151-0741-00L Sustainable Material - Dr. Lea Deillon

Sustainability Study of AirPods

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1 Abstract

This report is written in the context of Dr. Lea Deillon's Sustainable Materials masters course at ETHZ. The task at hand is to realise a case study of an existing product by identifying the components, estimating their emissions and resource consumption through a life cycle assessment and finally proposing design changes to the product to make it more sustainable. Our group chose to work on Apple's AirPods, a very popular model of truly wireless Bluetooth earphones. Following the guidelines of the project, we will first identify all the components of the AirPods, clearly identify the assumptions made to then conduct an LCA of both the AirPods and a self-proclaimed sustainable alternative, compare the results and suggest ways to reduce the impact of the earphones on the environment.

2 Introduction

In 2016, Apple did the unthinkable by removing the headphone jack on the brand new iPhone 7, the plug nearly everyone used to listen to music. Their solution to this new problem? A 180 $ pair of wireless earphones called the AirPods. Two years later, nearly every phone manufacturer had removed the head phone jack and offered equivalent Bluetooth earphones to the AirPods. Today AirPods are everywhere, with the sales of wireless ear bud rising from 48 million in 2018 to over 310 million in 2021 and Apple clearly leading with a quarter of the market share [1]. For perspective, if AirPods was a separate company from Apple, it would be a Fortune 200 company and generate 23 billion dollars of revenue in 2020, only 2 billion shy of Netflix's revenue and more than double of giants like Uber or Spotify [2]. This enormous popularity for an electronic device raises sustainability concerns, notably over their manufacturing impact and the e-waste they generate.

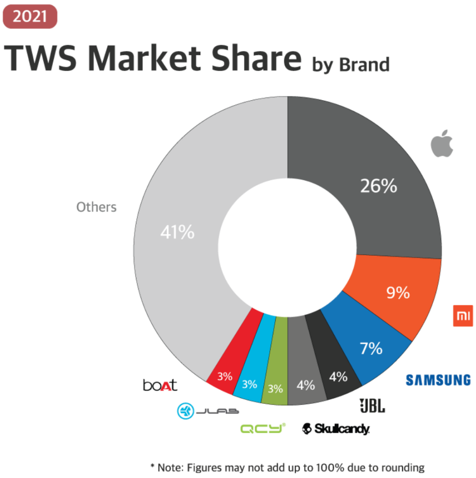


Figure 1: Global Market Share of Truly Wireless Earphones in 2021 [3]

Out of all the possible wireless earbuds, we chose to study the AirPods for a number of reasons. First of all they were the first mass market truly wireless earphones and have always been by far the most popular model. This makes them an icon and what we think of when talking about wireless earphones. Furthermore, Apple often boasts about its steps to make its products more sustainable and always details the way it does so when announcing new products. However this marketing tool bizarrely does not apply to the AirPods. They are in fact the only Apple product without an environmental report on their website that details the environmentally conscious parts of a given product. This hints at the fact that the AirPods are an inherently unsustainable product with not a single trait Apple can claim as being eco-conscious. This combination of very high popularity and complete lack of efforts towards the environment is why we chose to study the AirPods above any other model of wireless earphones.

Choosing to focus the study on AirPods however does not come without its challenges. Apple is a very secretive company that does not like to give any precise information as to where it sources its raw materials, the processes it uses to manufacture its products, or even how it ships them from its factories in China to its customers around the world. This makes the search for reliable data a real challenge and affects the accuracy of any calculation we make. To make up for the lack of data, we will make assumptions and approximations which we will clearly detail and from which we will try to estimate the corresponding error on our results when possible.

Another challenge in our study will be to understand the function of the many components of the

AirPods and evaluate how important they are to the quality of the product. As we know, Apple is a premium electronics company that markets sleek and feature rich products to justify their higher price tag. If we are to suggest improvements in design towards sustainability, we must take into account that Apple would not change their design if it were to affect the quality of its product. We must also be weary of the price of any change we make as Apple sells their product slightly above the average price of equivalent devices but still tries to stay competitive and would not pursue a change for environmental motivations if it were to significantly affect the price of manufacturing. Thus any change we propose will be done without compromising the features and functions of the AirPods and will respect the current price.

In this study, we will attempt to estimate the environmental impact of Apple's AirPods through the raw materials used, manufacturing processes used, shipping, use and end of life treatment. To complete such a thorough estimation of the impact of these earbuds, we will be using the life cycle assessment (LCA) software Granta EduPack ©. This software will detail the CO_2 emissions of each step of the product life and detail which components in the AirPods contribute the most to the environmental impact. On top of the LCA, we will attempt to understand the current refurbishing and recycling programs in place by Apple and third-party companies to see if there are any efforts to prolong the lifetime of a pair of AirPods and whether they are properly recycled or simply discarded. Following this, we will propose solutions to decrease the environmental damage of the AirPods. We will be looking at the materials and processes used but also the design to make the AirPods more repairable and more easily recycled. We will also study if simple software updates could potentially prolong the battery lifespan like Apple has done in the past for iPhones.

3 Overview on the system and its components

Before deep diving into an analysis of the environmental impact of Apple's AirPods, we must first gather a general understanding of the different components that make up AirPods, their function as well as the process with which they are manufactured. Seeing as this product is so complex and secretive we will also attempt to judge which components are important for the LCA and which can be neglected or approximated by a material.

3.1 Model of AirPods

Figure 2: All Models of AirPods (left: 1^{st} and 2^{nd} gen, middle: 3^{rd} gen, right: Pro 1^{st} and 2^{nd} gen [4]

Since 2016, Apple has released 5 different versions of AirPods: the AirPods 1st, 2nd and 3rd generation and the AirPods Pro 1st and 2nd generation. All of these models have a similar construction albeit with some minor design variation. The regular 1st and 2nd generation are nearly identical apart from a different chip and the addition of a wireless charging coil. With the introduction of the AirPods pro and now the third generation regular AirPods, Apple changed geometry and switched the long thin battery in the stem to a standard 'button' battery in the main body. This welcome changes most likely facilitates recycling as the earlier generation have a battery that is very difficult to extract from the thin stem. However, the 2nd generation AirPods with the older design are still on sale on Apple's website and are most likely the best selling model as they are cheaper than the third generation while having nearly identical features and are almost half the price of the more feature complete AirPod Pros. Furthermore, seeing as this is the oldest design, it is certainly the most produced design and is therefore the one we will focus on for this study. From now on, when AirPods are mentioned, it is to be assumed the first or second generation AirPods are concerned unless specified otherwise.

3.2 Components of AirPods

Figure 3: Disassembled AirPod [5]

Figure 4: Disassembled AirPod case [5]

As the images above highlight, inside the buds and the case are a complicated series of intertwined cables, microprocessors and larger electrical components like the battery surrounded by a white plastic casing. We opted to create a table regrouping all the main components of both the buds and charging case with a column for the material, the environmental impact, and the importance of the component. Knowing exactly what materials are in each component is sometimes difficult to find out, especially for electric component, which leads to some uncertainty in the cited materials. However, the major and most polluting materials of each component are always found: the uncertainty lies in secondary materials, like the plastics and small wires in sensors or chips, which have a small impact.

To get a general idea of the environmental impact we created the following tags:

- energy intensive: *EI*
- difficult to recycle: *DTR*
- limited resource: *LR*
- toxic material: *TM*

We assigned these tags to components based on common findings; for example electronic components are notoriously difficult to recycle thus they receive the DTR tag. It's important to note these characterisations are a bit arbitrary and do not go in depth into how polluting the components are: this will be done with the LCA. For now, the environmental impact column serves only to give a general idea of the problematic components of the AirPods and guide how they could be improved.

Similarly we created tags to identify how easily we could replace the concerned component with a more sustainable alternative. When attributing these, we considered that if we were to replace a part, the AirPods should maintain exactly the same functionality.

- Indispensable : *I*
- Limited alternatives: *LA*
- Easily replaced: *ER*

These criteria will be useful when trying to offer a more sustainable design to the AirPods It will guide us in what we can change and what must be kept to maintain the features that Apple currently has to offer.

Table 1: Components of AirPod bud [5],[6],[7],[8]

Category	Part	Material	Environmental Impact	Improvability
Outer Casing	White plastic shell	ABS	TM	ER
	Synthetic adhesive	PVA, Ethanol, Acetone	TM	ER
	Metal grills	Stainless Steel		ER
	Charging points	Stainless Steel		LA
	Internal rubber padding	synthetic rubber		LA
Power electronics	Battery (93mWh)	Lithium, Cobalt	TM, LR, DTR	LA
	Speaker	Nickel, Copper, Platic, Neodymium	DTR, LR	I
	Antenna	copper	DTR	I
Sensors	IR Proximity Sensor	Plastic, gallium arsenide, gold	LR, DTR	I
	Accelerometer (Bosch sensortec BMA282)	Silicium, platic	DTR, EI	I
	Gyroscope (STMicroelectronics gyroscope)	Silicium, platic	DTR, EI	I
	Microphones	Nickel, Copper, Plastic, Neodymium	DTR, LR	I
Logic Board and Other Electronics	Printed circuit board	Prepreg, Copper, Soldermask	DTR, TM	I
	W1 communication chip	Silicium, platic	DTR, EI	I
	Programmable system on a chip (Cypress CY8C4146FN)	Silicium, platic	DTR, EI	I
	Stereo audio codec (Maxim MAX98730EWJ)	Silicium, platic	DTR, EI	I
	DC-DC Converter (TI TPS62743)	Silicium, platic	DTR, EI	I
	Resistors	Carbon, ceramic	DTR	I
	Ribon cables	plastic and copper	DTR	I
	Connectors	gold, copper	DTR, LR	I

Table 2: Components of AirPod case [5],[6],[7],[8]

Category	Part	Material	Enviormental Impact	Improvability
Outer Casing	White plastic shell	ABS	TM	ER
	Synthetic adhesive	PVA, Ethanol, Acetone	TM, DTR	ER
	Aluminum hinge	Aluminum		ER
	Gasket	synthetic rubber	DTR	LA
	Magnets	Neodymium	EI, LR	LA
Power Electronics	Battery (398 mWh)	Lithium, cobalt	TM, LR, DTR	I
	Inductive charging coil	Copper	DTR	I
	Antenna	copper	DTR	I
	Lightning charging port	metal, plastic	DTR	I
Logic Board and Other Electronics	Printed circuit board	Prepreg, Copper, Soldermask	DTR, TM	I
	STMicroelectonics STM32L072 ARM Cortex-M0+ MCU	Silicium, platic	DTR, EI	I
	NXP Semiconductor CBTL1610A3 charging/port controller IC	Silicium, platic	DTR, EI	I
	Maxim Integrated MAX9028 1.8 V comparator	Silicium, platic	DTR, EI	I
	Texas Instruments BQ24232 power management IC	Silicium, platic	DTR, EI	I
	Maxim Integrated MAX9028 1.8 V comparator	Silicium, platic	DTR, EI	I
	AMS AS3441 power and communication interface	Silicium, platic	DTR, EI	I
	Resistors	carbon, ceramic	DTR	I
	Ribbon cables	plastic and copper	DTR	I
	Connectors	gold, copper	DTR, LR	I

From the two tables above, we can conclude the AirPods are almost entirely electrical components that cannot be eliminated or replaced by other components if the product is to maintain its set of features. Indeed nearly all the components hold the tag “Indispensable”, apart from the components of the outer casing of which there are only a few. Furthermore nearly all the components pose at least one threat to the environment. The main issue is the difficulty to recycle for a large part of the components; as we will now discuss, this problem is amplified by the difficulty to disassemble AirPods.

Another conclusion we can draw from the overview of the components concerns the tight packaging of all the components inside the AirPods. Looking at Figures 3 and 4, as well as Tables 1 and 2, we can see the shear amount of components packed in such a small product. To do this, the engineers have had to cram everything together and optimize the use of space as much as possible. Unfortunately, this sort of design usually leads to difficulties in repairing and recycling as we will discuss **later on**, because gluing and soldering components together takes up less space than creating attachments that can be dismantled like clips and screws. In the case of the AirPods, they've also had to do things like create an extremely thin battery that snugly fits into the stem of the earphone, wrapped around by the antenna. While this sort of design is impressive, it will inevitably lead to complications when it comes to the end of life of the product.

3.3 Assumptions and focus of study

Now that we have a good overview of the composition of a pair of AirPods, we can develop the assumptions we will be making for our study as well as the main points of interest and what we will focus on the most.

As previously mentioned, it is very hard to know exactly what materials are in each component and even harder to determine the mass of those materials. This is problematic as an LCA requires the mass of each element present in the product. To circumvent this issue, a number of assumptions will be made to get an idea of the mass of the most critical materials in the AirPods. These assumptions will be further discussed in the **Life Cycle Assessment (LCA)** section.

Looking at Table 1 and 2, the AirPods are mostly made up of electrical components that are difficult to substitute for greener alternatives. Given this study is being made in the context of a Materials course, and that we come from a mechanical engineering background, we chose to focus our work mostly around the plastic housing which we can analyse more in depth and find alternatives for. In our life cycle assessment, we will be able to give a rather precise description of the composition of the plastic. Furthermore, finding alternative materials to create a sustainable housing for the AirPods is a very feasible feat. In contrast, it is nearly impossible to determine the composition of all the different electrical components. Respecting our constraint of keeping all the features of the AirPods while making them more sustainable, swapping out any electronic component is not an option. Nonetheless, we still chose to include the electronics in the LCA using gross assumptions and estimations of materials to get an order of magnitude of their environmental impact and see how much we can reduce the total environmental damage of the AirPods by modifying only some parts.

4 Life Cycle Assessment (LCA)

To begin with, the AirPods, as much as all other electronic devices contain a wide variety of different materials. For some, even though they represent a minor part of the mass, they still have a major impact on the carbon footprint, the energy or the water demand involved in different processes throughout the product's lifetime.

In order to realize a complete and precise LCA, it is crucial to identify the components the study will focus on. As previously stated, we are seeking through this study to identify and compare the environmental impact of the materials used in the AirPods. Of course, the battery represents a major part of the footprint of the product , but we chose to focus more on the comparison with the other materials and the abilities of improvement in terms of pollution. Indeed, nowadays the battery improvability is limited by the rare earths, even if some alternatives begin to emerge.

The software Granta EduPack© enabled us to carry out the LCA studies with the tool EcoAudit©. A wide database about the materials mechanical and sustainable properties is used, together with the mass of each material contained in the AirPods. We used especially the third level of database sustainability, which enables us to use some predefined electronic components for the material definition.

As a second step in the study, a second LCA has been performed on the basis of the earbuds called Redemption, sold by the brand House Of Marley ©. They cover almost the same functionalities as the AirPods and are said to be produced with only sustainable materials. Therefore it enables us to step back from our first results and compare them with a product said to be more "sustainable".

