The environmental impact of reusing iPhones

A case study looking into the environmental benefits of reusing iPhones through Twig

Master thesis
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Abstract

The use of smartphones worldwide is rapidly growing and thereby their contribution to their impact on the environment. Twig is a company that facilitates the reuse of electronics and other products via an app to increase circularity, decrease waste, and increase sustainability awareness. To assist the electronics industry in becoming more sustainable and for Twig to understand the quantitative impact reduction achieved by reusing smartphones, a case study was conducted to answer the question: *What is the environmental impact of reusing an iPhone through Twig's business model?* The study employed a life cycle assessment approach with a functional unit defined as *using an iPhone for one year*. Three consumer scenarios (conscious, average, and polluter) were considered, reflecting usage duration and intensity of use during the primary and secondary use phase. System expansion was employed to compare the environmental impacts of the smartphone reuse system with its linear reference system. The findings revealed that in the conscious consumer scenario, reuse generated 42.64% more greenhouse gas (GHG) emissions than the linear reference system (i.e. buying a new phone) while in the average and polluter scenarios, reuse led to 12.02% and 47.57% fewer GHG emissions. This means that the average and polluter consumer type, independent of the second use phase consumer (buyer) type, should always resell their iPhone. Conscious consumers can benefit the environment by purchasing a new phone rather than reselling it. Although a sensitivity analysis demonstrated the potential environmental benefit of reuse in the conscious scenario, where the phone is sold to the same consumer type as during its primary use phase, this finding does not impact the conclusion. In reality, it is impractical to determine the buyer and uncertain how they will use the phone, making the finding inconclusive. In societal terms, the study's findings are useful to raise awareness about the benefits of reuse and highlight the influence of smartphone usage impacts. Furthermore, the study showed that the duration and intensity of smartphone use by different consumer types significantly influenced the LCA results. This highlights the crucial role of understanding consumer behavior. Therefore, conducting further consumer research on usage patterns like network usage, intensity, and duration of use, as well as dynamics related to consumer preferences and demands, is crucial for accurate LCA results. This consumer research is essential for fostering the development of strategies and policies that promote sustainable consumption patterns and maximize the advantages of product reuse.

Executive Summary

Through this study, Twig wants to be able to inform its customers about the quantitative impact reduction of re-commerce. The research findings suggest that Twig has the option to display the average consumer scenario to all customers, which represents a general estimate of environmental impact reductions. However, to offer a more equitable representation of emissions for both sellers and buyers in their app, it is recommended for Twig to collect information on the smartphone's duration and intensity of use from customers. By incorporating this data, Twig can enhance its communication with customers by providing tailored information on avoided impacts.

In addition, it is advised to conduct a survey targeting both sellers and buyers to gather valuable data on consumer behavior. This survey will contribute to a better understanding of how consumers perceive and utilize new items compared to second-hand items. The insights obtained from the survey will address the existing knowledge gap on smartphone use and support future LCAs on smartphone reuse. Furthermore, the survey results will enable Twig to contribute to the broader understanding of consumer preferences and behavior in the context of electronic reuse.

Overall, this research offers Twig an opportunity to refine its environmental messaging, strengthen customer engagement, and contribute to the advancement of knowledge in the field of smartphone reuse through LCAs.

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1. Introduction

1.1 Societal background & problem

The pervasive integration of electronics, including smartphones, into our daily lives has made them indispensable. However, a concerning trend persists where these devices are often treated as disposable items, leading to the escalating issue of waste electrical and electronic equipment (WEEE) on a global scale (Ellen MacArthur Foundation, 2017; Kiddee et al., 2013). The magnitude of this problem is staggering, with a total of 44.7 million tonnes of e-waste generated in 2016, including 435 thousand tonnes of mobile phones alone, which exceeds the weight of the Empire State Building (Baldé et al., 2017). Within Europe, the disposal of WEEE is recognized as one of the fastest-growing waste streams, exhibiting an annual growth rate of approximately 3-5%, a stark contrast to other waste streams (Corsini et al., 2020). Moreover, projections by Forti et al. (2020) suggest that global e-waste generation will reach a staggering 74.7 million tons by 2030. Shockingly, according to the United Nations' Global E-Waste Monitor report, a mere 20% of WEEE was adequately recycled in 2016, leaving the remaining 80% in suboptimal conditions due to insufficient recycling infrastructure and commercialization (Baldé et al., 2017).

A relatively small electronic such as a smartphone has more than 60 chemical elements in its composition (Prado et al., 2016). The extraction of these elements and the production of components are energy-intensive operations. The production also involves the use of heavy metals which are highly toxic and can pose a significant risk to the environment and human health. When these devices are disposed of improperly or their residues come into contact with human beings, they become harmful (Jaunich et al., 2020). As a consequence, the disposal of electronic waste gives rise to a plethora of environmental and health impacts (Nunes et al., 2021).

The electronics industry predominantly operates under a linear model of take, make, and dispose, yet there exists a substantial potential for transitioning to a circular economy (CE), as highlighted by the Ellen MacArthur Foundation (2017). The global importance of embracing sustainable practices for consumption and resource management is on the rise, with the adoption of the 3Rs concept (reduce, reuse, recycle) offering significant environmental and economic benefits within the smartphone industry (de Oliveira Neto et al., 2017). This concept emphasizes reducing production and consumption, reusing products or components, and recycling them as the primary strategies for achieving sustainability objectives. Reuse strategies encompass activities like resale, repair, and remanufacturing, which provide a second life for products or components (Zlamparet et al., 2017). From a sustainability standpoint, recycling should be considered as the final option before resorting to landfilling materials (Singhal et al., 2019). By employing these sustainable strategies, the environmental impact of smartphone production and usage can be significantly reduced.

1.2 Scientific background & societal relevance

Several studies have been conducted to assess the environmental impact of different strategies that give smartphones a second life, as smartphones are the fastest-growing source of electronic waste (Gill, 2022). These studies commonly employ a Life Cycle Assessment (LCA) methodology, which examines the environmental impacts of a product throughout its entire life cycle (Hauschild et al., 2018).

One of these recent studies is the study of Hischier et al. (2021). The environmental and economic benefits of promoting the reuse of electronics were investigated through a simplified LCA approach. The study focused on the purchase of a secondhand smartphone, without specifying the activity that gave the device a second life. The main conclusion was that the longer smartphones are in use, the lower their environmental impact. Through a similar methodology, and assessing multiple life extension scenarios, Canetta et al. (2018) draw a comparable conclusion. From an environmental standpoint, reusing smartphones regardless of their age is always the best solution. However, both studies used many assumptions such as average use-phase behavior to draw these conclusions.

In addition, Hischier et al. (2020) published another study on the environmental impact of electronics, utilizing a simplified LCA and exploring scenarios involving changes in consumer behavior. The results of this study demonstrated that consumer behavior during the use phase, particularly in terms of intensity of use (related to electricity consumption), significantly influenced the environmental impact of various household appliances. Therefore, it is somewhat surprising to note that the study conducted by Hischier et al. (2021) relied on an average approach to derive conclusions regarding use-phase behavior, which contradicts their previous study in 2020, wherein the significance of consumer behavior was emphasized.

Cordella et al. (2021) conducted a comprehensive LCA study to evaluate the environmental impact of reusing smartphones, reinforcing the findings of Hischier et al. (2021) and Canetta et al. (2018) while considering various circular strategies. Despite utilizing averages to account for user behavior, the authors acknowledged the influence of user behavior on the environmental assessment of smartphone reuse. They highlighted the importance of user engagement in implementing circular strategies and suggested that future research incorporate real case studies and broader sustainability metrics to enhance understanding.

From a different perspective, Zink et al. (2014) explored an alternative approach by repurposing smartphones for different applications, such as transforming them into parking meters. Through a comparative LCA analysis, the study indicated that repurposing smartphones was the most environmentally preferable choice. However, the authors recognized consumer behavior as a potential source of uncertainty in evaluating environmental impacts.

Where environmental impact studies on reusing smartphones took averages for consumer behavior, existing studies that examined the life cycle of a smartphone did attempt to consider consumer behavior. For example, Sánchez et. al. (2022) created three different consumer profiles regarding the intensity of use and duration of use when conducting an LCA on the Fairphone 4. Similarly, Ercan et al., (2016) created three different consumer profiles that include an intensity of use and duration of use for a smartphone. This creation of consumer profiles is not applied in studies that conducted an LCA on smartphone reuse.

Studies have identified various factors that can influence consumer behavior toward circular solutions, including tangible and intangible product properties (Camacha-Otero et al., 2018). Tangible properties relate to product characteristics such as repairability and large memory size. Intangible properties relate to mental depreciation and perceived obsolescence (Makov and Fitzpatrick, 2021). Tangible properties can increase the second-hand value of a smartphone and promote circular consumption (Makov et al., 2018a). However, intangible properties such as brands also have an impact, with stronger brands extending the economic lifespan (time at which a product is economically viable to use or resell) of a smartphone by 12.5 months (Makov et al., 2018a). On the other hand, if consumers decide to buy a second-hand device, Makov and Font Vivanco (2018) highlight the potential for rebound effects due to consumers re-spending the economic savings from buying or selling a used device. However, research indicates that consumer behavior plays a crucial role in the success of implementing CE models for smartphones and affects the overall environmental impact of a circular strategy (Mostaghel & Chirumalla, 2021).

Therefore, there is a need to further explore strategies that encourage consumer acceptance and adoption of CE practices (Camacho-Otero et al., 2018). By delving into the relationship between consumer behavior and the environmental impact of reusing smartphones, a foundation can be established to develop such strategies. These strategies can be applied to other electronics and support the creation of a CE.

1.3 Literature gap

Previous studies in the field of LCA have acknowledged the crucial role of consumer behavior in the environmental impact of smartphone reuse and have called for further research to better understand its influence. However, these studies fall short of reflecting consumer behavior in the modeling phase.

They have primarily relied on average data for the primary and secondary use phases, overlooking variations among different types of consumers. Moreover, they have primarily focused on a single sustainability metric, such as Global Warming Potential, without considering a more comprehensive range of impact categories that could provide a holistic view of the environmental benefits of reuse. Additionally, the lack of data on consumer smartphone behavior and attitudes toward CE models has hindered the accurate representation of use phase impacts in LCA studies.

Given the time constraints of this research, gathering primary data on consumer behavior and attitudes may not be feasible. However, an alternative approach would involve conducting an LCA that incorporates different consumer scenarios, utilizes primary data for specific circular strategies, and evaluates impacts across multiple impact categories. This approach would help fill the knowledge gap regarding the influence of consumer behavior on smartphone reuse and provide valuable insights into the environmental benefits of CE models. While the lack of comprehensive primary data poses a challenge, incorporating diverse consumer scenarios and considering a wider range of impact categories can still contribute to a more nuanced understanding of the relationship between consumer behavior and smartphone reuse.

1.4 Research aim & question

To address the literature gap, a case study is conducted on the circular economy company, Twig. Twig is a company with a mission to increase circularity, decrease waste, and increase sustainability awareness. Through the Twig app, users can sell secondary electronics and fashion items to Twig, which then -depending on the item condition, model, and some other factors- repurposes, recycles, or resells them to businesses and individuals. Since Twig is in direct contact with different types of consumers and uses different reuse strategies for electronics, it is considered a perfect case study to attempt to fill the literature gap.

This case study aims to gain insights into the environmental impact of reusing iPhones and the effect of consumer behavior on the avoided impacts due to reuse. The study has been designed to assist the electronics industry in becoming more sustainable and for Twig to understand the quantitative impact reduction achieved by reusing iPhones within their value chains.

The iPhone is a prime example of a brand name that affects consumer preferences, as it is the most preferred and popular brand of smartphones in the UK (Das, 2022). This is also reflected in the data from Twig, which indicate that the iPhone 11 is the most processed item over the last six months. Therefore, in consultation with Twig, the decision was made to focus on this specific iPhone model. This led to the main research question of this study:

What is the environmental impact of reusing an iPhone through Twig's business model?

Consumer behavior plays a role in shaping the environmental impact of using iPhones. Creating consumer profiles can be considered a method to take consumer behavior into account in an LCA. Therefore, understanding how to create these profiles is necessary before beginning with the Life Cycle Inventory (LCI). The following sub-question is answered:

How can different consumer profiles be defined for smartphone use?

To understand the impact of consumer behavior on the overall environmental impact, LCA results of different consumer profiles should be compared. The following sub-question is answered to evaluate this impact:

What is the effect of consumer behavior on the environmental impact of using iPhones?

Answering the main research question requires an understanding of the difference between the environmental impact of the reuse and reference linear consumer scenarios. By comparing the reuse and linear consumer scenarios it becomes clear what impact the reuse of iPhones through Twig has. Therefore, this research follows the LCA methodology to answer the following sub-question:

What is the environmental impact of reusing iPhones compared to a linear (reference) system?

2. Conceptual background

To fully grasp the connections between concepts, it is crucial to comprehend each one individually and relate them to one another. In this section of the theory, an in-depth exploration is conducted on Twig's circular strategies, while simultaneously examining the relation between the CE and consumer behavior using the LCA methodology.

2.1 Circular economy & Twig’s circular strategies

The CE concept explains strategies to avoid environmental burdens. The concept can be defined as an economic system that replaces the ‘end-of-life’ (EoL) concept with reducing, (alternatively) reusing, recycling, and recovering materials in production and consumption processes (Kirchherr et al., 2017). Circular business models are business models that operate circular strategies, such as reuse through direct resale, repair, and remanufacturing (Nußholz, 2017). Figure 1 visualizes the circular strategies (reverse flows).

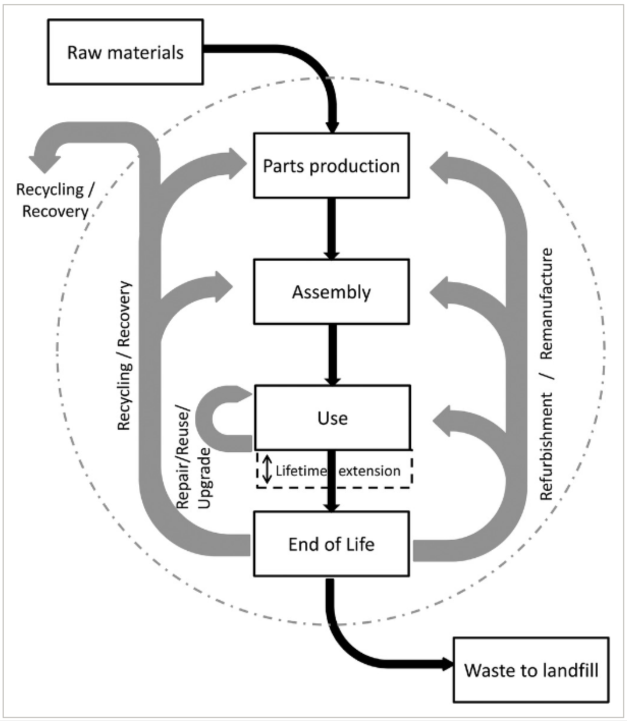

Figure 1: Circular economy reverse flows (Cordella et al, 2019)

Twig operates and facilitates circular business models. The Twig app allows individuals to sell their electronics, including iPhones, to Twig. Once an iPhone is sold, it will be inspected at Twig. Based on the outcome of the inspection, the phone may be directly resold, given a value-add operation, or sent to a repair or remanufacturing partner. Direct resale is the environmentally preferred strategy, involving the direct use of a product without any additional activities. The value-add operation includes polishing the screen and cleaning the phone and can be considered as an operation in-between direct resale and repair. In case of a repair, a component such as a screen or battery is replaced by the repair partner. If the phone's resell value is too low and not worth repairing, it is sent to a remanufacturing partner. Remanufacturing, often referred to as refurbishment, involves remaking the product or its parts with a mixture of recycled and replacement parts, making it almost “new” (Zlamparet et al., 2017). These circular strategies allow Twig to replace primary material inputs with secondary production and prolong the useful life of smartphones.

2.2 Circular economy in the context of LCA

LCA methodology is a comprehensive tool that is often required by regulations and standards to assess the environmental impacts associated with the use of a smartphone. This objective approach provides a complete picture of the overall environmental impact of a product throughout its life cycle (Hauschild et al., 2018, pp. 31). Through LCA, it is possible to identify where the greatest environmental impacts occur and identify opportunities for improvement. Two types of LCA can be distinguished: attributional and consequential. Attributional LCA studies the environmentally relevant flows to and from a life cycle, while consequential LCA shows how environmentally relevant flows will change in response to possible decisions (Finnveden et al., 2009).

LCA is useful when assessing the environmental impact of reusing iPhones since it considers reuse as one stage in the life cycle. By looking at reuse as one stage, it is possible to see how the overall impact of the product is affected by this stage. Furthermore, LCA provides a common framework for comparing the environmental impact of different options, such as using different types of disposal methods. This allows for a more informed decision-making process (Ingemarsdotter & Dumont, 2022). However, in the context of the CE, LCA also has some limitations (Ellen MacArthur Foundation, 2022):

- Limited focus on resource efficiency;
- Lack of holistic approach;
- Difficulty in considering consumer behavior;
- Data availability.

Despite its limitations, LCA is considered the best method for evaluating the environmental impact of smartphones as it is the recommended framework by the European Commission (EPLCA, 2003). It provides an objective picture of the overall environmental impact and identifies areas for improvement. LCA can be modified to address some of its limitations and provide a more thorough evaluation of reusing smartphones (Ingemarsdotter & Dumont, 2022). One way to do this is by creating different consumer profiles to touch upon the limitation of consumer behavior.

Twig uses different circular strategies to give new life to smartphones. Even when eventually disposing of used smartphones, materials can be recovered through recycling. This means that both Twig's circular strategies and disposal of smartphones can create new products or materials. These multioutput processes make it difficult to measure the environmental impact when using LCA because it can be hard to divide the burdens and credits between primary and secondary products or materials. A choice should be made in allocating these burdens and credits to find out the environmental impact of both the linear and the reuse consumer scenarios. The following are options to consider when dealing with the allocation of impacts in an LCA on smartphone reuse:

- System Expansion: One approach is to employ system expansion, which involves expanding the system boundaries to include the impacts of both the original use phase and the reuse phase. This allows for a comprehensive assessment by comparing the environmental impacts of the smartphone reuse scenario with a reference scenario that represents the production of a new smartphone. System expansion helps capture the potential avoided impacts resulting from the reuse of smartphones.
- The Circular Footprint Formula (CCF): The European Commission has developed the CCF to address the allocation of environmental burdens and credit issues. The formula defines the rule for allocating the environmental burdens or credits of recycling or reusing between the producer and the user of recycled materials (Rickert & Ciroth, 2020). It suggests allocating the environmental burdens and credits to different life cycle stages based on their relative contributions. Credits should be given to stages with the lowest environmental impact, while burdens should be assigned to stages with the highest environmental impact.
- Cut-off Allocation: Another option is to use a cutoff allocation method, where a specific point in the life cycle is chosen to allocate impacts between the original use phase and the reuse phase. For example, impacts up to the point of collection for reuse can be allocated solely to the original

use phase, while impacts occurring after the collection can be allocated to the reuse phase. This simplifies the allocation by separating the impacts based on a predefined criterion.

There exist many more allocation methods, such as physical allocation which is allocation based on the physical properties or attributes of the product being reused, or hybrid allocation which involves considering multiple allocation factors, such as time, functionality, or mass, to allocate impacts between the original use phase and the reuse phase. However, based on ISO 14044, if possible, allocation should be avoided by system expansion to avoid burden shifting, capture system-wide effects, reflect real-world scenarios, and be able to address multiple environmental impact categories.

2.3 Consumer behavior in the context LCA

Consumer behavior involves more than purchasing products. Consumer behavior is studied to find out who buys, uses, and disposes of goods and services (Hoyer et al., 2012). In an iPhone's life cycle, the use phase and EoL phase are stages where consumer behavior can contribute to the environmental impact of an iPhone. Therefore, robust modeling of these stages by including the behavioral component is fundamental (Polizzi di Sorrentino et al., 2016).

However, dealing with consumer behavior in an LCA can be challenging, as it is a complex and dynamic aspect that can vary greatly between individuals and contexts. According to ISO standards, consumer behavior should be considered a source of uncertainty and included in the LCA as a sensitivity analysis (ISO 14040:2006, ISO 14044:2006).

Consumer behavior can be taken into account in an LCA by setting up consumer profiles. These profiles can be based on a variety of factors such as usage patterns, product lifetimes, and EoL behaviors (Cordella et al., 2021; Hischier et al., 2020). These factors can, for example, be based on consumers' intensity of use, time of use, and willingness or knowledge on giving their phone a second life.

