) and gold (Au) as well as yttrium (Y). In addition, Table 1 summarizes the composition of a

![Photograph of a white LED bulb (a) and their components (b), showing several LED chips mounted in the LED module.](image)

![Cross sectional diagram of a white LED chip, indicating its components (a), and the EDS elemental maps of the cross-sectional area of a LED chip (b).](image)

![Table 1](image)
white LED chip, analyzed by using a X-ray fluorescence spectroroscope (XRF). Table 2, on the other hand, shows the list of the main components of a LED bulb. Polycarbonate (PC), and polybutylene terephthalate (PBT) are the main materials being used in the lens and the body of LED bulbs. Various Al or Cu based alloys are the main components of the heat sink and the Edison screw. The electric driver, on the other hand, consists of a noise filter, a condenser, and a voltage transducer that is composed of a ferrite magnet and a coil made of copper. Table 2 also shows the physical properties of the main components of a LED bulb. The densities of the components of the sample were measured by using a pycnometer. It was found that components made of PC and PBT plastics have slightly lower densities than other components (Table 2). Thus, the plastics can be recovered by taking advantages of the differences in densities. The magnetic separation, on the other hand, can effectively recover the magnetic parts of the electric driver, whereas other high conductive materials can be recovered by using an eddy current separator (ECS).

### 2.2. Treatment of spent LED light bulbs for recycling

Figure 3 shows the simplified flowsheet for sorting components of LED bulbs and recovering their LED chips. Eddy current separation (ECS) and air table separation were primarily employed for sorting components of the shredded spent LED bulbs. Not shown in Fig. 3 is the size reduction process that was carried out prior to ECS, using a commercially available shredder. In this work, three different size fractions were prepared: +20 mm, –20 mm, and –10 mm. Figure 4 shows photographs of sample after the size reduction process. Considering the results of the size distribution analysis, the authors calculated the energy required for size reduction by using the Bond’s equation (Eq. 1)\(^{13}\).

$$W = 10W_B \left[ \frac{1}{\sqrt{D_P}} - \frac{1}{\sqrt{D_F}} \right]$$

where \(D_F\) is the size which 80% of the feed would pass; \(D_P\) is the size which 80% of the collected product would pass; and \(W_B\) represents the work index, which value was evaluated to be 13.81 kWh/t\(^{14}\).

ECS was introduced for separating and recovering those pieces of shredded LED bulbs that contain aluminium alloy. ECS is a method that separates materials according to their conductivity\(^{15}\). During each test, conductive particles are accelerated due to the eddy current force originating from an interaction between the induced magnetic force and the applied magnetic field. Non-conductive or less conductive particles, on the

### Table 2  Physical properties of various components LED light bulbs

| Components       | Material           | Mass (wt%) | Density (g/cm\(^3\)) | Magnetic property* | Conductivity (S) |
|------------------|--------------------|------------|-----------------------|-------------------|------------------|
| Lens             | PC                 | 17         | 1.17                  | x                 | <2.0 E-08        |
| Body             | PBT polymer        | 19         | 1.48                  | x                 | <2.0 E-08        |
| Heat sink        | Al-Zn-Mg alloy     | 20         | 2.61                  | x                 | 3.33             |
| Façade           | Al-Mg alloy        | 15         | 1.94                  | x                 | 0.14             |
| LED module       | Combined           | 3          | 2.13                  | x                 | <2.0 E-08        |
| Electric driver  | Combined           | 13         | —                     | o                 | <2.0 E-08        |
| Edison screw     | Cu-Zn-alloy, Ni and black glass | 12 | 5.21                  | x                 | 3.33             |

* Tested by ferric magnet 0.5 mT; Magnetic = o, Non-magnetic = x
other hand, fall down due to the gravity underneath the rotating drum.

After ECS, the air table (manufactured by Triple/S Dynamics, Inc.; model no. V-135E) was employed to separate and recover LED chip from plastics, taking advantages of their differences in density. In operation, the feed was introduced onto the porous deck creating a bed of materials over its surface. This caused high-density particles to settle on the deck and contact its surface, while the low-density ones to float on top of the bed. The high-density particles were then vibrated uphill along the end slope towards the higher side. The low-density particles, which remained fluidized, drifted downhill in the direction of the deck’s inclination due to gravitational pull and left the deck at its lower end. The efficiency of air tabling was controlled by adjusting three different parameters, namely: end slope of the deck, upward air velocity, and vibration frequency of the deck. It should be noted, that in some cases, LED chips or fractions of relatively large pieces (i.e. larger than +20 mm in size) were manually sorted or separated by means of hand-picking.