Figure 5: AirPods 2nd Generation (left) and House of Marley redemption ANC 2 (right)

4.1 Assumptions

Some information about the materials used by Apple are very complicated to obtain, especially the manufacturing and the transport. In order to carry out the LCA and compensate this lack of information on the software, some assumptions have been made. In that section, the assumptions will be explained more in details, in order to have an objective look on the results and understand why the values obtained can be considered as more or less reasonable.

4.1.1 Materials

Only the exact mass of the components and materials contained in the AirPods are considered in the LCA, even though the raw materials used are significantly more important in terms of mass. As a comparison, 70 Kg of raw materials are used to produce a 120g iPhone [21] (page 7). This results in a significant uncertainty on the embodied energy and more precisely the manufacturing energy consumption of the device. It is unfortunately too hard to find any information about how Apple recycles or use the material derived from the manufacturing of the components. Therefore it compromises the possibility of evaluating the energy consumption of the manufacturing of AirPods.

Table 3: Materials chosen for the setting of the LCA study.

	Component	Material
Case	Casing	ABS
	Battery	Li-ion
	Motherboard	printed circuit board assembly
	Copper	CuBe2CoNi
	Steel	Stainless steel AiSi 304
	Magnet	Neodynium magnet N45SH
	Gold	Gold-germanium alloy Au88
Buds	Casing	ABS
	Battery	printed circuit board assembly
	Motherboard	CuBe2CoNi
	Copper	Stainless steel AiSi 304
	Steel	Neodynium magnet N45SH
	Gold	Gold-germanium alloy Au88

Moreover, some assumptions have been done considering the materials composing the AirPods, as it can be seen in the table 3. Indeed, based on the two tables 1 and 2 and on additional researches, the most polluting parts of the AirPods have been determined. One has to be careful concerning that part, as the mass proportion of the material in the device is not proportional to the amount of embodied energy it represents.

For example, as it will be seen later, although the gold's mass in the AirPods is around a microgramm, its emobodied energy can be significantly more important than the steel, which represents around a gramm in the total mass.

The advantage of having used the third level of database in the software becomes clearer now. The motherboard and the battery are entered as predefined components for the material definition. Therefore we spare an important loss of accuracy that we would have had by approximating the mass of each components.

The last assumption that has to be done considering the materials definitions concerns the magnet used to close the case of the AirPods. The environmental impact of the magnet depends on the material use for the magnet. Therefore the choice can not be done following a rule of thumb. As Apple are much more transparent about the materials composing the iPhones, we decided to base our choice on the magnet used for the technology MagSafe by Apple which enables the iPhone's owner to stick different sorts of accessories to the back of the phone, or stick the phone to a surface. The material can be seen in the table 3.

Finally, all the types of glue or joints that are present in the AirPods have been neglected, as the environmental impact is very small considering their mass proportion. This also simplifies significantly our study as the type of materials used are not shared by Apple.

4.1.2 Transport

The different steps of transport of the AirPods have been simplified in order to make the LCA feasible and meaningful.

According to the obtained information [7], the transport is considered as a three steps process. As the AirPods are assembled in China, the transport of Lithium from Chili and the transport of Cobalt from Democratic Republic of Congo have been considered towards China. Then, as it is described in the figure 6, the assembled AirPods are shipped towards USA and then delivered into the USA.

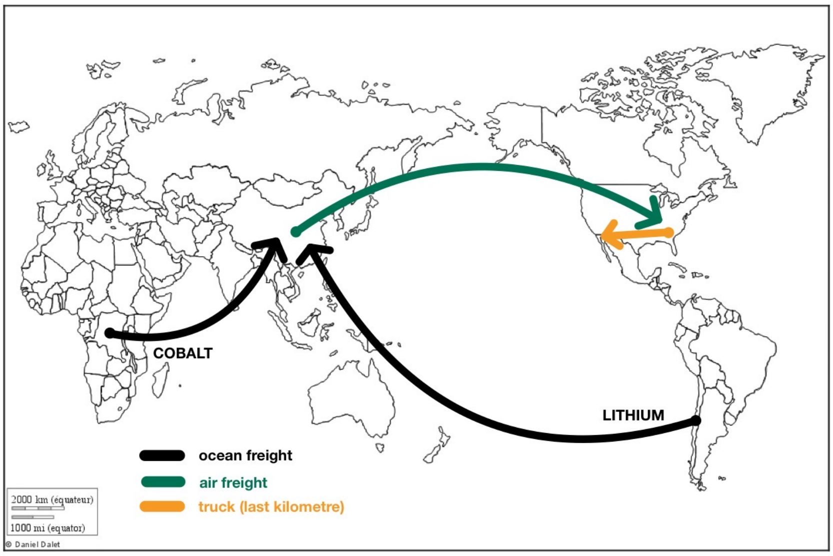
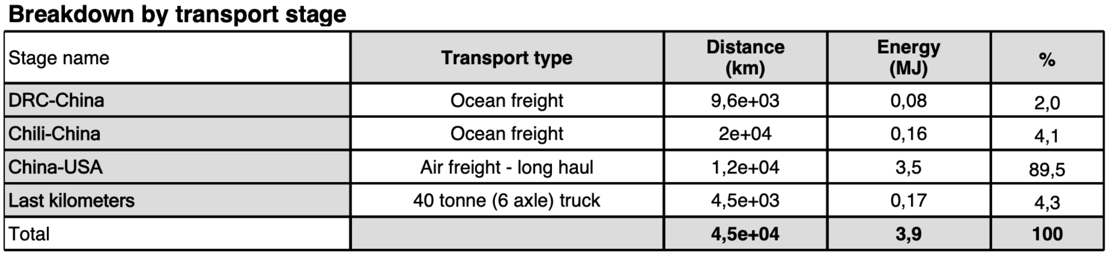


Figure 6: Transport during manufacturing and shiping of AirPods

An additional simplification has been made concerning the masses transported. Indeed, the whole mass of the AirPods has been considered for the first step of the transport instead of only the mass of cobalt and lithium contained in a battery. It is clear that these simplifications are very far from representing the reality. Indeed all the different materials composing the AirPods should be considered, and in different quantities as the raw materials are sent to China to be manufactured. This would demand a whole study to itself and needs a lot of time. We understood that the information about which countries the subcontractors of Apple import the raw materials from and in which quantities are very hard to find. Thus it has been decided to not focus on that specific part of the study. For this reason, part of the LCA results is already shown in figure 7, where it is obvious to see that airfreight represents the biggest part of energy consumption as well as CO_2 emission. Indeed, Apple ships the majority of its products by airfreight, which is the less sustainable way of transportation compared to ocean freight or road transportation.



Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
DRC-China	Ocean freight	9,6e+03	0,08	2,0
Chili-China	Ocean freight	2e+04	0,16	4,1
China-USA	Air freight - long haul	1,2e+04	3,5	89,5
Last kilometers	40 tonne (6 axle) truck	4,5e+03	0,17	4,3
Total		**4,5e+04**	**3,9**	**100**

Figure 7: Distribution of the contribution to the energy consumption relates to the transportation of the Airpods

Therefore the results we get about transport emissions can not be trusted, but at least they give us an overview about which type of transport is polluting the most.

4.1.3 Geometry

In order to determine the mass of the ABS contained in the AirPods, it has been needed to simplify the geometry and approximate the total volume of the casing of the buds and their case. The density of the ABS used by Apple being known, it enables us therefore to determine the mass of ABS.

Based on the few information given by Apple and some customer's dismantling, the geometry considered can be seen in the figure 8.

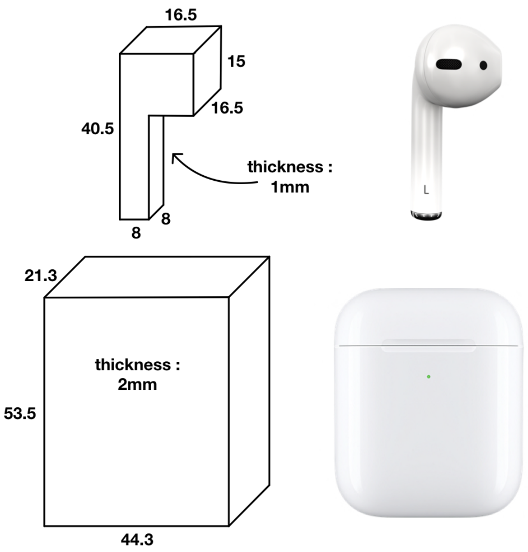


Figure 8: Geometry assumptions

Thus the mass of ABS per bud and for the case is approximated. The obtained value seemed reasonable compared to the total weight of the AirPods. But it has been rounded up as the geometry assumptions were considered to be underestimating the volume of plastic inside the case (plastic holding the buds). The final value is visible in the material table 9.

4.1.4 Approximation of the uncertain masses

Having listed the materials in table 3, the next step is to determine an approximate mass for each of them. The battery mass is known from the model specifications and we consider the mass of ABS to be certain as well, considering the geometry assumption done above [6]. Moreover, it is known that AirPods contain gold, but the exact amount was not found. Therefore, the fraction of gold in the AirPods was estimated to be similar to that of an iPhone, which is approximately 0.034 grams for a 200-gram iPhone [22]. These three masses being considered as known (casing, batteries, gold), the mass of the remaining components are chosen by volume/fraction approximations to reach the total known mass. To make sure the assumptions are valid, a test was performed by varying the mass of the components and analysing the results. It will be discussed further in the section Validity of the mass assumption.

4.1.5 Material's recycling

The second generation of Apple's AirPods, used in the study, is composed only of non-recycled materials. Apple has been using 100% of certified recycled gold for iPhone since the 13th generation, but AirPods are still composed of newly mined gold. However, since the third generation of AirPods they have been using 100 percent of recycled rare earth metals (page 40) [22].

4.1.6 Use

The use phase of the product is the last stage before being able to calculate the full embodied energy of the AirPods. Namely it represents the energy consumption of the product during the time it is used by the owner. For the AirPods, it is only the energy used to charge the case.

In this study, the product life time has been estimated to be 2 years long, knowing that the battery of the buds looses in certain cases 50% of its capacity in around 18 months [6]. Concerning the electric consumption [7], a power of charge of 1.5W, 1 hour per day on average during 250 days per year has been considered.

These assumptions seem to be reliable, and so the it will be considered that the results can be trusted.

4.1.7 House of Marley earbuds

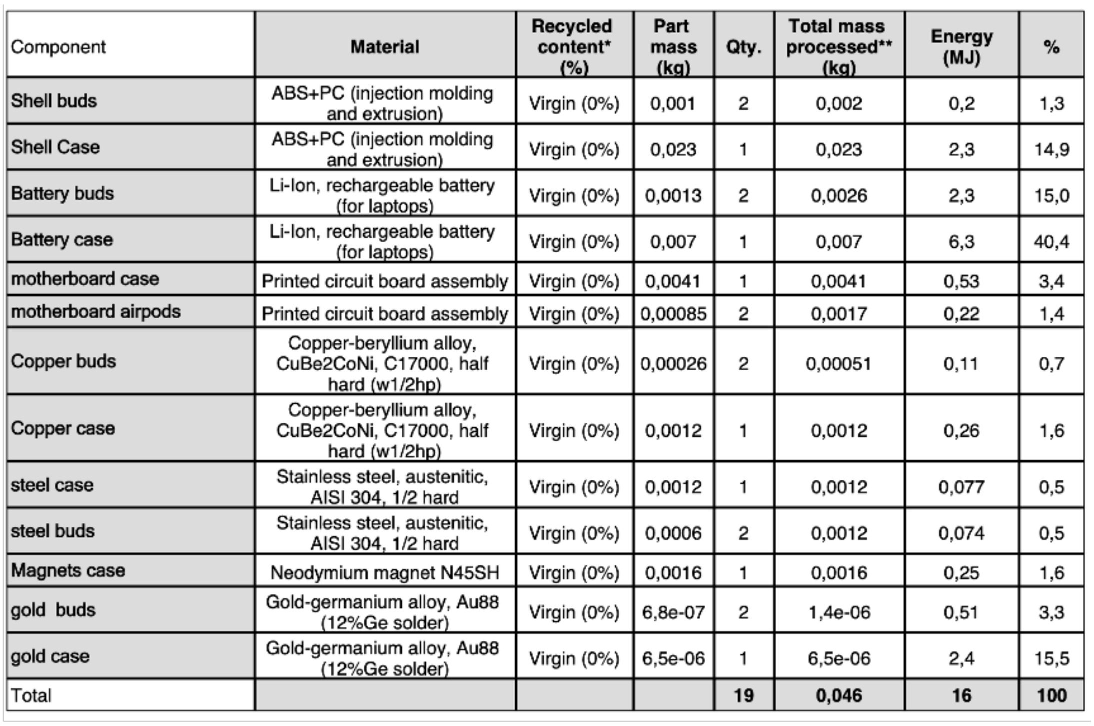
The study for the House of Marley is done only by changing the material of the case. And they were considered to be composed of 100% recycled gold even if it is not the case. The idea is to have a more sustainable product that still meets the same technical criteria as the AirPods (quality of sound, reduced size, design...). The study does not aim to have an analysis of the House of Marley earbuds but to have an idea of the improvements done by changing the materials to more sustainable alternatives. Therefore, the total mass of the product stays the same.
The charging case is supposed to be in wood fiber and recycled PET, it was decided to only be recycled PET reinforced with 35% of glass fiber (average value of glass fiber) and a part of decorative bamboo on top. The data base does not include wood fiber. For the transportation part, it is considered to have the same carbon emission impact, as the factories are also in China and 90% of carbon is from the air fret China-USA before commercializing it.

4.2 Analysis of the results

All these assumptions being done, the LCA study can be carried out properly. The following parts present the results obtained for the different studies that we have done and the conclusions which can be drawn from them.

It is to be noted that the results obtained in the following parts are given with two different metrics, namely Energy [J] and Carbon Footprint [Kg]. Whereas the first one represents the energy demanded by the considered process, the carbon footprint represents the carbon emissions resulting from the combustion of fossil fuels to generate that energy. It depends on the energy mix of the country in which the process is done and therefore is more expected to be varying.

4.2.1 AirPods report



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,3
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	14,9
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	15,0
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	40,4
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	3,4
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	0,7
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	1,6
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,5
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,5
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	1,6
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,8e-07	2	1,4e-06	0,51	3,3
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,5e-06	1	6,5e-06	2,4	15,5
Total				**19**	**0,046**	**16**	**100**

Figure 9: Distribution of the contribution to the energy consumption related to the materials of the AirPods

The table 9 shows in the last column the contribution of each component in the total energy consumption related to the materials of the AirPods.