One way to determine consumer profiles is through surveys and interviews. These can provide data on consumer behavior, preferences, and decision-making processes (Cordella et al., 2021; Hischier et al., 2020). This approach allows for the inclusion of real-world data on how consumers use and dispose of products, providing a more realistic picture of the environmental impacts. Another way is by collecting data from existing sources such as market research reports and consumer databases (Mostaghel & Chirumalla, 2021; Makov et al., 2018). This approach can provide a general idea of the environmental impacts of a smartphone, but it may not fully capture the variability and complexity of consumer behavior.

Once consumer profiles are established, they can be used to create different scenarios for the LCA analysis. These scenarios can reflect different usage patterns and product lifetimes. By analyzing these scenarios, it is possible to understand the impact of consumer behavior on the environmental performance of a smartphone to identify opportunities for improvement (Cordella et al., 2021; Hischier et al., 2020).

However, including consumer behavior in an LCA can also have limitations. For example, consumer behavior is often difficult to predict, can be subject to change, and can vary greatly among different regions or cultures (Cordella et al., 2021; Hischier et al., 2020). Additionally, including consumer behavior in an LCA can increase the complexity of the analysis and require additional data and assumptions (Mostaghel & Chirumalla, 2021; Makov et al., 2018).

Overall, taking consumer behavior into account can provide a more comprehensive and realistic assessment of the environmental impact of a smartphone (Hischier et al., 2020; Mostaghel & Chirumalla, 2021).

3. Methodology

This chapter presents the research design, system boundaries, investigated systems, and the approach to addressing consumer behavior. It also describes the data collection methods, including impact allocation and data quality measurements. Lastly, it outlines the assessment method and interpretation used in this study.

3.1 Research design

To answer the research question, Twig was used as a case study. Through LCA methodology combined with a literature review, and by taking different research steps (sub-questions) the research question was answered. The literature review was conducted to define consumer profiles based on secondary data about consumers' smartphone behavior (chapter 4. Literature review: creating consumer profiles). The consumer profiles represented the primary and secondary use phase in the LCA. In the next step, in section 6.2, an answer was provided on the effect of consumer behavior on the environmental impact of using iPhones. Finally, in section 6.4, reuse was compared to a linear reference system to find the saved environmental impacts.

The goal of Twig's circular strategies is to reduce the environmental impact of iPhones. This study focused on assessing the environmental impact of these circular strategies by comparing them to a reference scenario and did not account for any potential changes in the supply chain. This means we do not study the effect of a change or a decision but try to identify and compare all relevant flows to and from a life cycle. Therefore, an attributional LCA was conducted.

The ISO 14025, ISO 14040/14044 standards, and other standards such as Product Category Rules (PCR) were developed to guide LCAs and enhance transparency and comparability (EPD, 2019). Therefore, this research mainly followed these standards.

3.2 Goal & scope

The study compared the environmental impact of reusing iPhones through Twig to the reference scenario. This scenario depicts the linear economy model of using and disposing of an iPhone. The goal of this study is to enable Twig to understand the quantitative impact reduction of re-commerce (selling of previously owned items**)** and to inform its app users about the avoided emissions of giving smartphones a second life. The intended audience for this study includes Twig, (its) consumers, the general public, and Utrecht University. The study assumes that the iPhones are sold, used, and (possibly) reused in the UK since this is Twig's core market and it was launched in the UK. Concerning the raw material acquisition, a global scope was taken since this takes place in several countries. The production and assembly take place in China (Costello, 2021). The cut-off value for the inventory data was set at 1% of the total environmental impacts (EPD, 2019).

The focus of this study lied on the reuse of iPhones and therefore a cradle-to-grave approach was taken. A visualization of the system boundaries and flow diagram of the reference and reuse system can be found in figures 2 and 3. For the reuse scenario (figure 3), both the first user and second user are included in the product system by following a system expansion approach. This will be explained in section 3.3.1. The scope of this study includes the raw material acquisition, production & assembly, distribution, primary use, processing for secondary life (Twig's business boundaries), secondary use, and EoL management. Regarding the processing for secondary life, the iPhones are purchased from individuals through the Twig app. A certain amount of the processed iPhones are sold to businesses and another part to individuals. The value-add operation is conducted in Twig's warehouse, while all repairs are done by a third-party company. Phones will be shipped to this company and after repair, shipped back to Twig. The remanufacturing is also conducted by a third party, which remanufactures the phone and sends it back to Twig. Both scenarios (linear and reuse) assume the same EoL management, simulating the average EoL of smartphones. The red dotted square in figure 3 indicates the business boundaries of Twig.

In general, two main systems are considered in this research:

- **The reference (linear) system**: when iPhones do not travel through Twig but have the average smartphone EoL;
- **The reuse system**: When iPhones are bought by Twig via its app, all phones are sent to their warehouse in Burton On Trent (UK) and will be checked visually and with software. After which it can go in four directions:
  - The direct resale flow (A): iPhones will go directly to their second use phase;
  - The value-add operation flow (B): iPhones are not directly sellable, Twig determines that a phone needs a value-add operation before it gets a second life;
  - The repair flow (C): If a value-add operation will not bring an iPhone to the desired state, Twig determines that the phone needs a repair before it gets a second life;
  - The remanufacturing flow (D): If the resell value of the iPhone is too low and not worth a repair, the iPhone will be sold to a remanufacturing partner.

For this study, the functional unit (FU) is defined as *using an iPhone for one year*. Through this FU, the environmental impact of different consumer profiles is compared and the difference between the environmental impact of linear and reuse scenarios is measured. Hence, in this study, the perspective of the phone was taken instead of one of the users to avoid allocation. By taking the perspective of the phone and comparing scenarios based on a reference time, the results suit the goal of this study to understand the quantitative impact reduction of re-commerce and to be able to inform Twig's app users about the emissions savings of reusing smartphones.

An official technical lifetime or a date of planned obsolescence for the iPhone 11 is not disclosed by Apple. The technical lifetime was estimated at around 7-8 years. This does not mean that no cleaning or component replacements take place. The 7-8 years are based on the software and security updates that Apple provided on the iPhone 6. The last versions of the iPhone 6 were released in 2015 and recently, in 2023, Apple plans on dropping the security updates for the iPhone 6 (Keach, 2021). Therefore, from a technical perspective, the iPhone is no longer safe to use and could be perceived as obsolete after 7 to 8 years.

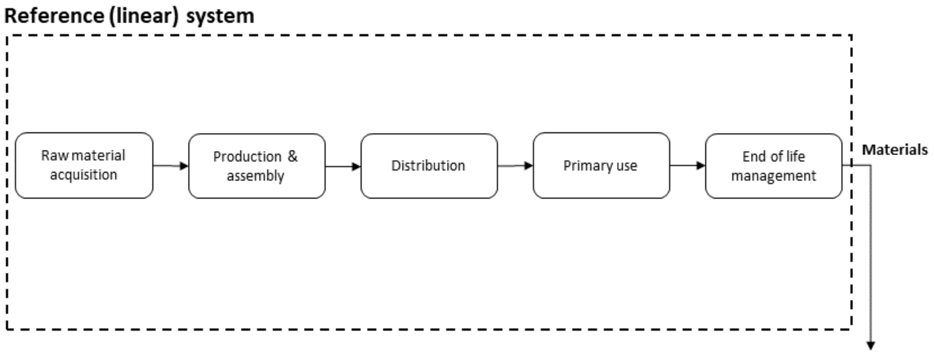

Figure 2: System boundaries and flow diagram of the linear (reference) system

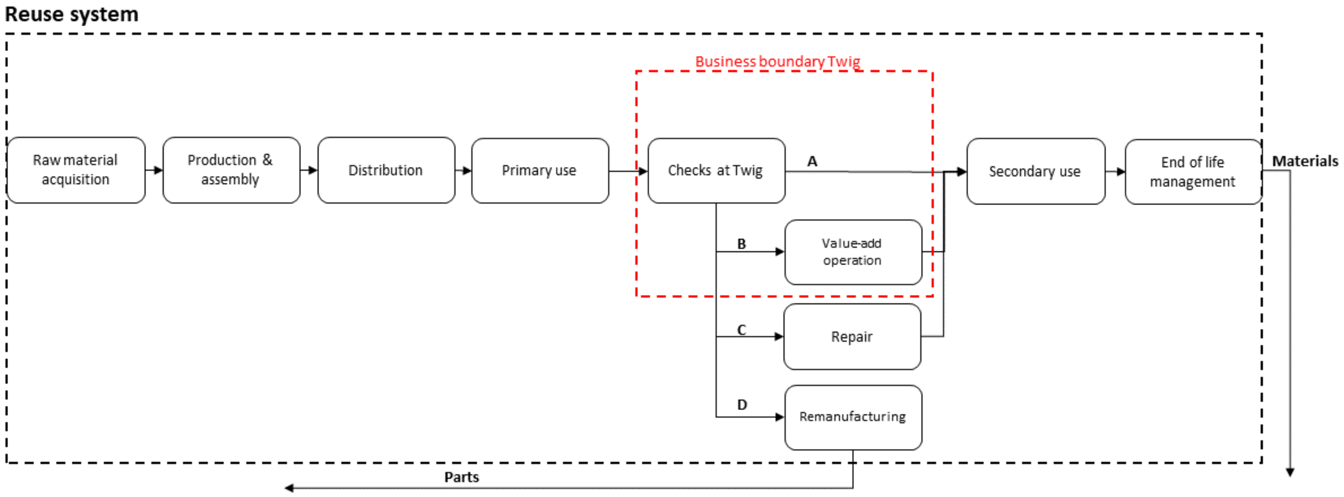

Figure 3: System boundaries and flow diagram of the reuse system

3.2.1 Consumer behavior: literature review

Before data was gathered for the LCI, it was important to understand how consumer behavior can be integrated into an LCA. To integrate consumer behavior into the LCA, primary data collection through a real case study was not feasible within the study's time constraints. Also, it was not possible to access consumers to examine their behaviors. Instead, consumer profiles were established to account for consumer behavior. To find out how to create these consumer profiles and make them as realistic as possible, a literature review was conducted. The literature review took focused on three key themes: (1) methods for creating consumer profiles, (2) information on consumers' smartphone behaviors, and (3) existing studies addressing consumer behavior in LCA within a similar context. Relevant literature was identified through online databases using appropriate keywords and Boolean operators (see table 1). The selected literature was evaluated, summarized, and analyzed to determine key findings for defining consumer profiles. These consumer profiles are detailed in section 4.2 of the study.

Table 1: Search terms per theme for literature review

Theme 1: Methodology for consumer profiles in an LCA	**Theme 2: Consumers' smartphone behavior**	**Theme 3: Existing studies dealing with consumer behavior in LCA**
Set up OR create AND user profiles or consumer profiles AND LCA	Smartphone AND usage AND behavior OR pattern OR habits	LCA on AND smartphones OR iPhones OR electronics
Consumer OR user AND scenarios AND LCA	End-of-life behavior AND smartphone	Environmental impact assessment AND smartphones
User profile AND methodology	Smartphone obsolescence	LCA AND recycling OR reusing AND smartphones

3.3 Data collection

For the LCI, the primary data for processing iPhones for their second life was gathered through Twig. This primary data gathering was done through interviews with the head of operations, financial manager, and sustainability manager. As a data quality criterion, the primary data was required to be from 2020 or later and as accurate as possible.

For other data (secondary data), databases, literature, or publicly available data were used. Ecoinvent is a database recommended to be used when assessing electronics (EPD, 2019), and can be accessed through Utrecht University's subscription. The ecoinvent datasets were used as secondary data input and assessed using data quality indicators to find weak spots in data quality. This is further explained in section 3.4.2. All secondary data was required to be no older than 2010 and as accurate as possible.

The inputs and outputs of all processes were determined for 1 FU to determine the reference flows. The data represent average values for a specific reference year. In case this was not possible, a representative annual average value for a specified reference period is used (EPD, 2019). To give the most updated view, the reference year was 2022.

3.3.1. Allocation

In this study, multifunctionality was observed during the phone's processing for a second life and its EoL treatment involving recycling. To adhere to ISO standards and avoid allocation, the system boundaries were expanded. System expansion provides the best view of avoided impacts, especially in the case where the function of the product does not change, only the user. This expansion occurred at the stage of processing for a second life, considering the phone's perspective. By employing system expansion, all activities of both the first and second users were included, encompassing all stages from production to EoL and utilizing corresponding inventory inputs for each consumer scenario. The LCI was adjusted by normalizing the linear and reuse scenarios to the FU, allowing for a comparison between linear and reuse scenarios per consumer profile. The linear scenario represents new smartphone production, while the reuse scenario avoids new production. The inventory inputs per scenario can be found in section 5.6. Through the use of system expansion, a comprehensive analysis of the iPhone's environmental impacts was achieved, encompassing the entire cascade of processes and providing an accurate assessment of the environmental benefits associated with iPhone reuse.

To specifically analyze the environmental benefits of smartphone reuse, this study opted for the cut-off approach during the EoL phase. The cut-off point was defined as the moment the phone enters the recycling facility. By adopting this approach, the system boundaries of the study were intentionally limited to exclude any credits or burdens associated with the recycling activities. This deliberate choice allows for a more focused assessment by narrowing the scope to the reuse phase. It offers a clearer understanding of the environmental advantages and trade-offs related specifically to smartphone reuse rather than attempting to capture all potential impacts across the entire life cycle of the device.

3.3.2 Data quality indicators

A data quality indicator was assigned to each process that was modeled using secondary data (ecoinvent datasets). The data quality indicator shows to what extent secondary data or an ecoinvent database represents the modeled process. These indicators were added to spot processes that have a high contribution to the total impact of the phone and at the same time poor data quality. If this is the case, the quality of how the process was modeled was improved or analyzed through a sensitivity analysis.

To create these data quality indicators, the pedigree matrix method was used. This method was used to characterize the data quality aspects and quantify the quality rating (Ciroth et al., 2016). See Appendix 10.1.1 for the Pedigree matrix. Per process, the Pedigree matrix was used to find a quality indicator. The quality indicator ranges from 1 to 5. The closer the rating is to 1, the higher the data quality, and vice versa. All processes were assigned a data quality indicator per life cycle stage in Appendix 10.1.2.

3.4 Selection of impact categories and assessment method

The impact assessment utilized the data obtained from the LCI to obtain results. In accordance with the PCR for electronics, the study considered the 8 default impact categories outlined in table 9 (EPD, 2019) as the most relevant for electronics. These impact categories were evaluated using the ReCiPe Midpoint (H) 2016 characterization model. Translating the 8 default impact categories to the impact categories used by the ReCiPe midpoint characterization resulted in the second column of table 9. Due to data availability constraints, the decision was made to solely focus on these ReCiPe impact categories. Additionally, the study excluded long-term emissions from the results, as the primary focus was on assessing the current environmental impact rather than the release of impacts over an extended period.

Table 9: The impact categories used to assess the environmental impact of reusing iPhones

Impact category (EPD)	Impact category (ReCiPe)	Unit (ReCiPe)
Global Warming Potential (GWP)	Global Warming Potential (GWP)	kg CO2 eq
Abiotic depletion potential (ADP) for minerals and metals (non-fossil resources)	Mineral resource scarcity	kg Cu eq
Abiotic depletion potential (ADP) for fossil resources	Fossil resource scarcity	Kg oil eq
Water deprivation potential (WDP)	Water consumption	m3
Acidification Potential (AP)	Terrestrial acidification	Kg SO2 eq
Ozone depletion potential (ODP)	Stratospheric ozone depletion	kg CFC11 eq
Eutrophication Potential (EP)	Freshwater/marine eutrophication	kg P/N eq
Photochemical ozone creation potential (POCP)	Ozone formation	kg NOx eq

3.5 Interpretation to be used

To interpret the results of this study, a contribution analysis and sensitivity analysis was conducted. The contribution analysis was used to identify the major contributors to the avoided impacts of iPhones. The sensitivity analysis was used to test the robustness of the results obtained from the LCA by examining the impact of changes in assumptions and data on the results.

For the contribution analysis, the environmental impacts were broken down into their underlying processes that had high contributions to the total impacts. This involved tracing the impacts of each process and input in the life cycle of the iPhone, from the production phase to EoL disposal. The results were used to identify the major contributors to the impacts and to assess the potential for improvements in the life cycle of the iPhone.

The sensitivity analysis involved implementing methodological changes in the LCA model. This included varying the allocation method used, modifying the data input based on the data quality indicators, and varying the consumer profiles and duration of use for the second use phase. The results of the sensitivity analysis were used to assess the uncertainty associated with the LCA results and to identify areas where additional data or research may be needed to improve the accuracy of the results.

For both the contribution and sensitivity analysis the decision was made to focus the interpretation of the results on four impact categories: global warming, ozone formation (covering human health and terrestrial ecosystems), marine eutrophication, and mineral resource scarcity. A presentation of impacts in all impact categories did not foster the interpretability of the results. Notably, impacts in most categories exhibited similar distributions across all life cycle activities and diverse consumer scenarios, indicating the absence of tradeoffs. Furthermore, certain impact categories demonstrated correlation, such as the correlation between fossil resource depletion and climate change, as the combustion of fossil fuels serves as the primary contributor to greenhouse gas (GHG) emissions. Consequently, exhibiting both categories concurrently held reduced relevance. Moreover, some absolute impact values within certain categories failed to exhibit significant distinctions between consumer scenarios or linear and reuse systems, diminishing their interpretive significance. Hence, the aforementioned four categories were specifically chosen for focus in the interpretation of results within the impact assessment section. However, excluding these categories did not affect the conclusion. The overall conclusions drew upon all impact categories. Detailed results and visual representations of impacts across all categories can be found in Appendix 10.6, 10.7, 10.8, 10.9, and 10.10.

4. Literature review: creating consumer profiles

In this chapter, the results from the literature review are discussed per theme. Based on the results a fundament for the consumer profiles of this study was created (see section 4.2). The created consumer profiles were translated into inventory input for the use phase of the different scenarios in section 5.3.

4.1 Search results per theme

4.1.1 Theme 1: methodology for consumer profiles in LCA

Although there was not much literature found regarding clear guidance or methodology on how to deal with consumer behavior or how to set up consumer profiles when doing an LCA, two sources gave some interpretation on this theme. The ILCD handbook (2010) and Polizzi di Sorrentino et al. (2016) provided some guidance when using consumer profiles in an LCA study (described in table 2).

Table 2: Explanation of how to set up consumer profiles per literature source

Source	Theory
ILCD handbook (2010)	When creating consumer profiles the focus should lie on behavior that relates to energy consumption or other relevant characteristics leading to environmental impacts
Polizzi di Sorrentino et al. (2016)	To create consumer profiles direct observation of a small sample can be combined with a representative survey or secondary data from existing behavioral studies could be used to create these sets of behavior

4.1.2 Theme 2: consumers' smartphone behavior

In this section, literature was analyzed that related to consumers' environmentally impactful behaviors. The intensity of use and functional lifetime (period of use) were considered environmentally impactful behaviors. The more intensive the use, the more electricity will be needed for a smartphone in its entire functional lifetime. Also, how long a smartphone is used influences the environmental impacts. Furthermore, replacement reasons were addressed since they influence how long a person uses their phone. Eventually, phones are not used anymore, therefore, the EoL paths were also considered in this theme. Different sub-sections will address the topics under this theme.

4.1.2.1 Intensity of use

Different studies researched the average daily use of smartphone users. In table 3 the average daily hours of smartphone use per study can be found.

Table 3: Average daily hours of smartphone use

Source	Average daily hours of use	Ages	Country
Zimmermann (2021)	+- 3	16–64	Worldwide
Ataş & Çelik (2019)	4.66	18-45	Bangladesh
Zilka (2018)	6.8	Children, adolescents, and young adults	Israel
Suckling & Lee (2015)	1.75	N.A.	N.A.
Statista (2022)	4	Adults	United Kingdom

Furthermore, data from Statista (2022a) also showed the distribution (in percentages) of Americans' daily smartphone use per hours of daily use. See table 4 for an overview of the spread of daily smartphone use.

Table 4: Distribution of daily smartphone use in the United States of America (Statista, 2022a)

Hours of daily use	Less than 1 hour	1-2 hours	3-4 hours	5-6 hours	7 hours or more
Percentage	5%	16%	22%	46%	11%

4.1.2.2 Functional lifetime

The functional lifetime is referred to as the time a person uses their phone. The average functional lifetime of a smartphone also varied per study. All studies based the average functional lifetime on data from people of all ages. See table 5 for the average functional lifetimes of a smartphone.

