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A circular economy approach for lifecycles of products and services

Eco-credits method final definition

Deliverable 2.4

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Summary

The development of a methodology to calculate eco-credits is defined in this document. Eco-credits and eco-debits are the basis of the consumer's eco-account proposed in CIRC4LIFE project. While eco-debits track the consumption behaviour of the user under a framework of responsible purchases, which in turn are associated to their environmental impact, the eco-credits aim to incentivize an adequate disposal of the products after their end-of-life in order to reuse or recycle their components and setting the bases for rewarding sustainable consumption by enlarging the lifetime use by repairing. Thus, eco-credits tackle with the main aspects fundamental in the reuse and recycling stages.

Eco-credits methodology is applicable to all kinds of products, but the present document focuses on WEEEs (Waste electrical and electronic equipment) and organic urban wastes and food products, which are the main sectors considered for the CIRC4LIFE project.

As the reuse, recycling or repairing of a product is going to avoid the extraction and consumption of new raw materials, the first aspect taken into account in the eco-credits methodology is the evaluation of the materials found in a product. To that end, a novel concept called **thermodynamic rarity**, based on the exergy analysis is used. Rarity is a measure of the physical value of raw materials as a function of their relative scarcity in the crust and the energy costs required to extract and refine the materials. Hence, the scarcer and the more difficult is to obtain a given material, the greater its physical value. Furthermore, the EoL (end-of-life) **state** of a product has been taken into account for being determinant parameter in terms of reuse. Finally, a third parameter that considers the used lifetime of a product compared to the expected lifespan is considered. This parameter is important because we do not want to incentivize the "throw away culture" and hence promote the use of the given product during its whole lifetime. Thus, the resulting proposed general equation is:

$$Eco-credits = A \cdot \sum_{i=1}^{n} a_i \, rarity_i + B \cdot EoL \text{ state} + \mathrm{C} \cdot lifetime\ factor$$

where A and B are parameters that will be used in order to promote the importance of materials and EoL state and C the eco-points associated to the products (see DLV 1.3). Additionally, a parameter multiplying the thermodynamic rarity is also included. This parameter, a_i, will consider the recyclability of the materials. All the terms of this equation are calculated in this report.

The importance of each of these terms in the case of WEEEs has been adjusted taking into account the opinion of all the stakeholders involved in the process but also the circular economy principles.

In the case of food or organic urban waste, the determination of the state of the EoL products and the lifetime factor is not possible, so the formula needed to be simplified:

$$Eco-credits = D \cdot b_{ch,organic\ waste} \cdot m_{organic\ waste}$$

In this case the thermodynamic rarity of organic materials has been calculated directly by means of its chemical exergy ($b_{ch,organic\ waste}$). This has been developed assuming an average value for organic urban waste and the energy content (calories) for meat or vegetable products. The parameter D will be applied in the expression in order to balance the expected incentives associated to Eco-credits to the final incentive provided.

In both cases, the resulting eco-credits are dimensionless (being the functional unit one device/good) and should be adjusted to an economic value or any other incentive depending on the possibilities of each specific incentive scheme (developed in Task 2.5). This economic value will be settled for demonstration and exploitation periods in the project according to the final kind of incentives provided to users.

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Acronyms and abbreviations

Abbreviation	Description
ABS	Acrylonitrile Butadiene Styrene
EEE	Electrical and electronic equipment
EoL	End-of-Life
HHV	Higher heating value
LCIA	Life Cycle Impact Assessment
PCB	Printed circuit board
PH	Plastic housing
PMMA	Polymethyl methacrylate
REE	Rare earth elements
WEEE	Waste electrical and electronic equipment

1 Introduction

1.1 CIRC4Life Project Overview

Within CIRC4life project, the design of a consumer´s eco-account that will enable the consumer to record and track their daily footprints on the environment will be developed. The eco-account gathers the eco balance between the consumption behaviour of the user (eco-debits) and subsequently an adequate disposal after its end-of-life (eco-credits). Additionally, eco-credits could be provided as a manner to stimulate repairing activities, linked directly with sustainable consumption, because similar principles (avoiding raw materials) could be associated to repairing.

Eco-debits (calculated by means of **Eco-points** as it explained in detail in deliverable 1.3) is a cumulative value of the ecological impacts of a product considering its whole supply chain and is calculated by means of the LCIA method. Thus, eco-debits gives information to the customer about the impacts of the different products, facilitating a responsible purchase (under an environmental perspective) and a track of the ecological impact of its consumption.

Eco-credit is a concept focussing on the reuse, recycling and repairing stage. Eco-credits can be obtained and recorded in the consumer's eco-account when the customer returns a product to a collection facility for its reuse or recycling or is sent to a reparation facility (potentially associated to eco-account program). Its aim is to mainly incentivize costumers to perform a proper disposal of a product after its lifetime, avoiding its dumping or the storage of no-longer (but valuable) used products in households. It may occur that increasing the collection of these products for recycling, which were previously stored in households, will lead to an increase in the amount of waste generated in the short term, however it will enable a proper reuse and recycling of these products when their end-of-life period happens. In a second step, eco-credits could be also used as a sustainable consumption tool, promoting repairing activities.

Eco-credits, as eco-debits, are dimensionless and are referred to a specific product (i.e. one tablet, one smartphone, etc.). In addition, and based on the concept of fostering recycling and reuse, they will be accompanied by a system of incentives, that could be paid in cash or other goods to the consumers, that will be defined under the framework of task 2.5. This conversion of eco-credits into incentives needs to be done according to the possibilities of each specific demo site.

As explained in detail later, in the calculation of eco-credits three main aspects are taken into account: the physical value of the materials found in the product, the EoL state of the product (if reusable or not) and the adequacy of the used time compared to the expected lifespan.

These aspects have been chosen due to their importance in the EoL of a product. A compromise among the opinion of all the stakeholders involved in the process and the general principles of the circular economy is the main goal of this methodology.

Eco-credit calculation methodology is applicable to all kinds of products but the present document focuses on WEEE and food waste.

2 Eco-credits evaluation for small electronic devices and LED systems

2.1 WEEE: definition, classification and directive

WEEE (Waste electrical and Electronic Equipment), also called e-waste, comprehend a wide range of products with circuitry or electrical components. Although different classification systems have been proposed, the directive 2012/19/EU[1] classified WEEE within six categories:

1. Temperature exchange equipment: this category includes, for example, refrigerators, freezers, air conditioners or heat pumps.
2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2: typical equipment includes televisions, monitors, laptops, notebooks and tablets.
3. Lamps: as fluorescent lamps, high intensity discharge lamps and LED lamps.
4. Large equipment (any external dimension more than 50 cm) including, but no limited to: household appliances; IT and telecommunication equipment; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sport equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.

   This category includes washing machines, clothes dryers, dish-washing machines, copying equipment or photovoltaic panels.
5. Small equipment (no external dimension more than 50 cm) including, but not limited to: Household appliances; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sports equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.

   Typical equipment includes vacuum cleaners, microwaves, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras etc.
6. Small IT and telecommunication equipment (no external dimension more than 50 cm): as mobile phones, Global Positioning System (GPS), routers, personal computers or printers.

The main common aspects of WEEE is its high content in scarce raw materials and dangerous substances. That said, each category has different characteristics in terms of waste quantities, economic values and environmental and health impacts (Balde et al. 2015).

Globally, the generation of WEEE is growing fast due to a short lifecycle and the costumer's attitudes towards disposing or early replacing of them. According to "Global E-waste Monitor Report 2017" (Balde et al. 2017) 44.7 million tonnes (Mt) of e-waste was generated in the world and only 20% was recycled through proper channels. Europe is the second largest generator of e-waste per inhabitant with an average of 16.6 kg/inh; however, Europe has the highest collection rate (35%) (Islam & Huda 2018) due to the existence of a directive that regulates the flows of WEEE.

In Europe, the first directive in electrical and electronic equipment was approved in 2002 (Directive 2002/96/CE). This directive recognised the responsibility of producers once the product becomes a waste.

In 2012, the directive 2012/19/EU entered into force to intent to reduce the environmental impact of WEEE acting through all the different stakeholders involved. Among all stakeholders, producers have the main

[1] https://eur-lex.europa.eu/eli/dir/2012/19/oj

responsibility as they should finance at least the collection from collection facilities, and the treatment, recovery and disposal of WEEE.

From 2016, the minimum collection rate shall be 45% calculated on the basis of the total weight of WEEE collected in a given year in the Member State concerned, expressed as a percentage of the average weight of EEE placed on the market in the three preceding years in that Member State. From 2019, the minimum collection rate shall be 65% of the average weight of EEE placed to the market in the preceding years in the Member State concerned.

2.2 Methodology for calculating eco-credits

According to the requirements established in the WEEE directive, the recycling rate should be increased yearly in order to achieve the goals set. One of the activities that could improve recycling ratios would be the use of monetary-ish incentives directly provided to device users when they actively participate in the recycling process (currently this is already being tested in pilot experiences). Eco-credits are directly related to the incentives that could be given to the users to boost the return of EoL products for its later reuse or recycling.

In this DLV 2.4, a methodology based on the circular economy principles has been developed. This methodology is able to face two main issues: on the one hand, it should be able to evaluate the composition of the raw materials. This is mandatory as most of the WEEE are composed of critical (now or in the future) materials. On the other hand, the methodology needs to consider the point of view of all the stakeholders involved in the recycling process.

In order to consider these two approaches, the equation able to calculate the Eco-credits, has been developed in the bases of rarity (a term explained in the following section) and the opinions of recycling and repairing companies and other stakeholders involved in the process.

In order to reach an equilibrium among the different factors, the developed eco-credit formula includes three terms as shown in equation 1:

$$Eco-credits = A \cdot \sum_{i=1}^{n} a_i \, rarity_i + B \cdot EoL \text{ state} + \mathrm{C} \cdot lifetime\ factor \ (Eq. 1)$$

The first term of the equation is related to the impact in the environment of WEEEs, mainly associated to their high demand of natural resources. As explained in detail in the following section, this is represented by the thermodynamic rarity factor, called rarity in the equation.

It is important to clarify that within this methodology the rarity term is calculated for a specific product (a cell-phone, a computer, a tablet, etc.). In the framework of the task, average values for tablets and LEDs were obtained in order to be consistent with the demo activities. Different brands were analysed by means of literature review, considering the composition of metals and plastics as an average product (see Appendix B). Additionally, other WEEEs could be already characterized by means of literature reviews such as cell phones (see Appendix B), laptops, etc.

According to RECYCLIA and INDUMETAL propositions, one of the main aims of the methodology when the materials are considered (in terms of providing incentives) should be the recyclability of the materials. To take this into account, for each raw material included in a device, its rarity needs to be multiplied by a factor that confirms its recyclability, a_i, which will be equal to its recyclability ratio whenever it can be recycled (a value that will vary from 0 to 1). Recycling companies according to their capacity for extracting materials to be used again will provide this recyclability ratio. This parameter will be considered as 0 when a material is not recyclable at all and will be set to 0.5 if it can be recycled in a mixture of different materials.

The recyclability ratios used in this report are based on the information provided by INDUMETAL and they could be updated in the future if recycling processes are improved. In this way, the eco-credit formula is valid also for the future, just by changing the given factor, since the physical value of the material is already assessed through the rarity indicator.

According to the circular economy principles, reuse is always preferred over recycling. The state of a product at its end of life is going to determine its reusability. This is included in the second term of equation 1. In contrast to the first term of the equation, where the value will take different numerical solutions depending on the composition of a LED or the electronic device, the EoL state value will only account for three different values: 1 if the device works perfectly, 0.5 if it is not working but can be repaired and 0 if it is not possible to repair the product.

In order to obtain this EoL value, during the disposal process in the intelligent bin, the user will be asked about the current state of the device (working or not working). This could be asked by means of the collecting bin or by means of the APP associated to the incentives developed in the project. Then, a technician will corroborate the information introduced by the user in the recycling facilities.

The third term of equation 1 is related to the used lifetime compared to the expected lifespan of a device. Two opposite approaches can be considered regarding this term. On the one hand, the newer a device, the higher its value and hence it is more cost effective to eventually fix it for reuse. That said, to incentivize the disposal of products with a short lifetime is against the circular economy principles because the longer time we use a product the lower is its overall environmental impact. On the other hand, the incentive system pretends to avoid stockpiling in households of products that are no longer in use because they will never be reused again (lower features, out of update, etc.). All of this is taken into account in the lifetime factor and its development is explained in section 2.4 of this deliverable according to five different models. In a similar manner to the EoL value, in order to obtain the incentives associated to the eco-credits, the users should provide the used lifetime by means of the collecting bin or the APP and then, a technician in the recycling facilities should confirm the information.