Next, the recovered LED chips were incinerated at 1023 K in air atmosphere for 30 minutes, and then the sample was ground until it passed through a sieve with openings of 0.5 mm in diameter. In order to extract valuable metals, incinerated LED chips were subjected to acid leaching by using aqua regia for 30 minutes, and the leaching solution was then analyzed by using inductively coupled plasma optical emission spectrometry (ICP-OES). This study was focused primarily on the leaching of Ag and Au.

2.3. Environmental and economic assessment

2.3.1. Life cycle assessment of spent LED bulbs

Figure 5 shows the simplified life cycle of spent LED light bulbs, indicating the system boundary. The processes included in this analysis were either tested experimentally or are already employed in an industrial operation. Methods primarily tested in this study are: (1) ECS, (2) air tabling, (3) incineration-oxidation of LED chips, as well as (4) size reduction and classification by size. In addition, processes currently being implemented in an industrial scale, namely: aluminium refinery, manufacturing of plastic pellets, energy recovery from the incineration of waste plastic, and refining precious of metals (Ag/Au) were also included in the analysis. It should be noted that the collection and transportation processes were excluded from the analysis.

In this study, five different scenarios have been considered in order to compare and find out the most suitable alternative for treatment of spent LED light bulbs:

**Scenario 1**: Secondary production of aluminium ingots, followed by incineration of plastics and landfilling

**Scenario 2**: Secondary production of aluminium ingots, and incineration of plastics for energy recovery

**Scenario 3**: Secondary production of aluminium ingots, and secondary production of plastic pellets

**Scenario 4**: Secondary production of aluminium ingots, secondary production of plastic pellets, and recovery of LED chips by means of air tabling prior to secondary production of Au and Ag

**Scenario 5**: Secondary production of aluminium ingots and plastic pellets followed by hand-picking of LED module from LED bulb, prior to secondary production of Au and Ag from LED chips

MiLCA software, which was developed by Japan Environmental Management Association.
for Industry (JEMAI), is a state of the art LCA tool that was used to calculate the environmental impact of all the scenarios under the consideration. The software was employed together with IDEA ver. 1.1 database, which is also developed by JEMAI. Although the data inventory of most of processes that were considered for the treatment of the spent LED bulbs were found in IDEA database, some other processes require environmental impact datasets, which were found in that particular database. Therefore, when necessary, the inventory tables of some processes were compiled by using the world’s biggest inventory database “Ecoinvent v3”17.

2.3.2. Cost-benefit analysis

A cost-benefit analysis was also carried out in order to evaluate the economic feasibility of all scenarios taken into consideration. Cost was calculated by aggregating the following four categories:

1. Initial cost of investment
   The initial cost of investment, of which interest rate of 2% was taken as a rough estimation, was considered to have been amortized by the end of plant’s lifetime of 10 years. Investment costs and throughputs for shredders, screens, ECS and air table were from Combs18.

2. Cost of electricity
   Amounts of electricity consumed during each process were also from Combs18. Note that cost of electricity used in operation was estimated to be 0.15 USD/kWh.

3. Maintenance cost
   Maintenance costs for all equipment were from Combs18.

4. Labor cost
   Generally speaking, the labor cost is different in different countries around the world19. For example, the labor cost in Japan is 116.2%, 85.9% and 67.5% of the labor costs in South Korea, Germany, and USA respectively. In this work, labor cost was estimated at 15 USD/hr. per person. The revenues from secondary production of materials being recycled were also included in the cost-benefit analysis.

   The net profit was then calculated by using Eq. 2:

\[
\text{Net profit from recycling} = \text{(Cost of treatment)} - \text{(Revenue from secondary production)}
\]