Table 5: Average functional lifetime of a smartphone per literature source

Source	**Average functional lifetime**	**Country/region**
Bieser et al. (2022)	3.3 years	Switzerland
Thiébaud -Müller et al. (2017)	3.3 years	Switzerland
Ataş & Çelik (2019)	3.3 years	Bangladesh
Bai et al. (2018)	2.24 years	China
Statista (2023)	2.8 years	Worldwide
uSwitch (2021b)	3 years	United Kingdom
Proske (2022)	2 to 3 years	Europe
Apple (2019)	3 years	Worldwide
Belkhir and Elmeligi (2018)	2 years	Worldwide
Sarigöllü et al. (2020)	3 years	Worldwide

4.1.2.3 Correlation between the intensity of use and the functional lifetime

Based on a survey of UK consumers conducted in 2017, Deloitte's study revealed a correlation between the frequency of smartphone replacement and usage intensity. The study indicated that individuals who replace their smartphones more frequently are typically heavy users who rely on their devices for a larger number of activities and exhibit a higher degree of dependency on them (Deloitte, 2017). Conversely, the study also noted that those who replace their phones less often tend to be less intensive users.

4.1.2.4 Replacement reasons

People use their smartphones for a different number of years. At a certain moment, people have different reasons to replace their smartphone. See table 6 for the replacement reasons found in different studies.

Table 6: Replacement reasons per literature source

Source	**Want the latest model**	**Not properly functioning**	**Other reasons (ending contract/want latest software/missing)**
Uswitch (2021)	43%	40%	17%
Cordella, Alfieri, Clemm, et al. (2021a)	47%	40%	13%
Sarigöllü et al. (2020)	51.97%	45.88%	6%

Table 6: Replacement reasons per literature source

4.1.2.5 Smartphone end-of-life

When a smartphone is replaced or not used anymore, it can follow different EoL paths depending on the owner's choice. Table 7 shows the percentages per study of a smartphone's EoL path directly after replacing it.

Table 7: Smartphone end-of-life paths per literature source (N.A. = Not Applicable)

Source	Stored at home (stockpiling)	Reuse (Reselling/passing along/donating)	Recycled/ remanufactured	Thrown away	Country/region
Suckling & Lee (2015)	N.A.	N.A.	3-6%	N.A.	Czech Republic
Buchert et al. (2012)	N.A.	N.A.	5%	N.A.	Germany
Thiébaud -Müller et al. (2017)	58%	15%	7%	N.A.	Switzerland
Winter (2022)	48%	N.A.	29%	N.A.	United Kingdom
Deloitte (2022)	48%	21%	24%	7%	United Kingdom
Sarigöllü et al. (2020)	17.20%	79,93%	N.A.	2,87%	Worldwide
Cordella et al. (2021)	49%	36%	15%	N.A.	Worldwide

4.1.3 Theme 3: existing studies dealing with consumer behavior in LCA

Existing studies in the field of LCAs on smartphones took into account the use phase by either taking averages or creating different consumer profiles. The studies mainly focused on the intensity of use and functional lifetime as variables that affect the environmental impact of the use phase.

Some studies created consumer profiles by linking a functional lifetime to the intensity of use, some only created profiles for a functional lifetime and took an average for the intensity of use (or the other way around), and others took averages for both. See table 8 for the approaches of different studies on dealing with consumer behavior.

Table 8: Approaches of different smartphone LCA studies on dealing with consumer behavior during the use phase (FL=Functional lifetime, IOU=Intensity Of Use)

Source	Consumer profiles including both IOU & FL	Only consumer profiles for FL, averages for IOU	Only consumer profiles for IOU, averages for FL	Took averages for both (FL&IOU)	Type of phone
Ercan et al. (2016)	X				Sony Z5
Sánchez et al. (2022)		X			Fairphone

Cordella et al. (2021)	X			N.A.
Ecran (2013)		X		Sony Xperia T
Güvendik (2014)	X			Fairphone
Wiche et al. (2022)			X	N.A.
Clément et al. (2020)			X	N.A.

4.2 Creating consumer profiles based on search results

As per the results in section 4.1.1 (theme 1) the ILCD handbook (2010) mentions that if there are significant differences in consumer behavior that could affect the environmental impacts of the product, these should be taken into account. The handbook recommends using representative scenarios (consumer profiles) that reflect the different patterns of use.

The intensity of use and functional lifetime are factors that relate to consumer behavior and can significantly influence the environmental impacts during the use phase. Polizzi di Sorrentino et al. (2016) notes that existing behavioral studies can provide secondary data for the creation of consumer profiles (sets of behavior). Section 4.1.2 of the literature review (theme 2: consumers' smartphone behavior) supplied this secondary data on smartphone behavior and highlighted correlations between the intensity of use and a functional lifetime, which made it possible to create sets of behavior from an environmental perspective. Therefore consumer profiles were created that included both a specific intensity of use and a functional lifetime to represent a type of consumer.

Ecran et al. (2016) created profiles with "extreme," "average," and "lowest" environmental impacts in which every profile related to a certain intensity of use and functional lifetime (see table 8). Similarly, this study also created profiles with similar names - "polluter," "average," and "conscious" - based on principles to ensure their realistic representation. To fill these profiles with an intensity of use and functional lifetime, the first step of this study was to establish the "average" profile by using UK studies on the average intensity of use and functional lifetime as a baseline (Tables 3 and 5). For the "polluter" and "conscious" profiles, no specific data regarding functional lifetime and intensity of use in the UK was found in the literature. However, table 6 shows the main reasons for replacement and the Deloitte (2017) study explains the existing correlation between high intensity of use and a short functional lifetime, and the other way around. Consequently, based on these studies principles were created to set up these profiles, which will be explained in the following sub-sections. The Statista (2022a) study was used as a baseline to determine the intensity of use for the environmentally worst (polluter) and best (conscious) profile because Statista is a large peer-reviewed statistical database and the only source providing shares of a population per hours of daily smartphone use (see table 4). However, in the literature review, no studies were found that have examined the consumer behavior of individuals using secondhand phones. Therefore, only an average profile was assumed to represent the second use phase.

Furthermore, two assumptions were made since these are common to the three profiles. First of all, it was assumed that consumers only use one smartphone at a time for all consumer profiles (both in the primary and secondary use phase). Additionally, it was assumed that the battery condition of an iPhone is 100% when it is purchased for the first time and 80% when it receives a second life. This assumption was based on Twig's minimal requirement for reselling a smartphone, which will not be sold with a battery condition below 80%. The following sections provide a more detailed explanation of the creation of the different consumer profiles of which the main parameters per profile are summarized in table 9.

4.2.1 Consumer profiles: profile creation

4.2.1.1 Primary average profile

Based on the literature review, one UK study was found for the intensity of use and one UK study for the functional lifetime. Looking at these studies, an average smartphone user uses their phone for 3 years on average for around 4 hours per day in the UK (Statista, 2022). After three years of use, there is a high chance that this person wants a newer model, has its contract ended or the phone is underperforming. This means that after 3 years the user decides to replace their phone. The combination of these findings led to an average consumer type using their phone for 4 hours per day for 3 years. See table 9 for the details of the average profile.

4.2.1.2 Primary polluter profile

From an environmental standpoint, a smartphone user who contributes to pollution can be characterized as someone who uses their device more frequently daily but has a shorter overall functional lifetime compared to the average user. With the Deloitte (2017) study as a starting point, this correlation exists. To achieve this characterization, principles were created to utilize this correlation between functional lifetime and intensity of use to identify values for both parameters. The following set of principles was used to create a profile of a polluter user:

- The length of the functional lifetime should be based on a logical way of reasoning in which a short functional lifetime corresponds to a replacement reason in table 6;
- The intensity of use should be based on the environmental worst case according to a realistic share of a population that shows high daily smartphone use, i.e. it should represent at least 10% of Statista's (2022a) respondents with the highest intensity of use (see table 4);
- A relation should exist between a high intensity of use and a short functional lifetime.

The biggest replacement reason for smartphone users is to switch to a newer model (Cordella et al., 2021a). Since an environmentally worst case was assumed for this profile, this could mean that a person switches to a newer model every year because Apple introduces a new model every year. Based on the data from Statista (2022a) at least 10% uses their smartphone for 7 hours per day. This number of hours can be seen as the most extreme representative case of intensive daily smartphone use. Combining these findings led to the creation of a polluting consumer profile that has 7 hours of daily use and a functional lifetime of 1 year. See table 9 for the details of the polluter profile.

4.2.1.3 Primary conscious profile

Taking an environmental perspective into account, a smartphone user who is considered more mindful can be characterized as someone who utilizes their device less frequently daily but has a longer functional lifetime than the average user. To establish this characterization of a conscious user, again the correlations discovered in Deloitte's (2017) study between these parameters were employed to determine the appropriate values for the conscious consumer profile. To construct this profile, the following set of principles was used:

- The length of the functional lifetime should be based on a logical way of reasoning in which a long functional lifetime corresponds to a replacement reason in table 6;
- The intensity of use should be based on the environmental best case according to a realistic share of a population that shows low daily smartphone use, i.e. it should represent at least 10% of Statista's (2022a) respondents with the lowest intensity of use (see table 4);
- A relation should exist between a low intensity of use and a long functional lifetime.

Based on table 6, a large share of people tend to replace their phone when it starts underperforming (Cordella et al., 2021a). For this profile, the environmentally best case was assumed, which means that in an extreme case, without any component replacements, an iPhone could be used for 4 years on average without any issues (McAllister, 2021). Using the data from Statista (2022a), at least 10% use their smartphone for 1 hour per day. Which is the most extreme representative case of low daily smartphone use. Employing Deloitte’s (2017) correlation, these findings led to the creation of a conscious consumer profile with 1 hour of daily use and a functional lifetime of 4 years. See table 9 for the details of the conscious profile.

4.2.1.4 Secondary average profile

The decision was made to not create different profiles for the secondary use phase because little data is available about secondary users’ smartphone behavior. Also, this would lead to many different scenarios for this study which does not enhance the interpretation of the results and does not necessarily contribute to the goal of this study. The assumption was made that the differences in the profiles of the primary users will already indicate the impact of the different types of smartphone users. Based on data from Twig, and for the sake of simplicity, the secondary user’s profile characteristics were assumed to be similar to that of the primary average profile. Therefore, only an average consumer profile was considered for the second use phase. Hence, 3 years of use with 4 hours per day. However, the smartphone’s battery condition is in most cases lower than at the start of its first use phase. Since Twig only resells smartphones with a minimum battery condition of 80%, this battery condition was considered for the secondary consumer profile. A lower battery condition will result in more recharging cycles compared to the same use pattern with a battery condition of 100%.

Table 9: The consumer profiles considered in this study with their respective names, functional lifetimes, intensity of use, and battery condition

Primary/secondary consumer	Profile name	Functional lifetime	Intensity of use (hours/day)	Battery condition
Primary	Polluter	1 year	7	100%
Primary	Average	3 years	4	100%
Primary	Conscious	4 years	1	100%
Secondary	Average	3 years	4	80%

5. Life Cycle Inventory analysis

The LCI provides a comprehensive overview of all the data inputs used in the study, from raw material extraction to EoL management, as well as the inventory inputs per FU.

5.1 Production phase

The production phase encompasses several key activities, including the extraction of raw materials, the manufacturing of components and accessories, the transportation of these materials to the assembly facility, the assembly process itself, and the final product packaging. To accurately model and assess the environmental impact of the production phase, we relied on the utilization of ecoinvent datasets within the Simapro software.

For all processes within the production phase, market-type ecoinvent datasets were utilized. These datasets encompass various stages, such as the extraction of raw materials, the transportation of these materials to the manufacturing site, and the electricity consumption required for sub-component production.

To account for the level of uncertainty within the datasets representing each sub-component, a data quality indicator is provided. This indicator serves as a measure of the reliability and precision of the dataset, which enables to evaluate the accuracy of the represented component. The same approach was applied to the iPhone packaging (rigid box), sim ejector tool, charging cable, transport to the assembly facility, and the phone assembly process. Please refer to Appendix 10.1.2.1 for detailed information on the data quality indicators associated with all processes and components involved in the production phase.

5.1.1 Raw material extraction

The raw material extraction was referred to as a background process. The background data include energy and materials that are delivered to the foreground system as aggregated datasets in which individual plants and operations are not identified. This means that the extraction of the materials was included in the manufacturing process of the sub-components.

5.1.2 Manufacturing of components: bill of components and materials

The iPhone 11 includes components such as a display, battery, main logic board, cameras, casing, and various sensors, among others. These components are sourced from various suppliers and manufacturers around the world. A detailed bill of materials (BOM) for the iPhone 11 was not publicly available and is considered proprietary information by Apple Inc.

Apple has made some information available regarding the iPhone 11, including a product information sheet (Apple, 2019c), technical specifications (Apple, 2019a), and an environmental report (Apple, 2019b). Additionally, third-party reports such as Techinsights (2019), iFixit (2023), and iPhonewired (2022) have conducted iPhone teardowns, providing insights into the main components of the iPhone 11 (Yang et al., 2019). Although the environmental report for the iPhone 11 does not reveal its material composition (Apple, 2019b), reference was made to the environmental report of the iPhone XR, a previous model with similar dimensions, weight, and display technology as the iPhone 11. The material composition of the iPhone XR is available in table 10 (Apple, 2018).

The determination of the components and materials of the iPhone 11 was based on Güvendik's study (2014), where a bill of materials for a Fairphone was obtained and a complete dismantling was conducted, with the weight of each component recorded. The assumption was made that the iPhone 11 shares similar components, considering Güvendik's study along with information from Apple and the teardown reports. This approach guaranteed the creation of a precise list detailing the components and materials of the iPhone 11. The upcoming section offers in-depth information on the exact steps and methodology utilized to compile this list.

Table 10: iPhone XR material composition (Apple, 2018)

Material/component	Weight
Battery	43g
Glass	39g
Stainless steel	39g
Display	19g
Aluminum	17g
Other	16g
Circuit boards	12g
Plastics	9g
Total	194g

5.1.2.1 Approach to set up the list of components

For a comprehensive understanding of the steps and adjustments made to compile the bill of components for the iPhone 11, please refer to Appendix 10.3. The following procedures were implemented to create the bill of components, along with their corresponding weights, and model the production phase in SimaPro:

1. Verification Process:
    - As a starting point, all components in the Fairphone were assumed to be also present in the iPhone. Through examination of the teardown reports, iPhone 11 and XR environmental reports, product information sheet, and iPhone 11 technical specifications, it was found that some components were not present in the Fairphone but do reside in the iPhone. These were added to the list of components. See the next section 5.1.2.2 for the determination of their weights.
2. Material Search:
    - For each sub-component of the iPhone 11, an investigation was conducted to determine the materials it comprised based on the available reports. If the materials matched those in the Fairphone, the same ecoinvent (material) type utilized in Güvendik's (2014) study was assigned to that specific sub-component. However, if the materials differed, the ecoinvent type that best represented the sub-component was sourced from the ecoinvent database.
3. Weight Calculation:
    - The weight of the battery and LCD screen was known from the product information sheet and the iPhone XR environmental report (Apple, 2018). To determine the assumed weight of each sub-component, the shares of the total weight excluding the battery and LCD screen were determined for each sub-component in the Fairphone. These shares were then multiplied by the weight of the iPhone, excluding its battery and LCD screen weights. This resulted in an estimated weight per sub-component.
4. Weight and Quantity Adjustments:
    - After the determination of the weight per sub-component for the iPhone, certain adjustments regarding the weight and quantity of certain sub-components were applied. The details of these adjustments are explained in the subsequent section.

5.1.2.2 Adjustments to approach

The first adjustments were made to account for differences in the quantities of certain sub-components. Unlike the Fairphone, the iPhone 11 features two back cameras, two speakers, and three microphones. Additionally, due to the 2.108 times larger size of the iPhone's LCD screen, it incorporates a higher number of white LEDs. Therefore it was estimated that the iPhone contains around 21 LEDs, representing a factor of 2.108 times more. Moreover, an iPhone 11 teardown report indicates the presence of approximately 29 stainless steel screws (Gordon, 2023). Based on the assumed and observed quantities of these sub-components, the weights were adjusted by multiplying the previously determined weights per unit by the new quantity. In the absence of specific information, it was assumed that the quantities of other sub-components were similar.

The allocation of weight shares per sub-component was determined based on the material density of the respective sub-component in the Fairphone. However, modifications were made to account for differences in materials between the Fairphone and the iPhone. Notable differences were identified in the LCD shell and various casing sub-components. By considering the densities of materials used in both devices, the weights of these sub-components were adjusted accordingly. The material densities utilized in this analysis can be found in Appendix 10.2.

By comparing the technical specifications of the Fairphone and the iPhone 11, it became apparent that the iPhone incorporates additional sensors that are not present in the Fairphone. The following sensors are specific to the iPhone (Apple, 2019):

- Face ID sensor;
- Proximity sensor;
- Barometer;
- Three-axis gyroscope;
- Ultra-Wideband chip.

Considering the absence of these sensors in the Fairphone, it was assumed that they account for the remaining weight difference of 5.66 grams (194 – 188.33), please refer to Appendix 10.3. These sensors were aggregated as a single unit in table 11 under the category "others" due to the lack of precise information regarding their material composition (see table 11). Consequently, in SimaPro, these sensors are represented using the "Electronic component, active, unspecified" ecoinvent type. This ecoinvent component type encompasses diodes, integrated circuits, and transistors, constituting an active component. Given that those iPhone sensors typically consist of such components and qualify as active electronic components, which necessitate an energy source to function and can amplify or regulate electrical signals (Kumar Saini, 2022), they are appropriately categorized as active electronic components. Please refer to table 11 for a detailed breakdown of the iPhone 11's components and materials.

5.1.2.3 Ecoinvent process types for iPhone's sub-components

The manufacturing of most sub-components was modeled in SimaPro using a component or module ecoinvent market dataset type, these datasets already include the processes involved in producing that component.

However, for some sub-components ecoinvent processes were added because these are not included in the ecoinvent material's dataset. These processes are needed to create the sub-component's desired shapes. See table 11 below for the ecoinvent process types added to some of the sub-components in Simapro. The sub-components that do not have an ecoinvent process type, are referred to as "Not Applicable" (N.A.) in table 11.

The production processes for the aluminum shell and frame in the ecoinvent database were modeled using the "impact extrusion of aluminum, 2 strokes" process type, following a similar approach as Cordella et al. (2021). Similarly, the production processes for the battery cap and SIM card holder were modeled based on Güvendik's (2014) study, employing the "Sheet rolling, chromium steel" process type. However, the ecoinvent database lacks a specific process for the thread rolling method used to manufacture chromium steel screws. To address this, the process was modeled similarly to Güvendik (2014) by utilizing the "metal working, average for chromium steel product" process type. For the PCB covers and magnetic beads, the same ecoinvent process types employed in Güvendik's (2014) study was utilized due to the identical materials involved.

The manufacturing process for all polycarbonate (plastic) sub-components was assumed to be injection molding, as this method is commonly utilized for producing polycarbonate parts in LCD displays (Kuo & Su, 2007). Likewise, for thin film and plastic tape, the plastic film extrusion process was assumed, as it is widely employed for manufacturing such materials (Proplastex, n.d.). Cordella et al. (2021) and Güvendik (2014) also employed the "injection molding" process type for modeling the production of polycarbonate components and the "extrusion, plastic film" process type for modeling the production of thin film or plastic tape.

In the case of glass components, the "tempering, flat glass" process was added to the sub-component's manufacturing processes. According to Apple (2019a), the iPhone 11 incorporates "durable front and back glass" composed of a custom blend of Corning Gorilla Glass, which is a form of tempered glass.