As it can be observed in the above formula the three different terms (rarity, EoL state and lifetime) are preceded by a factor, A/B/C that will allow giving the adequate importance to each of them. In order to link lifetime and environmental impact associated to the products, "C" value is equal to the eco-points. "A" and "B" could be fixed by policymakers, municipalities or alternative "incentive providers" in order to give a high relevance to the materials to be recycled or the current EoL state of the device (in order to foster reuse). For this report, A and B has been set to specific values (see the following sections) and C will be associated to the specific products according to the eco-points.

2.3 Thermodynamic rarity

2.3.1 Description

One of the main characteristics of every electronic system is its intrinsic need of using precious and scarce materials such as Ag, Au, Co, Ga, In, Mg, Nb, Pd, Pt or V, for transistors, semiconductors, capacitors, wiring, screens, etc. Many of these elements are considered also critical from very different perspectives as economic importance, ecological risk, vulnerability or supply.

A mass evaluation of these materials in electronic devices uses to lead to underestimate the relevance of scarce but valuable metals, commonly used in small quantities compared to other materials such as plastics or glass. In this respect, the Second Law of Thermodynamics allows us formulating an indicator able to measure the physical value of such materials. Such indicator is called thermodynamic rarity (Valero et al. 2013; Valero &

Valero 2014; Valero & Valero 2015) and contrary to a mass-based approach it gives more weight to valuable and scarce raw materials. One could think that avoiding the problem of "mixing apples with oranges" could be readily solved using a price-based approach. Indeed, prices use to give more weight to scarce materials. The problem with price is that it is volatile, because it depends on many factors alien to the physical reality of the material and is not a universal numeraire. In turn, the advantage of rarity over a price-based approach is that it is strictly based on physical aspects of the resource and is therefore stable and universal. Moreover, it shares with the price approach that it reflects well the social perception of "value". Accordingly, thermodynamic rarity allows us assigning properly numeric values to measure the low availability of some minerals as platinum, niobium or gold compared to other minerals with higher availability as silicon, iron or lead.

This methodology is based on the recognition that the physical value of minerals is mainly due to their chemical properties and their degree of scarcity in the crust. The scarcer a resource, the greater its extraction costs and these, in turn, increase exponentially as the ore grades become depleted. It is important to remark that this methodology, that owns some similar aspects to LCA methodologies, does not take into account all the steps from-cradle-to-grave (considering all the operations for assembling, using and disposal after use), but only considers the scarcity and the energy intensity to extract and refine the materials contained in a given device.

Thermodynamic rarity incorporates two aspects. The first and the most evident one is the **embodied exergy cost** (kJ), i.e. the useful energy required to extract and process a given mineral from the cradle to the gate (i.e., until it becomes a raw material for the manufacturing industry). The second is in fact an avoided cost for having minerals concentrated in mines and not dispersed throughout the crust (i.e. it can be seen as a natural bonus). As mines become depleted, it becomes exponentially harder to obtain commodities (embodied costs increase), whereas the bonus reduces. This bonus is calculated as a hypothetical exergy cost required if the given mineral would be restored to its initial conditions of composition and concentration in the original mines from a completely dispersed state. This is the **exergy replacement cost** (kJ) and can be seen as a grave-to-cradle-approach.

Both approaches, cradle-to-gate and grave-to-cradle, are equally important, as the first apprehends 1) efficiency, because embodied exergies indicate real energy expenditures that should be decreased in order to be cost-effective and 2) conservation, because it suggests through exergy replacement costs the preservation of minerals that are scarce.

The process to calculate the Thermodynamic rarity of a component according to its components (metals and non-metals) is developed in Appendix A.

2.3.2 Determination for tablets

As previously stated, thermodynamic rarity has to be calculated for each relevant component of the tablet. It is important to highlight that it would be possible to distinguish between different tablet models or manufacturers. In Appendix B, the thermodynamic rarity corresponding to different metals is already calculated, accounting for 52,011.3 kJ corresponding to 11.38 g of minor metals and 48.4 g of aluminum.

Additionally, according to Table 8, also plastic components and glass from screen account for a representative mass share. According to these data, 22.5 g of PMMA, 165 g of plastics (considered as ABS) and 62.02 g of silicon are additionally included in the rarity calculation.

From Appendix A we can obtain the rarity for silicon as 1.4 kJ/g. Additionally for PMMA and ABS the rarity can be considered as the HHV that could be considered as 26.75 kJ/g and 39.84 kJ/g respectively (Walters et al. 2000). According to these data, the final value for the thermodynamic rarity in an average tablets is considered as 59,276.7 kJ.

From the perspective of the reuse, in case the user provides to the recyclers a working or a reparable tablet, he or she would lead to avoid the extraction and manufacturing of the raw materials to build a new one so, the rarity in both cases will be considered as the whole value, 59,276.7 kJ.

From the perspective of recycling, in case the user provides a device that is neither working nor reparable, the only way to take advantage of it is to recycle their components. According to INDUMETAL suggestions, only PMMA (100% recyclability), plastics (95% recyclability) and some metals (Aluminum 85%, Iron, 100% and copper 100%) can be easily recycled. For these materials, a recyclability value of 1, 0.95, 0.85, 1 and 1 are respectively assigned for a_i.

Additionally, palladium, platinum, gold and silver, could be extracted together (mixed) so a value of 0.5 are provided to them for a_i. The rest of the raw materials are considered as non-recyclable so their value for the a_i is 0.

According to this, the first term of the equation 1 will be considered as 59,276.7 kJ when the tablet is working or reparable and 41,126.6 kJ whenever the tablet is not reusable.

2.3.3 Determination for LEDs

In a similar manner for Tablets, the rarity for LEDs can be also calculated according to its material composition. In Appendix B, the thermodynamic rarity corresponding to different metals is calculated for a 50W LED system, accounting for 4,839.9 kJ corresponding to 16.68 mg of minor metals, 13.62 mg of aluminum and 300 mg of Zinc. Additionally, 30 g of plastic (assumed as ABS) can be found in this kind of systems. According to these data, the final value for the thermodynamic rarity in an average 50W LED system is considered as 6040 kJ.

In a similar manner to tablets, from the perspective of reuse, the rarity for a working or reparable LED will consider as the whole value, 6,040 kJ for 50 W.

From the perspective of recycling, according to (Buchert M, 2012) Gallium can by recovered in a ratio of 40% meanwhile Indium and Yttrium are not recovered at all at this moment. Silver, Gold and Zinc can be recovered in the best case approximately in a ratio of 50, 80 and 50%. For Aluminum and ABS a 100% ratio has been considered considering the recyclability ratio for tablets, but no info is found in literature.

According to this, the first term of the equation 1 will be considered as 6,040 kJ when the LEDs are working or reparable and 3,944 kJ whenever is not reusable for a 50W system.

2.4 End-of-life (EoL) state determination

As previously stated, In order to obtain the EoL value, during the disposal process in the intelligent bin, the user will be asked about the current state of the device (working or not working). This could be asked by means of the collecting bin or by means of the APP associated to the incentives developed in the project. Then, a technician will corroborate the information introduced by the user in the recycling facilities.

According to the status, the EoL value in the second term of the equation 1 will be assumed as 1 if the Tablet or LED (or another kind of WEEE) is working, so it could be reused without any issue. Whenever the WEEE is reusable but with some reparations or operations the EoL value will be assigned as 0.5.

Finally, whenever the WEEE is totally broken and only is feasible to recover its materials, the EoL value will be 0.

2.5 Lifespan: Average lifetime and lifetime usage

As it was described in the previous section, lifetime seems to be a relevant parameter when reuse and recycling is considered. In this manner, it is necessary to find the expected average lifetime for WEEE devices. Lifespan is an essential parameter to estimate WEEE generation. It can be considered as a fixed parameter that represents an average value and gives an expectation of the time that an equipment is going to work properly without becoming obsolete.

After a literature review, one of the most accurate methodologies to foresee the lifespan of WEEE is the Weibull distribution. Weibull distribution function is able to represent a probability distribution that takes into account the different lifespans between individual owners and the dynamic nature of product obsolescence. In addition, it has been demonstrated to best fit the lifespan of most products (Parajuly et al. 2017; C.P. Balde et al. 2015; Balde et al. 2017; Wang et al. 2013). In fact this is the formula included in the Commission Implementing Regulation (EU) 2017/699 of 18 April 2017 that establishes a common methodology for the calculation of the weight of electrical and electronic equipment (EEE) placed on the market of each Member State and a common methodology for the calculation of the quantity of waste electrical and electronic equipment (WEEE) generated by weight in each Member State.

The Weibull distribution is defined by a time varying shape parameter α(t) and a scale parameter β (t) as is shown in the following equation 2:

$$L^{(p)}(t,n)= \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-[(n-t)/\beta(t)^{\alpha(t)}]} \quad Eq\ 2.$$

where α is the shape parameter (related to time-varying) β is the scale parameter, n is the evaluation year and t is the discard-based lifespan profile for the batch of EEE placed n the market n year t.

Due to social and technical factors (Federico Magalini et al. 2014), lifespan time can differ by product and country, so it is a time dependent term in the eco-credit equation. Some countries have this information available through consumer surveys, stock levels and the beginning and the end of a certain period and from sorting and sampling of the waste stream, however it is difficult to find governments that collect and publish this information and normally is out of date.

One of the main aims of including a lifetime factor into the eco-credit calculation is to avoid the storage of WEEE that are no longer used, rewarding users when they return the WEEEs as soon as possible because its value and the reuse capacity decreases with its age.

On the other hand, circular economy principles are in line with the extension of the lifetime of products as much as possible, thus fewer resources are needed. Thus, the goal is to incentivize the longest possible lifetime of a product and the fastest return once the product is not used, avoiding its storage in houses.

It is impossible to determine if a five-year-old tablet has been used during its whole lifetime or it has been used during three years and then stored the last two years. Due to this contradiction, five different forms for the lifetime factor have been analysed.

2.5.1 Approach 1: Weibull distribution

The first approach considered was the Weibull distribution as recommended in the Commission Implementing Regulation (EU) 2017/699 of 18 April 2017Lifespan data from France, Italy, Netherlands and Belgium have been obtained using consumer surveys (Wang et al. 2013; Balde et al. 2015; Balde et al. 2017). In the absence of more recent and detail data they have been included in the calculations performed in the present deliverable but if data were updated later they could be incorporated easily in the methodology. Data used for calculated lifespan profiles are shown in Appendix C.

Due to the related demo activities of the CIRC4LIFE project, where tablets and LEDs are considered as demo cases, the Weibull distribution for both are included in Figure 1 and Figure 2:

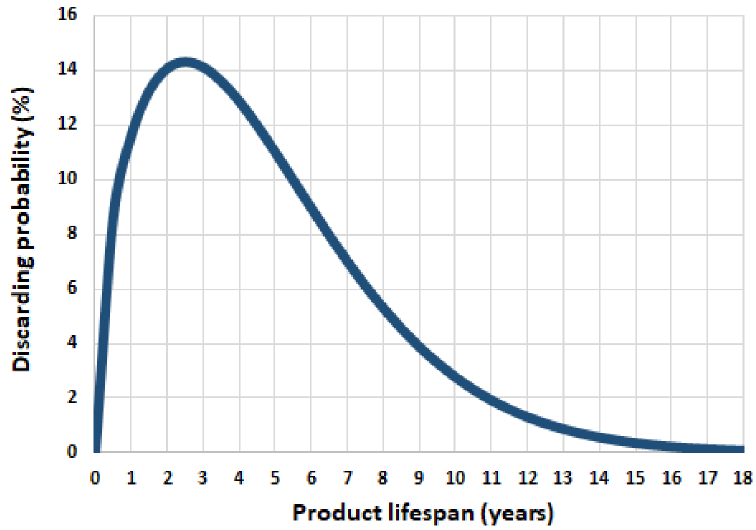

Figure 1: Weibull distribution for tablets, classified in the group 0303 with α=1.5 β=5.2.