3. Results and Discussion

3.1. Treatment of spent LED bulbs by means of ECS and air tabling

Figure 6 shows photographs of various fractions being separated, indicating their amounts in wt% and particle sizes, whereas Figure 7 shows a three-stage flowsheet for treatment of spent LED bulb, and the results of separation. Note that plastic fraction recovered after ECS was termed as “plastic concentrate 1”, whereas the plastic fraction recovered after air tabling was termed as “plastic concentrate 2” (Fig. 7). Next, both fractions entered either the process named as “secondary production of plastic pellets” or the process named as “treatment of plastics”, i.e. incineration of waste plastics for landfilling or energy recovery (Fig. 5). Figure 8, on the other hand, shows the results of ECS in term of grade and recovery of aluminium. It was found that reducing the size of LED bulbs to less than 10 mm, increased the grade of Al up to 93.4% (Fig. 8). However, the recovery of aluminium was relatively low (ca. 55%). These results were due to the fact that the efficiency of ECS depends on conductivity and shape of materials to be treated. In other words, the efficiency of ECS was especially affected by the behaviour of those round-shaped pieces of aluminium that cannot attain enough force to be deflected. Experimental results also
Fig. 7 A three-stage flowsheet for treatment of spent LED bulbs, indicating separation results in terms of grade and recovery: (a) first stage, (b) second stage, and (c) the third stage of separation.

Fig. 8 Result of eddy current separation (ECS) in terms of grade and recovery of aluminum as a function of particle size (see Fig. 7a).

Fig. 9 Result of air tabling in terms of grade and recovery of LED chips as a function of end slope of the deck, (see Fig. 7b).
indicated that even though the grade of Al was relatively low, 100% of aluminium was recovered from the +20 mm size fraction (Fig. 8). In addition, Figure 9 shows the experimental results of air tabling. It was found that when end slope was adjusted at 5 degrees, the recovery of LED chips reached its highest value.

3.2. Environmental performance

Inventory data for Scenarios 1, 2, 3, 4, and 5 are listed in Tables 3, 4, 5, 6, and 7, respectively. In addition, the calculated impacts for Scenarios 1, 2, 3, 4, and 5 are shown in Tables 8, 9, 10, 11, and 12, respectively. Figure 10, on the other hand, shows the environmental burden of 5 different scenarios in terms of global warming potential (GWP), in kg CO₂-eq. In addition, the avoided global warming potentials of all five scenarios taken into consideration are shown in Figure 11.

3.2.1. Eddy current separation and air table separation

ECS process was considered in all Scenarios but it has only marginal contributions to GWP (Fig. 10). On the other hand, air table separation process has a certain impact only in case of Scenario 4, where it was employed for recovering LED chips (Fig. 10). It is important to note that the throughput for ECS is the amount of materials processed during an industrial operation, whereas throughput and energy consumption for the air tabling were estimated from the experimental work where a laboratory scale separator was employed.

The difference in throughputs between ECS

| Table 3 | Parts of inventory tables of Scenario 1 |
|---------|---------------------------------------|
| Type    | Name                                | Amount | Unit |
| Input product | LED bulb, post-consumer             | 1.00E+00 | t/hr |
| From industrial operation | Eddy current separation             | 1.00E+00 | t/hr |
| From industrial operation | Aluminium refinery process           | 3.90E+02 | kg/hr |
| From industrial operation | Waste plastic treatment Incineration and landfilling | 5.01E+02 | kg/hr |
| Substitution; avoided production | Aluminium ingot, secondary         | 2.74E+02 | kg/hr |

Eddy Current Separation

| Type       | Name                                | Amount | Unit | Comments |
|------------|-------------------------------------|--------|------|----------|
| Input product | Eddy current separation service     | 1.00 E+00 | t/hr |          |
| Output product | Aluminium concentrate              | 3.90 E+02 | kg/hr | Grade of Al = 88% |
| Output product | Plastic components                 | 5.01 E+02 | kg/hr | Grade of Plastics = 67% |
| From industrial operation | Electricity grid mix, JP       | 4.49 E+00 | kg/hr | “Size reduction”, “Screening”, “Dry magnetic separator”, “Eddy current separator” |
| Exiting product | Waste plastics                    | 3.40 E+01 | kg/hr |          |
| Exiting product | Landfilling, waste metals         | 6.80 E+01 | Kg/hr |          |

Aluminium Refinery Process

| Type            | Name                                | Amount | Unit | Comments |
|-----------------|-------------------------------------|--------|------|----------|
| Input product   | Aluminium refinery process          | 1.00E+00 | kg/hr | Grade of Al = 88% |
| By product      | Aluminium ingot,                    | 6.98E–01 | kg/hr |          |
| From industrial operation | secondary treatment of aluminium scrap | 1.00E+00 | kg/hr | Efficiency factor of 0.8 |
| From industrial operation | treatment of aluminium scrap for recycling | 4.46E+00 | kWh/t | Efficiency factor of 0.8 |