Table 11: The iPhone 11's list of components with their assumed materials, quantity, and weight, and the ecoinvent material and process datasets representing the respective sub-components (N.A. = Not Applicable)

No.	**Main component**	**Sub-component name**	**Main materials**	**Ecoinvent material type**	**Ecoinvent process type**	**Quantity**	**Weight per sub-component (g)**
1.	Liquid Crystal Display (LCD)	1.1 Flexible printed Circuit	1.1 Copper/silver/ gold, polymide/polyester, adhesive, silicone	1.1 PWB, surface mount, Pb-free	N.A.	1	0.82
		1.2 Flexible Printed circuit	1.2 Copper/silver/ gold, polymide/polyester, adhesive, silicone	1.2 PWB, surface mount, Pb-free	N.A.	1	0.44
		1.3 LCD screen (LED Backlit)	1.3 Glass, plastic, copper/aluminum, liquid crystals	1.3 (mod.) LCD glass	N.A.	1	19.00
		1.4 Plastic	1.4 Plastic	1.4 Polycarbonate	Injection molding	1	0.96
		1.5 Shell	1.5 Aluminum 7075-T6; 7075-T651	1.5 Aluminum, primary, cast alloy slab from continuous casting	Impact extrusion of aluminum, 2 strokes	1	4.86
		1.6 (White) LEDs	1.6 Gallium nitride (GaN)	1.6 Light emitting diode, LED	N.A.	21	1.21

		1.7 IC	1.7 Silicon	1.7 Integrated circuit, IC, logic type	N.A.	1	0.01
2.	Battery	2.1 Li-ion Battery	2.1 Lithium-Ion polymer	2.1 Battery, Li-Io, rechargeable, prismatic	N.A.	1	47.00
3.	Casing	3.1 Shell/frame	3.1 Aluminum 7075-T6; 7075-T651	3.1 Aluminium, primary, cast alloy slab from continuous casting {GLO} market	Impact extrusion of aluminum, 2 strokes {GLO}| market	1	10.06
		3.2 Front housing	3.2 Cover (Gorilla) glass	3.2 Flat glass, coated	Tempering, flat glass	1	9.85
		3.3 Back housing	3.3 Rear (Gorilla) glass	3.3 Flat glass, coated	Tempering, flat glass	1	21.45
4.	Camera, vibrator, speaker & microphone	4.1 Front camera	4.1 Glass, aluminum, plastic	4.1 Electronic component, passive, unspecified	N.A.	1	0.23
		4.2 Vibration motor	4.2 Aluminum, plastic, ceramics (coil)	4.2 Electronic component, passive, unspecified	N.A.	1	1.01
		4.3 Camera	4.3 Glass, aluminum, plastic	4.3 Electronic component, passive, unspecified	N.A.	2	1.44

		4.4 Speaker	4.4 Aluminum, plastic, ceramics (coil)	4.4 Electronic component, passive, unspecified	N.A.	2	3.74
		4.5 Microphone	4.5 Aluminum, plastic, ceramics (coil)	4.5 Electronic component, passive, unspecified	N.A.	3	3.08
5.	Printed circuit boards	5.1 Mainboard	5.1 Fiberglass, epoxy/polymide, copper, ink	5.1 PWB, surface mount, Pb-free	N.A.	1	7.43
		5.2 Daughterboard	5.2 Fiberglass, epoxy/polymide, copper, ink	5.2 PWB, surface mount, Pb-free	N.A.	1	1.62
6.	Integrated Circuits	6.1 IC, memory	6.1 Copper oxide, silicon, germanium	6.1 IC, memory type	N.A.	5	0.91
		6.2 IC, logic	6.2 Copper oxide, silicon, germanium	6.2 IC, logic type	N.A.	4	0.58
7.	Capacitors, Diodes, Varistors & Transistors	7.1 Diodes	7.1 silicon/ germanium/zinc oxide	7.1 Diode, glass-, SMD type	N.A.	58	0.21
		7.2 Varistors	7.2 silicon/ germanium/zinc oxide	7.2 Diode, glass-, SMD type	N.A.	142	0.52
		7.3 Transistors	7.3 silicon, copper/gold	7.3 Transistor, SMD type	N.A.	3	0.03
		7.4 Capacitor	7.4 Aluminum	7.4 Capacitor, SMD type	N.A.	283	0.65

		7.5 Tantalum capacitor	7.5 Tantalum	7.5 Capacitor, Tantalum	N.A.	1	0.03
		7.6 Surface acoustic wave (S.A.W.)	7.6 Quartz, lithium niobate or lithium tantalate	7.6 Capacitor, SMD type	N.A.	3	0.06
8.	Others	8.1 Battery Cap	8.1. Chromium steel (stainless steel)	8.1. Chromium steel 18/8	Sheet rolling, chromium steel	1	35.07
		8.2 PCB Covers	8.2 Copper, Nickel	8.2 Copper, anode	Metal working, average for copper product	3	5.55
		8.3 Simcard Holder	8.3 Chromium steel	8.3 Chromium steel 18/8	Sheet rolling, chromium steel	1	1.82
		8.4 CT oils	8.4 Silicon (oil)	8.4 Inductor, miniature RF chip type, MRFI	N.A.	37	0.08
		8.5 Magnetic bead	8.5 Iron	8.5 Ferrite, at plant	Metal working, average for metal product	13	0.03
		8.6 Unspecified	8.6 Unspecified	8.6 Electronic component, passive, unspecified	N.A.	1	0.52
		8.7 Cable	8.7 Copper, polyester	8.7 Cable, ribbon cable, 20-pin, with plugs	N.A.	1	0.27
		8.8 Screws	8.8 Stainless steel	8.8 Chromium steel 18/8	Metal working, average for chromiu	29	1.32

				m steel product		
	8.9 Copper coil	8.9 Copper	8.9 Copper, anode	Metal working, average for chromium steel product	1	0.04
	8.10 Connectors	8.11 brass/chromium steel/aluminum & plastic	8.11 Connector, computer, peripherical Type	N.A.	1	2.69
	8.11 Thin film	8.12 PET	8.12 PET, granulate, amorphous	Extrusion, plastic film	1	0.44
	8.12 Plastic tape	8.13 PET	8.13 PET, granulate, amorphous	Extrusion, plastic film	1	0.34
	8.13 Net	8.14 Fiber-reinforced plastic	8.14 Glass fibre reinforced plastic, polyester resin	N.A.	1	1.10
	8.14 Plastic pieces	8.15 Polycarbonate	8.15 Polycarbonate	Injection moulding	1	1.89
	8.15 Sensors: Face ID, proximity, barometer, three-axis gyroscope, ultra-wideband chip	8.16 Silicon, metal, plastic, glass	8.16 Electronic component, active, unspecified	N.A.	1	5.67
Total:						194

5.1.2.4 Manufacturing of iPhone accessories: rigid box, plastic protective film, charging cable, and SIM ejector tool

When the iPhone is purchased as new it is supplied in a rigid box. This contains the iPhone with a plastic film covering the front, a USB-C to lightning charging cable (1m), and a sim ejector tool. The weight, material, and ecoinvent material and process types for the rigid box, plastic film, cable, and sim ejector can be found in table 12. The production of these accessories was modeled separately from the iPhone manufacturing in Simapro to be able to see the impacts of the iPhone and accessories individually.

The rigid box is supplied with a separate lid and base. The base and lid are mainly made of virgin fiber paperboard (boxboard carton). However, there is a plastic wrap that covers the entire box, which is made of polypropylene (PP). 93% of the box is made of fiber paperboard, while 7% is made of PP (Apple, 2019b). The plastic film covering the iPhone, with an estimated weight of 0.5 grams, is made of polyethylene terephthalate (PET). The total weight of the rigid box (excluding the device) is 142 grams. Based on these percentages, materials, and total weight, the manufacturing of the rigid box was modeled in Simapro (see table 12).

According to a teardown report of iPhonewired (2022) of the Apple USB-C to Lightning Cable, the cable consists of tinned copper wire, polyethylene insulation, and a nylon braided jacket, with plastic connector housings (a blend of polycarbonate and thermoplastic elastomer (TPE) and metal contacts (copper, nickel, and gold). Similarly, a report by Purcher (n.d.) on a patent application filed by Apple for a "reinforced cable" also mentions the use of materials such as tinned copper wire, polyethylene insulation, nylon braided jackets, and plastic connector housings in Apple's cables. To model the cable in Simapro the “cable, unspecified” ecoinvent type was used since it consists of similar materials in comparable amounts as mentioned in the teardown report and patent application. The total weight of the 1m cable is 19.5 grams.

The SIM ejector tool that comes with the iPhone 11 is made of stainless steel. The weight of the tool is around 0.5 grams. Based on this information, the sim ejector was modeled with the “Steel, chromium 18/8” ecoinvent material type and the “Metalworking, average for chromium steel product” ecoinvent process type (see table 12).

Table 12: Weight, materials, ecoinvent material, and process dataset types of all accessories supplied with the iPhone 11

Accessory	Weight (grams)	Material	Ecoinvent material type(s)	Ecoinvent process type(s)
Rigid box	132.06	Virgin fiber paperboard	Packaging, folding boxboard carton	-
Rigid box	9.94	Polypropylene	Polypropylene, granulate	Plastic film
Plastic (protective) film	0.5	Polyethylene terephthalate (PET)	PET, granulate, amorphous	Extrusion, plastic film
Charging cable	19.5	Copper, polyethylene, nylon, plastic, metals	Cable, unspecified	-
Sim ejector tool	0.5	Stainless steel	Steel, chromium 18/8	Metal working, average for chromium steel product

5.1.2.5 Packaging of sub-components and accessories

The estimation of industrial packaging materials for the sub-components and accessories during their shipment from the manufacturer to the assembly plant was based on the weight of each component, following the approach outlined in Güvendik's (2014) study. For sub-components and accessories weighing more than 0.5 grams, the packaging weight was assumed to be 10% of the sub-component's weight. The packaging was assumed to consist of cardboard and plastics. Similar to Güvendik (2014), the ecoinvent datasets "Packaging film, low-density polyethylene {GLO}" and "Corrugated board box [ROW] market for corrugated board box" were used for industrial packaging, with an estimated weight of half the packaging weight.

For sub-components and accessories weighing less than 0.5 grams, more packaging is used compared to the component itself. A factor of 1.94, as suggested by Güvendik (2014), was used to estimate the weight of the packaging, which is then multiplied by the weight of the sub-component. Reels and tapes are commonly used for packaging these components, partly made of polystyrene. To model this, the ecoinvent datasets "Polystyrene, high impact {GLO}" and "Corrugated board box [ROW] market for corrugated board box" were utilized, with both estimated to weigh half of the packaging weight.

By calculating the industrial packaging for each sub-component and accessory (refer to Appendix 10.3), the total weight per packaging type was determined. The overall weight of industrial packaging for the sub-components is 24.44 grams, while for the accessories it is 18.09 grams. Table 13 provides the weight per packaging type for both sub-components and accessories, along with the relevant ecoinvent material types used for the total packaging. These total amounts of industrial packaging per packaging material type were added to the manufacturing process of the components. For accessories, the industrial packaging was individually incorporated into each accessory manufacturing process in SimaPro.

Table 13: Amount of packaging material used and ecoinvent material types for sub-components and accessories

	Plastic film (g)	Cardboard (g)	Polystyrene (g)
iPhone components	9.590	11.720	2.130
Rigid box	7.1	7.1	-
Plastic (protective) film	-	0.485	0.485
Charging cable	0.975	0.975	-
Sim ejector tool	-	0.485	0.485
Total	17.665	20.765	3.10
Ecoinvent (material) type	Packaging film, low-density polyethylene {GLO}	Corrugated board box [ROW] market for corrugated board box	Polystyrene, high impact {GLO}

5.1.3 Transport to the assembly facility

While Apple does not disclose the locations of its component suppliers, the assembly of the iPhone 11 is assumed to take place at Foxconn's assembly facility in Zhengzhou, China, based on information from StudyCorgi (2023). The LCA study conducted by Cordella et al. (2021) also lacks information about the component suppliers' locations. Similar to Cordella et al.'s study, it was assumed that the component suppliers are situated worldwide, and assembly occurs in China. Therefore, following Cordella et al.'s (2021) approach, for the transport of main components to the assembling facility, it was assumed that casing sub-components and smartphone rigid box are transported by lorry for 1000 km and 100 km, respectively. All other components, primarily electronics, are assumed to be transported by flight for 1000 km and by lorry for 100 km. Similar to Cordella et al. (2021), for the other accessories (plastic protective film, charging cable, and sim ejector tool) it was assumed that they are transported by lorry for a distance of 100 km to the assembly facility. This was based on the assumption that these components are manufactured in proximity to the assembly facility. These assumptions were made to reflect the geographical availability of parts and materials, as well as the relative ease or difficulty in sourcing them from different locations. Table 14 provides the ecoinvent datasets used to model the transportation to the assembly facility.

By conducting calculations on the transportation of each sub-component (refer to Appendix 10.3), the total tons*km for both lorry and flight transport to the assembly facility was determined. Table 14 provides an overview of the total t*km for lorry and flight transport, including the t*km for all accessories (rigid box, plastic protective film, charging cable, and sim ejector tool). These calculations involve summing the total weight of each sub-component or accessory, including its packaging weight, and multiplying it by the estimated distance in kilometers.

For air transport, the "short haul" dataset was selected, as the air distance of 1000 km falls within the range of 800-1500 km specified in the dataset's description. The total t*km for each transportation type was incorporated into the iPhone assembly phase in SimaPro.

Table 14: Transport types from the manufacturing facility to the assembly facility for components and accessories

	Transport by heavy truck (t*km)	**Transport by air (t*km)**
iPhone sub-components	0.0623	0.1719
Rigid box	0.01562	-
Plastic (protective) film	0.000147	-
Charging cable	0.002145	-
Sim ejector tool	0.018059	-
Total	0.0808	0.1719
Ecoinvent (material) type	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} market	Transport, freight, aircraft, short-haul {GLO} market

5.1.4 Assembly of the phone

Due to the lack of disclosed information on electricity consumption at Foxconn's assembly facility, the study conducted by Sánchez et al. (2022) is used as a basis. They determined that the assembly of the Fairphone 4 required 0.8 kWh, which translates to approximately 0.0035 kWh per gram of the phone. Applying this conversion, it was estimated that the assembly of the iPhone 11 consumes around 0.69 kWh of electricity.

Although Apple has made strides in transitioning to 100 percent renewable energy for its manufacturing and assembly facilities (Apple, 2019b), for the purpose of this analysis, it was assumed that grid electricity is used. Therefore, the electricity production mix of China from the ecoinvent database (Electricity, medium voltage {CN} market group) was employed as the LCI input for the assembly phase within the production stage.

5.2 Distribution

After the final assembly, the iPhones go to Foxconn's customs facility. The airport of Zhengzhou is on the same campus as the assembly and customs facility. Therefore, no lorry transport is assumed to take place from the facility to the airport. Similar to Cordella et al. (2021), the following transportation methods were considered for the distribution of iPhones: 8515 km by flight (distance between Zhengzhou Airport and London Heathrow Airport) and 300 km by heavy truck (transport distance proxy within the UK). Since the distance for transportation by air is more than 4000 km, the "long haul" transportation dataset was chosen. See table 15 for the ecoinvent datasets used for the distribution phase. The total weight of the iPhone including the accessories (rigid box, charging cable, protective film, and sim ejector tool) is 356.5 grams. 356.5 grams is 0,0003565 tons. So for the transport by a heavy truck, this resulted in 0.0003565*300= 0.10695 t*km. For the transport by flight, this resulted in 0.0003565*8515= 3.0355975 t*km. See Appendix 10.1.2.2 for the data quality indicators for all processes in the distribution phase.

Table 15: Transportation used for the distribution of iPhones to customers

	Transport by heavy truck (t*km)	Transport by air (t*km)
T*km	0.10695	3.0355975
Ecoinvent type	Transport, freight, lorry 16-32 metric ton, EURO4 {RER} market	Transport, freight, aircraft, long haul {GLO} market

5.3 Use phase

For the primary use phase consumer profiles, the battery conditions were considered 100%. For the secondary use phase only an average profile was considered with a battery condition of 80%, which is the minimal battery condition Twig requires for resale. See table 16 for the electricity consumption per consumer profile. All data was based on the consumer profiles explained in section 4.2 in the results of the literature review. See Appendix 10.1.2.3 for the data quality indicators for all processes in the primary and secondary use phase.

The electricity consumption of consumer profiles was determined based on the required recharging cycles, which are influenced by the intensity of use. The intensity of use was measured in hours per day, specifically referring to the daily screen time. While Apple states that the iPhone 11 can provide up to 10 hours of screen time (iPhone 11, 2019a), independent measurements suggest that this battery performance claim may be overstated. Actual tests showed that a fully charged iPhone 11 can last up to 5.33 hours of screen time when using Wi-Fi and various applications (such as YouTube, games, and social media) with a brightness level of 90%. Additionally, the same test indicated that an iPhone 11 with a battery condition of 80% can last up to 5.08 hours (Dynamic Tech, 2022).

By dividing the daily hours of use by the maximum screen time of 5.33 hours, the number of recharging cycles per day was calculated for each primary consumer profile (assuming a battery condition of 100%). Similarly, for the secondary profile (assuming a battery condition of 80%), the recharging cycles per day were calculated by dividing the hours of daily use by 5.08 hours. The annual recharging cycles per consumer profile were obtained by multiplying the recharging cycles per day by 365 days (refer to table 16 for details).

The battery capacity of an iPhone 11 is 3110 milliampere-hours (mAh) or 3.11 ampere-hours (Ah) (Apple, 2019a). To convert this capacity to watt-hours (Wh), this was multiplied by the nominal voltage of the iPhone 11 battery, which is 3.7 volts: 3.11 Ah x 3.7 V = 11.47 Wh = 0.01147 kilowatt-hours (kWh). Therefore, it takes approximately 0.01147 kWh to fully recharge an iPhone 11.

However, when using the Apple 5W USB power adapter with the lightning to USB cable (1m), the efficiency of the power adapter is reported to be 73.1% when plugged into a 230V supply voltage in the U.K. (Apple, 2019b). As a result, for one full recharge cycle, the following amount of kWh is used: (1 + (1 – 0.731)) x 0.01147 = 0.01455546 kWh. This calculation took into account the percentage of energy lost during charging. By multiplying this value (0.01455546 kWh) by the recharging cycles per year for each consumer profile, the electricity consumption for battery recharging per year was determined (see table 16 for specific values).

In addition to recharging batteries, the operation of communication services, such as mobile networks, Wi-Fi, servers, and core networks, requires energy. Cordella et al. (2021) estimated that a heavy user consumes approximately 55.7 kWh of electricity annually for these services. In this study, this estimation was used as the annual electricity consumption for network usage by the polluter (heavy user) consumer profile. Based on the intensity of use, the annual electricity consumption for other profiles was estimated.

The polluter profile represents the maximum intensity of use and, therefore, the highest network usage per year. By multiplying the share of usage intensity for the average profile (4/7) by the maximum network usage, the network usage for the average was calculated. The same calculation was applied to determine the network usage for the conscious profile.

Since the electricity consumption for network usage was not affected by the battery condition, the network usage for the secondary average profile was assumed to be the same as the primary average profile. For each consumer profile, the electricity consumption due to battery recharge and network usage (per year) was added together to determine the total electricity consumption per profile per year (see table 16 for specific values).

For all electricity consumption in the use phase, the electricity production mix of the United Kingdom (Electricity, low voltage {GB} market group) from the ecoinvent database was used to model the use phase in Simapro.

Table 16: Characteristics and data of the consumer profiles where all primary profiles represent the first use phase and the secondary profile the second use phase

	Primary polluter	**Primary average**	**Primary conscious**	**Secondary average**
Functional lifetime (years)	1	3	4	3
Intensity of use (hours/day)	7	4	1	4
Battery condition	100%	100%	100%	80%
Recharging cycles per year	478.15	273.75	65.7	287.4
Electricity usage per recharging cycle (kWh)	0.015	0.015	0.015	0.015
Recharge electricity usage per year (kWh)	6.96	3.98	0.96	4.18
Network usage per year (kWh)	55.7	31.89	7.96	31.89
Total electricity consumption per year (kWh)	62.66	35.87	8.92	36.07

5.4 Twig: processing for secondary life

Twig acquired Mobimarket for their electronic re-commerce business. To gather data for the study, interviews were conducted with the head of operations and the financial director of Mobimarket. As part of their business operations, Mobimarket outsources smartphone repairs and remanufacturing to Company X located in the UK. Although attempts were made to contact Company X for cooperation in this study, no response was received.

During the interviews, data were collected regarding the number of phones associated with each circular strategy, transportation methods, operational processes, distances traveled, and packaging details. This data was crucial for modeling the LCI input per phone for each circular strategy. By modeling the individual circular strategies and considering the share of total phones processed per circular strategy in 2022, the "processing for secondary life" phase was represented as a single assembly in Simapro, accurately capturing Twig's operations. See Appendix 10.1.2.4 for the data quality indicators for all processes in the ‘’processing for secondary life” phase.

5.4.1 Mobimarket: inbound/internal transport and packaging

Appendix 10.4 contains a table displaying the sequential steps involved in calculating the total packaging and transportation for both inbound and internal processes. Inbound processes pertain to the transport and packaging from the seller to Mobimarket, while internal processes encompass the transport and packaging to and from Company X. Each shipment's transportation in t*km was determined by multiplying the combined weight of the packaging and phone by the total distance traveled. The summation of t*km across all shipments yielded the total inbound and internal transportation. Please refer to table 17 for information regarding the ecoinvent types, total packaging, and transportation (t*km) for all inbound and internal processes.

The operations at Mobimarket commence when an individual (specifically, a Twig app user) sends a phone to Mobimarket's warehouse. The estimated distance from the seller to Mobimarket is approximately 100 km, and this leg of the journey is facilitated by UPS or DPD, utilizing smaller cargo vans weighing around 1.4 metric tons. Considering their cargo capacity, these vans fall under the classification of light commercial vehicles (Aljohani & Thompson, 2020). Hence, this transportation was modeled using the "transport, freight, light commercial vehicle (RER)" market ecoinvent dataset (refer to table 17).