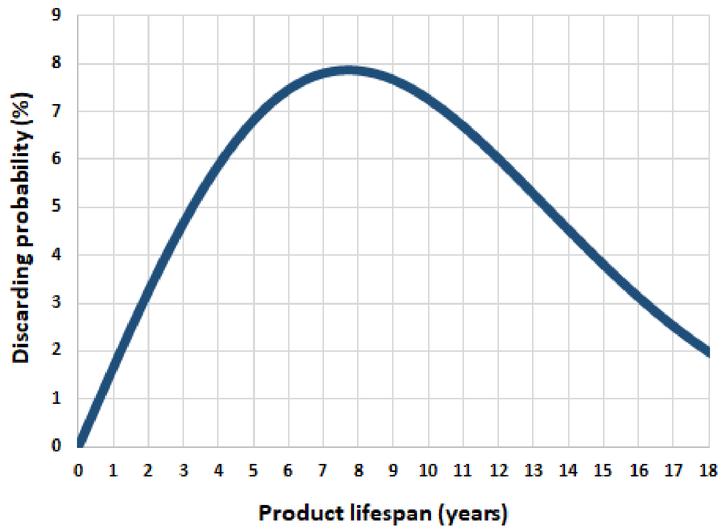

Figure 2: Weibull distribution for LEDs, classified in the group 0505 (LED lamps including retrofit LED lamps and household led luminaire) with α=1.2 β=4.57[2].

As can be observed, the maximum peak for tablets is around 2.5 years, then the function decreases until 17 years. In the case of LEDs the peak is found at 7.5 years and decreases until 27 years.

In both cases we can observe the peaks are extended for a long period, the reason is that the lifespan reported covers the interval between the shipment of a new product and the end point when discarded out of the house, including both the period of use and hibernation (Wang et al. 2013). Data including only the period of use have not been found in bibliography.

One of the main aims of the incentive scheme is to avoid the storage of WEEE that are no longer used, rewarding its deposition as soon as possible because its value decreases with its age. On the other hand, circular economy

[2] Data shown in table 12 and used in this figure for 0505 are obtained from(Wang et al. 2013) and correspond to the year 2005 in the Netherlands, as the original data in the table present by (Balde et al. 2015) do not make sense because the maximum of the peak is 1 year.

principles are in line with the extension of the lifetime of products as much as possible, thus less energy and resources are needed. Thus, our aim is to incentivize the longest possible lifetime of a product and the fastest deposit once the product is not used, avoiding its storage in houses. But it is impossible to determine if a five year old tablet has been used during its whole lifetime or it has been used during three years and then stored the last two years.

As can be observed in the above figures this option penalizes severely early returns before the expected lifespan and penalizes, but less, the return after the expected lifespan. For example, someone that uses a tablet during four years will be slightly penalise for using it longer than its expected lifespan and this will be against the circular economy principle of using something as long as possible.

Within this option, the lifetime factor of the equation 1 will be calculated by means of the Weibull distribution by following the next procedure. First, the Weibull distribution is obtained for the WEEEs (in this case for tablets and LEDs). Then this distribution is normalized between 0 a 1. Finally, the normalized value is assimilated to the lifetime factor in the equation 1. This is shown in the Figure 3 for Tablets (top) and LEDs (bottom) and the values are included in the Appendix D.

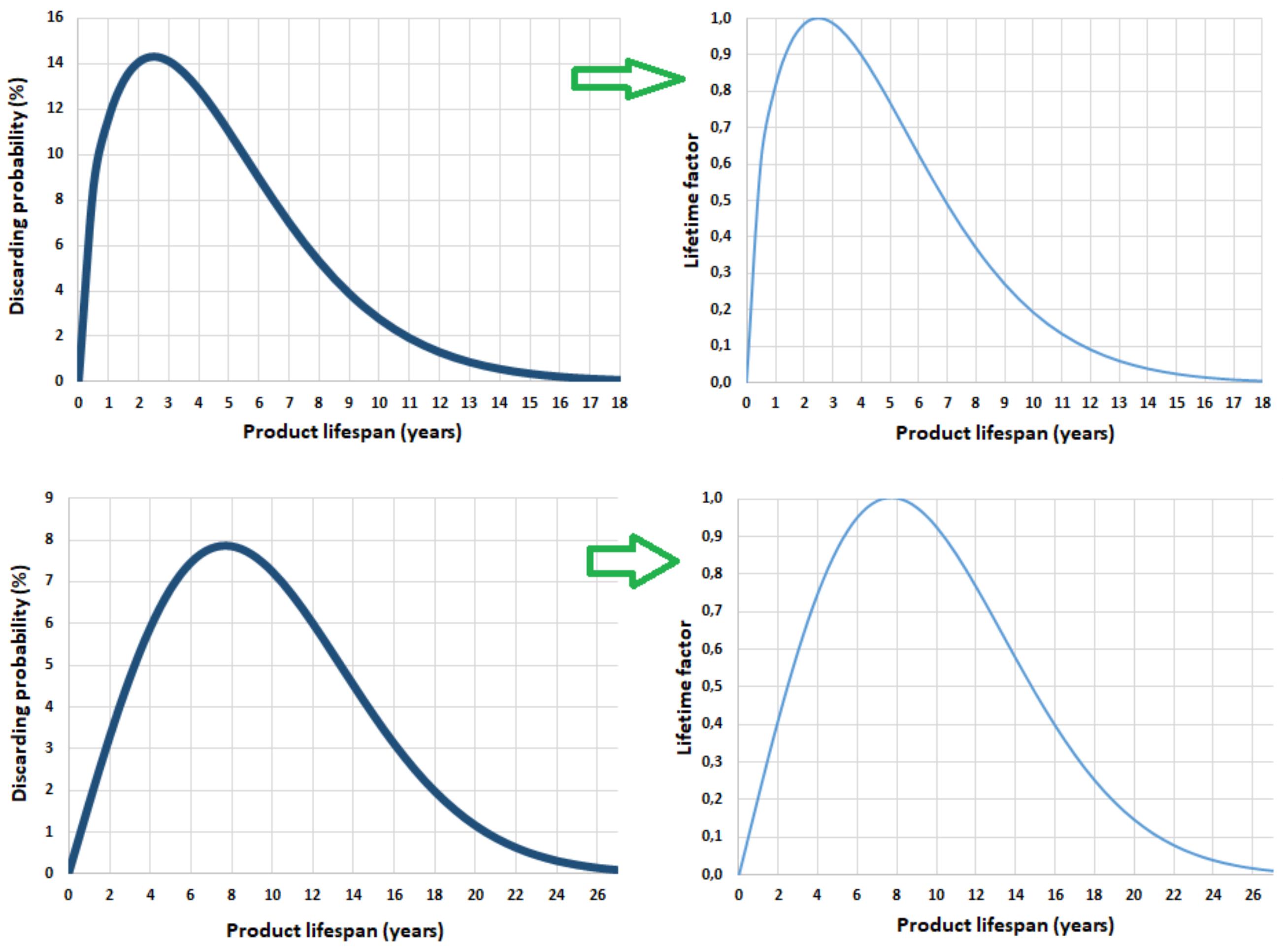

Figure 3: Approach 1. Lifetime factor calculation for Tablets (top) and LEDs (bottom).

This approach 1 is able to impulse late returns over early returns presenting the best value (and consequently providing the highest amount of eco-credits) at the expected lifespan. On the other hand, this approach is not supporting a longer use but the expected use.

2.5.2 Approach 2: Truncated Weibull distribution

This approach is based on a similar approach than the first one, but the lifetime factor is truncated at the maximum value, 1, in order to provide the maximum amount of ecocredits once the expected lifespan is reached.

The Figure 4 shows the lifetime factor for this approach for tablets and LEDs:

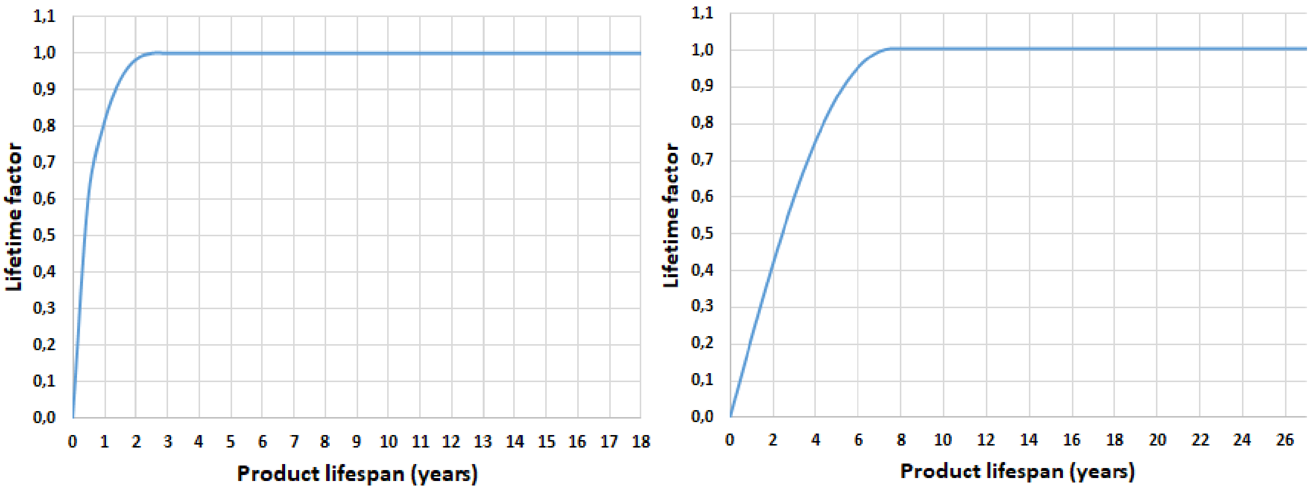

Figure 4: Approach 2. Lifetime factor calculation for Tablets (left) and LEDs (right)

By means of this second approach, someone that uses a WEEE for additional time over the expected lifespan will not be penalised. However, someone that uses that WEEE the expected lifespan and then stockpile it at home during additional years, will receive the same amount of eco-credits than another user that return it at the expected lifespan. Stockpiling WEEEs that we do not use anymore but are still working is a very extended behaviour and avoiding it is one of the main concerns of recycling and reusing centres. Avoiding stockpile of non-used products is also align with the circular economy principles because it possibilities the reuse. This approach is discarded because it could support stockpiling.

2.5.3 Approach 3: Fixed standard life

Instead of using a normalized Weibull distribution for calculating the lifetime factor, the approach 3 considers a standard life for a specific device and then according to the Equation 3 the lifetime factor will depend on the used time and that standard life:

$$lifetime\ factor = \frac{(used\ time - standard\ life)}{standard\ life}\ (Eq. 3)$$

In order to compare all the approaches, the standard life has been set to the expected lifespan provided by Weibull distribution for this report (3 years for a tablet and 7 year for a LED), but it could be set to another different value according to the manufacturers or recycling companies. As it can be observed in the Figure 5, this approach could provide negative and positive lifetime factors:

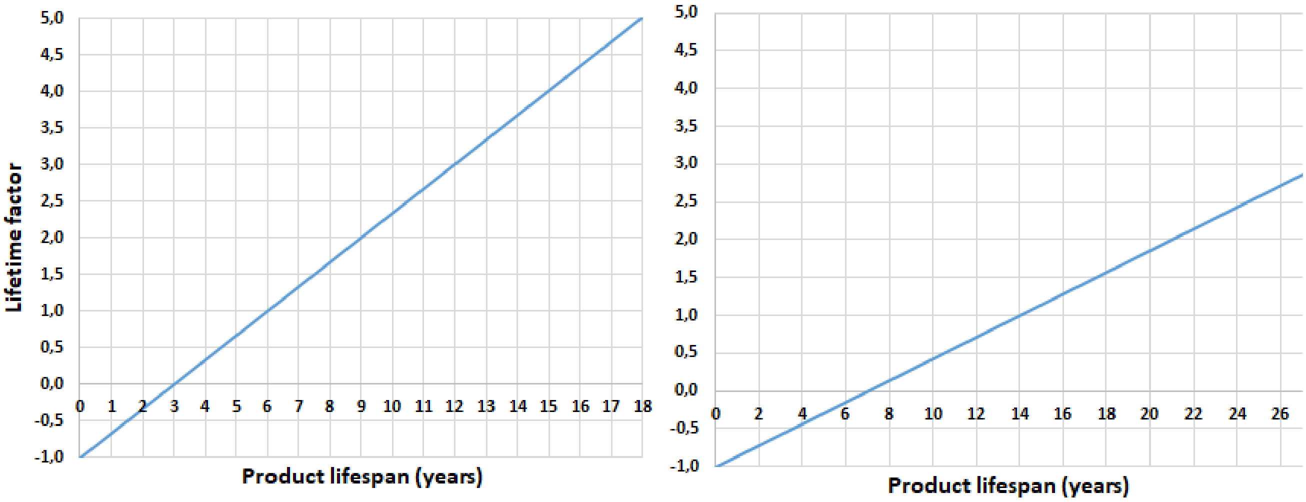

Figure 5: Approach 3. Lifetime factor calculation for Tablets (left) and LEDS (right).

This approach, as Weibull distribution does, provides a high penalisation when early returns are performed by the users (in this case with a negative value). On the other hand, a growing positive value will be obtained from the standard life, encouraging users to keep their devices as much time as possible.