Firstly, the two first rows consider the casing of both the buds and the case of the AirPods. It can be seen that the ABS casing generates in total around 16% of the total energy consumption related to materials. This result is meaningful in the sense that the use of the ABS plastic as the casing material is not strictly necessary to the conservation of the quality and the functionality of the AirPods. Therefore this significantly high percentage opens the study of sustainable materials to the reflection and the development in order to decrease the environmental impact. This shows already that without changing the technological functionalities of the the AirPods, Apple could reduce meaningfully its environmental impact by developing new sustainable materials.

However, it must be understood that the ABS does not represent a part of 16% in the embodied energy of the AirPods. The figure 10 shows the relative contribution of the different life phases to the embodied energy. It can be seen that the the materials represent around 60% of the embodied energy. Actually we consider that this value is not very reliable, knowing that some of the assumptions made previously considering the manufacturing, the transport or the the use are not strong enough. Thus the impact of the materials in the embodied energy may be smaller. For instance, if the materials represent 50% of the embodied energy, decreasing the impact of the casing material from 16% to 6% would lead to a 10% decreasing of the materials energy, but of 5% of the total embodied energy, which is still significant when we consider the worldwide scale of the AirPod's sales.

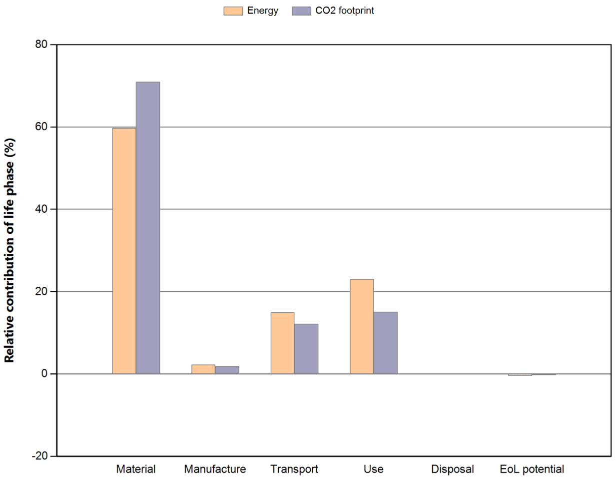


Figure 10: Distribution of the relative contributions to the embodied energy and CO_2 footprint

Then, looking back at the table 9, it can be seen that the battery represent around 55% of the energy consumption due to materials. This is obviously the most critical component, but at the same time the most complicated to improve. Indeed they are a main concern for the industry all over the world, as they are strongly energy demanding for their production, and some parts are hard to recycle, even more for a small batteries like the AirPods. However, this topic will not be discussed in that study. Firstly, it would actually require a whole study on its own, and then the industry and thousands of scientists are already working on that topic with major economic issues. This study focus on the components that are technologically easy to improve environmentally speaking.

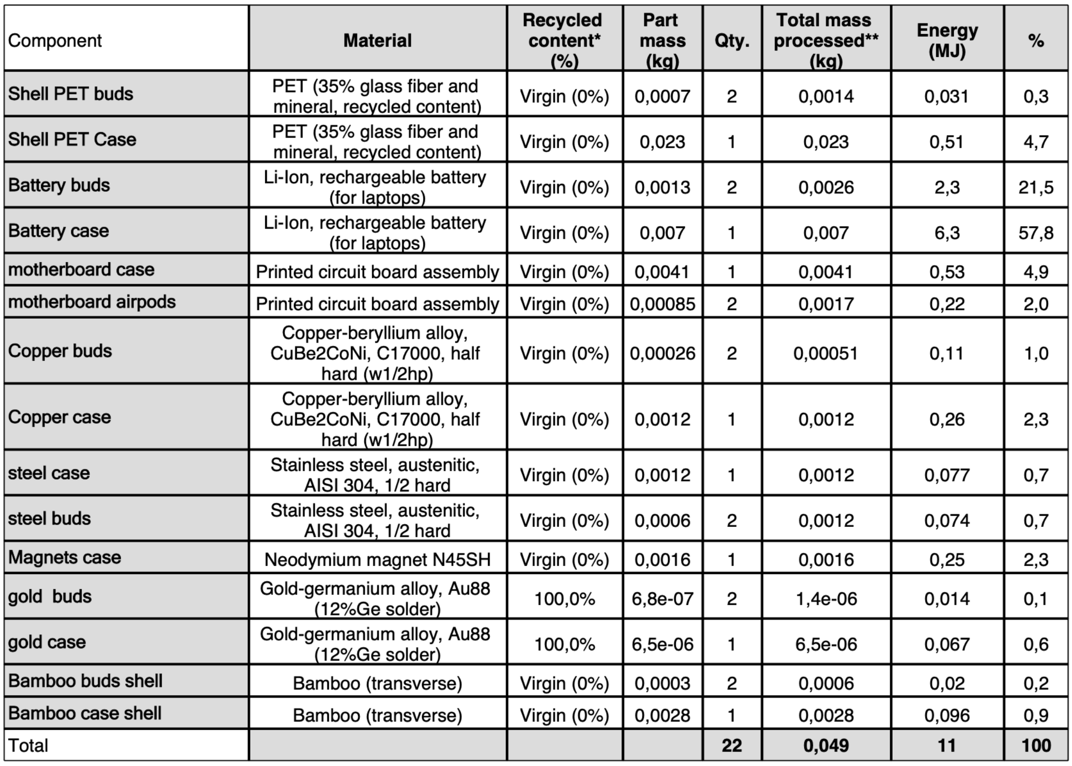
Similarly the motherboard, copper and steel represent all together a proportion of around 8% of the energy consumption due to materials. Put together they represent the full set of components composing the AirPods without the batteries. Thus it is positive to see that they represent such a small amount because this value is complicated to improve without involving a change in the functionality of the device.

Considering the gold, the resulting energy consumption of 20% is a crucial result in the study. Actually, one fifth of the energy consumption due to the materials of the AirPods is due to a material representing 0.2% of the total mass. This topic will be discussed in details in the part **Impact of gold**.

Finally, even if it could seem to be a negligible impact, the proportion in the energy consumption of the magnet used to close the case is 1.6%. This value is meaningful to the extent that the magnet could be replaced easily by an other technology in order to cover the same function.

Just by analyzing the results of the LCA we can already conclude that only by changing two materials of the AirPods, it could be ideally possible to decrease by 30% the energy consumption generated by the materials of the AirPods.

4.2.2 Comparison with House of Marley earbuds



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell PET buds	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,0007	2	0,0014	0,031	0,3
Shell PET Case	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,023	1	0,023	0,51	4,7
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	21,5
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	57,8
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	4,9
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	2,0
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	1,0
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	2,3
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,7
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,7
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	2,3
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,014	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,067	0,6
Bamboo buds shell	Bamboo (transverse)	Virgin (0%)	0,0003	2	0,0006	0,02	0,2
Bamboo case shell	Bamboo (transverse)	Virgin (0%)	0,0028	1	0,0028	0,096	0,9
Total				22	0,049	11	100

Figure 11: House of Marley contribution of life phase

It has been seen in the part **House of Marley earbuds** that this LCA study is carried out in order to compare the environmental impact of earbuds that are using only sustainable materials for their casing. In addition the House of Marley earbuds were considered to be using recycled gold only and none of their manufacturing processes were taken into account. Which could be a source of important emissions. Otherwise, the whole set of components remains the same so that the comparison still makes sense.

The table 11 shows the result of the LCA of the House of Marley earbuds in the total energy consumption related to the materials of the AirPods. Comparing to the table 9, it can be seen at first sight that the total energy goes down from 16 MJ to 11 MJ. Concerning the carbon footprint, the values are decreasing following the exact same ratio, going down from 1.6 Kg to 1.1 Kg (cf Annex AirPods). This noteworthy improvement of 30% compared to the AirPods is due to the recycled gold up to 60% and thus due to the change in the materials of the casing up to 40%. These results are even more obvious looking at the graphs in the figure 12.

Therefore, it can be confirmed that using sustainable materials only for the casing could reduce drastically the environmental impact of the AirPods. Even with the bamboo that is added to the PET on the case and the buds as an aesthetic element, the casing of the House of Marley's buds is 70% less energy consuming than the one of the AirPods. Concerning the gold, the improvement is up to around 95%. These results are even more meaningful as recycled gold could be used and is used in the newest iPhones.

It can moreover be noticed that the materials on which it is considered that they can not me modified represent 93% of the energy consumption, instead of 64% for the AirPods. That shows that the materials modifications that have been tested are close to the ideal potential of improvement.

Looking at the table 12, it is important to remind that only the improvement in the material's subpart of the embodied energy is considered, as the results of the other subparts make less sense and are not trustful due to the weakness of the assumptions. It is though decided to focus mainly on the first column of the graphs.

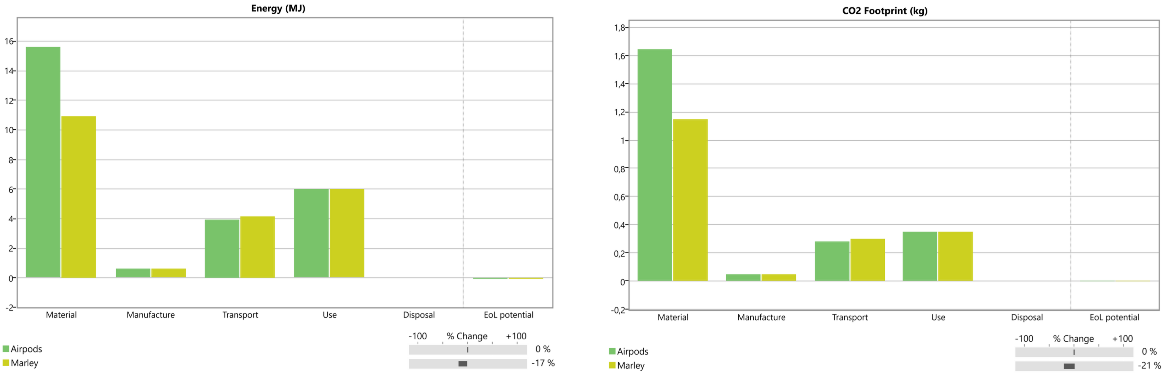


Figure 12: Comparison with the AirPods having 0% of recycled gold

4.2.3 Impact of gold

After a first comparison of the AirPods and House of Marley earbuds, a more detailed study on the gold environmental impact appeared to be relevant. Two comparison are done, one with the AirPods having 0% of their gold recycled and another one with 100%.

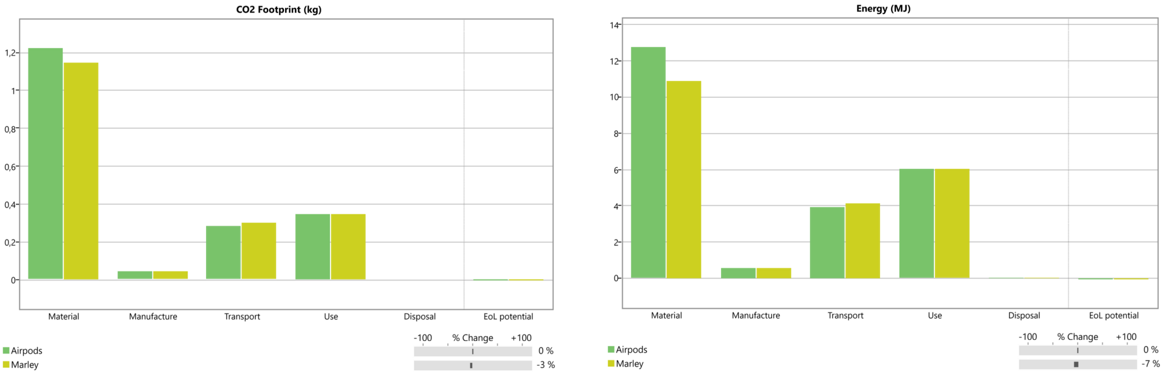
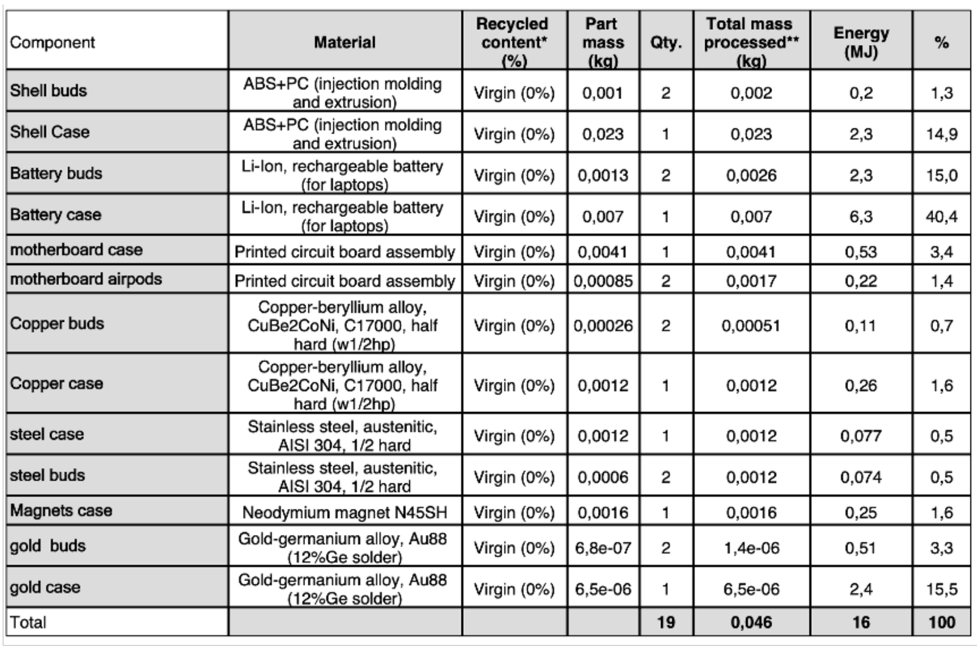


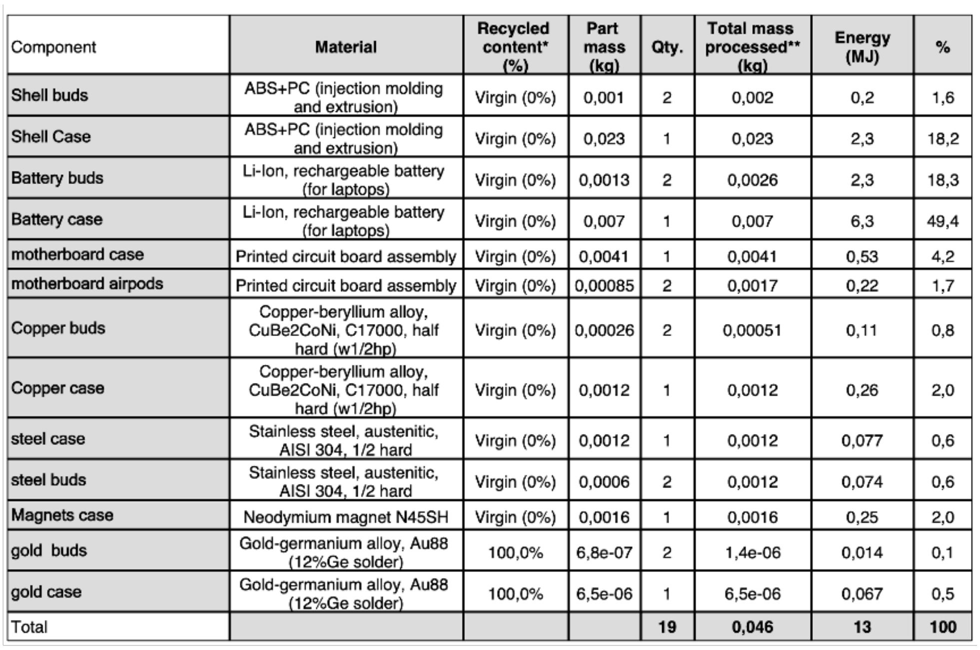
Figure 13: Comparison with the AirPods having 100% of their gold recycled

By looking at the graphs in figure 12 and figure 13, a first general observations can be done. Having recycled gold in the AirPods reduces a lot the gap of total embodied energy and CO_2 footprint. First, with 0% gold recycled in the AirPods, the House Marley product has respectively 17% less embodied energy and 21% less CO_2 footprint. These numbers go down to 3% and 7% for a 100% recycled gold composed product, a difference of more than 10% for both indicators. To have a deeper analysis, the material tables of Granta Eco audit tool 15 give us more precise numbers.