To transport the phone from the seller to Mobimarket, one folding boxboard carton packaging weighing 150 grams is employed. When a phone follows thew directly resold or value-add strategy it will not be sent to Company X. So only one packaging box of 150 grams is used for these strategies. However, when a phone has to be repaired or remanufactured it is sent to Company X in a new packaging box. It was assumed that the identical packaging box is used for the round trips to and from Company X. Therefore, in total, two packaging boxes are used for the repair and remanufacturing strategy resulting in a total packaging weight of 300 grams per phone (see table 17). Additionally, all packaging was presumed to be recycled and was modeled by the "folding boxboard carton (RER)" ecoinvent market dataset in Simapro (see table 17).

Table 17: Data and ecoinvent datasets per circular strategy for inbound transport, internal transport (between Mobimarket and Company X), and all packaging used for this transport

	Directly resold	Value-add	Repaired	Remanufactured
Ecoinvent transport process type (seller-Mobimarket)	Transport, freight, light commercial vehicle (RER)	Transport, freight, light commercial vehicle (RER)	Transport, freight, light commercial vehicle (RER)	Transport, freight, light commercial vehicle (RER)
Ecoinvent transport process type (Mobimarket-Company X)	-	-	Transport, freight, light commercial vehicle (RER)	Transport, freight, light commercial vehicle (RER)
Ecoinvent packaging material type (seller-Mobimarket)	folding boxboard carton	folding boxboard carton	folding boxboard carton	folding boxboard carton
Ecoinvent packaging material type (Mobimarket-Company X)	-	-	folding boxboard carton	folding boxboard carton
Weight of total packaging used per phone (g)	150	150	300	300
Total inbound/internal transport per phone (t*km)	0.0344	0.0344	0.07568	0.07568

5.4.2 Mobimarket and Company X: electricity consumption

In 2022, Mobimarket processed >10.000 smartphones and consumed >10.000 kWh of electricity. Per circular strategy, the electricity consumption per phone was determined based on the annual electricity consumption of Mobimarket’s warehouse. Interviews suggested that directly resold phones contribute to 13% of Mobimarket's overall electricity usage, value-added phones account for 85%, repaired phones contribute 1.8%, and remanufactured phones make up 0.2%. Multiplying the total electricity consumption by these proportions allowed for the determination of electricity consumption per circular strategy. Dividing that value by the corresponding number of phones in each circular strategy provided the electricity consumption per smartphone within that strategy. Consequently, the electricity consumption at Mobimarket amounts to 0.328199 kWh per phone for direct resale and 1.155478 kWh per phone for value-added operations. The electricity production mix utilized for both Mobimarket and Company X was based on the United Kingdom's Electricity, low voltage {GB} market group from the ecoinvent database. For more precise details on estimated electricity consumption at Mobimarket and Company X, please refer to table 18.

At Company X, electricity was consumed to repair or remanufacture the phone. Based on Cordella et al. (2021), the electricity consumption for remanufacturing was assumed to be the same as the assembly of a smartphone. Hence, 0.69 kWh per phone is used for remanufacturing which means that around 60% of the phone’s components are replaced. In total this results in 1.382545 kWh per phone for remanufacturing.

When a phone is remanufactured, on average (and based on Company X quality standards) 60% of the phone’s components are replaced. It cannot be said which components are exactly replaced. Consequently, 60% of the original bill of materials for the phone was assumed to be manufactured in order to serve as replacements for the old or defective components. To accurately model the manufacturing process and transportation associated with the remanufacturing strategy, 60% of the iPhone’s manufacturing (without distinguishing between components) and distribution process was included in the remanufacturing scenario in Simapro.

To find out the electricity consumption for a repair at Company X, the kWh per gram of phone was calculated. Replacing 60% of the phone’s components (116.4g) required 0.69 kWh of electricity. 0.69 Kwh /116,4g = 0.0059 kWh/g. For a repair, in the worst case, both the LCD screen and battery are replaced, which amounts to 74.3 grams (47 g+27.3 g). 74.3g * 0,0059 Kwh/g = 0.44 kWh for one repair in a worst-case scenario. This estimation was used for the electricity consumption for one repair at Company X. In total this results in 1.137832 kWh per phone for a repair.

Based on the insights gathered from interviews conducted at Mobimarket, a repair operation involves replacing either the screen, battery, or both components. Consequently, when a repair is performed, two new components are manufactured and utilized as replacements for the old or damaged ones. To accurately represent the manufacturing process of these new components for repairs, the manufacturing processes and transportation associated with both the battery and LCD screen were included in the repair scenario of this life cycle phase in Simapro. The industrial packaging used for the shipment of components was already encompassed within the manufacturing process of the components. The transportation was calculated by multiplying the weight of the components with the corresponding distribution parameters used for iPhones (8515 km by air and 300 km by truck).

Table 18: Electricity consumption per circular strategy at Mobimarket and Company X (e.c.=electricity consumption, C=confidential)

	Directly resold	**Value-add**	**Repair**	**Remanufactured**	**Total**
Number of smartphones in 2022	C	C	C	C	>10.000
Share of total phones	0.3413	0.6339	0.0222	0.0025	1
Share of e.c. at Mobimarket	0.13	0.85	0.018	0.002	1
E.c. at Mobimarket per year (kWh)	C	C	C	C	>10.000
E.c. at Mobimarket per smartphone (kWh)	0.328199	1.155478	0.697832	0.692545	2.874055
E.c. at Company X per smartphone (kWh)	-	-	0.44	0.69	1.13
Total e.c. per phone (kWh)	0.328199	1.155478	1.137832	1.382545	4.004055

5.4.3 Mobimarket: outbound transport and packaging

This section focuses on outbound transport and packaging, specifically referring to the shipment of smartphones from Mobimarket to its customers. Irrespective of the circular strategy employed, smartphones can be sent to various types of Mobimarket customers. Due to Brexit, smartphones are no longer shipped from the UK to Europe, and as a result, all customers are located within the UK.

Phones are sold to two types of customers: individual customers (B2C) and businesses (B2B). The transportation of phones to both customer types is carried out by a courier service, utilizing road transport with a small cargo van (refer to table 19 for the ecoinvent dataset utilized). This transportation method aligns with the one used for inbound phone shipments and those sent to the Company X. For all customer shipments, 150 grams of folding boxboard carton packaging is utilized per phone (see table 19).

Based on data from Mobimarket, the share of B2C customers was estimated to be C (confidential), while B2B customers account for the remaining C. The average distance to B2C customers set at 100 km, was based on an estimation provided by Mobimarket's head of operations. The distance to B2B customers was determined based on the distance to Mobimarket's largest customer, Telefonica. To calculate a customer type's total outbound transport (t*km), the weight of the phone and packaging was summed and multiplied by the average distance associated with that customer type. In the final step, the customer type's share was multiplied by its total outbound transport, resulting in the overall outbound transport based on the B2C and B2B proportions. By summing this column, the average total outbound transport used in t*km was obtained.

Both the packaging for shipment to the customer and the average total transport were incorporated into every circular strategy within Simapro. Hence, for any circular strategy, the modeling included 150 grams of folding boxboard packaging and 0.02924 t*km of light commercial transport for the outbound transportation of a single iPhone. All relevant data can be found in table 19.

Table 19: Data and ecoinvent datasets for outbound transport and packaging (after phones are processed for secondary life they are shipped to the customers). (B2B=Business to Business, B2C=Business to Customer) (C=confidential)

	B2B	**B2C**	**Total**
Share of customer type	C	C	1
Ecoinvent transport process type	Transport, freight, light commercial vehicle (RER)	Transport, freight, light commercial vehicle (RER)”	
Average distance (km)	80	100	180
Ecoinvent packaging material type	folding boxboard carton	folding boxboard carton	-
Weight packaging per phone (g)	150	150	300
Weight packaging per phone (tons)	0.00015	0.00015	0.0003
Weight of phone	0.000194	0.000194	0.000388
Total outbound transport per phone (t*km)	0.02752	0.0344	0.06192
Total transport (t*km) based on customer shares	0.02064	0.0086	0.02924

5.4.4 Data servers Twig

For every phone processed through Twig (Mobimarket), a server was running to enable an individual to sell and/or buy the phone through the app. However, Twig moved to Amazon Web Services (AWS) which uses renewable energy. Based on an interview with the head of sustainability, the total annual footprint from AWS green infrastructure usage was around 1-2t of CO_2 emissions. These are the emissions for all processes, products, and services that Twig does. The emissions per smartphone were estimated as extremely marginal (M. Henry, personal communication, April 4, 2023) and will only impact the Global Warming Potential impact category. Therefore, this data was not included in this study.

5.4.5 Total electricity, transport, and packaging due to reuse

Based on the previous sections, the total electricity consumption, transport, and packaging per circular strategy were found. This data can be found in table 20. For every circular strategy, an assembly was created in Simapro in which the total electricity consumption, transport, and packaging for one phone were modeled using the mentioned ecoinvent datasets. A complete “processing for secondary life” assembly was then modeled that includes all circular strategies based on their respective shares of the total phones that were processed in 2022. Hence, direct resell counts for 34.13%, the value-add operation for 63.39%, the repair strategy for 2.22%, and the remanufacturing strategy for 0.25% (see table 20). This way, the average reuse of one smartphone through Twig was modeled.

Table 20: The table shows the total electricity consumption, transport, and packaging needed for one phone per circular strategy. The totals per strategy are multiplied by their respective shares of phones processed by Twig to model one assembly for "processing for secondary life" in Simapro which represents an average for reusing one smartphone through Twig (C=confidential)

	Directly resold	**Value-add**	**Repair**	**Remanufactured**	**Total**
Number of smartphones	C	C	C	C	>10.000
Share of total phones	34.13%	63.39%	2.22%	0.25%	100%
Total electricity consumption per phone (Kwh)	0.328199	1.155478	1.137832	1.382545	4.004055
Total inbound/internal packaging (g)	150	150	300	300	900
Total outbound packaging (g)	150	150	150	150	600
Total packaging used (g)	300	300	450	450	1500
Total inbound/internal transport (t*km)	0.0344	0.0344	0.07568	0.07568	0.22016
Total outbound transport (t*km)	0.02924	0.02924	0.02924	0.02924	0.11696
Total transport (t*km)	0.06364	0.06364	0.10492	0.10492	0.33712

5.5 End-of-life waste management

The literature review indicated that smartphone owners typically retain their old phones in personal storage after purchasing a new one, as highlighted in table 7. This behavior of stockpiling phones does not have a direct environmental impact, which made it unnecessary to model this particular aspect. Drawing upon the works of Güvendik (2014), Cordella et al. (2021), and Sánchez et al. (2022), it was assumed that all smartphones will be collected and sent for recycling at the end of their life cycle. To simplify the LCA, it was assumed that 100% of iPhones are recycled at a dedicated recycling facility. The device as considered to be disposed of in its entirety, without any mass losses occurring between the disposal stage and the recycling plant. See Appendix 10.1.2.5 for the data quality indicators for the EoL processes of sub-components and accessories.

In Simapro, an EoL waste scenario was constructed to effectively model the final stage of the iPhone's life cycle. This waste scenario was incorporated into any linear or reuse scenario within Simapro, allowing for the appropriate handling of the materials inputted during earlier stages of the life cycle.

The initial step in the EoL process involves separating the battery from the iPhone, which undergoes a combined pyro-hydrometallurgical recycling process, as described by Güvendik (2014). To model this recycling process for the Li-ion battery, the "Used Li-ion battery {GLO}" ecoinvent waste treatment dataset was utilized. It was assumed that 95% of the batteries are correctly separated, as indicated by Sánchez et al. (2022).

For all iPhone materials, an ecoinvent recycling waste treatment was assigned, and table 21 provides details on the waste treatments and recovery rates for each ecoinvent material type. These recovery rates were based on data obtained from the UK government's Department for Environment, Food and Rural Affairs (DEFRA). Any materials or parts that are not recovered during the recycling process will be either incinerated or landfilled. Components or materials without a designated waste treatment in the model will be directly incinerated or landfilled. This applied to all iPhone components modeled as module or component datasets in Simapro. Based on DEFRA statistics from UK Statistics on Waste (2022), 19.15% of the waste is incinerated, while the remaining 80.85% is landfilled. See Appendix 10.5 for the recovery rates per material and the shares per waste treatment method.

The transportation from a smartphone user to a recycling point was assumed to be similar to the distance proxy used for the distribution of an iPhone in the UK. The proxy used was 300km of transport by heavy truck (Transport, freight, lorry 16-32 metric ton, EURO4 {RER} market). The total weight of the iPhone including the accessories was multiplied by the distance resulting in 0.10695 t*km.

Table 21: Waste treatments and Department for Environment, Food and Rural Affairs (DEFRA) recovery rates in the U.K. per ecoinvent material type that was used in this study to manufacture an iPhone's component

Ecoinvent material type	Waste treatment	Recovery rate (%)
Polycarbonate	Mixed plastics (waste treatment)	47.2
Aluminum, primary, cast alloy slab from continuous casting	Aluminum (waste treatment)	78.8
Flat glass, coated	Packaging glass (waste treatment)	74.2
Chromium steel 18/8	Steel and iron (waste treatment)	78.8
Ferrite, at plant	-	-
Copper, anode	Steel and iron (waste treatment)	78.8
PET, granulate, amorphous	PET (Waste treatment)	47.2
Glass fiber reinforced plastic, polyester resin	Mixed plastics (waste treatment)	74.2
Packaging, corrugated board box	Core board (waste treatment)	69.1
Polypropylene, granulate	Mixed plastics (waste treatment)	47.2
Packaging, Folding boxboard carton	Core board (waste treatment)	69.1

The accessories of the iPhone 11 were assumed to follow the same waste stream as the iPhone itself and will be disposed of simultaneously. Each accessory consists of different materials, and for each accessory, a specific waste treatment and recovery rate was assigned. If no waste treatment was assigned, the accessory will be directly incinerated or landfilled. Overall, a total of 214.5 grams (iPhone + accessories) will be disposed of. For detailed information on the waste treatment and recovery rates per material type of the iPhone's accessories, please refer to table 22.

Table 22: Waste treatment types and Department for Environment, Food and Rural Affairs (DEFRA) recovery rates for accessories based on the accessories' materials

Accessories	Ecoinvent material type	Waste treatment	Recovery rate (%)
Rigid box	Packaging, folding boxboard carton	Core board (waste treatment)	69.1
Rigid box	Polypropylene, granulate	Mixed plastics (waste treatment)	47.2
Plastic (protective film)	PET, granulate, amorphous	Mixed plastics (waste treatment)	47.2
Charging cable	Cable, unspecified	-	-
Sim ejector tool	Steel, chromium 18/8	Steel and iron (waste treatment)	78.8

5.6 Life Cycle Inventory input per FU

Before generating results, the Simapro input per consumer scenario was provided to foster the transparency of this study and to be able to compare the different reuse systems to its reference linear system. Both systems consist of different consumer scenarios (conscious, average, and polluter) which were based on the consumer profile that represents its use phase. As mentioned earlier, system expansion was used to avoid allocation. For all linear and reuse systems, the inventory input was calculated based on the functional lifetimes per consumer scenario. See figure 4 for the functional lifetimes of the conscious, average, and polluter reuse and linear consumer scenarios. The maximum functional lifetime is 7 years, which is the conscious reuse scenario (figure 4). The shortest functional lifetime is one year, which is the polluter linear scenario (figure 4).

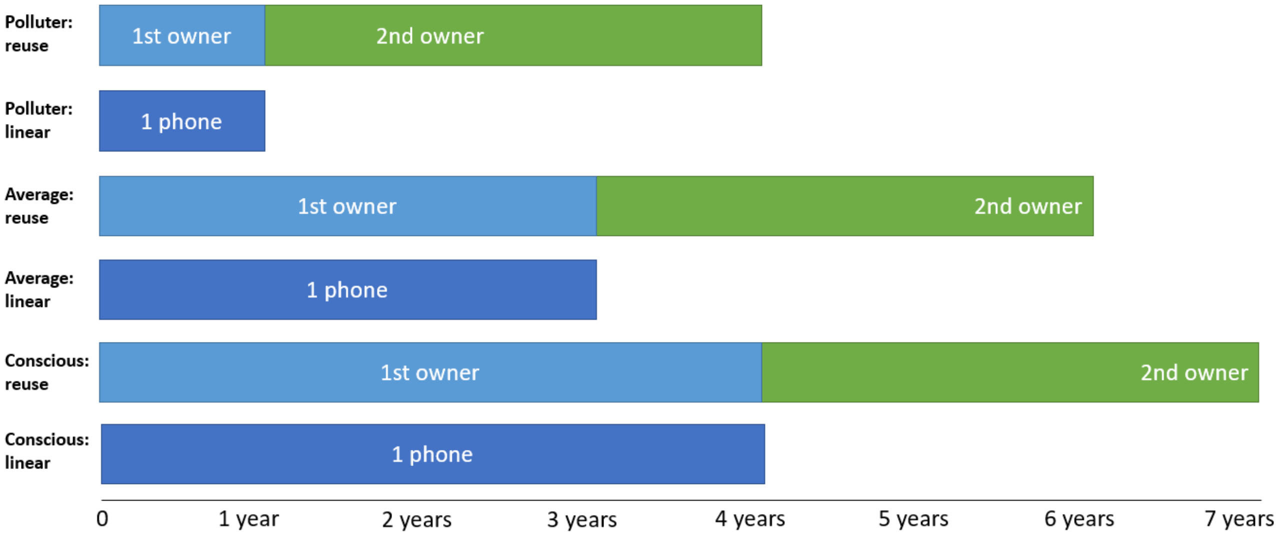

Figure 4: Different consumer reuse and linear scenarios based on their functional lifetimes

Table 23 shows the normalization factors applied to each product life cycle stage to normalize the inventory of the linear consumer scenarios to the FU (= 1 year of use). The factors were calculated by dividing the inventory inputs by the functional lifetimes of every consumer profile.

Table 23: Linear scenarios inventory input normalized to FU (1 year of use)

	Linear conscious	**Linear average**	**Linear polluter**
Production (#)	1/4	1/3	1
Distribution (#)	1/4	1/3	1
Use phase (years)	1	1	1

The same was done for the reuse consumer scenarios. The inventory input for the whole cascade of life cycle stages as determined based on the functional lifetimes per reuse consumer scenario. All inventory inputs per scenario were divided by the functional lifetimes of every consumer profile to get the normalization factors (see table 24).

Table 24: Reuse scenarios inventory input normalized to FU (1 year of use)

	Reuse conscious	**Reuse average**	**Reuse polluter**
Production (#)	1/7	1/6	1/4
Distribution (#)	1/7	1/6	1/4
First use phase (years)	4/7	1/2	1/4
Mobimarket (#)	1/7	1/6	1/4
Second use phase (years)	3/7	1/2	3/4

6. Life cycle impact assessment and interpretation

This chapter analyzed the environmental impacts of the baseline scenario and focused on the life cycle stages with significant impacts. The assessment exhibits the results on the four most relevant impact categories to keep the interpretation and visualization of the results manageable. The tables and figures of the results that include all impact categories can be found in Appendix 10.6, 10.7, 10.8, 10.9, and 10.10. In this chapter the reuse consumer scenarios were compared to their reference linear consumer scenarios, the differences in impact contributions were examined, and the research question was answered. Additionally, several sensitivity analyzes were conducted to check the robustness of the results.

6.1 Life cycle environmental impact of the baseline scenario: contribution analysis

The study's baseline scenario is the linear average consumer scenario (i.e. linear system with an average consumer profile), which served as a starting point for conducting the contribution analysis.

The contribution analysis aimed to identify the life cycle phases with the greatest impacts, as illustrated in Figure 5. The figure depicts the impacts of the various life cycle stages per impact category. The results indicated that the production and use phase significantly outweigh all other life cycle phases. This was also the case for every impact category analyzed (see Appendix 10.6.1). Appendix 10.6.2 lists the absolute values of the impacts for all life cycle stages per impact category. The EoL and distribution stages created relatively low impacts compared to the other stages and were therefore not analyzed in detail. In total, 16.8 kg CO_2-eq per year of use (i.e. per FU) is released in the baseline scenario. See table 25 for the total impacts of the baseline scenario's life cycle per impact category. Given that the production and use phase are the main contributors to the total impacts, in the subsequent sections it was delved deeper into these phases to ascertain the source of these impacts.