This approach is interesting because provide additional eco-credits when consumers use more time their devices than expected but presents two possible failures. The first and the main one is that the approach 3 could be incentivizing people to retain WEEEs at home because the incentive could be higher than the one obtained if they dispose them when are not used anymore. This is against the principles of circular economy because this do not allow reusing and it is against the recycling companies that will expect to collect WEEEs as soon as possible. Additionally, this approach would provide negative values for eco-credits that could lead to misunderstanding due to the negative value of the eco-debits. For both reasons this approach is discarded.

2.5.4 Approach 4: Truncated fixed standard life

This approach is based on the same approach that approach 3, seeking for an approach that could provide additional eco-credits to consumers when they use more time than the expected lifespan their devices but trying to avoid guile behaviors where you keep your device at home because later I would obtained additional eco-credits.

In this manner, the lifetime factor is calculated as presented in the approach 3 but after 25% over the expected standard life, the lifetime value will kept constant. For Tablets, this is set in this report to 3.75 years (rounded up to 4 years) and for LEDS this set to 8.75 years (rounded up to 8 years). The Figure 6 shows this approach lifetime calculations:

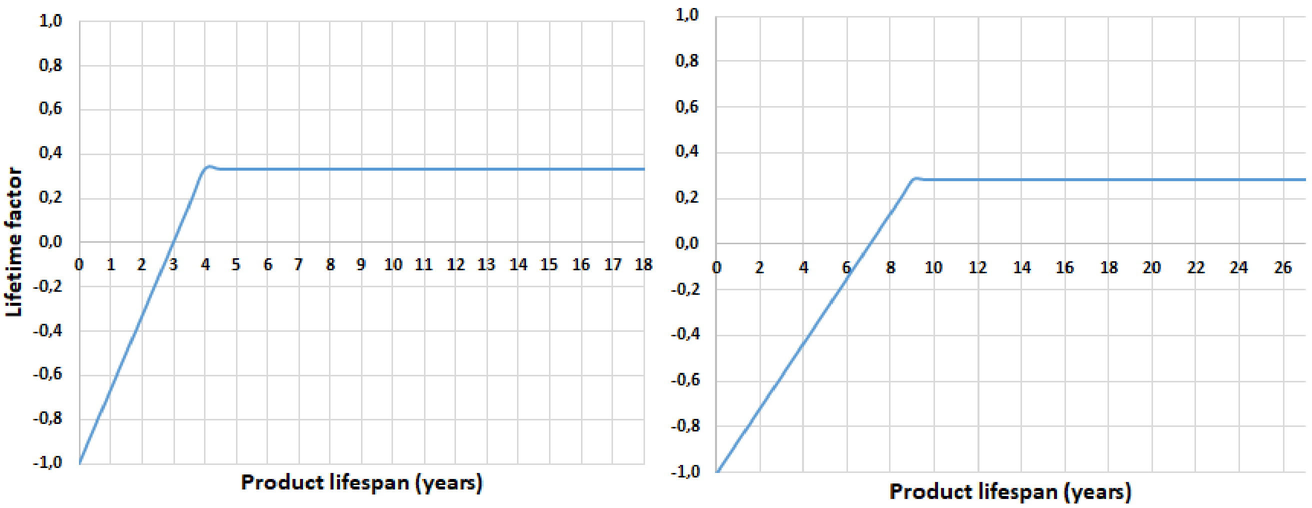

Figure 6: Approach 4. Lifetime factor calculation for Tablets (left) and LEDs (right).

As stated before, this approach rewards additional eco-credits when consumers use more time their devices than expected. On the other hand, as approach 3, it presents two drawbacks. The first one is the same presented by approach 2, it could also encourage stockpiling because it doesn't mind if return my WEEE one year or three years after the extended expected lifespan because I'm going to obtain the same eco-credits. Additionally it also could provide negative eco-credits that could lead to confusion.

2.5.5 Approach 5: Modified Weibull distribution

Based on the previous 4 approaches this fifth option is considering the best part of all of them. On the one hand, approach 1 penalizes the stockpiling of WEEEs and penalizes profusely early returns. Additionally it always provide positive values for the lifetime factor so, no negative eco-credits could be obtained. On the other hand, approach 1 does not lead consumers to use more time a device than the expected lifespan.

Meanwhile, approach 4 incentivizes consumers to use more time than the expected lifespan a device but it could provide negative eco-credits and it could provoke stockpiling because once the extended lifespan is reach it always provide the same eco-credits.

In this manner, approach 5 uses the Weibull distribution, providing always positive values and penalizing early and very late returns but modified in a manner that the maximum lifetime factor could be obtained at the 125% value of the lifespan. In this manner, the consumers are invited to keep using their devices more time than the expected lifespan (and will invite to manufacturers to extend the durability of their devices) but avoiding stockpiling.

The values for the normalized modified Weibull distribution are included in the Appendix D. The modification has consist on increasing the maximum value for the Weibull distribution a 3% (1.03 at 3 years for tablets and 7 years for LEDs), then increasing linearly a 2% up to the 25% extra time (1.05 at 4 years for tablets and 1.05 at 9 years for LEDs). Then the original Weibull distribution values are moved from this 25% extra time one year. The lifetime values can be seen in the Figure 7:

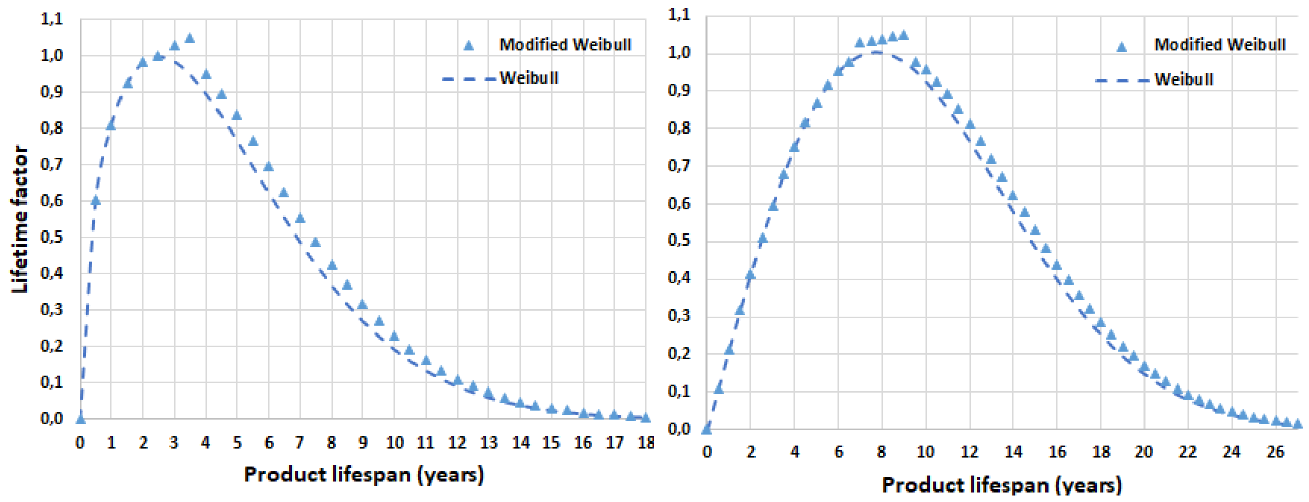

Figure 7: Approach 5. Lifetime factor calculation for Tablets (left) and LEDS (right)

2.6 Eco-credits calculation: Determination of A, B and C parameters

Once the three terms of the equation 1 have been defined can calculated for LEDs and Tablets in the sections 2.3, 2.4 and 2.5, in this section 2.6 the weighting parameters A, B and C will be determinate. The values for these parameters will allow promoting one or other term.

In general, it is possible to see that the first term of the equation 1, the rarity one, presents values 3 or 4 order of magnitude higher than the second and third terms of the equations that can only present values from 0 to 1.05. The relations between A, B and C should have into account this fact.

The approach of this report was to give similar importance to the three terms. Considering the order of magnitude difference, the first parameter A should be chosen in a manner that could equalize this difference, so the first term of the equation have to be divide by 10^4. The second parameter to be set, B, has been considered in a range of 1 to 10 due to the values that can present EoL (0 to 1). Setting the exact values for A and B is arbitrary and can be provided by the entities who will provide incentives associated to Eco-credits (depending on their interest in weighting the three terms of the equation) or be set under another criteria. These parameters, A and B, are multiplying terms that do not depend on time so, A and B' values will only change the cross with the ordinates in a figure where Eco-credits against time are represented.

For this report, the values for A and B have been set following these requirements: The eco-credits awarded at the maximum value presented by the lifetime factor term for the approach 5 by a working WEEE are a 10% higher than the eco-credits awarded for a reparable WEEE. Additionally, the difference between working and broken WEEE should be a 25%. Applied to Tablets and LEDs this will happen at 4 and 9 years respectively.

Considering that the third term of the equation is related to the used lifetime, the C value was set to the eco-points associated to the analysed product. In this manner, the environmental impact was linked to the used lifetime compared to the expected lifespan.

According to the previous reasoning, the equation 1 for WEEEs can be lightly modified resulting in the general equation 1':

$$Eco-credits = A \cdot \sum_{i=1}^{n} a_i\, rarity_i + B \cdot EoL \text{ state} + Eco-points \cdot lifetime\ factor\ (Eq.1')$$

By following, the values for A, B and C are obtained for Tablets and LEDs and a comparison between the 5 approaches, in terms of eco-credits calcuations, are shown.

2.6.1 Determination of A, B and C for tablets

As stated in the section 2.3.2, the first term of the equation 1’ for a working or reparable tablet was set to 59,276.7 kJ, meanwhile for a broken tablet was set to 41,126.6 kJ. This term has to be multiplied by a parameter A.

In a general way, the second term of the equation 1’ for a working, reparable and broken tablet were set to 1, 0.5 and 0 respectively. This second term has to be multiplied by a parameter B.

The third term of the equation 1’ for a tablet is composed by the eco-points and the lifetime factor. The lifetime factor for each approach is included in the figures 3 to 7. The eco-points for tablets will be calculated by means of the methodology shown in the Deliverable 1.3. At the moment of writing this report, specific eco-points values for tablets are not calculated in the framework of the project. In order to provide representative values for eco-credits that could help to understand the application of the methodology, an arbitrary value of 15 has been used for tablets. Therefore, the **value of C has been set to 15**.

According to the reasoning of the section 2.6, the **values for A and B** that would allow a 10% difference between working and reparable tablets and 25% between working and broken tablets **are $1{\cdot}10^{-4}$ and 5 respectively**.

In the figures 8 to 10 the eco-credits awarded by the chosen approach, the fifth, compared to the others are shown for working, reparable and broken tablets.

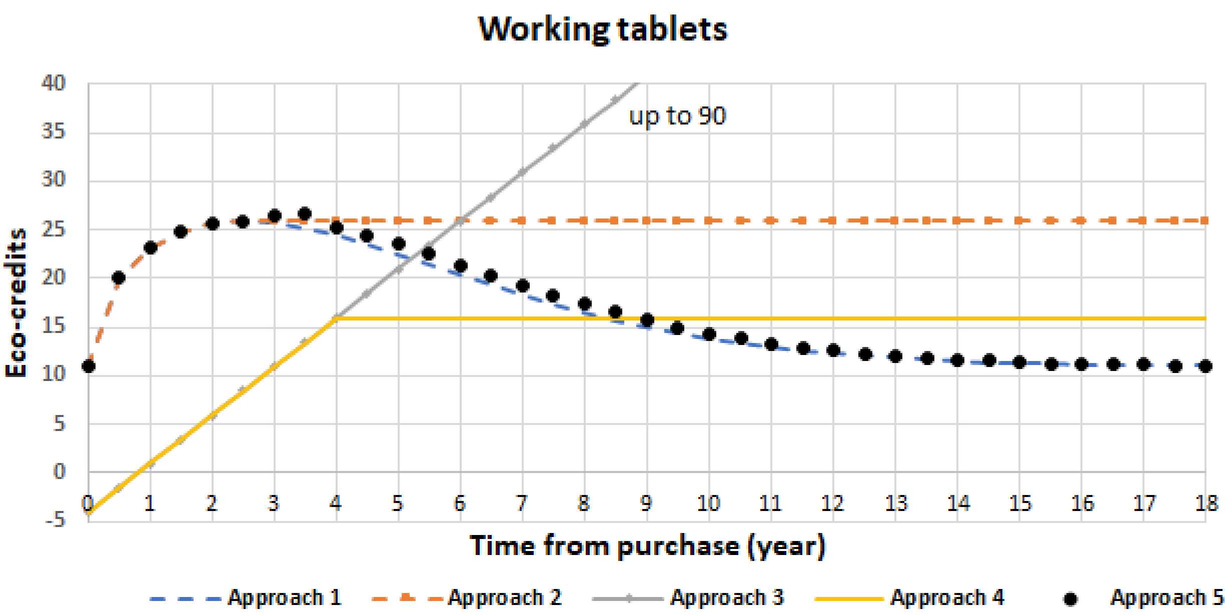

Figure 8: Eco-credits awarded for working tablets. Approaches comparison.