| Table 4 | Parts of inventory tables of Scenario 2 |
|---------|---------------------------------------|
| Type    | Name                                | Amount | Unit | Comment |
| Input product | LED bulb, post-consumer             | 1.00 E+00 | t/hr |          |
| From industrial operation | Eddy current separation             | 1.00 E+00 | t/hr |          |
| From industrial operation | Aluminium refinery process           | 3.90 E+02 | kg/hr |          |
| From industrial operation | Waste plastics incineration, kg/hr electricity recovered | 5.01 E+02 | kg/hr | Using same inventory as for “treatment of waste plastics, incineration and landfilling” IDEA ver 1.1 |
| Substitution/Avoided production | Aluminium ingot, secondary         | 2.74 E+02 | kg/hr | IDEA ver 1.1 |
| Substitution/Avoided production | Electricity, grid mix., JP     | 4.44 E+02 | kWh/hr | Electric generation, 0.887 kWh/kg of plastics waste feed is estimated |

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and air table is one of the main reasons why their contributions to GWP are different. Note that the energy required for size reduction before ECS or air table processes are also different, since before ECS the particle size was reduced from 60 mm to 20 mm, whereas before air tabling the size was reduced from 20 mm to 3 mm. In other words, the amount of energy required for size reduction is higher in case of air tabling, since a higher reduction ratio is required, which in turn increased the amount of energy consumed (Fig. 10).

3.2.2. Plastic incineration or separation for energy recovery

It was found that the “Treatment of Plastics” (i.e. incineration of waste plastics for landfilling or energy recovery) is the process that has the highest contribution to GWP (Fig. 10). Note that in Scenario 1, waste plastics were assumed to have been landfilled after incineration, whereas in Scenario 2, they were incinerated for energy recovery. Nevertheless, in both Scenarios 1 and 2, all recovered plastic fractions were incinerated, thus the contributions of “treatment of plastics” to GWP were higher when compared with the ones of other scenarios. In Scenarios 3, 4, and 5, on the other hand, contribution of “treatment of plastics” to GWP was relatively low, because the plastics were recovered for material recycling (i.e. secondary production of plastic pellets), and only the middlings (i.e. the fraction exiting the plastic separation process) entered the incineration process. In addition, the avoided GWP contribution due to the energy recovered (i.e. electricity being generated) from the incineration of plastics is slightly lower when compared with the ones of other secondary products (Fig. 11).

### Table 5 Parts of inventory table of Scenario 3

| Type | Name | Amount | Unit | Data acquired from |
|------|------|--------|------|--------------------|
| Input product | LED bulb, post-consumer | 1.00E+00 | t/hr |                     |
| From industrial operation | Eddy current separation | 1.00E+00 | t/hr |                     |
| From industrial operation | Aluminium refinery process | 3.90E+02 | kg/hr | IDEA ver 1.1 |
| From industrial operation | Plastic separation by type | 5.01E+02 | kg/hr | Grade of PC: 98% |
| From industrial operation | Plastic pellet manufacturing | 2.64E+02 | kg/hr |                     |
| From industrial operation | Waste plastic treatment | 2.38E+02 | kg/hr |                     |
| Substitution; avoided production | Aluminium ingot, secondary | 2.74E+02 | kg/hr | IDEA ver 1.1 |
| Substitution; avoided production | Polycarbonate, pellet manufacturing | 1.21E+02 | kg/hr | IDEA ver 1.1 |
| Substitution; avoided production | Polybutylene-terephthalate, pellet manufacturing | 1.37E+02 | kg/hr | IDEA ver 1.1 |

### Plastic Separation by type

| Type | Name | Amount | Unit | Comment |
|------|------|--------|------|---------|
| Input product | Plastics recovered after ECS | 1.00E+00 | t/hr | Grade of plastics: 67% PC/Plastics: 47% PBT/Plastics: 50% |
| By-product | Polycarbonate (PC) | 2.47E-01 | kg/hr | Grade of PC: 98% Recovery of PC: 80% is assumed |
| By-product | Polybutylene-terephthalate, (PBT) | 2.79E-01 | kg/hr | Grade of PBT: 98% Recovery of PBT: 80% is assumed |
| By-product | Waste plastics | 4.75E-01 | kg/hr | |
| From industrial operation | Electricity, grid mix, JP | 7.40E-01 | kWh | |