Table 25: Total impacts (per FU) of the baseline scenario's life cycle per impact category

Impact category	Unit	Total
Global warming	kg CO2 eq	16.77
Ozone formation	kg NOx eq	0.07
Marine eutrophication	kg N eq	5.67E-04
Mineral resource scarcity	kg Cu eq	0.22

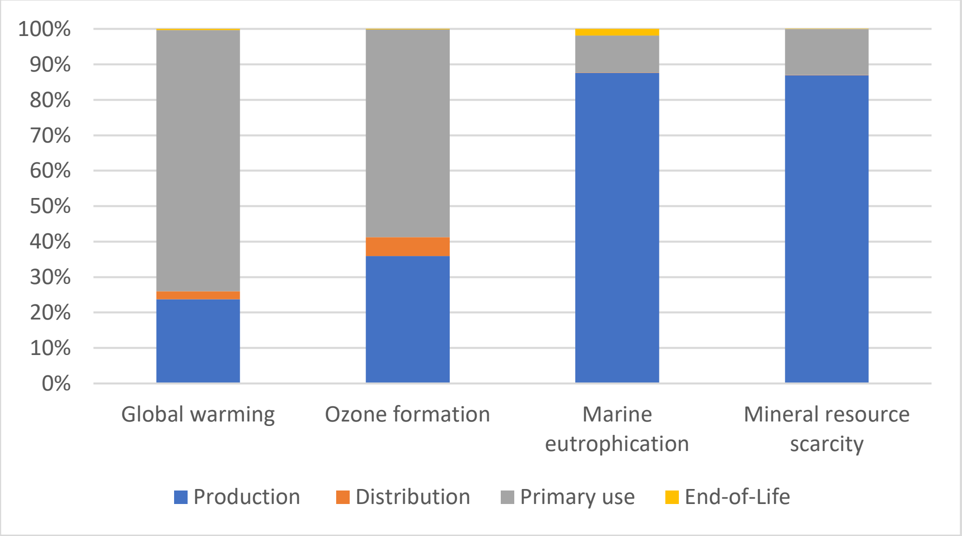

Figure 5: Share of environmental impacts per impact category for every life cycle stage of the baseline scenario with respect to the total impacts of the baseline scenario

6.1.1 Production phase

Figure 6 provides a visual representation of the production phase, which involved the manufacturing and assembly of the iPhone's components and accessories. The absolute values of the impacts of every manufacturing process in the production phase are provided in Appendix 10.6.3.2. As depicted in the figure, the manufacturing of the iPhone's components significantly outweighed the impacts of all other processes in the production phase.

The plastic protective film and sim ejector tool have relatively small weights, therefore their impacts are not even visible in figure 6. On the other hand, the rigid box and transportation from the manufacturing to the assembly facility are visible in most impact categories. However, these impacts were considered marginal compared to the manufacturing of the components.

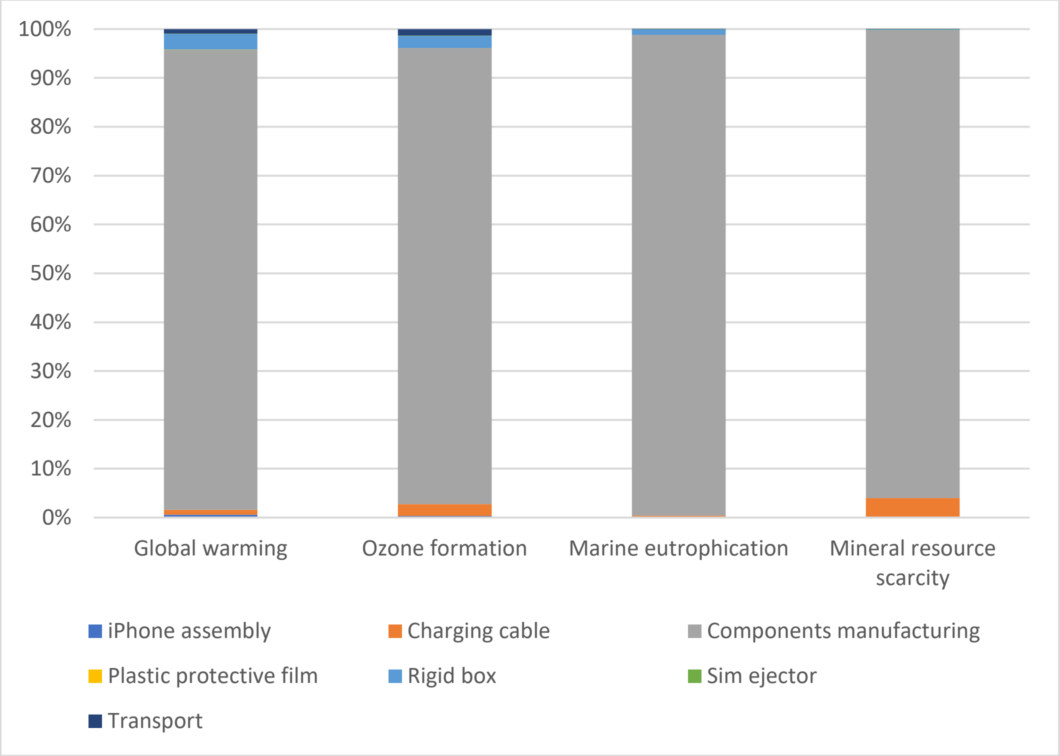

Figure 6: Share of environmental impacts per impact category for the different (manufacturing) processes in the production phase with respect to the total impacts in the production phase

To identify the components that have the most significant impacts during the iPhone's manufacturing process, the study delved deeper into the component manufacturing process. Figure 7 only includes sub-components responsible for more than 1% of the impacts per impact category to enhance the figure's readability. This means that, in total 14 sub-components were not visualized individually because each contributes to less than 1% of the impacts in an impact category. However, the 14 sub-components were aggregated in figure 7 under “other components”.

Based on the findings presented in Figure 7, and given the fact that “other components” consist of 14 different sub-components, three components dominate the iPhone's manufacturing phase in most impact categories: the mainboard (pink), integrated circuit logic (light green), and LCD screen production (yellow). These components had the most significant impacts compared to other components due to their energy-intensive manufacturing processes and materials used.

Interestingly, the LCD screen had the most substantial impact on the marine eutrophication category due to the nitrogen oxides (NOx) and sulfur dioxide (SO_2) emissions generated during its production. Although Apple does not disclose any information about the manufacturing process of the LCD screen, the production of raw materials (e.g., glass substrate), the deposition of thin films using chemical vapor deposition (CVD), or the use of etching processes that involve reactive gases can cause these emissions (Ueberschaar et al., 2017). Excessive nutrient addition, such as nitrogen and phosphorus, to aquatic ecosystems, causes marine eutrophication. On the other hand, in the mineral resource scarcity impact category, the white LEDs (blue) had a relatively large impact. This category relates to the extraction of minerals and materials that are from the earth's crust. For the production of white LEDs there is a high consumption of rare earth elements leading to this relatively large impact in this category.

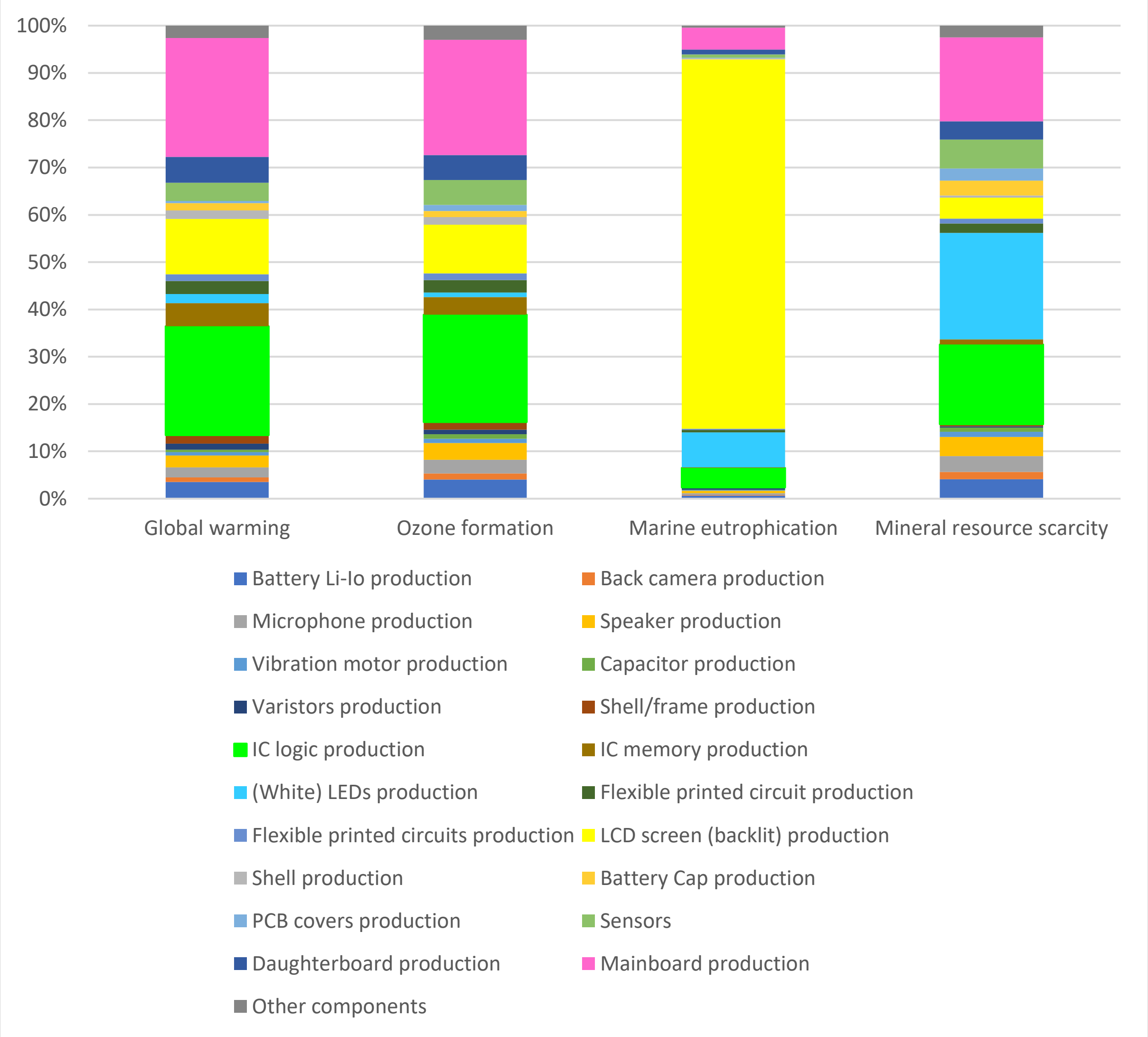

Figure 7: Share of environmental impacts per impact category for the different iPhone's sub-components with respect to the total impacts in the manufacturing of the iPhone's components process

6.1.2 Use phase

During the use phase, electricity is consumed to recharge the iPhone and power various communication services (network usage). Figure 8 visualizes the share of impacts of recharge and network usage for the baseline scenario of one year of use with respect to the total impacts during the use phase. The absolute values of the impacts of network usage and recharge per impact category for the baseline scenario are included in Appendix 10.6.4.2. In every impact category, network usage had the most significant impact, as shown in figure 8. Interestingly, the ratios between the impacts due to recharge and network usage were the same in every impact category, as seen in Figure 8. Recharge contributed to 11.1% of the impacts, while network usage accounted for 88.9%. This is due to both activities only relate to electricity consumption and were modeled with the same electricity mix, resulting in similar shares of impacts in all categories.

The same ratio between the shares of impact for recharge and network usage applied to the conscious and polluter linear scenarios because their electricity consumption amounts were determined in ratios based on usage intensity. However, for the secondary average consumer profile, the share of impacts due to recharge was larger (11.6%) compared to the other profiles because this consumer type has to recharge their phone more often, as detailed in Appendix 10.6.4.3. Additionally, the absolute values for the impacts in the use phase differed for each consumer profile because each profile relates to a different amount of electricity consumption, as shown in Appendix 10.6.4.4.

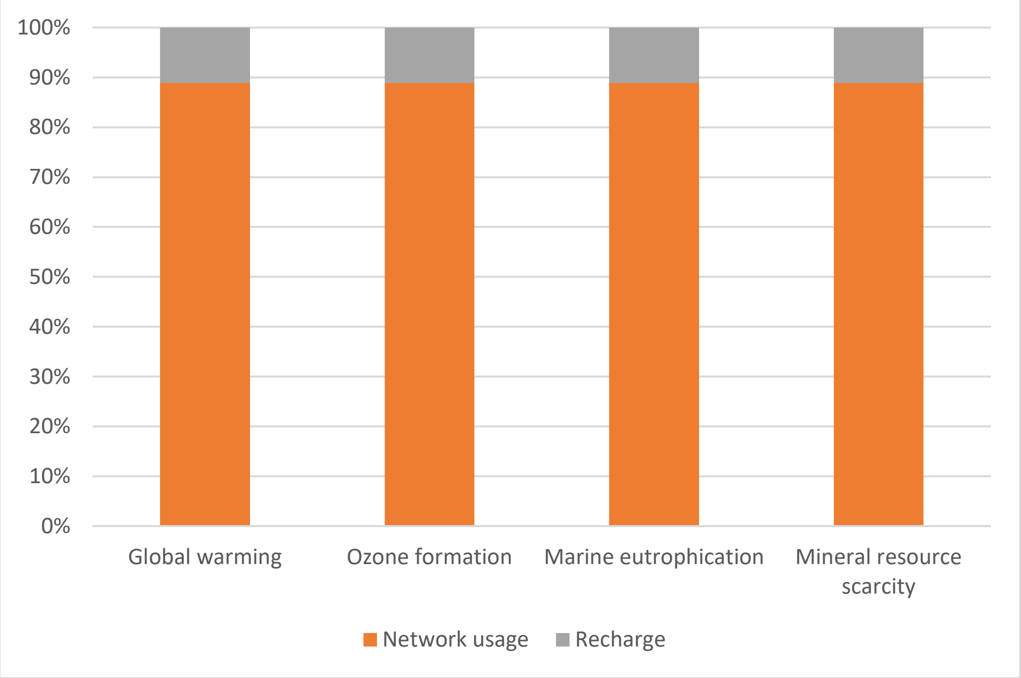

Figure 8: Share of environmental impacts per impact category for network usage and recharge in the baseline scenario with respect to the total impacts in the use phase

6.2 Linear consumer scenarios

This section compared different linear systems (per FU) to find the most favorable and unfavorable linear consumer scenario and identified the contributions per life cycle stage for the different linear consumer scenarios. There were three different linear consumer scenarios considered within the linear system: linear conscious, linear average, and linear polluter. All refer to their respective consumer profile (conscious, average, and polluter) that represent their use phase.

Figure 9 illustrates a comparison of the different linear scenarios in terms of their total impacts per impact category. The absolute values of the total impacts of each scenario can be found in table 26. The absolute values of the impacts in all impact categories can be found in Appendix 10.7.2. Figure 9 indicates that the linear polluter scenario creates the most impacts, while the linear average linear scenario generates at least 50% fewer impacts per impact category than the linear polluter scenario. On the other hand, the linear conscious scenario was considered the most environmentally friendly scenario as it produced the fewest impacts per impact category (almost 5 times less compared to the polluter scenario). The table shows that in the global warming impact category, the average scenario resulted in 18.059 kg CO_2-eq fewer impacts, and the conscious scenario even in 28.444 kg CO_2-eq fewer compared to the polluter scenario. The variations in environmental impacts among the scenarios are attributed to the functional lifetime and intensity of use associated with each consumer profile. The higher the intensity of use and the shorter the functional lifetime, the more electricity is consumed per FU (mainly due to network usage), resulting in a larger share of impacts from the use phase. Furthermore, the lower the functional lifetime, the more iPhones are used per FU, leading to more impacts related to production, distribution, and EoL.

Therefore, based on these different linear consumer scenarios that relate to a certain consumer profile it can be concluded that consumer behavior (intensity of use and functional lifetime) significantly influenced the environmental impact of using an iPhone.

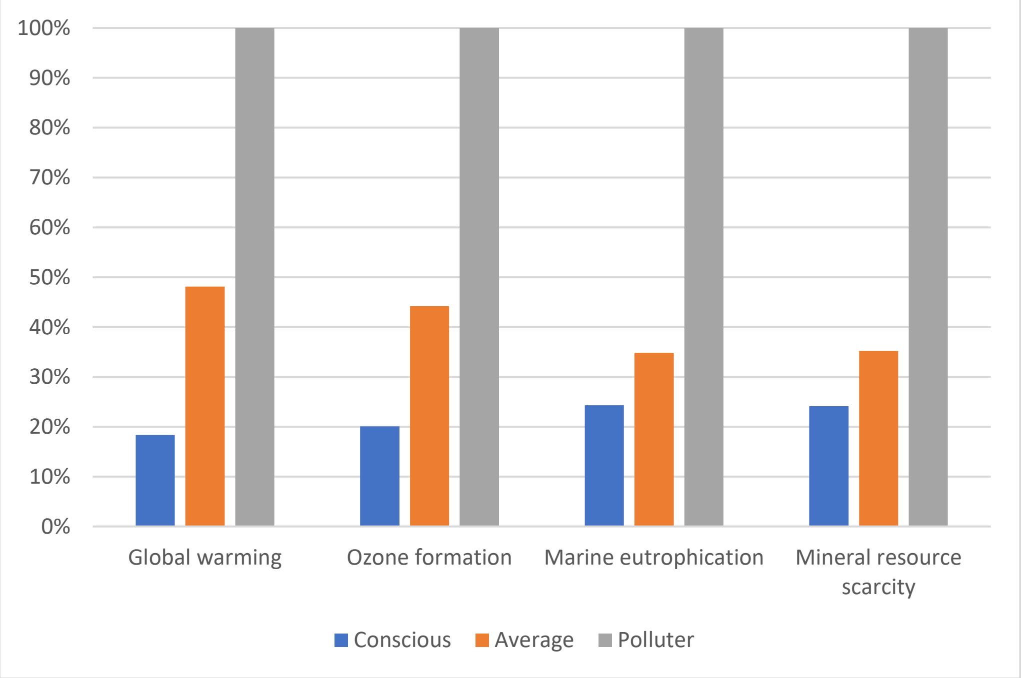

Figure 9: Comparison of the environmental impacts of the different linear consumer scenarios with respect to the total impacts of the linear polluter scenario

Table 26: Absolute values (per FU) of the total life cycle impacts of every linear scenario per impact category

Impact category	Unit	Conscious	Average	Polluter
Global warming	kg CO2 eq	6.38	16.77	34.83
Ozone formation	kg NOx eq	0.03	0.07	0.17
Marine eutrophication	kg N eq	4.02E-04	5.76E-04	1.65E-03
Mineral resource scarcity	kg Cu eq	0.15	0.22	0.63

Figure 10 provides an overview of the shares of impacts of different life cycle stages for all linear consumer scenarios in each impact category. See Appendix 10.7.4 for the absolute values of the impacts per life cycle stage as visualized in figure 10. The figure shows which life cycle phases in each linear scenario are responsible for the majority of impacts in an impact category. The linear conscious scenario demonstrated that the production phase is responsible for most impacts in the majority of impact categories. However, for the linear average and linear polluter scenarios, the use phase was more dominant than in the linear conscious scenario. This is attributed to the fact that the linear conscious consumer as assumed to consume less electricity and use fewer phones per FU than the other linear scenarios.

Overall, for all linear consumer scenarios, the production was most dominant in the marine (and freshwater-) eutrophication, and mineral resource scarcity impact categories. Freshwater eutrophication and marine eutrophication are linked to nutrient pollution. For the production of iPhones, some of the iPhone's components rely on inputs that can contribute to nutrient pollution, making this phase particularly impactful for these impact categories (see section 6.1.1). As earlier explained in section 6.1.1, mineral resource scarcity evaluates the potential impacts associated with the depletion of non-renewable mineral resources on which iPhone production depends. The extraction, processing, and transport of these materials can have significant environmental impacts. Moreover, mineral resources are limited, and the production of iPhones can exacerbate the depletion of these resources over time.

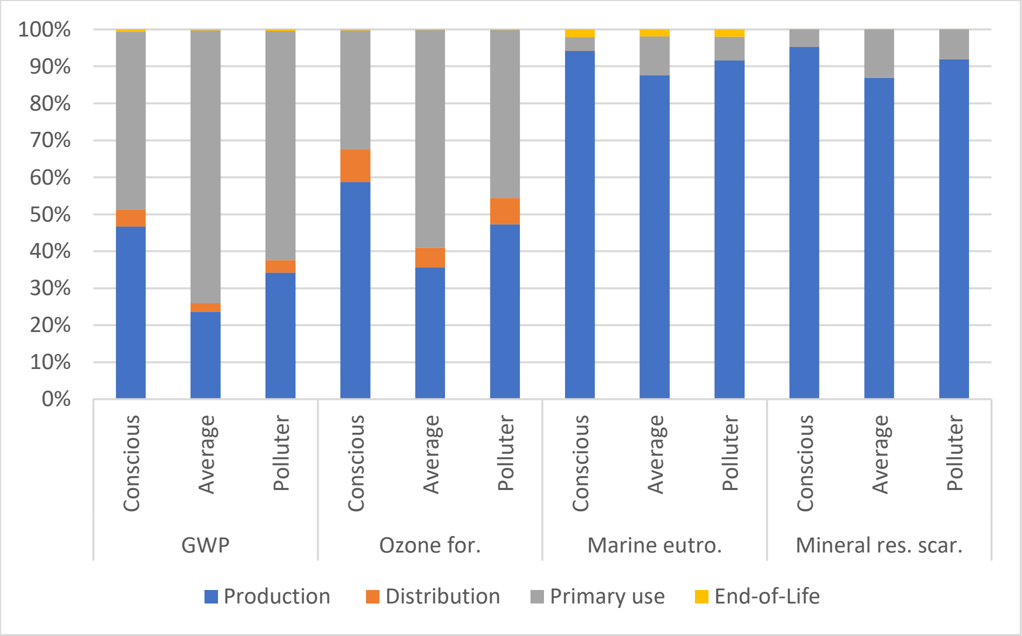

Figure 10: Share of environmental impacts of the life cycle stages of the linear consumer scenarios per impact category with respect to the total impacts in their full life cycles

6.3 Reuse consumer scenarios

To determine the best and worst reuse scenarios and understand which life cycle stages create the most impacts, a comparison was made between the reuse scenarios (per FU). There were three different reuse scenarios within the reuse system: reuse conscious, reuse average, and reuse polluter. All refer to their respective consumer profile (conscious, average, and polluter) that represent their primary use phase. The secondary use phase is in all reuse consumer scenarios represented by the secondary average consumer profile.