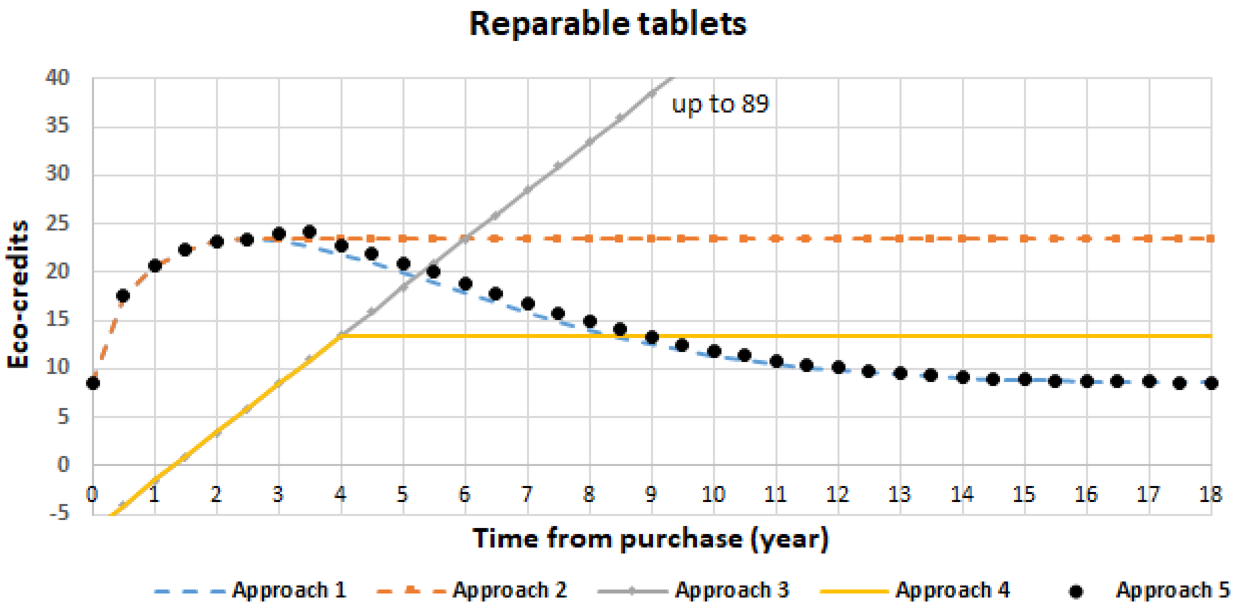

Figure 9: Eco-credits awarded for reparable tablets. Approaches comparison.

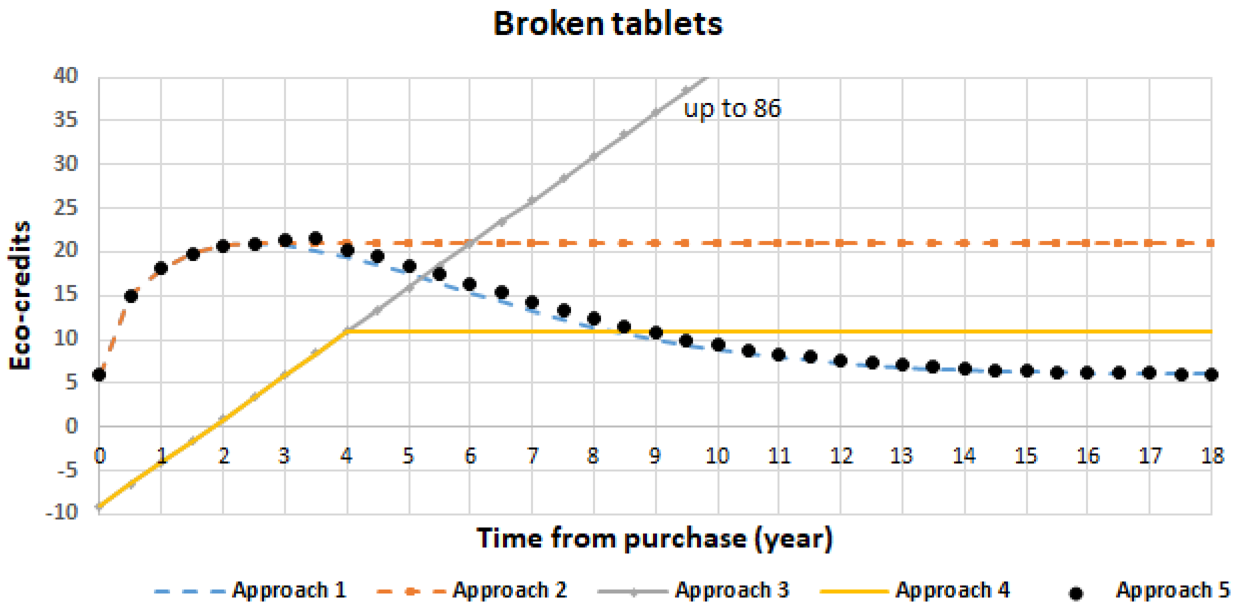

Figure 10: Eco-credits awarded for broken tablets. Approaches comparison.

2.6.2 Determination of A, B and C for 50 W LEDs system

As stated in the section 2.3.3, the first term of the equation 1' for a working or reparable 50W LED system was set to 6,040 kJ, meanwhile for a broken systems was set to 3,944 kJ. This term has to be multiplied by a parameter A.

In a general way, the second term of the equation 1' for a working, reparable and broken LED system were set to 1, 0.5 and 0 respectively. This second term has to be multiplied by a parameter B.

The third term of the equation 1' is composed by the eco-points and the lifetime factor. The lifetime factor for each approach is included in the figures 3 to 7. The eco-points for LEDs will be calculated by means of the methodology shown in the Deliverable 1.3. At the moment of writing this report, specific eco-points values for LEDs are not calculated in the framework of the project. In order to provide representative values for eco-credits that could help to understand the application of the methodology, an arbitrary value of 8 has been used for a 50 LED syste,. So, the **value of C has been set to 8**.

According to the reasoning of the section 2.6, the **values for A and B** that would allow a 10% difference between working and reparable 50W LEDs systems and 25% between working and broken **are $5 \cdot 10^{-4}$ and 3.8 respectively**.

In the figures 11 to 13 the eco-credits awarded by the chosen approach, the fifth, compared to the others are shown for working, reparable and broken 50W LEDs system.

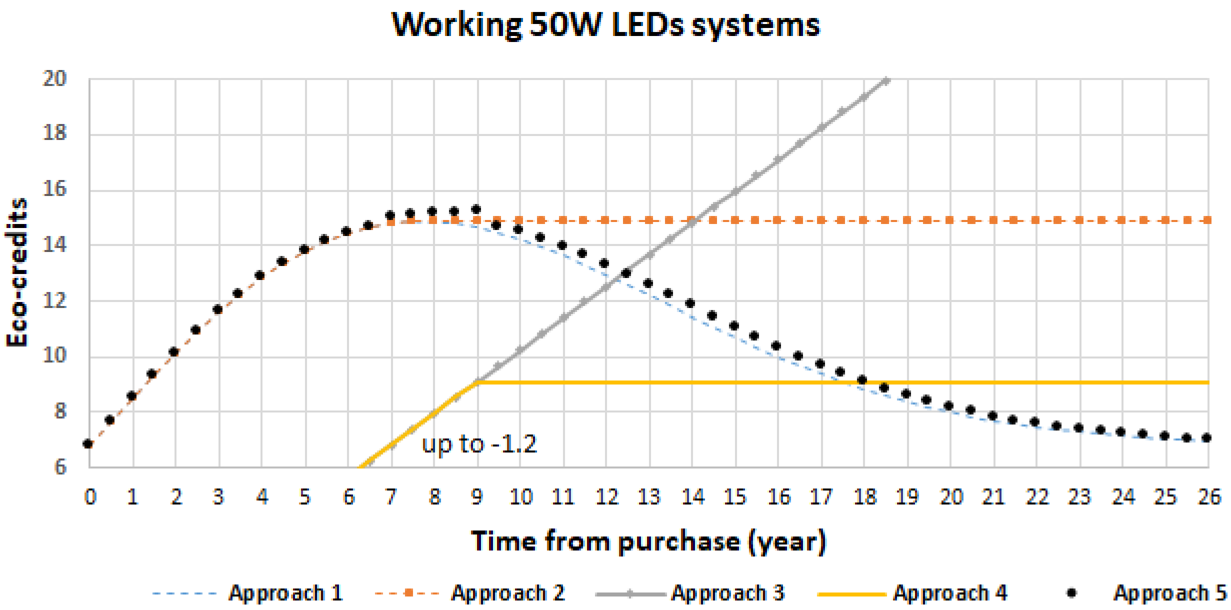

Figure 11: Eco-credits awarded for working 50W LEDs systems. Approaches comparison.

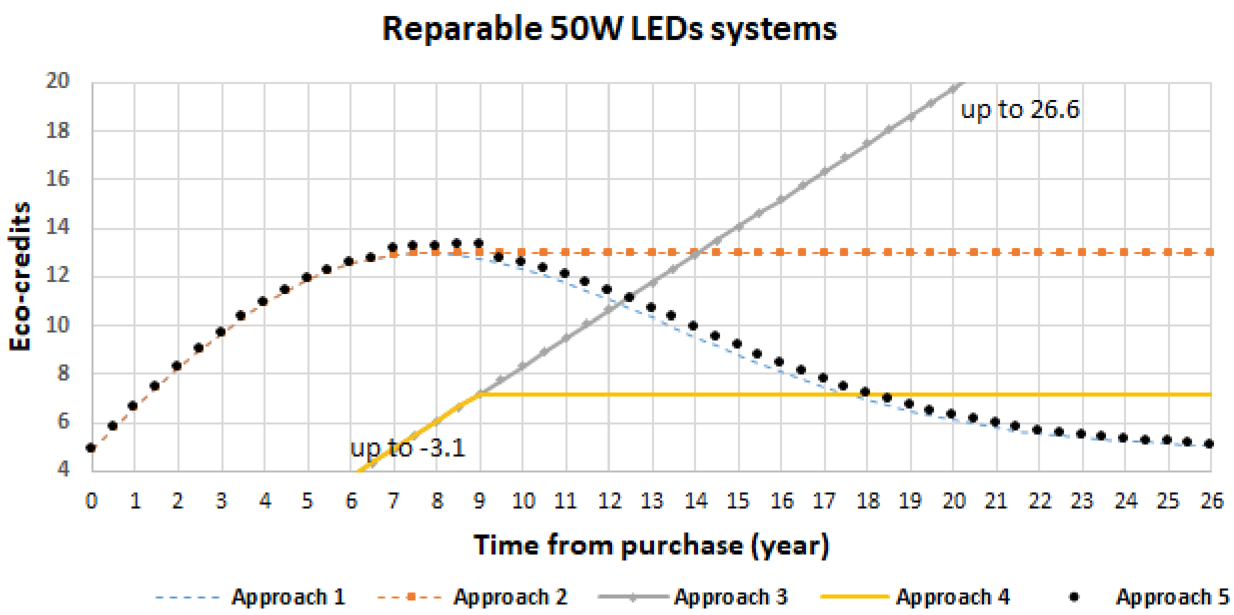

Figure 12: Eco-credits awarded for reparable 50W LEDs systems. Approaches comparison.