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,3
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	14,9
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	15,0
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	40,4
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	3,4
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	0,7
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	1,6
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,5
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,5
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	1,6
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,8e-07	2	1,4e-06	0,51	3,3
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,5e-06	1	6,5e-06	2,4	15,5
Total				19	0,046	16	100

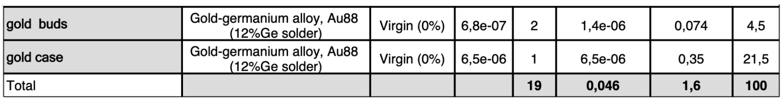
Figure 14: AirPods material table for 0% of recycled gold



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,6
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	18,2
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	18,3
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	49,4
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	4,2
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	1,7
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	0,8
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	2,0
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,6
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,6
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	2,0
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,014	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,067	0,5
Total				19	0,046	13	100

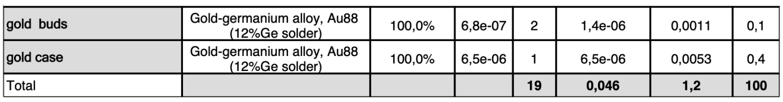
Figure 15: AirPods material table for 100% of recycled gold

These tables indicate that the material's energy goes from 16 MJ to 13 MJ (values rounded by the software). More precisely, the gold energy percentage of the buds and the case goes from nearly 20% to less then 1% (two last line in figures 21 and 15).



gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,8e-07	2	1,4e-06	0,074	4,5
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,5e-06	1	6,5e-06	0,35	21,5
Total				**19**	**0,046**	**1,6**	**100**

Figure 16: CO_2 footprint analysis : AirPods with 0% recycled gold



gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,0011	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,0053	0,4
Total				**19**	**0,046**	**1,2**	**100**

Figure 17: CO_2 footprint analysis : AirPods with 100% recycled gold

According to this table 16, it appears that gold has a significant impact on the carbon dioxide (CO_2) footprint of a product, contributing almost 25% of the total emissions (less than 1% for recycled gold, table 17). As this result is higher than for the energy, it indicates that the processes involved in obtaining and using gold have high levels of emissions. The gold composes a very small part of the total mass of the AirPods but still has more than a relevant impact on the environment and even more for a product that is manufactured in millions. Indeed, the extraction and processing of gold requires a significant amount of energy, as the ore must be separated from other minerals and then refined to remove impurities. This typically involves the use of large amounts of water and chemicals, as well as the transportation of the ore to the processing facility and the waste material generated during the process.

The energy required for the extraction and processing of gold can come from a variety of sources, including fossil fuels such as coal and natural gas, as well as renewable energy sources such as hydroelectric power. The energy intensity of the gold mining process can vary depending on the specific methods and technologies used, as well as the location and quality of the ore deposits. It was not possible to determine the specific gold mining origins of Apple's products. However, for these reasons, knowing the source of the gold used in their production could have been interesting. In addition to the environmental impacts already mentioned, it is worth noting that gold mining often involves the use of cyanide, a toxic chemical that can leak into the soil and water and cause pollution. This can have negative impacts on the health of nearby communities. Therefore, using recycled gold and recycling the gold in our electronics seems to be urgent. It is worth noting that one tonne of iPhones would contain 300 times more gold than a tonne of gold ore and 6.5 times more silver than a tonne of silver ore. [22]

However, using recycled gold can also have negative environmental impacts, as it typically involves the use of chemicals and energy in order to separate the gold from other materials. For example, gold can be recovered from electronic waste, e-waste, using a process called cyanide leaching (chemical mentioned before), which involves the use of a cyanide solution to dissolve the gold and separate it from other materials. While this process can be effective at recovering gold, it can also generate hazardous waste and is very toxic to the workers, which are usually poorly paid workers and children are reported to be used to break apart these electronics. For example, Guiyu, a town located in southeastern China, has gained notoriety as the world's largest e-waste site. The high levels of electronic waste in the town have led to serious health problems for its residents and have polluted the soil, rivers, and air with toxic substances such as mercury, arsenic, chromium, and lead.

Overall, gold recycling can be an important part of a sustainable materials management strategy, but it is important to carefully consider the potential environmental and social impacts of the recycling process in order to minimize any negative consequences.

4.2.4 Validity of the mass assumption

The results shown in the previous section are carried out accordingly to the mass assumptions. For this reason and in order to test the mass hypothesis, two other cases are being studied to check whether the results in embodied energy and CO_2 change or not.

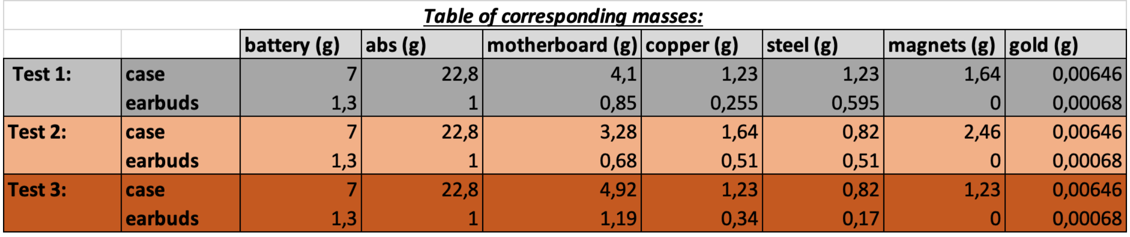


Table of corresponding masses:

		battery (g)	abs (g)	motherboard (g)	copper (g)	steel (g)	magnets (g)	gold (g)
Test 1:	**case**	7	22,8	4,1	1,23	1,23	1,64	0,00646
	earbuds	1,3	1	0,85	0,255	0,595	0	0,00068
Test 2:	**case**	7	22,8	3,28	1,64	0,82	2,46	0,00646
	earbuds	1,3	1	0,68	0,51	0,51	0	0,00068
Test 3:	**case**	7	22,8	4,92	1,23	0,82	1,23	0,00646
	earbuds	1,3	1	1,19	0,34	0,17	0	0,00068

Figure 18: Different mass assumptions

The table above shows the different changes in mass hypothesis. As seen before, the values for the battery's mass is know thanks to the battery model and ABS thanks to geometry assumptions. Therefore these values remain constant. The proportion of gold is known and then remains constant and is recycled in all three cases. There is still the masses of the motherboard, copper, steel and magnet that can vary. As the total mass is known, the uncertain mass can be calculated as the total mass minus the battery and ABS masses. The variations of the uncertain masses have been made arbitrarily. For instance concerning the test 2, the magnets weight more in order to hold the AirPods top stronger in that case. In test 2, the motherboard represents a larger proportion of the mass distribution.

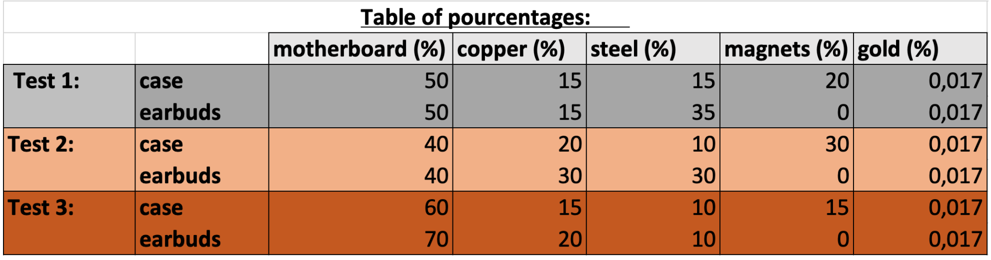


Table of pourcentages:

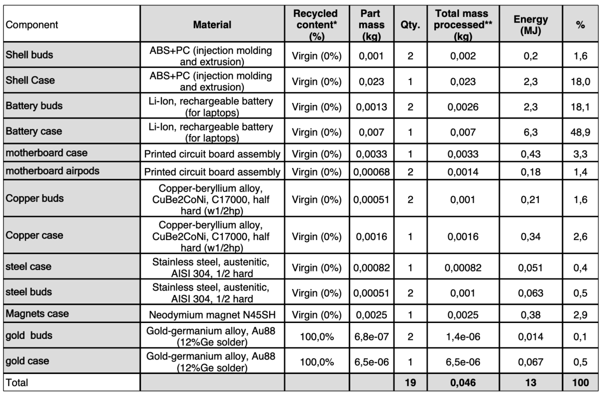
		motherboard (%)	copper (%)	steel (%)	magnets (%)	gold (%)
Test 1:	**case**	50	15	15	20	0,017
	earbuds	50	15	35	0	0,017
Test 2:	**case**	40	20	10	30	0,017
	earbuds	40	30	30	0	0,017
Test 3:	**case**	60	15	10	15	0,017
	earbuds	70	20	10	0	0,017

Figure 19: Breakdown of the component's masses

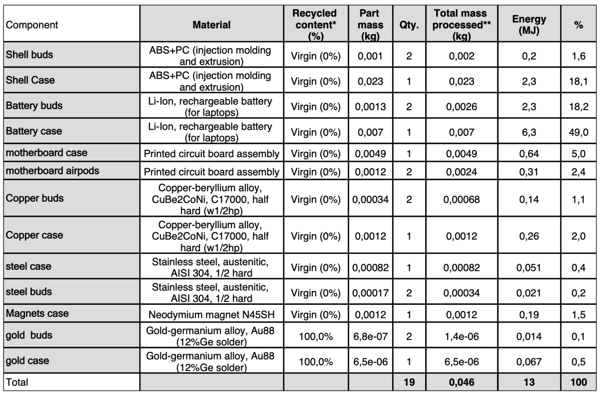
An other way to see the numbers, which gives a better understanding of the mass distribution is to use percentages. In this table only the uncertain mass is detailed. The sum of each line adds up to 100, neglecting the contribution of gold.

Then, two new tables are obtained for the material's energy. The results show that independently on the cases, the final energy is around 13 MJ and the total mass processed is also the same. In addition, the results are identical to the initial test of figure 15. This results prove that the mass assumptions are properly set. Indeed a change of the uncertain mass implying a significant change in the energy consumption would lead to an important uncertainty on the mass distribution that has been set for the study, and then lead to an uncertainty in the results.

The second aspect to look at is the CO_2 emission accordingly to the three tests. The conclusion is the same as the total CO_2 footprint is the same even if its distribution of the component differs.

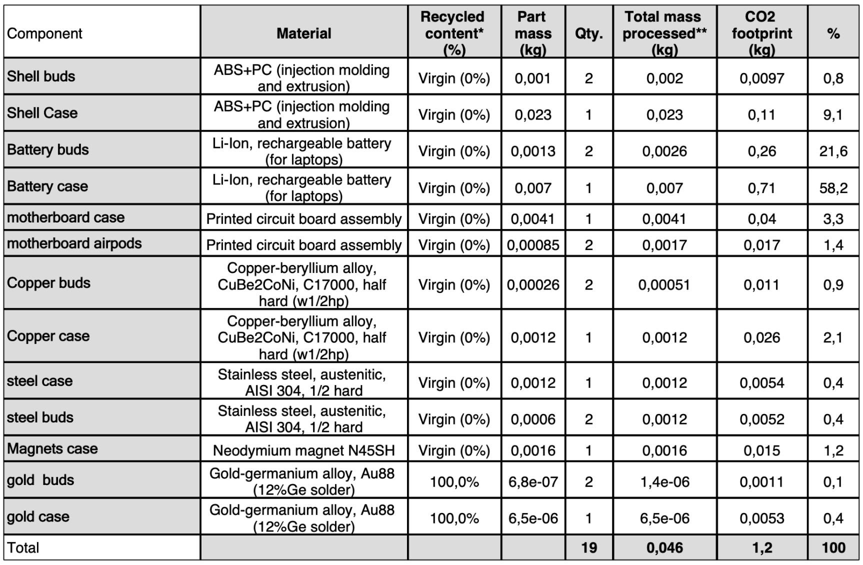


Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,6
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	18,0
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	18,1
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	48,9
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0033	1	0,0033	0,43	3,3
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00068	2	0,0014	0,18	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00051	2	0,001	0,21	1,6
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0016	1	0,0016	0,34	2,6
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00082	1	0,00082	0,051	0,4
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00051	2	0,001	0,063	0,5
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0025	1	0,0025	0,38	2,9
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,014	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,067	0,5
Total				**19**	**0,046**	**13**	**100**