### Pellet plastic manufacturing

| Type | Name | Amount | Unit | Data acquired from |
|------|------|--------|------|--------------------|
| Input product | Plastic waste | 1.00E+00 | kg/hr | Swiss polymer |
| By product | Plastic pellets | 9.80E-01 | kg/hr | IDEAv1.1 |
| From industrial operation | Electricity, grid mix, JP | 5.04E-01 | kWh/hr | IDEAv1.1 |
| From industrial operation | Industrial waste | 4.00E-01 | L/hr | IDEAv1.1 |
| Exiting product | Treated sewage water | 4.00E-01 | L/hr | IDEAv1.1 |
| Exiting product | Plastic waste | 2.00E-02 | kg/hr | IDEAv1.1 |
treatment process (Fig. 10). Nevertheless, GWP due to the aluminium refinery was only one-fourth of the avoided GWP due to the secondary production of the aluminium ingots (Figs. 10 and 11), indicating the advantages of the secondary AI production.

3.2.4. PC/PBT pellets manufacturing

Manufacturing of secondary plastic pellets had a marginal impact only in Scenarios 3, 4, and 5 (Fig. 10). However, the avoided GWP impact, derived from secondary production of PC or PBT pellets had the largest contribution, indicating the advantage of material recycling (Fig. 11). This was due to the fact that both PC and PBT polymers, the main recycled plastics, are valuable products, since they have a relatively high heat and impact resistances.

3.2.5. Au/Ag refinery and Au/Ag ingots manufacturing

It was found that both Au and Ag refinery processes have little contributions to the overall environmental performance of Scenarios 4 and 5 (Fig. 10). In addition, the avoided GWPs from both secondary productions of Au and Ag ingots (i.e. Scenarios 4 and 5) had much lower contributions, especially when compared to PC/PBT pellets and aluminium ingot (Fig. 11). The results of the assessment showed that, when compared per the same amount being produced, the avoided environmental burden (in terms of GWP) due to the secondary production of Au/Ag ingots was 10–20 times higher than the one caused by the secondary production of PC/PBT pellets. Nevertheless, the total amount of Au and Ag ingots being produced was about 100 times smaller than that of PC/PBT pellets.
pellets or aluminium ingot. Hence, in turn, the GWP contributions due to the secondary production of Au/Ag ingots were much lower (Fig. 11).

Considering the results, it was found that Scenarios 3, 4, and 5 are environmentally friendly alternatives for lowering GWP.

### 3.3. Economic feasibility

Economic feasibility of all 5 scenarios, taken into consideration, was assessed in terms of “Net profit from recycling” (Eq. 2). Figure 12 shows the results of cost-benefit analysis, which suggested that:

- both Scenarios 1 and 2 have a negative value of net profit. Thus, Scenarios 1 and 2 cannot be sustainably implemented for the treatment of spent LED light bulbs.
- air tabling employed in Scenario 4 has a significant contribution to the net profit, increasing the cost of recycling. This was due to the fact that the air table has a relatively low throughput value, and a high investment cost. Thus, a new density separation method, able to substitute the air table must be introduced in order to lower the environmental burden and increase the net profit.
- Scenario 5 has the second-best value in terms of the net profit, despite the fact that the labor cost for hand-picking is relatively high. It should be noted that the labor cost reflects the average salary of Japanese labor market, which is comparably higher when compared with other countries. The net profit might possibly be improved, if the hand-picking and other processes are to be conducted outside of Japan.
| Table 8 | Results of impact assessment for Scenario 1, showing contribution from different stages of treatment |
|---------|-------------------------------------------------|
| Impact category | Unit | Processes | Total impact from the process | % Al ingot | % total avoided impact | Env. performance |
| Energy | MJ | 7.75E+01 | 3.60E+03 | 2.06E+02 | 3.88E+02 | 1.12E+04 | 1.12E+04 | -7.28E+08 |
| Eutrophication Potential (EP) | kg eq. PO₄⁻ | 5.54E-05 | 5.23E-03 | 2.54E-02 | 3.07E-02 | 5.90E-02 | 5.90E-02 | -2.83E-02 |
| Human Toxicity Potential (HTP) | kg eq. Ph-H | 2.55E-05 | 2.50E-01 | 5.11E-05 | 2.50E-01 | 8.56E-04 | 8.56E-04 | 2.48E-01 |
| Photo-Oxidant Formation Potential (POCP) | kg eq. C₆H₄ | 1.18E-05 | 5.42E-04 | 3.59E-05 | 5.90E-04 | 1.65E-03 | 1.65E-03 | -1.06E-03 |
| Acidification Potential (AP) | kg eq. SO₂⁻ | 1.81E-03 | 1.81E-01 | 5.96E-01 | 7.79E-01 | 6.09E+00 | 6.09E+00 | -5.31E+00 |
| Abiotic Depletion Potential (ADP) | kg eq. Sb | 2.25E-02 | 1.14E+00 | 5.41E-02 | 1.22E+00 | 2.96E+00 | 2.96E+00 | -1.74E+00 |
| Global Warming Potential (GWP) | kg eq. CO₂ | 4.87E+00 | 2.46E+02 | 1.49E+03 | 1.74E+03 | 9.62E+02 | 9.62E+02 | 7.76E+02 |