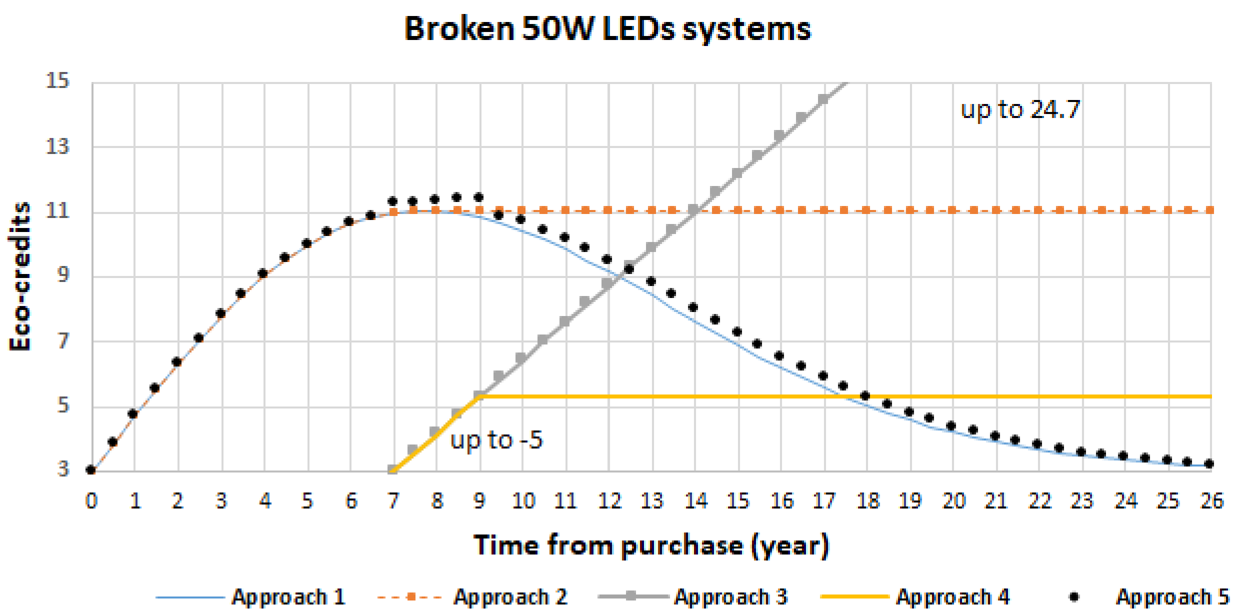

Figure 13: Eco-credits awarded for broken 50W LEDs systems. Approaches comparison.

2.6.3 Repairing application

The methodology to evaluate eco-credits was initially designed as a method to increase the collection ratio of durable items with rare or scarce raw materials, more oriented to collaborative recycling and reuse CEBM. Nevertheless, repairing also avoid raw materials (even though partially, depending on whether it is a repairing or a complete substitution of pieces) so, eco-credits could be also applied to repair.

Considering the current definition, the most similar approach is to consider the scenario where the item is collected as disposal and is repairable to be sold again as a second hand (refurbished) good. In this case, considering that the item, once is repaired, could be also providing eco-credits once is disposed at its end-of-life, the calculations for eco-credits under this application will provide half the eco-credits than the total amount provided under a repairable scenario (see above sections).

2.6.4 Examples of application

Once the methodology for calculating eco-credits have been developed and calculated for Tablets and 50W LEDs systems, by following some hypothetical but foreseeable example cases have been included in order to evaluate the eco-credits, and under the 15/8 eco-points assumption, to check the eco-account balance results.

Case 1: My tablet is completely broken by my fault after 10 months of use

	Eco-debits	Eco-credits	Eco-account balance
Result	-15	16.87	1.87

Case 2: My 50W LEDs system is broken/working after 9 years of use.

	Eco-debits	Eco-credits	Eco-account balance
Result	-8	11.42 / 15.22	3.42 / 7.22

Case 3: I want to change my tablet after 1 year of use but it is working

	Eco-debits	Eco-credits	Eco-account balance
Result	-15	23.1	6.1

Case 4: My 50W LED system was working but after 8 years of use, I bought a new one. I forgot to return the old one to the collecting bin and now 3 years after I am not using it anymore.

	Eco-debits	Eco-credits	Eco-account balance
Result	-8	14.0	6.0

Case 5: I want to repair my 1.5 years old tablet

	Eco-debits	Eco-credits	Eco-account balance
Result	-15	19.4	4.4

3 Eco-credit evaluation for meat and organic urban residues.

3.1 Organic waste: definition, possibilities and directive

CIRC4LIFE project intents to reduce food waste by means of the creation of business opportunities. Within this project it was proposed to include the final consumers into the collection of expired meat in specific intelligent bins. If a specific separation of meat products is performed, the waste acquires an added value because it can be treated thought different recycling processes.

The rendering industry turns not eatable meat into valuable ingredients for a different range of industries as paints and varnishes, cosmetics or lubricants. Furthermore, protein recovery process and pet food manufacturing process are studied alternatives. However, as explained in detail in deliverable 2.2, the implementation of specific collection for meat waste from domestic users is bond to legislation barriers due to the loss of tracking and possible contamination of the waste. In the European directive 2004/41/EC (concerning food hygiene and health conditions for the production and placing on the market of certain products of animal origin intended for human consumption) and the subsequently transposed national laws this is included. According to this legislative barriers, the consortium proposed as alternative the collection of organic urban waste separated from regular household wastes.

Organic waste material can be treated by means of different processes. One of the most extended alternatives is composting, where the organic matter is transformed in a dark brown colloidal humus later applied as fertilizer. This allows recovering valuable plant nutrients for agricultural use, and improving soil properties. Another typical solution for organic waste is the production of biofuel using anaerobic digestion processes, called biomethanation. Furthermore, other solutions as direct incineration, algae, weeds or fish production may be adequate in some situations. In these cases different directives apply depending on the final process used.

Thus, our aim in this section is to adapt the eco-credit methodology to all types of organic waste, from organic urban fraction to meat or vegetables collected separately, without knowing in advance their final destination.

3.2 Methodology for calculating eco-credits for organic waste

To apply the proposed equation 1 to food or organic urban residues some adaptations are needed. First, the terms referring to the EoL state and the lifetime factor should be removed from the equation because they cannot be applied to organic waste.

In the case of meat if it is collected separately from organic waste, the EoL state of this kind of waste can be good or expired but it is impossible to perform a characterization of each bag deposited in the collecting bin. The EoL losses all its logical sense due to the lack of usefulness (it is no possible to reuse). The same reason applies to the lifetime factor. In this case, it would be possible to consider two different situations: if the waste was supposed to be a waste (for example peels, bones…) or if it is a waste due to a misuse. However, both situation will take place and again it is impossible to determine and quantify this for each bag deposited.

For organic urban waste disposal the final destination of the waste is not known in advance and a general term that represents the value of the organic waste is needed. For WEEE the concept of thermodynamic rarity has been explained, it takes into account the energy associated with conventional mining, beneficiation, smelting and refining process, plus the bonus of found minerals concentrated in nature (exergy replacement cost). However, exergy replacement cost has not been developed for its application to organic matter. Thus thermodynamic rarity of organic matter can be calculated directly by means of its chemical exergy. The chemical exergy is, as will be seen in the next section, a physical measure of its calorific value, which in turn is associated to its general chemical composition. The greater its carbon content, the greater its chemical exergy.

Thus, in order to apply equation 1 to organic waste, the following assumptions are needed. First, the second and third term are removed from equation, second the first term is replaced by the chemical exergy. According to these changes equation 1 is transformed for organic matter (urban residues or food) into equation 3:

$$Eco - credits = D \cdot b_{ch,organic\ waste} \cdot m_{organic\ waste}\ Eq.3$$

The coefficient D will be responsible to convert the energy contained in the wastes into the incentive given to the final user and it can modified and adjusted to different incentive programmes. D will be defined later according to the incentive scheme developed in task 2.5, and WP 6 tasks.

3.2.1 Organic urban waste chemical exergy calculation

As it has been previously defined in the Appendix A, the chemical exergy (kJ/kg) can be assumed as the HHV when molecular weight and Gibbs free energies are not calculable. In order to obtain the HHV for organic urban wastes it is necessary to characterize the residues. Due to the inherent characteristic of this kind of residues (influenced by the social condition, food habits, family structures, etc.), in every urban environment and household, the composition of the organic waste will be different. Due to the impossibility of analyzing every bag deposited in the intelligent bins, an average composition for organic municipal solid waste must be considered. Average values of the elemental dry composition of organic fraction of municipal solid waste from 18 cities in 12 different countries are averaged in (Campuzano and González-Martínez 2016). The chemical composition assumed as average corresponds to C= 46.6 (%), H= 6.6 (%), N=2.9 (%), S=0.3 (%), Ash =10 (%) and O=33.6 (%).

Once the chemical composition is known, the HHV can be estimated as a function of its elemental composition using different approaches (Khuriati et al. 2017). Among the different equations Steuer's equation has been chosen in this methodology because it gives the most conservative estimation in terms of energy values. According to this equation 4, the average HHV value for urban organic waste can be assumed as 20,140 kJ/kg

$$HHV\ \left[\frac{kcal}{kg}\right] = 81\left(C - \frac{3 \cdot O}{8}\right) + 57\left(\frac{3 \cdot O}{8}\right) + 345\left(H - \frac{O}{16}\right) + 25 \cdot S - 6(9H + W)\ Eq.4$$

where C, O, H and S are the corresponding dry %wt and W the %wt of water.

3.2.2 Chemical exergy calculation for food

The previous equation (3) can also be applied for specific types of food waste (i.e. meat or vegetables) by means of calculating their chemical exergy. Due to the lack of literature in this topic, in this case and as a first approach, for this methodology the chemical exergy of food has been assumed as being equivalent to its calorific content.

In order to find the calorific content for each kind of food, the following food composition database (http://bedca.net/bdpub/) has been used. A snapshot of the database is included in the Figure 14.

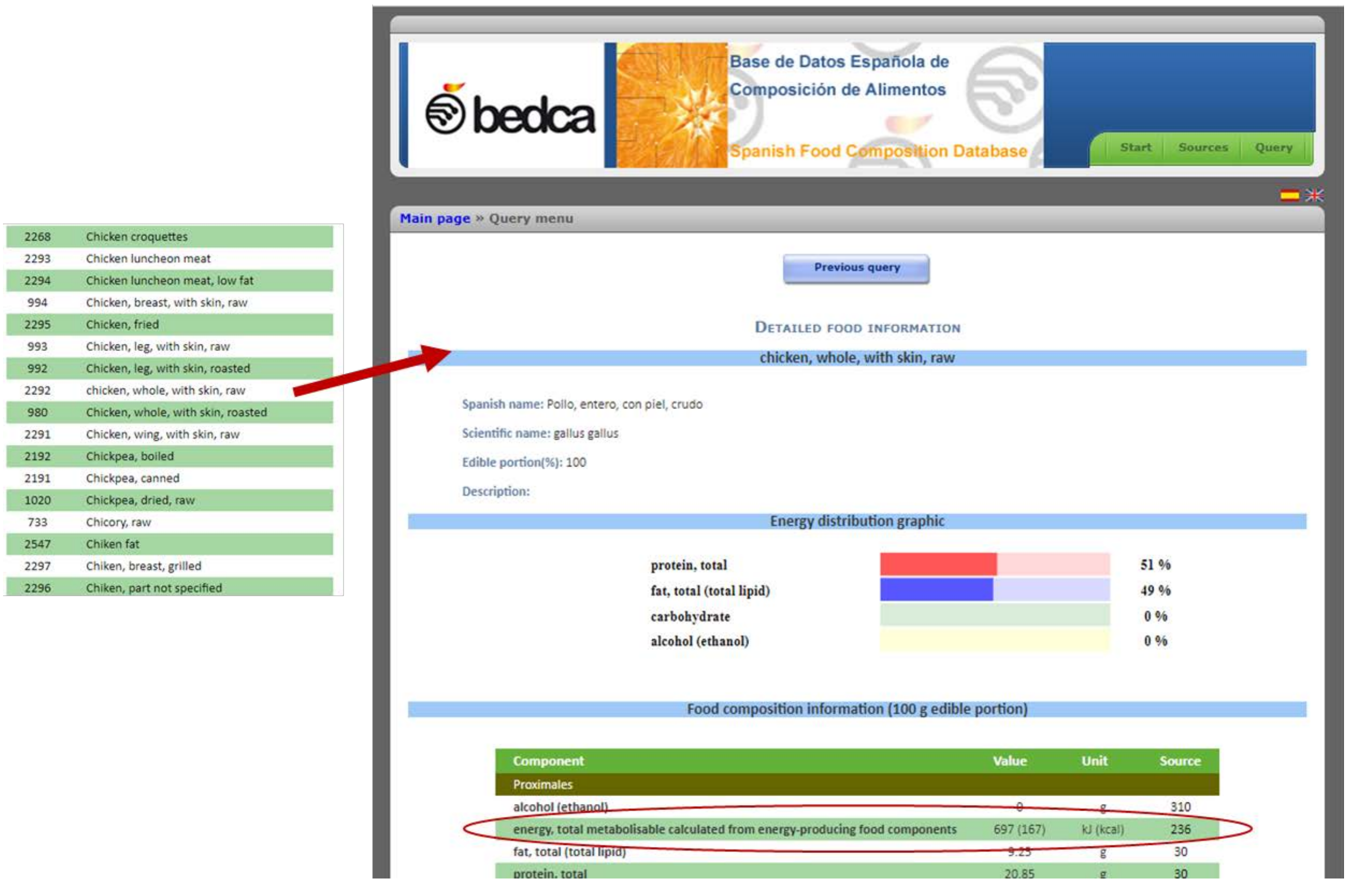

Figure 14: BEDCA's energy content and composition data for a whole chicken.