The impacts of the different reuse consumer scenarios are compared in Figure 11, which illustrates that the reuse polluter scenario created the most impacts across all impact categories. The reuse average scenario generated roughly 20% fewer impacts than the reuse polluter scenario. The reuse conscious scenario created the least impacts. Table 27 provides the absolute values of the total life cycle impacts of the different reuse consumer scenarios per impact category. See Appendix 10.8.2 for the absolute values of the impacts in all impact categories.

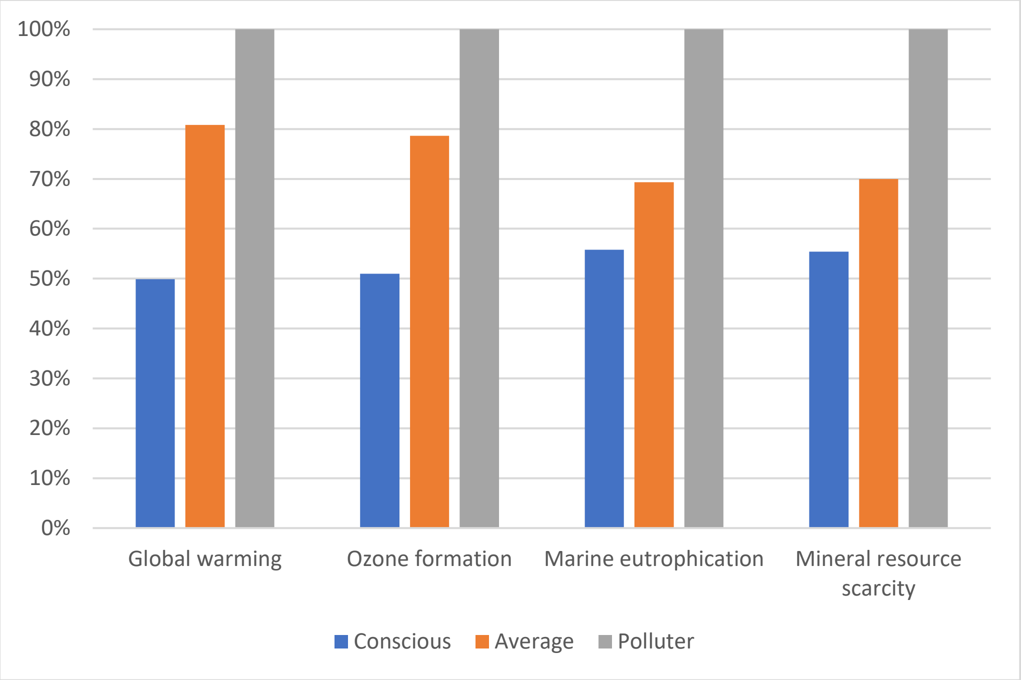

Figure 11: Comparison of the environmental impacts of the reuse consumer scenarios with respect to the total impacts of the reuse polluter scenario

Table 27: Absolute values of the total life cycle impacts of every reuse scenario per impact category

Impact category	Unit	Conscious	Average	Polluter
Global warming	kg CO2 eq	9.11	14.75	18.26
Ozone formation	kg NOx eq	0.04	0.06	0.08
Marine eutrophication	kg N eq	2.65E-04	3.29E-04	4.75E-04
Mineral resource scarcity	kg Cu eq	0.10	0.13	0.18

The shares of impacts of the life cycle stages of the reuse scenarios per impact category are shown in Figure 12. The absolute values of the impacts per life cycle stage are included in Appendix 10.8.410.7.3 Visualization of impacts per life cycle stage. It was observed that for all impact categories and reuse consumer scenarios, distribution, processing for secondary life, and EoL created the least impacts. On the other hand, the production, primary use, and secondary use phase were the primary sources of impacts per impact category.

Looking at the global warming impact category, the reuse average scenario had an almost equal share of impacts from the primary and secondary use phase because the primary and secondary average profiles are almost similar in electricity consumption and both represent an equal share of the total use phase.

On the other hand, the reuse conscious scenario had the largest share of impacts coming from the secondary use phase because the secondary average consumer profile (that represents the second use phase) consumes compared to the primary conscious consumer profile a lot more electricity in network usage and recharging.

The reuse polluter scenario showed that most impacts also come from the second use phase but also had a large share of impacts from the primary use phase. Although the secondary average consumer profile consumes less electricity than the primary polluter profile within the reuse polluter scenario, the secondary average profile had the largest share of use attributed (see table 24 in section 5.6). Similar to the linear scenarios, the production phase was responsible for the most significant impacts in the marine (and freshwater-) eutrophication, and mineral resource scarcity impact categories. The impacts in the processing for secondary life phase are explained in the next section.

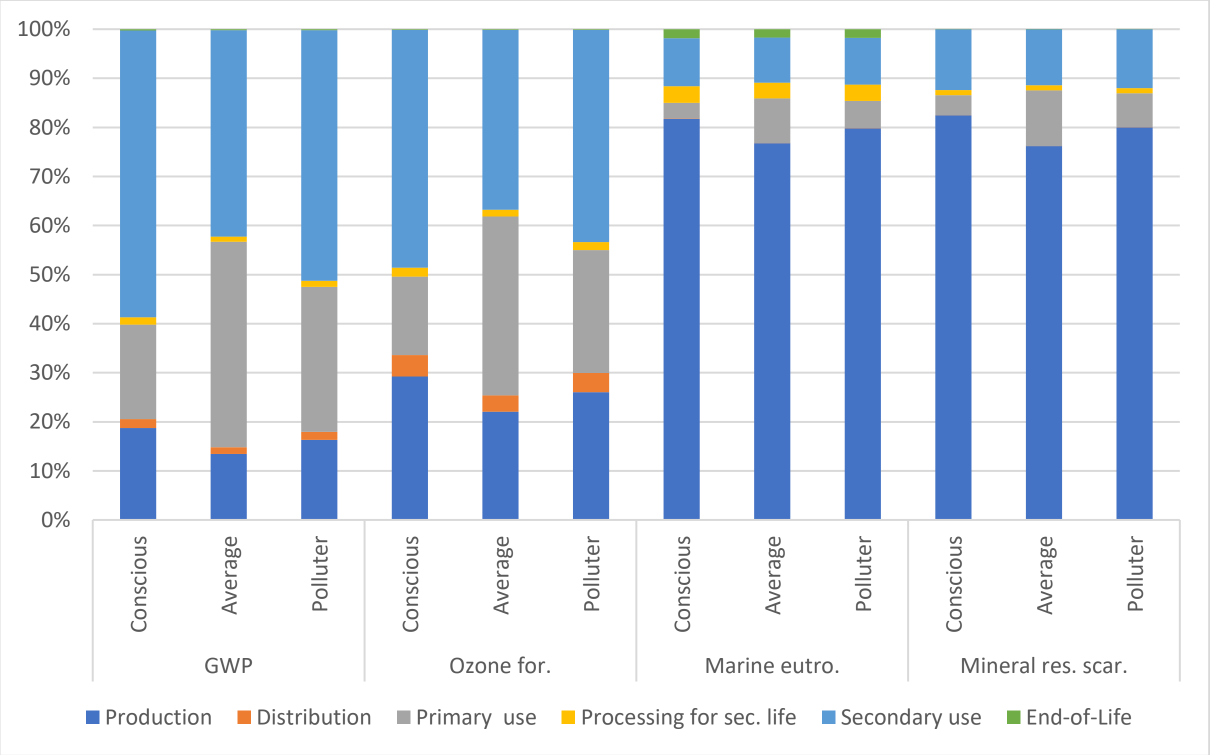

Figure 12: Share of environmental impacts of the life cycle stages of the reuse consumer scenarios per impact category with respect to the total impacts in their full life cycles

6.3.1 Processing for secondary life

When it comes to iPhone reuse, Twig processes smartphones for secondary life using various circular strategies (direct resale, value-add, repair, and remanufacturing) based on their condition at the point of sale. Figure 13 provides a comparison of the environmental impacts of the different circular strategies when processing a single phone. In other words, the circular strategies in figure 13 were not compared per FU, but per phone processed.

The direct resell strategy emerged as the most environmentally friendly option while remanufacturing was the least preferred. The value-add operation only had slightly higher impacts than direct resale. In the marine eutrophication category, repair created the most impacts due to the full screen and battery replacement assumed to take place causing even more impacts in this impact category than remanufacturing a phone. These results indicate that the fewer actions required to reuse a phone, the better.

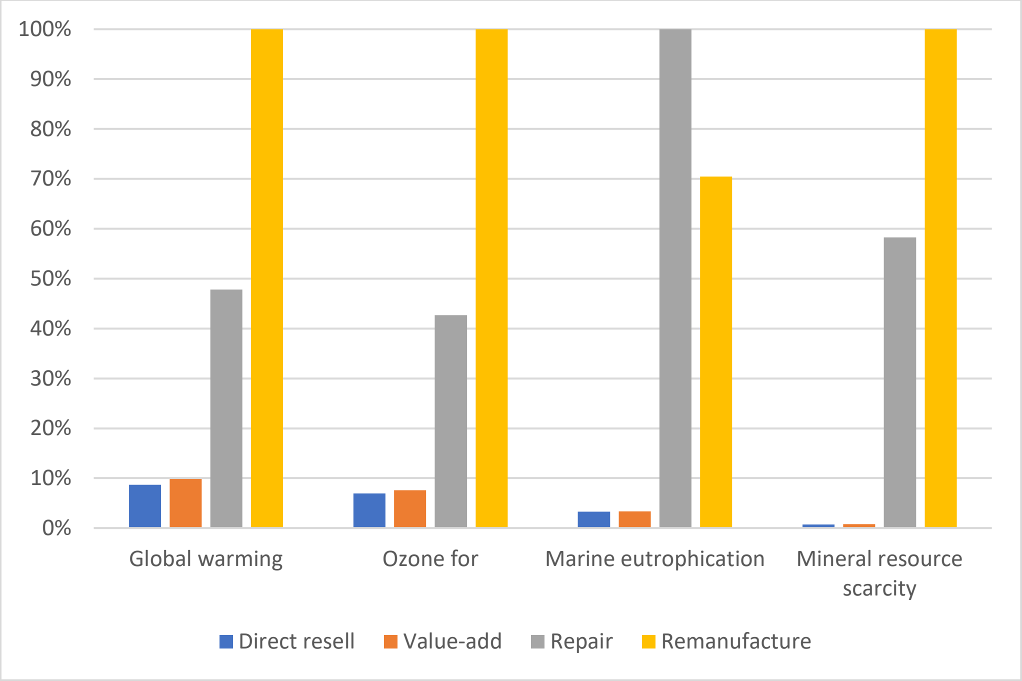

Figure 13: Comparison of the environmental impacts of the different circular strategies per phone processed (not per FU)

However, the reuse scenarios were modeled using the average of all circular strategies implemented by Twig because the goal of this study is to find out the environmental benefits of reuse, not the most beneficial strategy for Twig. Also, this would lead to many different scenarios which does not enhance the interpretation of the results. The average of all circular strategies was determined based on a share of processed phones per circular strategy in 2022. See table 28 for the shares per circular strategy.

Table 28: Number of phones and share of total phones processed by Twig per circular strategy (C=confidential)

	Directly resold	**Value-add**	**Repair**	**Remanufactured**	**Total**
Number of smartphones	C	C	C	C	>10.000
Share of total phones	34.13%	63.39%	2.22%	0.25%	100%

Figure 14 depicts the share of impacts for each circular strategy in a reuse scenario. For most impact categories, the value-add strategy had the highest impacts, followed by direct resell. This was attributed to the fact that the majority of phones received by Twig undergo a value-add operation, while the second largest share was directly resold (see table 28). However, in the case of marine eutrophication and mineral resource scarcity, the repair strategy had the most significant impacts due to the need for screen and battery replacements that require new component production. On the other hand, remanufacturing had the least impacts since it is by far the least frequently used circular strategy by Twig.

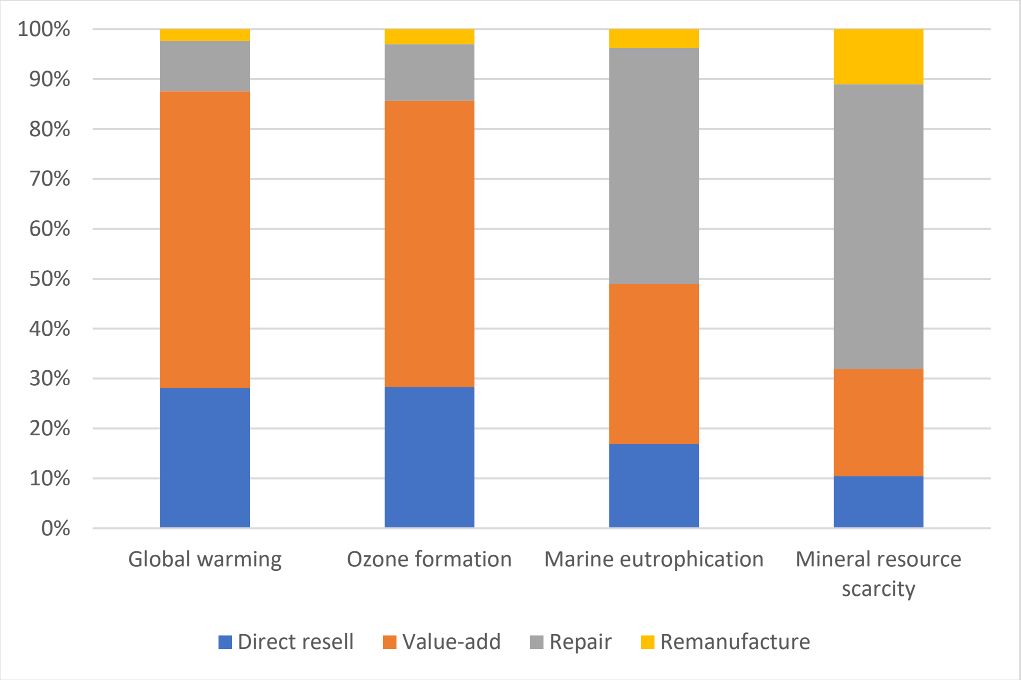

Figure 14: Share of environmental impacts of the different circular strategies per impact category (per FU) with respect to the total impacts of the processing for secondary life phase

6.4 Linear versus reuse consumer scenarios: avoided impacts due to reuse

This section aimed to answer the sub-question: *What is the environmental impact of reusing iPhones compared to a linear scenario?* Within the linear system, there were three linear reference scenarios (conscious, average, and polluter). Within the reuse system, there were three reuse consumer scenarios (conscious, average, and polluter) considered. Every reuse consumer scenario was compared to its respective linear consumer scenario. In other words, the reuse conscious consumer scenario was compared to the linear conscious consumer scenario, the reuse average consumer scenario to the linear average consumer scenario, and the reuse consumer polluter scenario to the linear polluter consumer scenario. The comparisons were made to identify differences in impacts between the linear and reuse system per impact category to find out the benefits of iPhone reuse. When the impacts of the reuse system were lower than its reference linear system, there was a difference (per FU) found which are the avoided impacts (see figure 15). The absolute values of the avoided impacts observed (per FU) can be found in table 29 where negative values for avoided impacts signify that the reuse system creates more impacts than the linear system. Figure 15 also visualizes this when a linear system creates fewer impacts than the reuse system in an impact category. The absolute values of the total and avoided impacts in all impact categories can be found in Appendix 10.10.4.

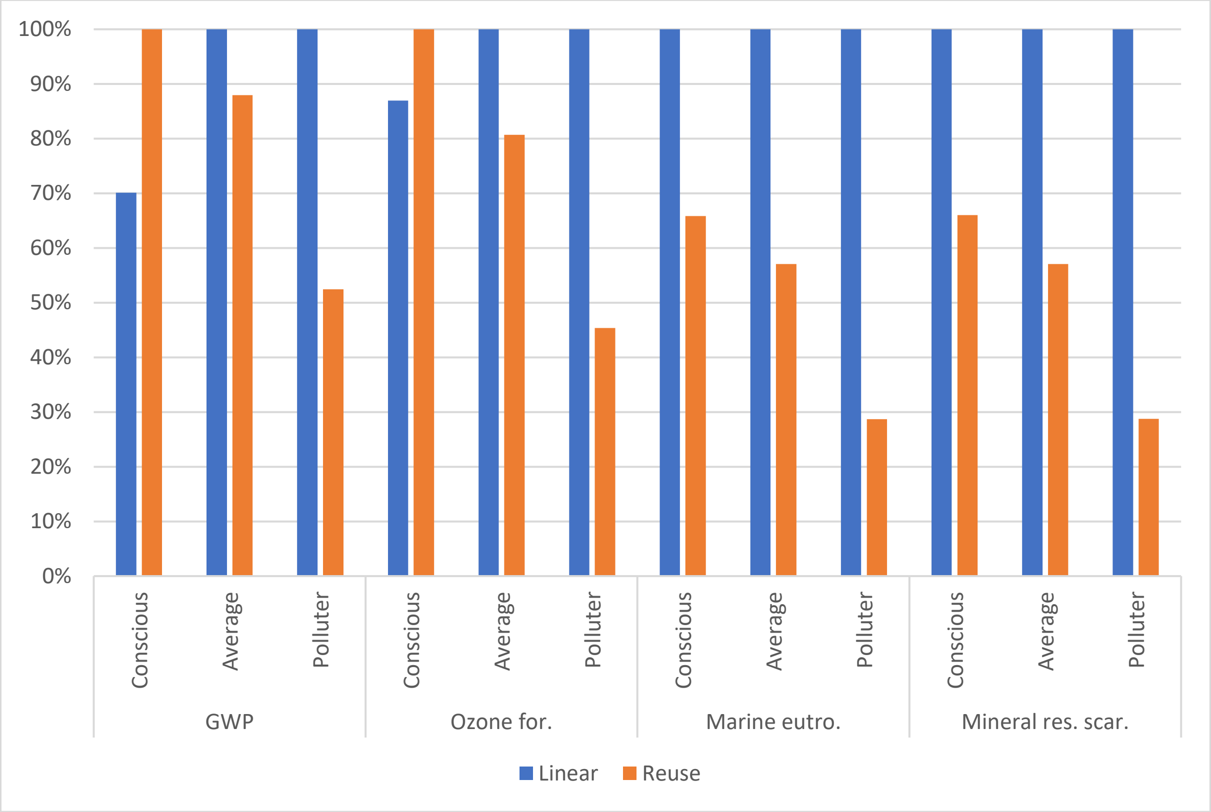

Figure 15: Environmental impacts per impact category of the comparison between the linear and reuse consumer scenarios with respect to their total impacts per comparison

Table 29: Total impacts and avoided impacts (linear minus reuse) of the different consumer scenarios per impact category (per FU)

Impact category	Scenario	Linear	Reuse	Avoided impacts
Global warming (kg CO2 eq)	Conscious	6.38	9.11	-2.72
	Average	16.77	14.75	2.02
	Polluter	34.83	18.26	16.57
Ozone formation (kg NOx eq)	Conscious	0.04	0.04	0.00
	Average	0.08	0.06	0.02
	Polluter	0.16	0.08	0.1
Marine eutrophication (kg N eq)	Conscious	4.02E-04	2.65E-04	1.37E-04
	Average	5.76E-04	3.29E-04	2.47E-04
	Polluter	1.65E-03	4.75E-04	1.18E-03
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.10	0.05
	Average	0.22	0.13	0.10
	Polluter	0.63	0.18	0.45

To assess the magnitude of avoided impacts throughout the iPhone's life cycle, percentages of impact change between the linear and reuse systems were calculated for each consumer scenario. The magnitude of avoided impacts in all impact categories can be found in Appendix 10.10.3. Figure 16 visually illustrates the variations in the magnitude of avoided impacts across the consumer scenarios. A negative percentage means that the reuse leads to fewer impacts than buying a new phone. While a positive percentage indicates that reuse leads to more impacts than buying a new phone

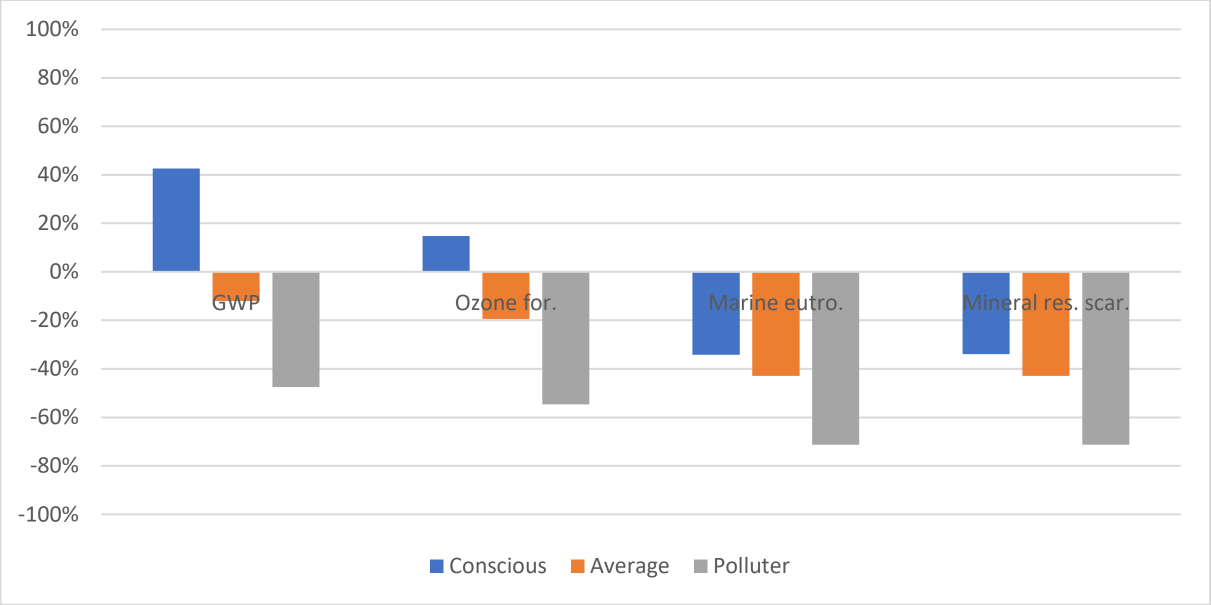

Figure 16: Magnitude of avoided impacts between the different consumer scenarios. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

Figure 16 reveals that in the average consumer scenario, there is a 12.02% reduction (equivalent to 2.02 kg CO_2-eq/yr) in GHG emissions within the global warming impact category through smartphone reuse. The polluter scenario demonstrated the most notable advantage, with a 47.57% decrease (equivalent to 16.57 kg CO_2-eq/yr) in emissions due to reuse within the global warming impact category.