| Table 9 | Results of impact assessment for Scenario 2, showing contribution from different stages of treatment |
|---------|-------------------------------------------------|
| Impact category | Unit | Processes | Total impact from the process | % Al ingot | % Electricity | % Total avoided impact | Env. Performance |
| Energy | MJ | 7.75E+01 | 3.60E+03 | 3.88E+03 | 1.12E-04 | 4.58E+03 | 1.57E+04 | -1.19E+04 |
| Eutrophication Potential (EP) | kg eq. PO₄⁻ | 5.54E-05 | 5.23E-03 | 3.07E-02 | 3.07E-02 | 5.90E-02 | 5.90E-02 | -2.83E-02 |
| Human Toxicity Potential (HTP) | kg eq. Ph-H | 2.55E-05 | 2.50E-01 | 2.50E-01 | 2.50E-01 | 8.56E-04 | 8.56E-04 | 2.48E-01 |
| Photo-Oxidant Formation Potential (POCP) | kg eq. C₆H₄ | 1.18E-05 | 5.42E-04 | 5.90E-04 | 5.90E-04 | 1.65E-03 | 1.65E-03 | -1.06E-03 |
| Acidification Potential (AP) | kg eq. SO₂⁻ | 1.81E-03 | 1.81E-01 | 7.79E-01 | 7.79E-01 | 6.09E+00 | 6.09E+00 | 5.31E+00 |
| Abiotic Depletion Potential (ADP) | kg eq. Sb | 2.25E-02 | 1.14E+00 | 5.41E-02 | 1.22E+00 | 2.96E+00 | 2.96E+00 | 1.74E+00 |
| Global Warming Potential (GWP) | kg eq. CO₂ | 4.87E+00 | 2.46E+02 | 1.49E+03 | 1.74E+03 | 9.62E+02 | 9.62E+02 | 7.76E+02 |

| Table 10 | Results of impact assessment for Scenario 3, showing contribution from different stages of treatment |
|---------|-------------------------------------------------|
| Impact category | Unit | Processes | Total impact from the process | % Al ingot | % PC | % PB T | % Total avoided impact | Env. Performance |
| Energy | MJ | 7.75E+01 | 3.60E+03 | 7.06E+01 | 3.82E+03 | 2.23E+03 | 3.75E+03 | 1.12E+04 | 1.12E+04 | 4.14E+04 | 4.14E+04 | -3.80E+04 |
| Eutrophication Potential (EP) | kg eq. PO₄⁻ | 5.54E-05 | 5.23E-03 | 8.72E-03 | 2.24E-03 | 1.52E-03 | 1.40E-02 | 5.90E-02 | 5.90E-02 | 1.46E-02 | 8.04E-03 | 8.15E-02 | -6.75E-02 |
| Human Toxicity Potential (HTP) | kg eq. Ph-H | 2.55E-05 | 2.50E-01 | 1.75E-05 | 1.10E-03 | 7.51E-04 | 2.50E-01 | 8.56E-04 | 4.53E-04 | 2.38E-04 | 1.55E-03 | 2.48E-01 |
| Photo-Oxidant Formation Potential (POCP) | kg eq. C₆H₄ | 1.18E-05 | 5.42E-04 | 1.23E-05 | 5.04E-04 | 3.49E-04 | 5.66E-04 | 1.65E-03 | 6.66E-03 | 6.58E-03 | 1.49E+02 | -1.43E-02 |
| Acidification Potential (AP) | kg eq. SO₂⁻ | 1.81E-03 | 1.81E-01 | 2.05E-01 | 7.34E-02 | 4.99E-02 | 3.87E-01 | 6.09E+00 | 9.99E-01 | 4.85E+01 | 7.57E+00 | 7.18E+00 |
| Abiotic Depletion Potential (ADP) | kg eq. Sb | 2.25E-02 | 1.14E+00 | 1.86E-02 | 9.45E-01 | 6.41E-01 | 1.18E+00 | 2.96E+00 | 5.81E+00 | 5.92E+00 | 1.47E+01 | 1.35E+01 |
| Global Warming Potential (GWP) | kg eq. CO₂ | 4.87E+00 | 2.46E+02 | 5.11E+02 | 2.05E+02 | 1.40E+02 | 1.11E+03 | 9.62E+02 | 9.06E+02 | 6.77E+02 | 2.55E+03 | -1.78E+03 |
### Table 11 Results of impact assessment for Scenario 4, showing contribution from different stages of treatment