In the Table 1 the calorific content of different meat and food products is shown:

Table 1: Energy content for different food products obtained from BEDCA.

Type of food	Characteristics	Chemical exergy (kJ/kg)
Beef	Part non specified, raw	10,610
Chicken	Whole with skin	6,970
Pork	Part non specified, raw	11,330
Lamb	Part non specified, raw	14,750
Meat	Average value	10,975
Banana	-	3,720

As it can be observed the chemical exergy for food is quite lower than that of organic municipal solid waste.

As explained before the specific separation of meat gives an added value to the waste that is not represented by its chemical exergy. Thus, this benefit and the additional afford to the user has to be considered in the translation-into-economic-value term D. This term needs to be adjusted in accordance with the additional reward that can be provided in each scene, for example, in a specific separation of meat the reward that the meat recycler can pay.

In order to use this methodology for other specific organic wastes the value of the chemical exergy needs to be changed according to the values provided in table 2, for example:

Pork waste: Eco-credits [- or €] = D [€/kJ or 1/kJ] * 11,330 [kJ/kg] * weight of waste [kg]
Meat waste: Eco-credits [- or €] = D [€/kJ or 1/kJ] * 10,975 [kJ/kg] * weight of waste [kg]
Banana waste: Eco-credits [- or €] = D [€/kJ or 1/kJ] * 3,720 [kJ/kg] * weight of waste [kg]

Table 2 shows eco-credits obtained for organic and meat waste according to different values of D:

Table 2: Eco-credits obtained for organic wastes in different schemes

Municipal organic waste		
D (€/kJ) or (1/kJ)	Weight (Kg)	Eco-credit (€ or -)
1,00 E-06	0.5	0.01
	1	0.02
	2	0.04
	3	0.06
	4	0.08
	5	0.10
3,00 E-06	0.5	0.03
	1	0.06
	2	0.12
	3	0.18
	4	0.24
	5	0.30
5,00 E-06	0.5	0.05
	1	0.10
	2	0.20
	3	0.30
	4	0.40
	5	0.50

Food				
D (€/kJ) or (1/kJ)	Weight (Kg)	Eco-credit pork (€ or -)	Eco-credit Meat (€ or -)	Eco-credit Banana (€ or -)
5,00 E-05	0.1	0.06	0.05	0.02
	0.2	0.11	0.11	0.04
	0.3	0.17	0.16	0.06
	0.5	0.28	0.27	0.09
	1	0.57	0.55	0.19
	2	1.13	1.10	0.37
1,00 E-04	0.1	0.11	0.11	0.04
	0.2	0.23	0.22	0.07
	0.3	0.34	0.33	0.11
	0.5	0.57	0.55	0.19
	1	1.13	1.10	0.37
	2	2.27	2.20	0.74
5,00 E-06	0.5	0.17	0.16	0.06
	1	0.34	0.33	0.11
	2	051	0.49	0.17
	3	0.,85	0.82	0.28
	4	1.70	1.65	0.56
	5	3.40	3.29	1.12

In the case of municipal organic waste a value of D in the order of 10^{-6} is recommended so that eco-credits can be directly transferred to incentives. The specific determination of D needs to be done according to the possibilities of each incentive scheme. A value of D around $3 \cdot 10^{-06}$ may be adequate in order to boost a selective pick up and deposit of organic wastes.

The user effort is much higher in the case of a selective deposit of meat waste. Furthermore the amount of waste expected in each deposit is lower. To compensate this the term D needs to increase to an order around 10^{-4}.

4 Conclusions

A methodology for the calculation of eco-credits has been developed and has been applied to tablets, LEDs, organic urban waste and specific food wastes.

This methodology takes into consideration the most important aspects concerning the recycling and reuse stage of products. It can be applied to all types of products and in the present deliverable its application to WEEEs and food waste has been explained in detail.

The results provided by this methodology are dimensionless and need to be fixed to convert the Eco-credits into the incentive given to the final user. This term can be modified according to the resources of the different sites and, during CIRC4LIFE project will be defined later according to the development of task 2.5 and WP6.

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Appendixes

A. Embodied exergy costs and exergy replacement costs calculations

Embodied exergy costs are obtained from the literature, assuming the average values of prevailing technologies for each commodity (Valero & Valero, 2014). In order to calculate exergy replacement costs, one should first define a baseline reference with which the current state of mineral deposits will be compared. That reference should be assimilated to a dead state of "zero utility" and as universal and stable as possible. (Valero & Valero, 2014) proposed "Thanatia" as the baseline, which represents a resource-exhausted Earth where all mineral deposits have been extracted and dispersed. The so-called crepuscular crust is composed of approximately the 300 most abundant minerals in the upper crust, with relative compositions and concentrations. For the current state of mineral deposits, the average weighted values of ore grades across the world were obtained, mainly derived from (Cox & Singer, 1992). Considering that each element is obtained from a single type of ore (e.g., for copper: chalcopyrite), and knowing the concentration of the given mineral in Thanatia (x_c) and that in the average mines (x_m), the exergy replacement cost for mineral i (b_{ci}*) is calculated as:

$$b_{ci}^{*} = k \cdot \Delta b_{ci}$$

$$\Delta b_{ci} = b_{ci(x=x_c)} - b_{ci(x=x_m)}$$

$$b_{ci} = -RT_0 \left[lnx_i + \frac{(1-x_i)}{x_i} ln(1-x_i) \right]$$

Starting with the last equation, b_{ci} is the concentration exergy and represents the exergy required to separate a given substance from a mixture. In our case, a given mineral from the ore. In the equation, R is the universal gas constant (8314 kJ/kmol K), T_0 is the temperature of the reference environment (298,15 K), and x_i is the concentration of the analysed mineral i, measured in grams of mineral per gram of ore. The difference between the concentration exergy obtained with x_i being Thanatia's concentration of the mineral (x_c) and with x_i being the ore grade of a given mine (x_m) is called "replacement exergy", denoted Δb_{ci}, and it represents the minimum energy (exergy) required to convert the mineral from the concentration in the Earth's crust (x_c) to the concentration in the mineral deposits (x_m). As exergy considers that processes are reversible and hence only provides minimum values, which are far removed from the societal perception of value, we must resort to exergy replacement costs (b_{ci}*). Hence, man-made processes that are irreversible require k-times the minimum exergy.

Variable k is a constant called unit exergy cost. It is the ratio between a) the real cumulative exergy required to accomplish the process of concentrating the mineral from the ore grade x_m to the commercial grade x_r and b) the minimum thermodynamic exergy required to accomplish the same process.

An implicit assumption in the methodology is, thus, that the same technology applies for concentrating a mineral from x_m to x_r as from x_c to x_m. Once exergy replacement costs of minerals are obtained, those of the element are calculated through their corresponding molecular weights. It is important to stress that thermodynamic rarity does not consider the distribution of materials in specific components. Materials can be homogenously spread throughout a whole system or found in almost the pure form in several components. This fact would certainly affect the recyclability of a device, but the rarity would remain the same.

In this manner we can calculate the Thermodynamic rarity of a whole system accounting for each of its parts and each of the minerals used:

$$R(A) = \sum_{i=1}^{n} m_i \, R_i$$

where R is the thermodynamic rarity, expressed in kJ/g, A the electronic system part, m the mineral mass (g) and i the metal assessed.

In the following Table 3, the rarity for some relevant metals, those that can be typically found in electronic devices and LEDS is included:

Table 3: Thermodynamic rarity of the metals mainly found in WEEE

Rarity	Ag	Al	As	Au	Cd	Cr	Cu	Fe	Hg	In
kJ/g	8,937	661	428	654,683	64,441	41	348	32	28,707	363,918
Rarity	Mg	Mn	Ni	Pb	Pd	Sb	Si	Sn	Ti	Zn
kJ/g	146	73	758	41	2,870,013	488	1.4	732	203	197

For plastics and wood, no exergy replacement costs are considered so thermodynamic rarity can be assimilated to their chemical exergy content, which in turn is almost equivalent to their High Heating Value (HHV) in case the materials are combustible.

B. Average material share composition for tablets and mobile phones

Table 4: Average PCB metals composition for cell phones (100 gr weight device). Different literature values.

	Ag	Au	Al	Cr	Fe	Ni	Cu	Zn	As	Cd	Sn	Hg	Pb	
PCB			1,030%	0,850%	5,890%	3,020%	1,770%	0,100%	0,006%	0,000%	0,084%	0,001%	0,580%	
			1,110%	0,069%	0,530%	1,470%	1,560%	0,220%	0,022%	0,001%	0,084%	0,004%	0,010%	
			0,640%	0,054%	0,710%	1,680%	1,270%	0,110%	0,007%	0,000%	0,140%	0,002%	2,700%	
			1,380%	0,440%	6,670%	2,160%	2,190%	0,300%	0,011%	0,046%	0,120%	0,004%	0,030%	
			1,580%	0,290%	1,960%	1,850%	1,650%	0,210%	0,022%		0,065%	0,005%	0,023%	
			1,410%	0,150%	0,480%	1,120%	1,810%	0,130%	0,090%	0,000%	0,071%	0,001%	0,051%	
	0,21%		0,260%		10,570%	2,630%	34,490%	5,920%			3,390%		1,870%	
	0,060%	0,0800%	0,610%		4,850%	2,540%	37,890%	1,820%			2,550%		1,230%	
							25,000%			0,000%			2,010%	
	0,200%	0,1200%		0,200%	0,660%	1,930%	41,800%				4,570%		0,190%	
		0,0450%				2,300%	66,000%							
	0,054%	0,0043%				0,396%	39,860%							
	0,027%	0,0880%				2,340%	37,930%				2,050%			
	0,106%	0,0065%			0,280%	0,390%	40,800%				3,390%		1,360%	
Average	0,1095	0,02456	0,5729	0,1466	2,32857	1,7019	23,8586	0,6293	0,0113	0,0033	1,1796	0,0013	0,7181	g

Data in Table 4 obtained from: (Tan et al. 2017; Kim et al. 2011; Jing-ying et al. 2012; Petter et al. 2014; Xiu et al. 2015; Maragkos et al. 2013; Yamane et al. 2011; Kasper et al. 2011; Hurst 2007).

Table 5: Average screen metals composition for cell phones (100 gr weight device). Different literature values.

	Cr	Ni	Zn	Cd	Hg	Pb
Screen	1,82	8,212	7,315	0	0	0,418
	3,317	10,715	9,985	0	0	2,528
	6,214	27,774	19,185	0	0,014	1,46
	2,744	13,765	9,347	0	0	1,028
	2,951	19,539	10,743	0	0,213	2,154
	4,715	17,437	9,505	0	0	0,849
	10,38	16,476	14,788	0	0	0,828
	10,229	4,34	5,332	0,327	0	3,396
	1,1	0	7,7	0	0	0,5
	0,107	0	0,05	0	0	0,32
Average	4,3577	11,8258	9,395	0,0327	0,0227	1,3481

Data in Table 5 obtained from: (Maragkos et al. 2013; Lin et al. 2009).

Table 6: Average PH metals composition for cell phones (100 gr weight device). Different literature values.

	Cr	Ni	Zn	Cd	Hg	Pb
PH	8,375	45,291	22,217	1,972	0,486	2,6
	6,304	8,241	7,01	2,577	0	2,249
	16,972	160,543	20,93	5,37	0	1,796
	39,581	20,065	8,441	4,864	0,022	84,281
	12,569	23,312	15,398	5,306	0	1,344
	6,527	11,721	8,131	4,783	0	1,818
	0	43,2	0	6,99	0	5,83
Average	12,90	44,62	11,73	4,55	0,07	14,27

Data in table 6 and table 7 is obtained from: (Maragkos et al. 2013; Nnorom & Osibanjo 2009).