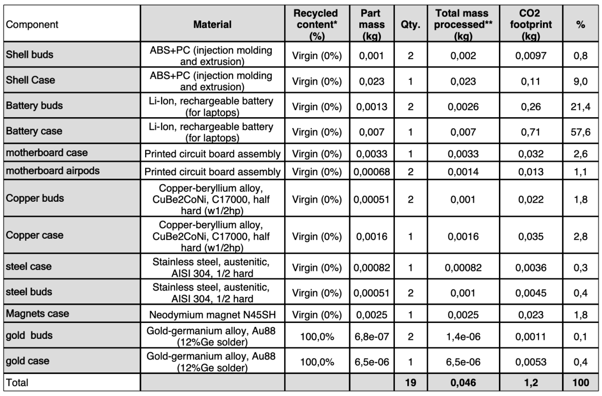
Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,6
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	18,1
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	18,2
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	49,0
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0049	1	0,0049	0,64	5,0
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,0012	2	0,0024	0,31	2,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00034	2	0,00068	0,14	1,1
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	2,0
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00082	1	0,00082	0,051	0,4
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00017	2	0,00034	0,021	0,2
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0012	1	0,0012	0,19	1,5
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,014	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,067	0,5
Total				**19**	**0,046**	**13**	**100**

Figure 20: Results for the material's energy for test 2 (left) and test 3 (right)

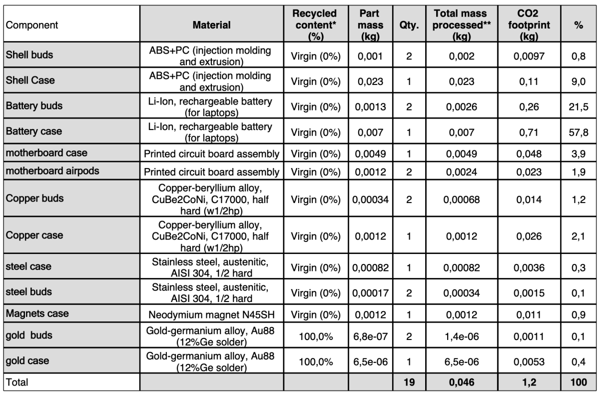


Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,0097	0,8
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	0,11	9,1
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	0,26	21,6
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	0,71	58,2
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,04	3,3
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,017	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,011	0,9
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,026	2,1
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,0054	0,4
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,0052	0,4
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,015	1,2
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,0011	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,0053	0,4
Total				**19**	**0,046**	**1,2**	**100**

Figure 21: CO_2's emission for the main test 1



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,0097	0,8
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	0,11	9,0
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	0,26	21,4
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	0,71	57,6
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0033	1	0,0033	0,032	2,6
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00068	2	0,0014	0,013	1,1
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00051	2	0,001	0,022	1,8
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0016	1	0,0016	0,035	2,8
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00082	1	0,00082	0,0036	0,3
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00051	2	0,001	0,0045	0,4
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0025	1	0,0025	0,023	1,8
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,0011	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,0053	0,4
Total				**19**	**0,046**	**1,2**	**100**



Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,0097	0,8
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	0,11	9,0
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	0,26	21,5
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	0,71	57,8
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0049	1	0,0049	0,048	3,9
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,0012	2	0,0024	0,023	1,9
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00034	2	0,00068	0,014	1,2
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,026	2,1
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00082	1	0,00082	0,0036	0,3
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,00017	2	0,00034	0,0015	0,1
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0012	1	0,0012	0,011	0,9
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,0011	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,0053	0,4
Total				**19**	**0,046**	**1,2**	**100**

Figure 22: Results for CO_2's emissions for test 2 (left) and test 3 (right)

5 Possibility of improvements

5.1 Repairability

One of the most important aspects of a product's lifespan is its ability to be repaired. Any device that can be easily repaired will have an increased life span which has a significant impact on the sustainability of a product. In the case of many electronic devices and especially the AirPods, the battery is the most critical part as it tends to degrade the fastest while having the largest carbon footprint of all the components. For instance, the battery of the AirPods generation loses around 50% of its capacity in 18 months. This is problematic as many users tend to discard a product if the battery is no longer sufficient for their needs. This leads to millions of pairs of AirPods being thrown away because the battery degraded too much and it was irreplaceable, while all the other components were still functioning. This problem could thus be eliminated if AirPods had repairable batteries, but they are in affect unattainable, as the plastic casing is permanently damaged when opened. This is highlighted by Ifixit, which gives a grade of 0/10 for repairability [6].

This score is due to the poor design of the construction of the AirPods. First of all the plastic casing is glued shut, so they cannot be opened without sustaining permanent damage on the plastic. Furthermore, the thin battery is lodged in the stem of the AirPod bud, inter-twinned with the antenna and covered by all the other electronic components. Lastly, there are no easily clip on connectors like most phones: instead the battery is soldered onto the logic board, making any attempt at replacing the battery risky and time intensive. The same is true for the AirPod case which contains even more battery capacity, rare metals, and resource intensive materials.

In the case where a user asks Apple to repair their AirPods, the firm will give either one or two new buds or suggest them to purchase a new product, therefore replacing and not repairing the product.

One could think this design is imposed by the small size of truly wireless earbuds. However this is not the case as competing companies, such as Samsung, which make equally small and sleek Bluetooth earphones, the Galaxy Buds, have a replaceable battery. This is achieved through a plastic casing closed with clips instead of glue, and standard watch style battery which are widely available. This earned them a 6/10 score on iFixit [6], a very net improvement on Apple. While this device remains flawed as the battery is the only replaceable component, it still covers the majority of repairs as speakers and logic boards tend to outlast batteries by years.

Figure 23: Opening of Samsung Galaxy Bud [9]

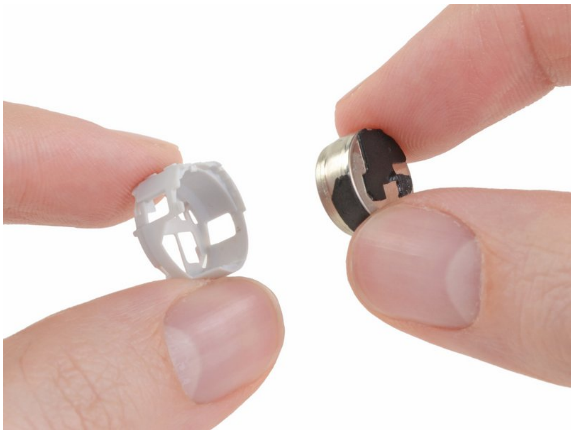


Figure 24: Samsung Galaxy Bud battery [9]

The AirPods did however make a small step forward in the Pro and third generation which we are not studying. Apple, like Samsung, started using standardized button batteries instead of their proprietary thin shaped batteries found in the first two generations. Unfortunately, this step forward is not capitalized on, as the casing remains glued shut making repairs impossible.

5.2 Recycling

Another critical component of a product's environmental impact is its ease of recycling; this is especially important for electronic devices which are notoriously difficult to recycle, use up significant amount of scarce resources, and are highly pollutant if not disposed of properly. The AirPods however are nearly impossible to recycle for the same reasons they are not repairable. The glued shut casing means no man or machine can open them quickly and cheaply without tearing the device to pieces.

Looking to Apple for answers, they never discuss how they recycle AirPods, in contrast to their campaigns advertising their ability to recycle iPhones. They offer Apple Trade-in, where they take back products at the end of their life from customers, but nothing mentions what they do with them. We asked an Apple technician what happened to AirPods after customers turned them in for new ones: he admitted he was not sure but he believed they were crushed and Apple "retrieved what they could". If the company does not openly discuss how it recycles its product, it is likely the components are more or less separated and disposed of in a safe manner without any attempt to recuperate the materials within them. Furthermore, most electronics recycling companies and facilities refuse to take AirPods in because they are impossible to efficiently separate.

Apple has in the past developed ways to recycle existing products, like when they created Liam and Daisy, the robots design to dismantle iPhones. They also recently opened a Materials recovery lab where they aim to develop new ways of recycling electronics, but this has not yielded any results for the recycling of AirPods yet.

5.3 Suggested design improvements

From section **5.1** and **5.2**, it is obvious the most evident and efficient way to improve repairability and recycling is to switch the closing mechanism of the plastic casing from glue to clips, similar to the Samsung galaxy buds (see Figure 23). This would make opening the device much easier which would lead to a host of replaceable parts while also making the separation of the plastic from the electronics much easier and enabling the recycling of the battery, casing and logic board. This could lead to some concerns over the water resistance of the device which Apple will want to maintain, but some simple rubber gaskets could ensure the AirPods remain sweat and rain resistant, just like the repairable Samsung earphones. The opening of the charging case should also be easy; this could be done by adding clips or screws, similar to the closing mechanism of an iPhone. Switching out the glue on the case should have no repercussions on the product as the case has no water, dust or sweat rating. Furthermore, water resistance can easily be achieved using screws and a gasket to reduce the risk of early replacement of the charging case in the event of an accident

Changing the plastic casing closing mechanism, however, will not improve much in terms of making the AirPods reparable if there are no internal changes as well. The batteries inside the earphones themselves should be switched to standardized button cell batteries, like what has been done in the Pro and third generation models. This enables much easier repairs as they are not wired into the logic board, and recycling chains are well in place for these types of batteries. The battery inside the charging case should also be made more easily accessible like what is done on iPhones.

Finally, many of the electrical components could use connectors instead of being permanently soldered to the logic board. Though it takes up slightly more space, this is already done in many smartphones and even the small and compact Apple Watch. This change could allow more complex repairs than just switching out the battery, and help further prolong the lifespan of a pair of AirPods.

While it is hard to quantify, all these changes could potentially add up to a significantly prolonged lifespan. Some claim AirPods batteries only last around 18 months before their capacity is no longer sufficient for a lot of users [12]. If we consider that the battery is the only point of failure for nearly every user given they are very hard to mechanically break, and all other electrical components typically last several years, and that Apple brings a meaningful upgrade to the AirPods every three years, the lifespan of AirPods could be effectively doubled, saving tons of CO_2, materials mined from the earth, and electronic waste generated every year. On top of that, the proposed changes would heavily facilitate recycling and enable the recuperation of many of the mined elements contained in the AirPods.

Finally the **AirPods report** showed that the magnets used to close the case represents 1.6% of the energy consumption for the materials. Instead of using magnets, it would be possible for instance to close the case of the AirPods with a silicone string. This solution was implemented in the LCA software in order to evaluate the reduction in energy use. Considering a 3cm long string with a 2.5mm diameter [19], the energy consumption in the material category would decrease from 1.6% to 0.005% of the energy consumption at the highest. This change actually implies a modification to the design, which could fall out of line with Apple's design language and standards, thus making the adoption less likely than other suggested changes.

5.4 Software Optimization

Another way to decrease the environmental impact of the AirPods is to increase the longevity of the components before they need to be replaced. As previously mentioned, the most common reason for throwing away AirPods is caused by the rapid deterioration of the batteries [11]. Interestingly though, one of the biggest improvements Apple can do on the battery also happens to be one of the easiest and cheapest to make: software optimizations.
Let's see what could be done on AirPods with current existing technology.

5.4.1 Depth of Discharge

For the past few years, Apple, in some of its devices, began to implement a software optimization designed to prolong the lifespan of its batteries. For now, it only concerns iPhones and applies when users charge their phone overnight. It consists in charging the phone to 80 % and waiting until the early hours of the morning to finish the charge from 80 to 100 %. This simple manipulation of the charging cycle allows significant gains in battery health, but this optimization could be even better.

Research has shown that keeping a Lithium-ion battery in a range between 20 and 80 percent charge is significantly better than to drain it and recharge it fully as holding a full charge induces mechanical stress and leaving the battery drained causes irreversible changes in the anode and cathode, and may trigger an internal short circuit when you recharge the battery [12]. Both of these factors deteriorate batteries much faster than if they are kept in a slightly smaller operating range.

In the study of the rechargeable battery, the depth of discharge (DoD) is an important parameter which refers to how much energy is channeled in and out of the battery on a given cycle. Figure 25 shows an experiment on a Lithium-ion battery, which is the same type of battery found in the AirPods. It shows the State of Health (SoH), a measurement that indicates the level of degradation and remaining capacity, for the batteries which have been subject to different depths of discharges during lots of cycles.

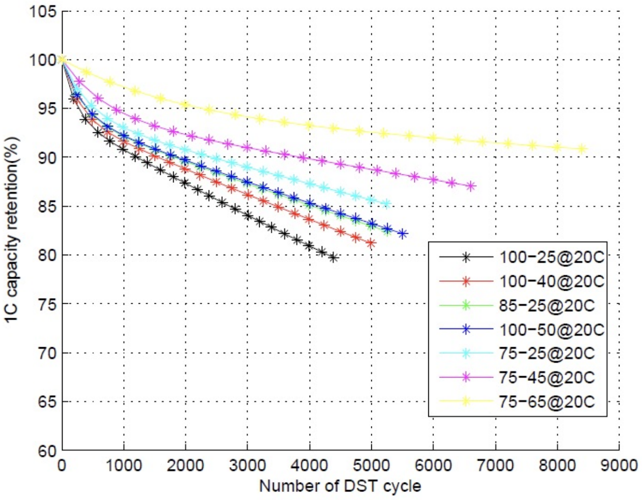


Figure 25: SoH according to the DoD over the cycles

As the graph shows, a depth in discharge between 75 and 25 % allows the battery to last twice as long as a DoD of 100-25 before reaching 85 % of its capacity retention. We can also see that the best range of use is between 65 and 75 % but that is not a realistic DoD for a daily life use of most of our electronic devices.

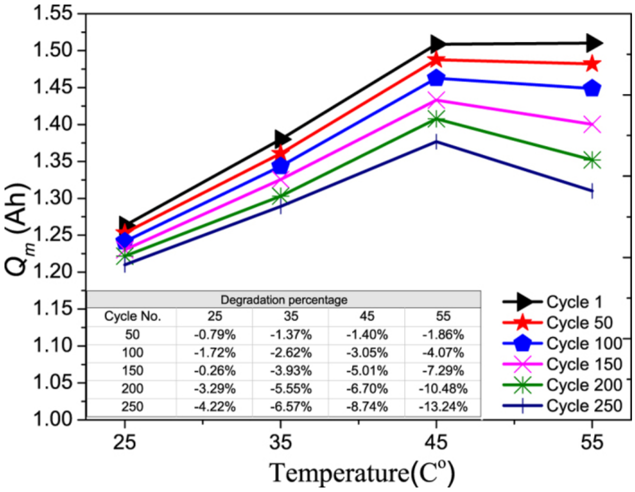
Nowadays, when you store your AirPods in the case, it charges them automatically until 100 %, which goes completely against the study we discussed. Seeing as most people only use their AirPods a few hours a day and keep them in their case the rest of the time, the AirPods are almost always charged to 100%, a very damaging state of charge. This leads to a very rapid deterioration of irreplaceable batteries: this undeniably causes many AirPods to be thrown out after only a couple of years, or less. One could think storing AirPods outside of their case could resolve this issue. However, beside the obvious inconvenience of doing so, another problem arises: there is no way to turn them off and the out-of-the-case AirPods will continuously attempt to pair to a device or use its proximity sensors to determine if they are in someone's ears. This will drain the battery down to 0% in a matter of hours, also leading to heavy battery deterioration.
To put it briefly, without some kind of battery optimization software, which could cut off the charge at a predefined percentage, the rapid decrease in capacity retention is inevitable for the AirPods.