| Impact category | Unit | ECS | Air table | AI refinery | Treatment of waste plastics | Separation of Plastics | Manufacturing of plastic pellets | LED chip: incineration and sieving | Ag refining | Au refining | Total impact from the process | % Al ingot | % PC | % PBT pellet | % Ag | % Au | % Total avoided impact | Env. Performance |
|-----------------|------|-----|-----------|-------------|-----------------------------|------------------------|-----------------------------|---------------------------------|-------------|-------------|----------------------------|----------|-----|----------------|------|------|---------------------|-----------------|
| Energy          | MJ   | 7.75 E+03 | 4.07 E+05 | 3.60 E+03 | 6.91 E+01 | 3.73 E+03 | 1.14 E+03 | 4.97 E+00 | 9.13 E+01 | 9.13 E+01 | 1.28 E+04 | 1.12 E+04 | 1.57 E+04 | 1.41 E+04 | 1.39 E+04 | 8.08 E+01 | 8.11 E+02 |
| Eutrophication Potential (EP) | kg eq. PO | 5.54 E-03 | 2.39 E-03 | 5.23 E-03 | 8.51 E-03 | 2.19 E-03 | 7.81 E-04 | 6.12 E-04 | 1.91 E-05 | 1.98 E-02 | 1.42 E-02 | 7.85 E-05 | 9.45 E-05 | 8.82 E-02 | 8.11 E-02 | 7.57 E-05 | 5.77 E-05 |
| Human Toxicity Potential (HTP) | kg eq. Ph-H | 2.55 E-05 | 1.18 E-03 | 2.50 E-01 | 1.71 E-05 | 1.07 E-03 | 3.85 E-04 | 1.23 E-06 | 9.36 E-06 | 2.52 E-02 | 8.56 E-04 | 4.43 E-04 | 2.32 E-04 | 1.91 E-03 | 4.78 E-05 | 3.49 E-03 | 3.49 E-01 |
| Photo-Oxidant Formation Potential (POCP) | kg eq. C,H4 | 1.18 E-05 | 5.41 E-04 | 5.42 E-04 | 1.20 E-05 | 4.92 E-04 | 1.79 E-04 | 8.66 E-07 | 6.98 E-06 | 1.82 E-03 | 1.65 E-05 | 6.50 E-03 | 4.60 E-03 | 2.20 E-05 | 1.46 E-02 |
| Acidification Potential (AP) | kg eq. SO2 | 1.81 E-03 | 7.81 E-02 | 1.81 E-01 | 2.00 E-01 | 7.16 E-02 | 2.56 E-02 | 1.44 E-02 | 6.36 E-04 | 3.23 E-04 | 6.09 E-00 | 9.75 E-01 | 4.74 E-01 | 3.01 E-03 | 7.54 E+00 | 7.54 E-03 |
| Abiotic Depletion Potential (ADP) | kg eq. Sb | 2.25 E-02 | 1.01 E-00 | 1.14 E-00 | 1.81 E-02 | 9.23 E-01 | 3.29 E-02 | 1.30 E-03 | 3.05 E-02 | 3.48 E+00 | 5.67 E+00 | 5.78 E+00 | 8.32 E-02 |
| Global Warming Potential (GWP) | kg eq. CO2 | 4.87 E+00 | 2.19 E+02 | 2.46 E+02 | 4.98 E+02 | 2.00 E+02 | 7.17 E+01 | 3.59 E+01 | 2.40 E+00 | 5.51 E+00 | 9.62 E+02 | 8.84 E+02 | 2.25 E+03 |