Table 7: Average rarity for cell phones (100 gr weight device)

	Ag	Au	Al	Cr	Fe	Ni	Cu	Zn	As	Cd	Sn	Hg	Pb	TOTAL
PCB	0,110	0,025	0,573	0,147	2,329	1,702	23,859	0,629	0,011	0,003	1,180	0,001	0,718	
PH				0,013		0,045		0,012		0,005		0,000	0,014	
Screen				0,004		0,012		0,009		0,000		0,000	0,001	
Total [g]	0,11	0,02	0,57	0,16	2,33	1,76	23,86	0,65	0,01	0,01	1,18	0,00	0,73	31,40
Rarity [kJ]	979	16077	379	7	75	1333	8312	128	5	51	863	39	30	28277
Rarity contribution	3,46%	56,86%	1,34%	0,02%	0,26%	4,71%	29,40%	0,45%	0,02%	0,18%	3,05%	0,14%	0,11%	

Table 8: Average composition for tablets

	materials	Airis	Woxter	Wolder	BQ	Average
PCB	mix	21,3	25,6	29,6	36,1	28,15
Battery	mix	37	87,8	55,9	72,8	63,375
Screen	mix	42,8	87,2	64,5	54	62,125
Lamp	mix	0,7	0,6	0,3	1,1	0,675
Wire	PVC+Metal	0,9	1,9	1,3	2,3	1,6
Frame	Plastic	3,1	3,2	2,6	4,1	3,25
Housings	Metallic	38,4	58,5	42	52,9	47,95
Housings	Plastic	119,8	201,9	173,5	143	159,55
Diffusers	Film PET	10,6	16,9	10,2	11,8	12,375
Diffusers	PMMA	14,6	21,4	16,7	37,3	22,5
Small parts	Plastic	2,6	1,7	2,8	2,8	2,475
Small parts	Stickers	0,4	0,4	0,3	0,5	0,4
Small parts	Screws	0	0	0,2	2,1	0,575
Total		292,2	507,1	399,9	420,8	405

Table 9: Average PCBs composition for tablets (28.15 g average weight). Different literature values.

	Ag	Al	Au	Cr	Cu	Fe	Mg	Mn	Ni	Pb	Pd	Sb	Sn	Ti	Zn
PCB		1,36%			58,22%	6,89%				7,15%			7,88%		3,56%
			0,03%		16,63%	0,22%			0,41%	0,06%			0,31%		0,38%
		1,00%			26,40%				0,50%	4,40%			10,10%		2,30%
	0,0124%	1,01%	0,0044%		52,36%	3,38%		0,13%	0,15%	5,01%	0,0007%		10,31%		11,48%
		1,91%			56,34%	11,72%				4,60%			8,63%		4,12%
					5,35%	6,06%	1,36%			1,31%			2,92%		1,99%
		2,70%		0,12%	20,14%	8,10%			0,32%	1,97%		0,24%	1,40%		3,20%
	0,02%	3,78%		0,07%	2,85%	11,51%	0,60%	2,47%	0,14%	0,39%			0,69%		1,48%
	0,20%		0,12%	0,002	41,80%	0,0066			1,93%	0,0019	0,00%		4,57%	0,0065	
		1,03%		0,85%	1,77%	5,89%			3,02%	0,58%			0,08%		0,10%
		1,11%		0,07%	1,56%	0,53%			1,47%	0,01%			0,08%		0,22%
		0,64%		0,05%	1,27%	0,71%			1,68%	2,70%			0,14%		0,11%
		1,38%		0,44%	2,19%	6,67%			2,16%	0,03%			0,12%		0,30%
		1,58%		0,29%	1,65%	1,96%			1,85%	0,02%			0,07%		0,21%
		1,41%		0,15%	1,81%	48,00%			1,12%	0,05%			0,07%		0,13%
	Ag	**Al**	**Au**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Ni**	**Pb**	**Pd**	**Sb**	**Sn**	**Ti**	**Zn**
Ave (%)	**0,08%**	**1,58%**	**0,05%**	**0,25%**	**19,36%**	**8,02%**	**0,98%**	**1,30%**	**1,23%**	**1,90%**	**0,00%**	**0,24%**	**3,16%**	**0,65%**	**2,11%**
Ave (g)	**0,0218**	**0,4523**	**0,0148**	**0,0717**	**5,5552**	**2,3022**	**0,2811**	**0,3731**	**0,3527**	**0,5447**	**0,0001**	**0,0689**	**0,9064**	**0,1866**	**0,6064**

Data in tables 8 and 9 has been obtained from: (Zhang et al. 2018; F. Wang et al. 2017; Meng et al. 2018; Paulo et al. 2018; Meng et al. 2017; Yang et al. 2017; Tan et al. 2017; Maragkos et al. 2013; Tadeua De Almeida & Borsato 2019; Pinho et al. 2018) and from INDUMETAL.

Table 10: Average screen composition for tablets (62.13 g average weight). Different literature values.

	Al	As	In	Cd	Cu	Cr	Fe	Hg	Ni	Pb	Sb	Sn	Zn
Screen						18,2			82,12	4,18			73,15
						33,17			107,15	26,28			99,85
						62,14		0,14	277,74	14,6			191,85
						27,44			137,65	10,28			93,47
						29,51		2,13	195,39	21,54			107,43
						47,15			174,37	8,49			95,05
						103,8			164,76	8,28			147,88
				3,27		102,29			43,40	33,96			53,32
		346,00	530,00								24,00		
			406,80									78,38	
			219,20									33,41	
			206,00									32,17	
			204,20									30,10	
			189,40									28,75	
	420,00		200,00		100,00	4,00	270,00		17,00			20,00	140,00
	7,78				15,98	220,00			169,00			762,00	
	Al	**As**	**In**	**Cd**	**Cu**	**Cr**	**Fe**	**Hg**	**Ni**	**Pb**	**Sb**	**Sn**	**Zn**
Ave (mg/kg)	**213,89**	**346,00**	**279,37**	**3,27**	**57,99**	**64,77**	**270,00**	**1,14**	**136,86**	**15,95**	**24,00**	**140,69**	**111,33**
Ave (tablet (g))	**0,0139**	**0,0225**	**0,0182**	**0,0002**	**0,0038**	**0,0042**	**0,0176**	**0,0001**	**0,0089**	**0,0010**	**0,0016**	**0,0091**	**0,0072**

Data in table 10 has been obtained from: (Maragkos et al. 2013; Silveira et al. 2015; Savvilotidou et al. 2014; S. Wang et al. 2017; Zhang et al. 2015; Zhang et al. 2017; Yang et al. 2013; Savvilotidou et al. 2015; Links et al. 2012).

Table 11: Average rarity composition due to metals for tablets and for LEDs (50W)

	Ag	Al	As	Au	Cd	Cr	Cu	Fe	Hg	In	Mg	Mn	Ni	Pb	Pd	Sb	Si	Sn	Ti	Zn	PMMA	ABS	Total
PCB (g)	0,022	0,452		0,015		0,072	5,555	2,302	0,000		0,281	0,373	0,353	0,545	0,000	0,069		0,906	0,187	0,606			
Screen (g)		0,014	0,022		0,000	0,004	0,004	0,018	0,000	0,018			0,009	0,001		0,002	62,020	0,009		0,007			
Housing (g)		47,950																					
Diffusers (g)																					22,500	165,000	
Total (g)	0,022	48,416	0,022	0,015	0,000	0,076	5,559	2,320	0,000	0,018	0,281	0,373	0,362	0,546	0,000	0,070	62,020	0,916	0,187	0,614	22,500	165,000	**121,82**
Total (kJ)	194,42	32.003,09	9,61	9.670,28	13,70	3,10	1.936,74	74,23	2,12	6.608,44	40,97	27,24	274,05	22,38	267,70	34,37	89,93	670,15	37,89	120,84	601,88	6.573,60	**59.276,7**
Rarity contribution	0,328%	53,989%	0,016%	16,314%	0,023%	0,005%	3,267%	0,125%	0,004%	11,148%	0,069%	0,046%	0,462%	0,038%	0,452%	0,058%	0,152%	1,131%	0,064%	0,204%	1,015%	11,090%	
Reciclability (%)	50	85	0	50	0	0	100	100	0	0	0	0	0	0	50	0	0	0	0	0	100	95	
Rarity recycling (kJ)	97,21	27.202,62	0,00	4.835,14	0,00	0,00	1.936,74	74,23	0,00	0,00	0,00	0,00	0,00	0,00	133,85	0,00	0,00	0,00	0,00	0,00	601,88	6.244,92	**41.126,6**

	Ag	Al	Au	Ga	In	Y	Zn	ABS	TOTAL	
[1]		13,62 mg								
[2]				1,920 mg	1,000 mg	0,032 mg		30 g	30 g	
[3]	10,11 mg		3,4 mg	2,45 mg			300 mg			
Promedio	10,11 mg	13,62 mg	3,35 mg	2,19 mg	1,00 mg	0,032 mg	300,00 mg		330,30 mg	
Total [kJ]	90,36318	9,284754	2222,07711	1649,299292	363,918	0,043425549	504,9	1200	6040	kJ
Rarity contribution	1,50%	0,15%	36,79%	27,31%	6,03%	0,00%	8,36%	19,87%		
recyclability	0,5	1	0,8	0,4	0	0	0,5	1		
recycling rarity	45,18159	9,284754	1777,661688	659,7197169	0	0	252,45	1200	3944	kJ

Data in table 11 (LEDs) has been obtained from: (Sangwan et al. 2014; Buchert M. 2012 and Umbeltbundesamt 2012)

C. Lifespan profiles for various EEE in the Netherlands, France and Belgium. Codes are in UNU-KEYs

Table 12: Lifespan for EEEs (Balde et al. 2015)

EEE Category	Lifespan distribution (Weibull)	
	α (shape)	β (scale)
1. Large household appliance		
0101	1.8	15.8
0102	1.6	13.1
0103	2.5	18
0104	2.2	13.9
0105	2.6	16.5
0106	2	13.5
0108	2.2	16.5
0109	2.6	23.2
0111	2.8	12.3
0112	2.4	13.6
0113	2.5	20.6
0114	0.8	14.7
2. Small household appliances		
0201	1.3	9.4
0202	1.3	12.3
0203	1.8	7.9
0204	1.5	10.3
0205	1.3	10.8
3. IT and telecom equipment		
0301	1.3	5.9
0302	2.1	9.6
0303	1.5	5.2
0304	1.7	10.1
0305	2.1	6.5
0306	0.7	7.6
0307	1.5	7.8
0308	2.2	8.5
0309	2.5	7.5
4. Consumer equipment		
0401	1.4	10..2
0402	0.8	8
0403	2.1	15.6
0404	1.7	10.5
0405	1.5	10.8
0406	1.4	8.2
0407	2	12.6
0408	2.1	12
5. Lighting equipment		
0501	1.4	8.72
0502	1.6	8.43
0503	1.9	8.43
0504	1.6	6.9
0505	2	10.9
0506	2.3	16.59
0507	2	11.84
6. Electrical and electronic tools		
0601	2	6.6
0602	1.9	11.6
7. Toys, leisure and sports equipment		
0701	2.6	15.7
0702	1.5	4.7
0703	1.2	5.6
8. Medical devices		
0801	2.4	11.6
0802	1.4	7.6
9. Monitoring and control instruments		
0901	2.6	19.2
0902	1.7	9.6
10. Automatic dispensers		
1001	1.9	11.6
1002	2	10.1

D. Normalized Weibull distribution values for tablets and LEDs depending on their lifetime.

Table 13: Normalizing process for lifetime factor for tablets and LEDs.

Time (years)	Normalized factor for tablets	Normalized factor for LEDs
0	0.00	0.00
1	0.81	0.21
2	0.98	0.42
3	0.99	0.60
4	0.90	0.75
5	0.77	0.87
6	0.63	0.95
7	0.49	1.00
8	0.37	1.00
9	0.27	0.98
10	0.19	0.93
11	0.14	0.85
12	0.09	0.77
13	0.06	0.67
14	0.04	0.58
15	0.03	0.49
16	0.02	0.40
17	0.01	0.32
18	0.01	0.25
19	0.00	0.20
20	0.00	0.15
21	0.00	0.11
22	0.00	0.08
23	0.00	0.06
24	0.00	0.04
25	0.00	0.03
26	0.00	0.02
27	0.00	0.01

Table 14: Normalizing and modifying process for lifetime factor for tablets and LEDs.

Time (years)	Normalized factor for tablets	Normalized factor for LEDs
0	0	0
1	0.81	0.21
2	0.98	0.42
3	1.03	0.6
4	1.05	0.75
5	0.9	0.87
6	0.77	0.95
7	0.63	1.03
8	0.49	1.04
9	0.37	1.05
10	0.27	0.98
11	0.19	0.93
12	0.14	0.85
13	0.09	0.77
14	0.06	0.67
15	0.04	0.58
16	0.03	0.49
17	0.02	0.4
18	0.01	0.32
19	0.01	0.25
20	0.00	0.2
21	0.00	0.11
22	0.00	0.08
23	0.00	0.06
24	0.00	0.04
25	0.00	0.03
26	0.00	0.02
27	0.00	0.01