A software update enabling users to pre-define a maximum charge percentage, like almost all electric cars, would significantly increase the SoH of AirPod batteries. Seeing as the advertised battery life is 6 hours, that most users rarely use earphones for 6 hours straight, and that they charge in only 15 minutes, this would have a very minor effect on the user experience. Should someone wish to use them for 6 hours, they could easily adjust the charging limit in their phone. Such an optimization program could be implemented in the AirPods with a simple update, so even the already-sold AirPods could benefit from it. Third-party companies already offer similar software on MacBooks [13] and iPhones [14], so there is no reason Apple could not implement this on AirPods.

Battery optimization should also be implemented for the Airpods' case, even if the earphone batteries are the most important ones to prolong, seeing as these are the most critical for a good user experience.

5.4.2 Heat protection

Another parameter which influences the battery's lifespan is its temperature. Every battery has an ideal range of temperature for use and storage[15]. If the temperature drops below this range, the battery could temporarily be affected and decrease capacity. If the temperature surpasses this range, that could damage the battery and irreversibly affect its lifespan.
As temperatures increase, so does the speed of the chemical reactions within batteries; this causes an increase in the battery output and can vastly increase the rate of degradation.



Degradation percentage				
Cycle No.	25	35	45	55
50	-0.79%	-1.37%	-1.40%	-1.86%
100	-1.72%	-2.62%	-3.05%	-4.07%
150	-0.26%	-3.93%	-5.01%	-7.29%
200	-3.29%	-5.55%	-6.70%	-10.48%
250	-4.22%	-6.57%	-8.74%	-13.24%

Figure 26: Effect of Temperature on a Lithium-ion battery

Figure 26 shows the effect of high temperature on a Lithium-ion battery [16]. A higher temperature allows a temporary overcharge of energy so a higher capacity, but after numerous cycles, this leads to a degradation of its lifespan. This overheating could occur because of the ambient temperature but also during the use or the charge of the device. Most electronic devices embed temperature sensors which shut down the device when the temperature is out of the predefined range, but that is not the case for the AirPods.
We can ask ourselves if the addition of a battery sensor, which leads to a better control on the battery and thus an improved battery lifespan, outweighs the additional environmental impact. Unfortunately the exact model of temperature sensor used by Apple for the iPhone are kept secret, and moreover it's impossible to do a LCA study directly for a temperature sensor. However, we can guess that thermistor would be the type of sensor used by Apple for AirPods. It is nowadays the most common types of temperature sensor used in smartphone because they can be small, inexpensive, and accurate over a wide range of temperatures. They are also relatively simple to integrate into electronic devices, can be used to measure temperature in a variety of smartphone components, and are low-consuming.
They are typically made from ceramics or polymers, two commons and relatively non-polluting materials, so even if an LCA study is not possible, the advantages of this component outweigh the few disadvantages it entails.

5.5 Materials improvement

As detailed in the **Life Cycle Assessment (LCA)**, the casing contributes for approximately 15 % of the material energy and necessitates scarce and polluting resources such as petroleum to be made. A switch to bio-based or recycled plastics could be made which have nearly identical properties. To get an idea of the price increase, we used a research paper that compares the price of ABS, the current petroleum-based plastic in AirPods, and BioABS, a material made mostly of engineered soybean hulls and corn, sugar beets or rice [10]. The results are that, currently, BioABS is 4% more expensive than traditional ABS, at $1896.55/t. For 25 grams, this yields the following increase in price:

$$\begin{aligned}\Delta P &= \Delta PRICE_{/mass} \cdot Mass \\ &= 1896.55 \cdot (1 - \frac{1}{1.04}) \cdot 25 \cdot 10^{-6}\ [g/t] \cdot 100\ [cents/\$] \\ &= 0.18\ cents\end{aligned}$$

Considering the AirPods retail for around 190 $, 18 cents corresponds to only $\frac{0.18}{190} \approx 0.1$ % of the total price. As the **results** of our LCA previously found, this negligible increase in the price of production would reduce the material's energy by around 10 % while also diminishing the use of fossil fuels and making the plastic bio degradable.

Some components of the AirPods are rare metals, which are very energy-demanding for their extraction. One of them is the cobalt, used on the cathode of the Lithium-ion battery. Beside the amount of electricity used in the extraction process, the extraction methods are very polluting [17]. Moreover, it raises ethical questions on the worker, mainly in the Democratic Republic of Congo.
The use of cobalt-free battery could avoid these previous problems by using lithium ferro-phosphate (LFP) instead; this technology already exists and allows equivalent efficiency score. Nevertheless, there are some drawbacks, like the battery volume and weight which should be 35 % higher, or the resistance to the cold which is significantly reduced.[18]
Unfortunately the software Granta EduPack doesn't allow us to evaluate the environmental impact for LFP battery, and because it's a very new technology, it is unlikely that Apple could implement it in the near future. It is however a promising idea which could be one day integrated.

Another conclusion in the LCA was the large contribution from the gold to the CO_2 emissions. If Apple used recycled gold in its AirPods, like it started doing in 2021 for iPhones [22], that would allow the preservation of this raw metal as well as reducing the total CO_2 footprint of the AirPods by 18 %. However, this change could lead to some difficulty in sourcing and a potential increase in price. This increase is hard to quantify though as prices of gold and recycled gold are highly variable and depend on whether Apple would source it from its own recycling chain or purchase it from a supplier.

5.6 Total impact of improvements

Estimating which changes could be applied in the very near future and determining how effective these changes are can be quite hard to quantify. This part however will attempt to give a meaningful approximation of the CO_2 reduction from changes that could be made today with reasonable effort and cost and that would keep the AirPods nearly identical for users.

As mentioned in Section 5.3, the estimated prolonged life span of the AirPods goes from around 18 months or 2 years to at least 3 years, with some users able to keep them more than 5 years thanks to the repairabilty. Furthermore, thanks to the software optimizations detailed in Section 5.4, most batteries should be able to last at least 3 years. These changes essentially double the lifespan of AirPods, which in turn halves the CO_2 footprint as users will replace them half as often.

Finally, limiting the material changes to only the plastic casing and the recycled gold as these could be implemented rather easily without any modification to the design, the reduction in carbon footprint could be in the order of 30 % according to the LCA.

Added up, these changes equate to a 65 % percent reduction in CO_2. While it's important to remember these are gross approximations, it still gives an idea of just how much the impact of AirPods could be reduced with simple changes. And this is before taking into account other damages to the environment such as water pollution or depleting resources among others, as well as ethical questions on the extraction of materials and manufacturing of products.

The major road block for these changes however, is most likely revenue. Indeed, Apple makes much more money selling new AirPods to a user after only one or two years, rather than developing software to prolong their lifespan and allowing users to repair them. This issue though, is beyond the reach of this study.

6 Conclusion

The purpose of this study was to assess the environmental impact of the AirPods, the most popular among a wide pool of truly wireless earphones, who's sales have exploded in the past few years, raising serious concerns over resource use, e-waste, and other issues alike. The results are centered around a life cycle assessment which gave an idea of the impact of the components and helped guide ways to diminish the environmental damage caused by AirPods.

Looking into the components that make up the AirPods, they are densely packed electronics sealed into a permanently glued plastic casing. This lead to the study being heavily centered around the ABS casing, as this was essentially the only modifiable element that does not change the function of the AirPods. Given Apple are very secretive about their products and that it is very difficult to quantify the mass of individual materials in electronics, a number of assumptions were made in order to complete the LCA and get an approximate energy use of the plastic casing relative to the unchangeable electronics. The LCA of the AirPods was then compared with the LCA of more sustainable wireless earphones, made by House of Marley, which uses bio sourced and recycled materials for the earphone enclosure and were considered to use recycled gold as well. The results were that the carbon footprint of the AirPods were around 1.6 kg and diminished by 30 % if recycled gold and sustainable casing materials were used, with gold contributing to 60 % of that reduction and the rest coming from plastic. Even when varying the assumptions made, the results remain in the same order of magnitude which suggests the results found can be trusted with a reasonably good level of confidence. Following the results of the LCA, a number of changes were suggested to diminish the impact of the AirPods. The first was to change the design of the plastic housing to make it possible to dismantle. The next were to change the battery and connection method between the electronics to make all the parts easily interchangeable. These two changes not only makes the AirPods repairable, it also facilitates recycling. Changes in software were also proposed to prolong the lifespan of the battery, the biggest contributor to the CO_2 emissions of the product, that could be implemented on AirPods already in use today. Finally, different alternative materials were investigated to diminish the carbon footprint as well as the resource use of the earphones. Combined these changes enable an estimated reduction of 65% of the carbon footprint, a very significant improvement considering the relative ease of the changes necessary.

From this study, it is obvious the impressive rise in popularity of the AirPods and wireless earphones alike raises some serious questions over their impact on the planet. While a return to wired earphones seems like an obvious solution to reducing environmental impact, it is highly unlikely considering electronics manufacturers have removed the headphone jack from nearly all phones and tablets. A handful of brands such as Shure offer a modular design which allows the battery to be removed, but as long as companies base the design of products solely on maximizing profits and governments do not impose the right to repair, the vast majority of wireless earphones will continue to become e-waste after only a couple of years of use.

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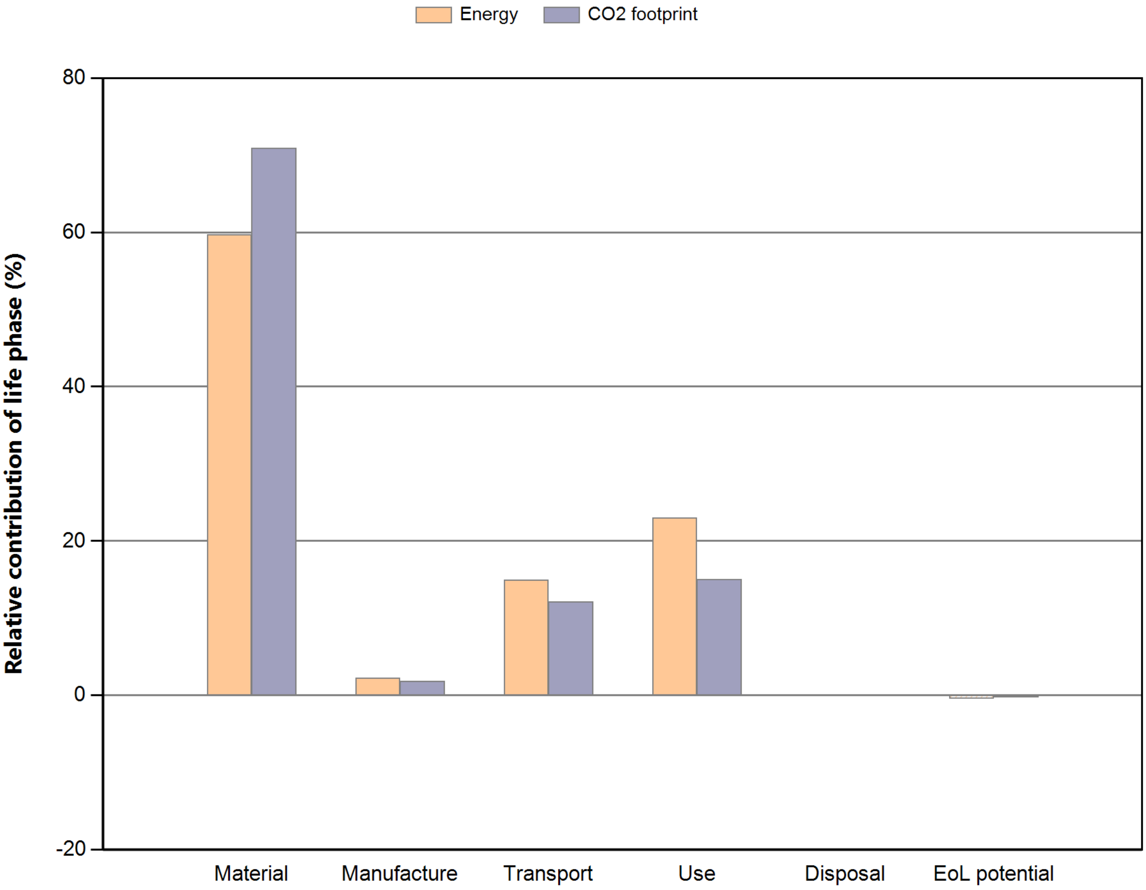
8 Annex

8.1 Report LCA of the AirPods

Eco Audit Report

Product name	Airpods
Country of use	North America
Product life (years)	2

Summary:

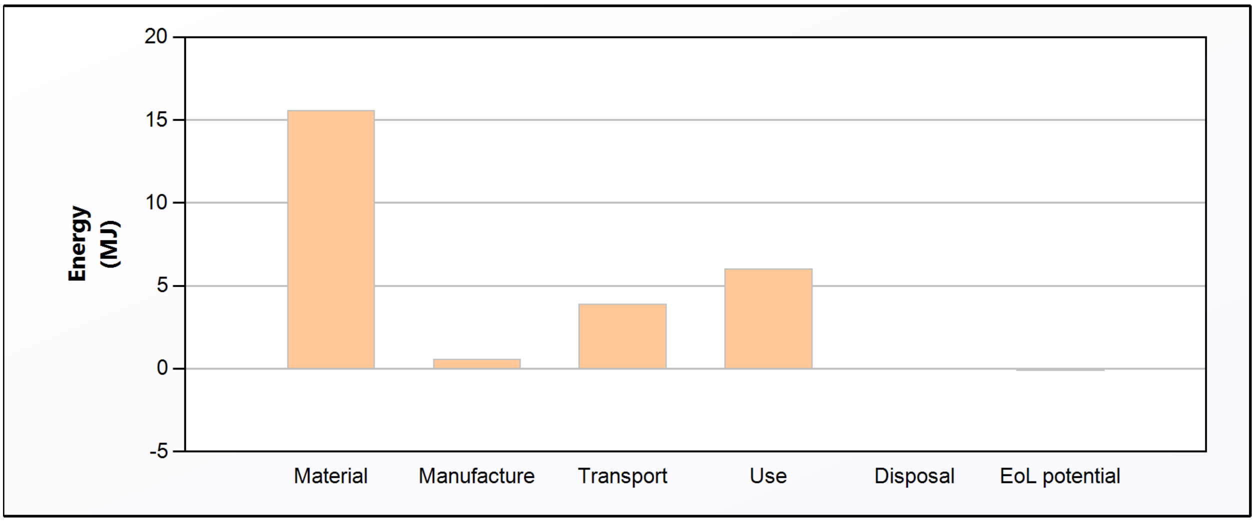


Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	15,6	59,7	1,64	70,9
Manufacture	0,579	2,2	0,0434	1,9
Transport	3,91	15,0	0,281	12,1
Use	6,02	23,0	0,348	15,0
Disposal	0,0126	0,0	0,00088	0,0
Total (for first life)	**26,1**	**100**	**2,32**	**100**
End of life potential	-0,103		-0,0058	