### Table 12 Results of impact assessment for Scenario 5, showing contribution from different stages of treatment

| Impact category | Unit | Hand picking | ECS | AI refinery | Treatment of waste plastics | Separation of Plastics | Manufacturing of plastic pellets | LED chip: incineration and sieving | Ag refining | Au refining | Total impact from the process | % Al ingot | % PC | % PBT pellet | % Ag | % Au | % Total avoided impact | Env. Performance |
|-----------------|------|--------------|-----|-------------|-----------------------------|------------------------|-----------------------------|---------------------------------|-------------|-------------|----------------------------|----------|-----|----------------|------|------|---------------------|-----------------|
| Energy          | MJ   | 2.72 E+00 | 7.38 E+01 | 3.60 E+03 | 5.10 E+01 | 3.45 E+03 | 1.17 E+03 | 1.99 E+01 | 1.23 E+02 | 3.60 E+02 | 8.85 E+04 | 1.12 E+04 | 1.61 E+04 | 1.45 E+04 | 1.39 E+04 | 8.18 E-02 | 8.18 E-02 |
| Eutrophication Potential (EP) | kg eq. PO | 1.19 E-06 | 5.27 E-05 | 5.23 E-03 | 6.27 E-03 | 2.02 E-03 | 8.00 E-04 | 2.44 E-03 | 7.53 E-05 | 2.38 E-05 | 1.69 E-02 | 5.90 E-02 | 1.46 E-02 | 8.04 E-03 | 7.37 E-02 | 1.18 E+02 | 8.18 E-02 |
| Human Toxicity Potential (HTP) | kg eq. Ph-H | 7.84 E-07 | 2.43 E-05 | 2.50 E-01 | 1.26 E-05 | 9.95 E-04 | 3.95 E-04 | 4.92 E-06 | 1.38 E-05 | 3.69 E-05 | 2.51 E-01 | 8.56 E-04 | 4.53 E-04 | 2.38 E-04 | 7.54 E-03 | 1.39 E-04 | 9.27 E-03 |
| Photo-Oxidant Formation Potential (POCP) | kg eq. C,H4 | 3.49 E-07 | 1.12 E-05 | 5.42 E-04 | 8.87 E-06 | 4.56 E-04 | 1.83 E-04 | 3.46 E-06 | 2.75 E-05 | 1.29 E-04 | 1.36 E-03 | 1.65 E-05 | 6.66 E-03 | 6.58 E-03 | 1.82 E-05 | 8.67 E-05 |
| Acidification Potential (AP) | kg eq. SO2 | 5.23 E-03 | 1.72 E-03 | 1.81 E-01 | 1.47 E-01 | 6.63 E-02 | 2.62 E-02 | 5.73 E-02 | 2.61 E-03 | 1.70 E-02 | 5.00 E-01 | 6.09 E+00 | 9.99 E-01 | 4.85 E-01 | 2.46 E-03 | 1.19 E-02 | 7.59 E+00 |
| Abiotic Depletion Potential (ADP) | kg eq. Sb | 6.73 E-04 | 2.14 E-02 | 1.14 E-00 | 1.34 E-02 | 8.54 E-01 | 3.37 E-01 | 5.20 E-03 | 4.14 E-02 | 1.20 E-01 | 2.54 E-00 | 2.96 E-00 | 5.81 E+00 | 5.92 E+00 | 2.71 E-01 | 3.28 E-01 |
| Global Warming Potential (GWP) | kg eq. CO2 | 1.46 E-01 | 4.64 E+00 | 2.46 E+02 | 3.67 E+02 | 1.86 E+02 | 7.34 E+01 | 1.43 E+02 | 9.46 E+00 | 2.17 E+00 | 1.03 E+03 | 9.62 E+02 | 9.06 E+02 | 5.00 E+00 | 1.78 E+01 |

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4. Conclusions

The results of this work suggested that the treatment of spent LED light bulbs is an environmentally friendly and cost-effective alternative, which promotes the secondary production of valuable materials that in turn would prevent the depletion of mineral resources and therefore would lower the global warming potential. The main findings of this work can be summarized as follows:

1. Both the eddy current separation and the air tabling affected the performance of the treatment of spent LEDs for recycling, especially the grade and recovery of Al and plastics.

2. The results of LCA indicated that Scenarios 3, 4, and 5, which primarily employed the secondary production of aluminium ingots, and plastic pellets, have all exhibited relatively low GWPs.

3. The results of the cost-benefit analysis, on the other hand, suggested that secondary production of aluminium ingots, and plastic pellets (i.e. Scenario 3) is the best alternative among five scenarios, since it ensures the highest net profit and a relatively low environmental burden.

At last but not least, the authors think that if a larger amount of spent LED chips would be collected in the future, the recycling of other critical metals (including Ga and rare earth elements) would be feasible.

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