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 2 year product life):	13,1

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,2	1,3
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	2,3	14,9
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	15,0
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	40,4
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	3,4
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	0,7
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	1,6
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,5
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,5
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	1,6
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,8e-07	2	1,4e-06	0,51	3,3
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,5e-06	1	6,5e-06	2,4	15,5
Total				**19**	**0,046**	**16**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Shell Case	Polymer molding	-	0,023 kg	0,49	84,0
Shell Case	Coarse machining	-	0 kg	0	0,0
Copper buds	Extrusion, foil rolling	-	0,00051 kg	0,0096	1,7
Copper case	Extrusion, foil rolling	-	0,0012 kg	0,023	4,0
steel case	Roll forming	-	0,0012 kg	0,008	1,4
steel buds	Roll forming	-	0,0012 kg	0,0078	1,3
Magnets case	Metal powder forming	-	0,0016 kg	0,044	7,6
Total				**0,58**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
DRC-China	Ocean freight	9,6e+03	0,08	2,0
Chili-China	Ocean freight	2e+04	0,16	4,1
China-USA	Air freight - long haul	1,2e+04	3,5	89,5
Last kilometers	40 tonne (6 axle) truck	4,5e+03	0,17	4,3
Total		**4,5e+04**	**3,9**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Shell buds	0,002	0,17	4,3
Shell Case	0,023	1,9	49,6
Battery buds	0,0026	0,22	5,7
Battery case	0,007	0,59	15,2
motherboard case	0,0041	0,35	8,9
motherboard airpods	0,0017	0,14	3,7
Copper buds	0,00051	0,043	1,1
Copper case	0,0012	0,1	2,7
steel case	0,0012	0,1	2,7
steel buds	0,0012	0,1	2,6
Magnets case	0,0016	0,14	3,6
gold buds	1,4e-06	0,00012	0,0
gold case	6,5e-06	0,00055	0,0
Total	**0,046**	**3,9**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to thermal
Country of use	North America
Power rating (W)	1,5
Usage (hours per day)	1
Usage (days per year)	2,5e+02
Product life (years)	2

Relative contribution of static and mobile modes

Mode	Energy (MJ)	%
Static	6	100,0
Mobile	0	
Total	**6**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Shell buds	Landfill	100,0	0,0004	3,2
Shell Case	Landfill	100,0	0,0046	36,3
Battery buds	Downcycle	100,0	0,0013	10,3
Battery case	Downcycle	100,0	0,0035	27,8
motherboard case	Landfill	100,0	0,00082	6,5
motherboard airpods	Landfill	100,0	0,00034	2,7
Copper buds	Landfill	100,0	0,0001	0,8
Copper case	Landfill	100,0	0,00025	2,0
steel case	Landfill	100,0	0,00025	2,0
steel buds	Landfill	100,0	0,00024	1,9
Magnets case	Downcycle	100,0	0,00082	6,5
gold buds	Landfill	100,0	2,7e-07	0,0
gold case	Landfill	100,0	1,3e-06	0,0
Total			**0,013**	**100**

EoL potential:

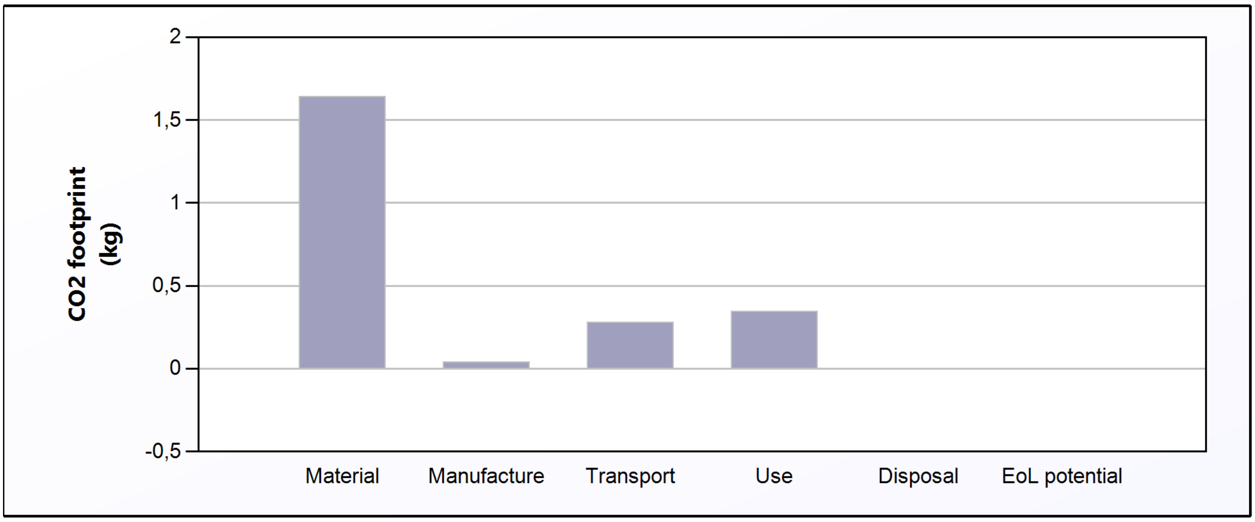
Component	End of life option	% recovered	Energy (MJ)	%
Shell buds	Landfill	100,0	0	0,0
Shell Case	Landfill	100,0	0	0,0
Battery buds	Downcycle	100,0	0	0,0
Battery case	Downcycle	100,0	0	0,0
motherboard case	Landfill	100,0	0	0,0
motherboard airpods	Landfill	100,0	0	0,0
Copper buds	Landfill	100,0	0	0,0
Copper case	Landfill	100,0	0	0,0
steel case	Landfill	100,0	0	0,0
steel buds	Landfill	100,0	0	0,0
Magnets case	Downcycle	100,0	-0,1	100,0
gold buds	Landfill	100,0	0	0,0
gold case	Landfill	100,0	0	0,0
Total			**-0,1**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 2 year product life):	1,16

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Shell buds	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,001	2	0,002	0,0097	0,6
Shell Case	ABS+PC (injection molding and extrusion)	Virgin (0%)	0,023	1	0,023	0,11	6,7
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	0,26	16,1
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	0,71	43,3
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,04	2,4
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,017	1,0
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,011	0,7
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,026	1,6
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,0054	0,3
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,0052	0,3
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,015	0,9
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,8e-07	2	1,4e-06	0,074	4,5
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	Virgin (0%)	6,5e-06	1	6,5e-06	0,35	21,5
Total				**19**	**0,046**	**1,6**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

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Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Shell Case	Polymer molding	-	0,023 kg	0,036	84,0
Shell Case	Coarse machining	-	0 kg	0	0,0
Copper buds	Extrusion, foil rolling	-	0,00051 kg	0,00072	1,7
Copper case	Extrusion, foil rolling	-	0,0012 kg	0,0017	4,0
steel case	Roll forming	-	0,0012 kg	0,0006	1,4
steel buds	Roll forming	-	0,0012 kg	0,00058	1,3
Magnets case	Metal powder forming	-	0,0016 kg	0,0033	7,6
Total				**0,043**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
DRC-China	Ocean freight	9,6e+03	0,0057	2,0
Chili-China	Ocean freight	2e+04	0,012	4,1
China-USA	Air freight - long haul	1,2e+04	0,25	89,5
Last kilometers	40 tonne (6 axle) truck	4,5e+03	0,012	4,3
Total		**4,5e+04**	**0,28**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Shell buds	0,002	0,012	4,3
Shell Case	0,023	0,14	49,6
Battery buds	0,0026	0,016	5,7
Battery case	0,007	0,043	15,2
motherboard case	0,0041	0,025	8,9
motherboard airpods	0,0017	0,01	3,7
Copper buds	0,00051	0,0031	1,1
Copper case	0,0012	0,0075	2,7
steel case	0,0012	0,0075	2,7
steel buds	0,0012	0,0073	2,6
Magnets case	0,0016	0,01	3,6
gold buds	1,4e-06	8,3e-06	0,0
gold case	6,5e-06	4e-05	0,0
Total	**0,046**	**0,28**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to thermal
Country of use	North America
Power rating (W)	1,5
Usage (hours per day)	1
Usage (days per year)	2,5e+02
Product life (years)	2

Relative contribution of static and mobile modes

Mode	CO2 footprint (kg)	%
Static	0,35	100,0
Mobile	0	
Total	**0,35**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Shell buds	Landfill	100,0	2,8e-05	3,2
Shell Case	Landfill	100,0	0,00032	36,3
Battery buds	Downcycle	100,0	9,1e-05	10,3
Battery case	Downcycle	100,0	0,00025	27,8
motherboard case	Landfill	100,0	5,7e-05	6,5
motherboard airpods	Landfill	100,0	2,4e-05	2,7
Copper buds	Landfill	100,0	7,1e-06	0,8
Copper case	Landfill	100,0	1,7e-05	2,0
steel case	Landfill	100,0	1,7e-05	2,0
steel buds	Landfill	100,0	1,7e-05	1,9
Magnets case	Downcycle	100,0	5,7e-05	6,5
gold buds	Landfill	100,0	1,9e-08	0,0
gold case	Landfill	100,0	9e-08	0,0
Total			**0,00088**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Shell buds	Landfill	100,0	0	0,0
Shell Case	Landfill	100,0	0	0,0
Battery buds	Downcycle	100,0	0	0,0
Battery case	Downcycle	100,0	0	0,0
motherboard case	Landfill	100,0	0	0,0
motherboard airpods	Landfill	100,0	0	0,0
Copper buds	Landfill	100,0	0	0,0
Copper case	Landfill	100,0	0	0,0
steel case	Landfill	100,0	0	0,0
steel buds	Landfill	100,0	0	0,0
Magnets case	Downcycle	100,0	-0,0058	100,0
gold buds	Landfill	100,0	0	0,0
gold case	Landfill	100,0	0	0,0
Total			**-0,0058**	**100**

Notes:

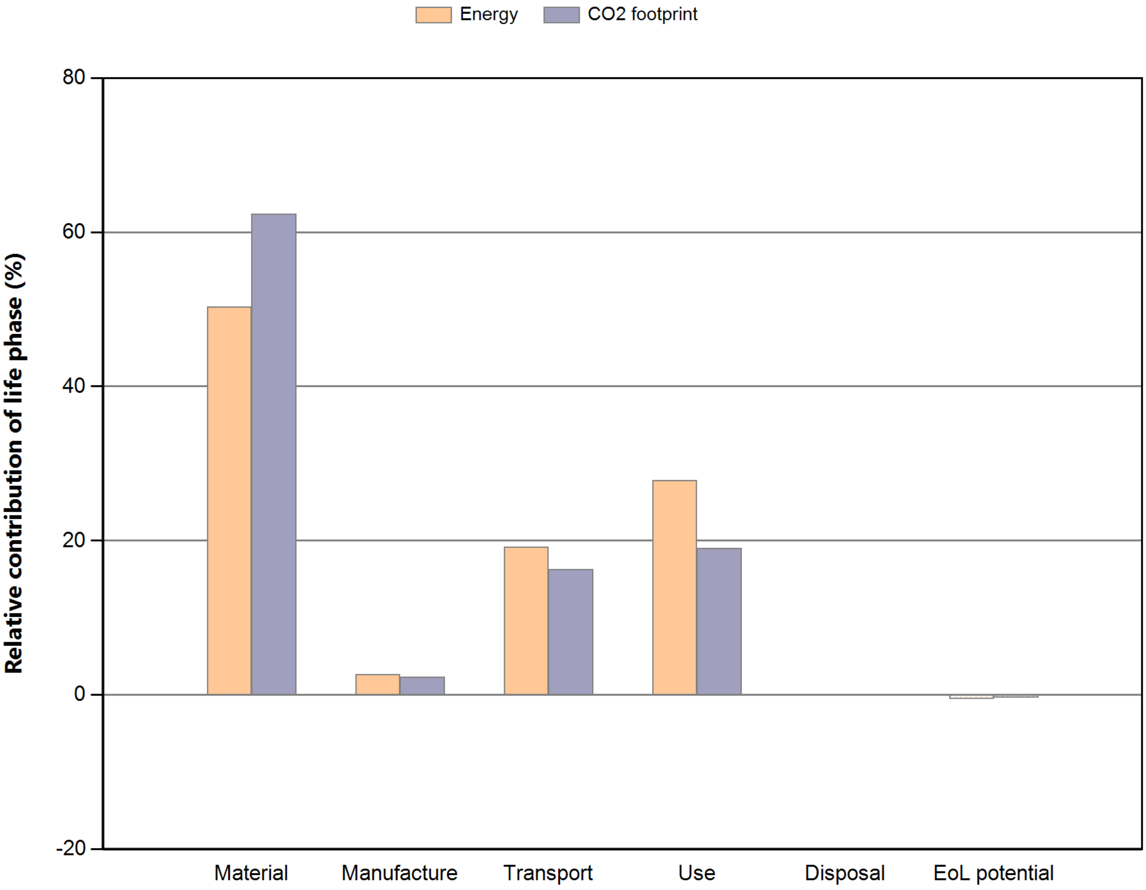
Summary

8.2 Report LCA House of Marley Redemption ANC 2

Eco Audit Report

Product name	Marley
Country of use	North America
Product life (years)	2

Summary:

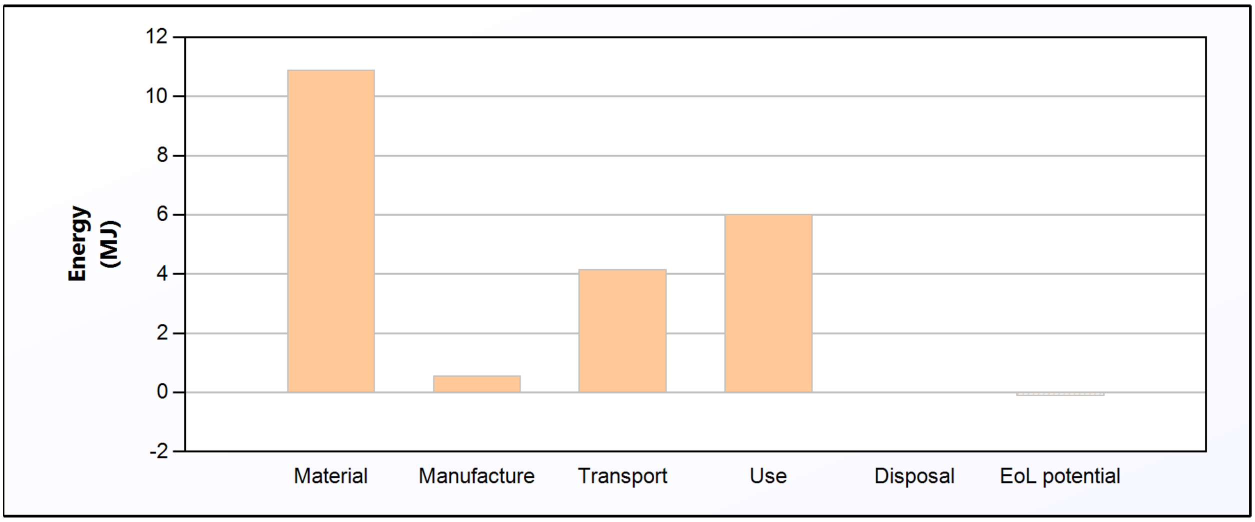


Energy details CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	10,9	50,3	1,14	62,4
Manufacture	0,571	2,6	0,0428	2,3
Transport	4,15	19,2	0,299	16,3
Use	6,02	27,8	0,348	19,0
Disposal	0,0131	0,1	0,000919	0,1
Total (for first life)	**21,6**	**100**	**1,83**	**100**
End of life potential	-0,103		-0,0058	

Energy Analysis

Summary



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 2 year product life):	10,8

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Shell PET buds	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,0007	2	0,0014	0,031	0,3
Shell PET Case	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,023	1	0,023	0,51	4,7
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	2,3	21,5
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	6,3	57,8
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,53	4,9
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,22	2,0
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,11	1,0
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,26	2,3
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,077	0,7
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,074	0,7
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,25	2,3
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,014	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,067	0,6
Bamboo buds shell	Bamboo (transverse)	Virgin (0%)	0,0003	2	0,0006	0,02	0,2
Bamboo case shell	Bamboo (transverse)	Virgin (0%)	0,0028	1	0,0028	0,096	0,9
Total				**22**	**0,049**	**11**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

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Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (MJ)	%
Shell PET buds	Polymer molding	-	0,0014 kg	0,027	4,8
Shell PET buds	Coarse machining	-	0 kg	0	0,0
Shell PET Case	Polymer molding	-	0,023 kg	0,44	77,5
Shell PET Case	Coarse machining	-	0 kg	0	0,0
Copper buds	Extrusion, foil rolling	-	0,00051 kg	0,0096	1,7
Copper case	Extrusion, foil rolling	-	0,0012 kg	0,023	4,1
steel case	Roll forming	-	0,0012 kg	0,008	1,4
steel buds	Roll forming	-	0,0012 kg	0,0078	1,4
Magnets case	Metal powder forming	-	0,0016 kg	0,044	7,7
gold buds	Vaporization	-	1,4e-06 kg	0,0015	0,3
gold case	Vaporization	-	6,5e-06 kg	0,0073	1,3
Total				**0,57**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	Energy (MJ)	%
DRC-China	Ocean freight	9,6e+03	0,084	2,0
Chili-China	Ocean freight	2e+04	0,17	4,1
China-USA	Air freight - long haul	1,2e+04	3,7	89,5
Last kilometers	40 tonne (6 axle) truck	4,5e+03	0,18	4,3
Total		**4,5e+04**	**4,1**	**100**

Breakdown by components

Component	Mass (kg)	Energy (MJ)	%
Shell PET buds	0,0014	0,12	2,9
Shell PET Case	0,023	1,9	46,7
Battery buds	0,0026	0,22	5,3
Battery case	0,007	0,59	14,3
motherboard case	0,0041	0,35	8,4
motherboard airpods	0,0017	0,14	3,5
Copper buds	0,00051	0,043	1,0
Copper case	0,0012	0,1	2,5
steel case	0,0012	0,1	2,5
steel buds	0,0012	0,1	2,4
Magnets case	0,0016	0,14	3,4
gold buds	1,4e-06	0,00012	0,0
gold case	6,5e-06	0,00055	0,0
Bamboo buds shell	0,0006	0,051	1,2
Bamboo case shell	0,0028	0,24	5,7
Total	**0,049**	**4,1**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to thermal
Country of use	North America
Power rating (W)	1,5
Usage (hours per day)	1
Usage (days per year)	2,5e+02
Product life (years)	2

Relative contribution of static and mobile modes

Mode	**Energy (MJ)**	**%**
Static	6	100,0
Mobile	0	
Total	**6**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (MJ)	%
Shell PET buds	Landfill	100,0	0,00028	2,1
Shell PET Case	Landfill	100,0	0,0046	34,7
Battery buds	Downcycle	100,0	0,0013	9,9
Battery case	Downcycle	100,0	0,0035	26,6
motherboard case	Landfill	100,0	0,00082	6,2
motherboard airpods	Landfill	100,0	0,00034	2,6
Copper buds	Landfill	100,0	0,0001	0,8
Copper case	Landfill	100,0	0,00025	1,9
steel case	Landfill	100,0	0,00025	1,9
steel buds	Landfill	100,0	0,00024	1,8
Magnets case	Downcycle	100,0	0,00082	6,2
gold buds	Landfill	100,0	2,7e-07	0,0
gold case	Landfill	100,0	1,3e-06	0,0
Bamboo buds shell	Landfill	100,0	0,00012	0,9
Bamboo case shell	Landfill	100,0	0,00056	4,3
Total			**0,013**	**100**

EoL potential:

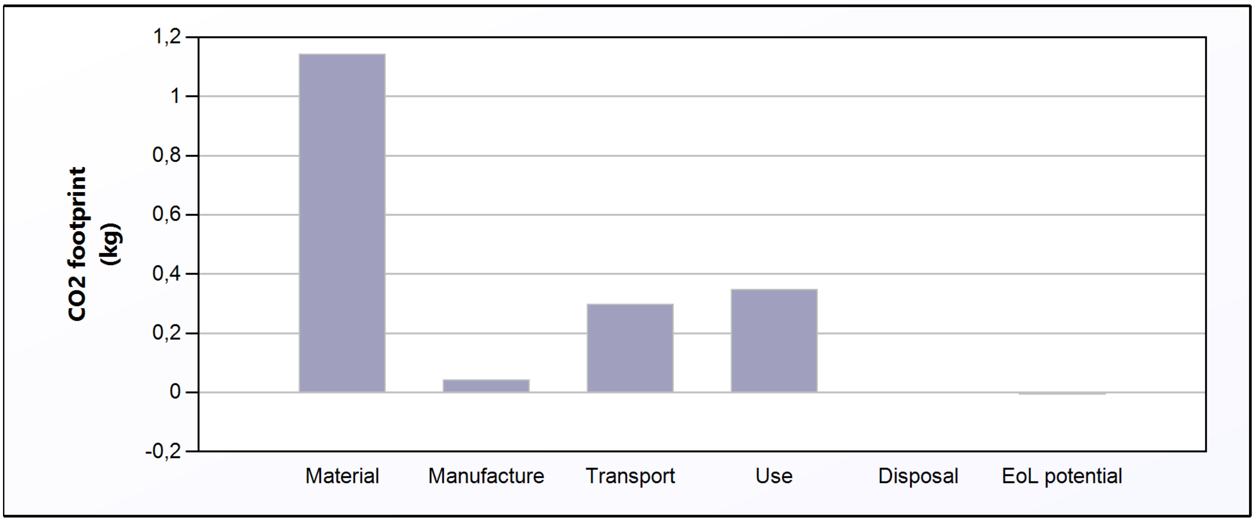
Component	End of life option	% recovered	Energy (MJ)	%
Shell PET buds	Landfill	100,0	0	0,0
Shell PET Case	Landfill	100,0	0	0,0
Battery buds	Downcycle	100,0	0	0,0
Battery case	Downcycle	100,0	0	0,0
motherboard case	Landfill	100,0	0	0,0
motherboard airpods	Landfill	100,0	0	0,0
Copper buds	Landfill	100,0	0	0,0
Copper case	Landfill	100,0	0	0,0
steel case	Landfill	100,0	0	0,0
steel buds	Landfill	100,0	0	0,0
Magnets case	Downcycle	100,0	-0,1	100,0
gold buds	Landfill	100,0	0	0,0
gold case	Landfill	100,0	0	0,0
Bamboo buds shell	Landfill	100,0	0	0,0
Bamboo case shell	Landfill	100,0	0	0,0
Total			**-0,1**	**100**

Notes:

Summary

CO2 Footprint Analysis

Summary



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 2 year product life):	0,917

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Shell PET buds	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,0007	2	0,0014	0,0022	0,2
Shell PET Case	PET (35% glass fiber and mineral, recycled content)	Virgin (0%)	0,023	1	0,023	0,036	3,2
Battery buds	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,0013	2	0,0026	0,26	23,1
Battery case	Li-Ion, rechargeable battery (for laptops)	Virgin (0%)	0,007	1	0,007	0,71	62,2
motherboard case	Printed circuit board assembly	Virgin (0%)	0,0041	1	0,0041	0,04	3,5
motherboard airpods	Printed circuit board assembly	Virgin (0%)	0,00085	2	0,0017	0,017	1,4
Copper buds	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,00026	2	0,00051	0,011	0,9
Copper case	Copper-beryllium alloy, CuBe2CoNi, C17000, half hard (w1/2hp)	Virgin (0%)	0,0012	1	0,0012	0,026	2,3
steel case	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0012	1	0,0012	0,0054	0,5
steel buds	Stainless steel, austenitic, AISI 304, 1/2 hard	Virgin (0%)	0,0006	2	0,0012	0,0052	0,5
Magnets case	Neodymium magnet N45SH	Virgin (0%)	0,0016	1	0,0016	0,015	1,3
gold buds	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,8e-07	2	1,4e-06	0,0011	0,1
gold case	Gold-germanium alloy, Au88 (12%Ge solder)	100,0%	6,5e-06	1	6,5e-06	0,0053	0,5
Bamboo buds shell	Bamboo (transverse)	Virgin (0%)	0,0003	2	0,0006	0,00063	0,1
Bamboo case shell	Bamboo (transverse)	Virgin (0%)	0,0028	1	0,0028	0,0029	0,3
Total				**22**	**0,049**	**1,1**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (kg)	%
Shell PET buds	Polymer molding	-	0,0014 kg	0,002	4,8
Shell PET buds	Coarse machining	-	0 kg	0	0,0
Shell PET Case	Polymer molding	-	0,023 kg	0,033	77,5
Shell PET Case	Coarse machining	-	0 kg	0	0,0
Copper buds	Extrusion, foil rolling	-	0,00051 kg	0,00072	1,7
Copper case	Extrusion, foil rolling	-	0,0012 kg	0,0017	4,1
steel case	Roll forming	-	0,0012 kg	0,0006	1,4
steel buds	Roll forming	-	0,0012 kg	0,00058	1,4
Magnets case	Metal powder forming	-	0,0016 kg	0,0033	7,7
gold buds	Vaporization	-	1,4e-06 kg	0,00012	0,3
gold case	Vaporization	-	6,5e-06 kg	0,00055	1,3
Total				**0,043**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (km)	CO2 footprint (kg)	%
DRC-China	Ocean freight	9,6e+03	0,0061	2,0
Chili-China	Ocean freight	2e+04	0,012	4,1
China-USA	Air freight - long haul	1,2e+04	0,27	89,5
Last kilometers	40 tonne (6 axle) truck	4,5e+03	0,013	4,3
Total		**4,5e+04**	**0,3**	**100**

Breakdown by components

Component	Mass (kg)	CO2 footprint (kg)	%
Shell PET buds	0,0014	0,0086	2,9
Shell PET Case	0,023	0,14	46,7
Battery buds	0,0026	0,016	5,3
Battery case	0,007	0,043	14,3
motherboard case	0,0041	0,025	8,4
motherboard airpods	0,0017	0,01	3,5
Copper buds	0,00051	0,0031	1,0
Copper case	0,0012	0,0075	2,5
steel case	0,0012	0,0075	2,5
steel buds	0,0012	0,0073	2,4
Magnets case	0,0016	0,01	3,4
gold buds	1,4e-06	8,3e-06	0,0
gold case	6,5e-06	4e-05	0,0
Bamboo buds shell	0,0006	0,0037	1,2
Bamboo case shell	0,0028	0,017	5,7
Total	**0,049**	**0,3**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to thermal
Country of use	North America
Power rating (W)	1,5
Usage (hours per day)	1
Usage (days per year)	2,5e+02
Product life (years)	2

Relative contribution of static and mobile modes

Mode	**CO2 footprint (kg)**	**%**
Static	0,35	100,0
Mobile	0	
Total	**0,35**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (kg)	%
Shell PET buds	Landfill	100,0	2e-05	2,1
Shell PET Case	Landfill	100,0	0,00032	34,7
Battery buds	Downcycle	100,0	9,1e-05	9,9
Battery case	Downcycle	100,0	0,00025	26,6
motherboard case	Landfill	100,0	5,7e-05	6,2
motherboard airpods	Landfill	100,0	2,4e-05	2,6
Copper buds	Landfill	100,0	7,1e-06	0,8
Copper case	Landfill	100,0	1,7e-05	1,9
steel case	Landfill	100,0	1,7e-05	1,9
steel buds	Landfill	100,0	1,7e-05	1,8
Magnets case	Downcycle	100,0	5,7e-05	6,2
gold buds	Landfill	100,0	1,9e-08	0,0
gold case	Landfill	100,0	9e-08	0,0
Bamboo buds shell	Landfill	100,0	8,4e-06	0,9
Bamboo case shell	Landfill	100,0	3,9e-05	4,3
Total			**0,00092**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (kg)	%
Shell PET buds	Landfill	100,0	0	0,0
Shell PET Case	Landfill	100,0	0	0,0
Battery buds	Downcycle	100,0	0	0,0
Battery case	Downcycle	100,0	0	0,0
motherboard case	Landfill	100,0	0	0,0
motherboard airpods	Landfill	100,0	0	0,0
Copper buds	Landfill	100,0	0	0,0
Copper case	Landfill	100,0	0	0,0
steel case	Landfill	100,0	0	0,0
steel buds	Landfill	100,0	0	0,0
Magnets case	Downcycle	100,0	-0,0058	100,0
gold buds	Landfill	100,0	0	0,0
gold case	Landfill	100,0	0	0,0
Bamboo buds shell	Landfill	100,0	0	0,0
Bamboo case shell	Landfill	100,0	0	0,0
Total			**-0,0058**	**100**

Notes:

Summary