In the conscious scenario, the reuse system created fewer impacts in the marine eutrophication and mineral resource scarcity categories than its reference linear system (see figure 16). These categories mainly relate to impacts associated with the production of an iPhone. Reuse extends the duration of use which decreases the impacts from production (no new phone has to be produced). However, looking at all impact categories, the conscious scenario revealed higher impacts in six of the nine impact categories within the reuse system (see Appendix 10.9.1). Specifically, in the global warming impact category, the conscious reuse scenario generated 42.64% more GHG emissions (equivalent to 2.72 kg CO_2-eq/yr) compared to its conscious linear reference scenario. This finding suggests that reuse is not as environmentally advantageous as conscious linear use, making it more beneficial to purchase a new phone instead. The increased impacts in the conscious reuse scenario can be attributed to the substantial contribution of its second use phase, wherein the secondary average consumer profile is involved. This profile's network usage significantly surpasses that of the conscious consumer profile that represents the reuse system’s primary use phase. Consequently, the impacts from the secondary use phase have a considerable influence on the overall impacts in the conscious reuse scenario, exceeding those of the total use phase in the conscious linear scenario. In essence, when the phone is initially used by a conscious consumer type but subsequently used by a consumer type with significantly higher environmental impacts, reuse does not offer environmental benefits.

Conversely, the polluter scenario exhibited a significant difference in electricity consumption between the secondary average profile and the polluter profile within the reuse system. Consequently, this discrepancy resulted in substantial differences in impacts between the reuse and linear system, which led to a significant number of avoided impacts.

These findings indicated that in the polluter scenario, reuse offers the greatest environmental benefits compared to purchasing a new phone, followed by the average scenario. However, in the conscious scenario, buying a new phone is more environmentally advantageous than reuse. Therefore, the impacts associated with producing, distributing, and processing the phone for secondary use are not compensated by the act of reuse in the conscious scenario.

6.5 Sensitivity analysis

To check the robustness of the results and find out whether smartphone reuse reduces the environmental impacts in all consumer scenarios, multiple sensitivity analyzes were conducted. First of all, a sensitivity analysis is conducted on the method of allocation to check the differences in the results. Additionally, another sensitivity analysis was carried out to assess the effect of excluding network usage, which is a significant contributor to impacts but has a relatively low data quality indicator. Furthermore, a sensitivity analysis was conducted on the second use phase, as the utilization of a single consumer profile during this phase appears to influence the outcomes. Lastly, a sensitivity analysis is conducted on the duration of the second use phase since a 3-year duration may not always be applicable for a phone's second life.

6.5.1 Allocation method: economic allocation

It is widely acknowledged that the choice of allocation method significantly impacts the presentation of results. While system expansion is preferred to avoid allocation, there may be an argument for allocating burdens and credits associated with reuse based on the prices of the purchase price of a primary and secondary phone. Consequently, economic allocation was employed in the sensitivity analysis to investigate the discrepancies in outcomes, given that the value of an iPhone decreases over time, resulting in the secondary user's device being worth less than the first user's. To employ this economic allocation method a different perspective was taken. Instead of taking the perspective of the phone, the first and second user’s perspective was taken, which means not all life cycle stages are included in the reuse scenario depending on the user’s perspective taken (see figure 17). The FU had to be altered to the perspective taken to conduct economic allocation.

The economic allocation method used in the analysis is based on the purchase price of new and second-hand devices. The current purchase price for an iPhone 11 at an official Apple dealer is 530 Euros (Amac, 2023). Based on data from Twig, an iPhone 11 with a battery condition of 80% can be sold for 290 Euros. As a result, 64.63% of the impacts were allocated to the first user and 35.37% (100%-64.63%) to the second user. In other words, the iPhone has a value retention of 35.37%. Figure 17 provides a visualization of economic allocation in the reuse system.

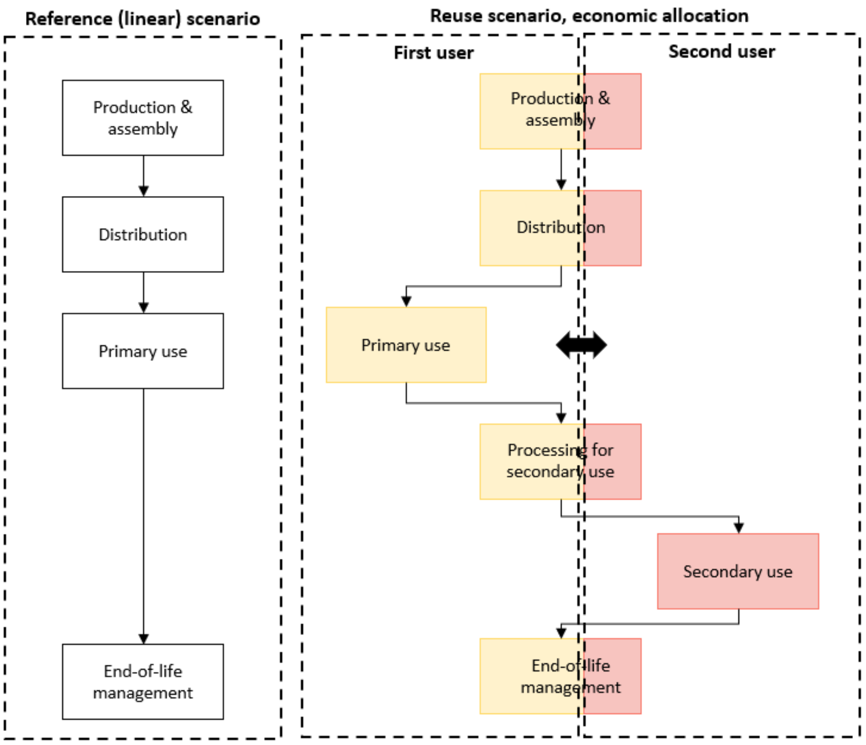

Figure 17: System boundaries when doing economic allocation for the sensitivity analysis. The first user is attributed to 64,63% of the impacts, the second user is attributed to 35,37% of the impacts

6.5.1.1 First user perspective (the seller)

The initial user who sells the phone in the reuse consumer scenario has 64.63% of the impacts allocated to them based on the economic value of their device. Table 30 displays the inputs per FU for the reuse consumer scenarios, which was utilized to determine the avoided impacts when applying economic allocation from the first user's viewpoint. The inputs contained in Table 30 exclusively pertain to the first use phase, and not the second. The inputs were calculated using values normalized to the FU, multiplied by the proportion of economically allocated impacts (64.63%). Notably, the inputs for the linear consumer scenarios remain unchanged since the linear system does not include two users.

Table 30: Reuse scenarios' inventory input normalized to FU (1 year of use) when doing economic allocation from the first user's perspective

	Conscious	**Average**	**Polluter**
Production (#)	0.0923	0.1077	0.1616
Distribution (#)	0.0923	0.1077	0.1616
First use phase (years)	1	1	1
Mobimarket (#)	0.0923	0.1077	0.1616
Second use phase (years)	-	-	-

Figure 18 exhibits the results of when the first user's perspective economic allocation was applied. Based on the figure it was observed that reuse is always beneficial because the reuse consumer scenarios led to fewer impacts than the reference linear consumer scenarios. Appendix 10.10.1.3 provides an overview of the absolute values of total impacts and avoided impacts of the different scenarios per impact category when the first user's perspective economic allocation is applied.

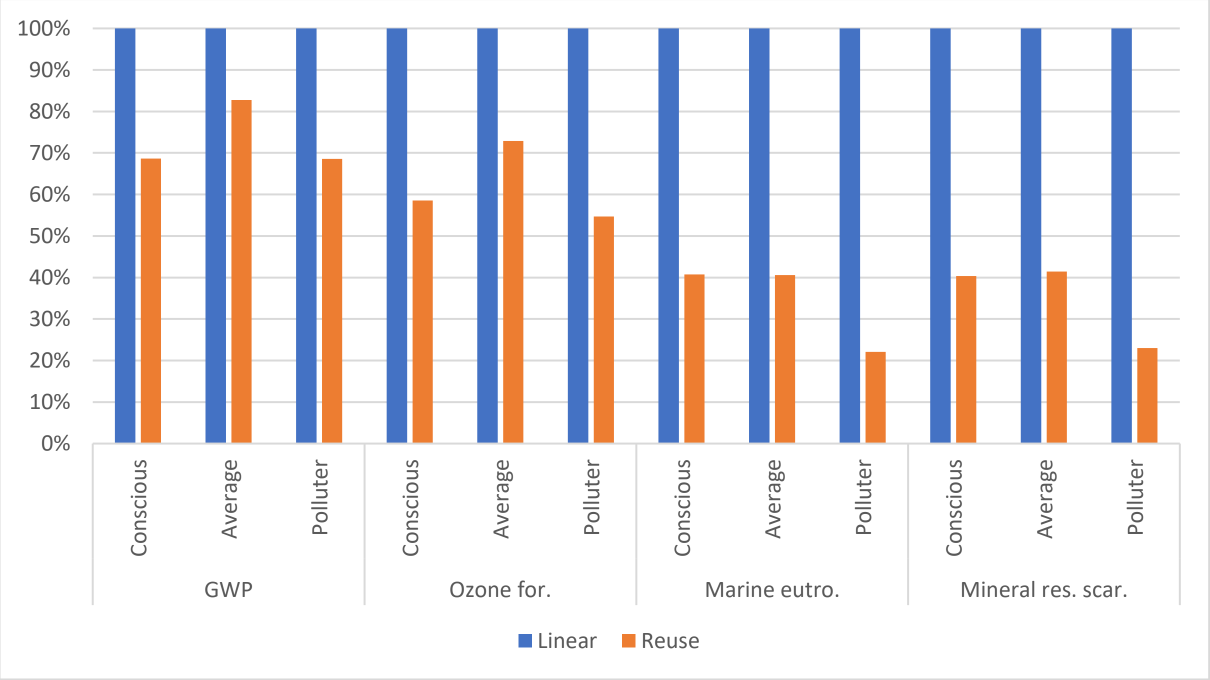

Figure 18: Results of the linear and reuse consumer scenario comparison when applying first user's perspective of economic allocation

Figure 19 illustrates the differences in avoided impacts when comparing the first user's perspective of economic allocation and system expansion. Per scenario (conscious, average, and polluter) the magnitude of avoided impacts (due to reuse) of first user economic allocation and system expansion were compared. The conscious and average scenarios showed higher avoided impacts across all impact categories when using the first user's perspective allocation. In the polluter scenario, system expansion led in most impact categories to more avoided impacts (see Appendix 10.10.1.2 for all impact categories).

The value retention factor (64.63%) played a significant role in the differences in avoided impacts between the methods of allocation. In the reuse consumer scenarios, the first user’s perspective of economic allocation considers the same LCI input as system expansion but excludes the second use phase and was multiplied by the proportion of economic allocated impacts (64.63%). This led to more avoided impacts for economic allocation.

However, previous findings emphasized that the use phase is the main contributor to the iPhone's environmental impacts. The linear consumer scenarios use the same LCI input for both allocation methods. Therefore, these differences in avoided impacts were determined by the profiles employed in the reuse consumer scenarios that represent the total use phase when applying an allocation method. When applying the first user's perspective of economic allocation, the second use phase was excluded (see figure 17). However, for system expansion, the second use phase was included and represented by the secondary average profile. In the conscious scenario, the use phase impacts were largely influenced by the secondary average profile when using system expansion. While when applying the first user's perspective of economic allocation the use phase was determined solely by the conscious consumer profile. The conscious profile had significantly lower impacts compared to the secondary average profile. As a result, both the value retention factor and the difference in use phase representation contribute to economic allocation having a greater magnitude of avoided impacts (see figure 19).

In the average scenario, the difference in avoided impacts between the allocation methods can mainly be attributed to the value retention factor. This is because both allocation methods represent their use phase with a similar consumer profile (the average consumer profile). Due to the lower LCI inputs in the average reuse scenario resulting from the value retention factor when applying economic allocation, economic allocation led to a higher magnitude of avoided impacts (see figure 19).

Although the value retention factor contributed to lower impacts in the conscious and average scenarios, it did not outweigh the avoided impacts gained by consumer profile differences in the reuse system when applying system expansion in the polluter scenario. In this polluter scenario, the use phase impacts for system expansion were largely determined by the secondary average profile, while economic allocation fully relied on the polluter profile. The polluter profile had significantly higher impacts than the secondary average profile. Therefore, system expansion achieved a higher magnitude of avoided impacts in most impact categories (see figure 19).

Based on these results it can be concluded that the method of allocation significantly influenced the results and that by applying the first user’s perspective economic allocation reuse is environmentally beneficial in each consumer scenario.

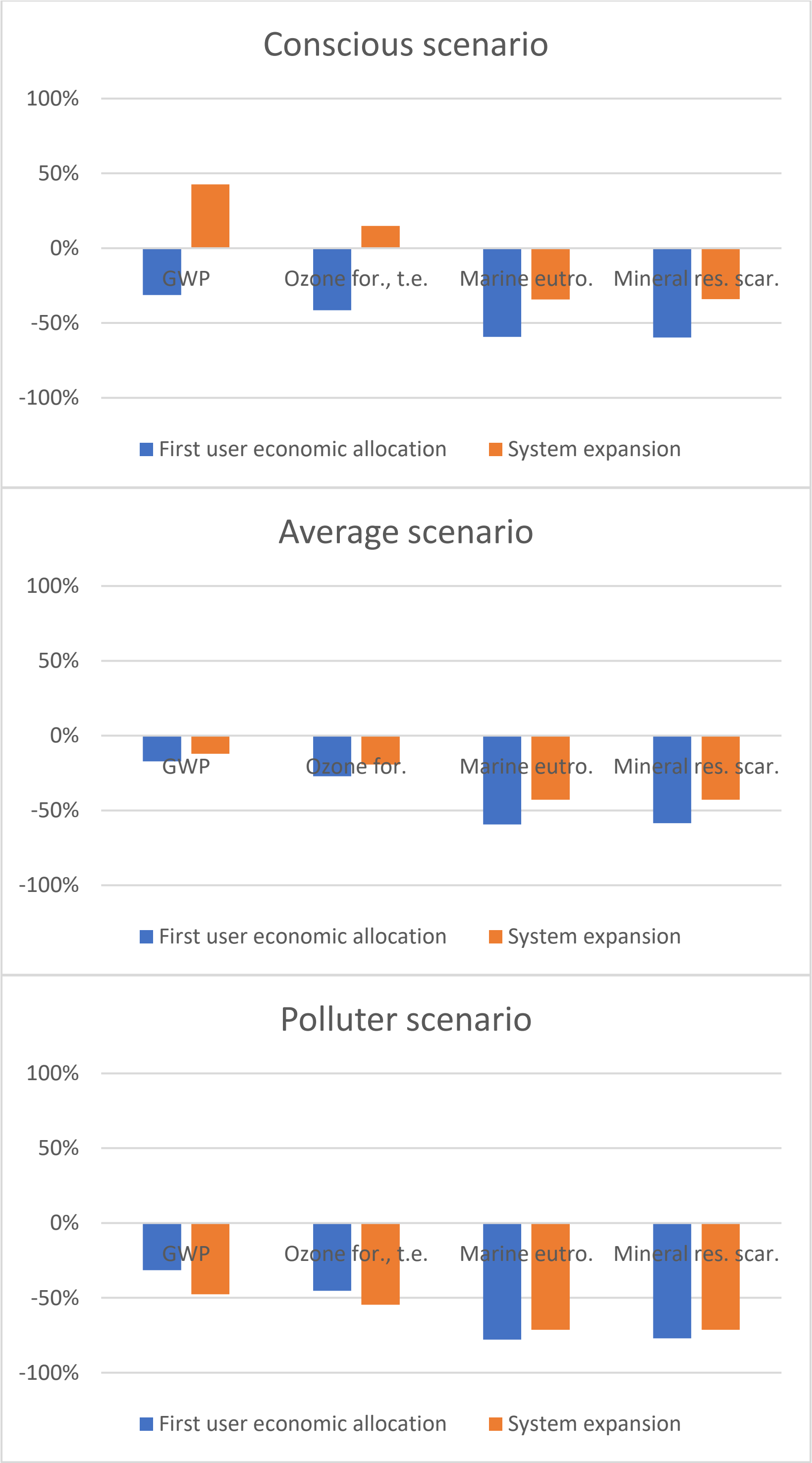

Figure 19: Differences in magnitudes of avoided impacts per scenario between applying the first user's perspective economic allocation and system expansion. A negative percentage shows that impacts are avoided due to reuse. A positive percentage shows that reuse does not lead to avoided impacts.

6.5.1.2 Second user perspective (the buyer)

Using the shares calculated based on the first and second-hand price, 35.37% of the impacts were allocated to the second user. To determine the avoided impacts resulting from reuse using the economic allocation method from the second user's perspective, the data presented in Table 31 were consulted. Table 31 indicates that from the second user's perspective, only the second use phase is taken into account, while the primary use phase is not. The second use phase was represented by a single consumer profile, namely the average secondary profile.

Table 31: Reuse scenarios inventory input normalized to FU (1 year of use) when doing economic allocation from the second user's perspective

	Conscious	Average	Polluter
Production (#)	0.0505	0.05895	0.088425
Distribution (#)	0.0505	0.05895	0.088425
First use phase (years)	-	-	-
Mobimarket (#)	0.0505	0.05895	0.088425
Second use phase (years)	1	1	1

Figure 20 displays the outcomes obtained from applying the second user's perspective economic allocation. In the conscious scenario, the results indicated that reuse did not result in fewer impacts compared to linear use. However, in both the average and polluter scenarios, reuse led to fewer impacts across all impact categories. For detailed values comparing the linear and reuse consumer scenarios under the second user's perspective of economic allocation, please refer to Appendix 10.10.2.3.

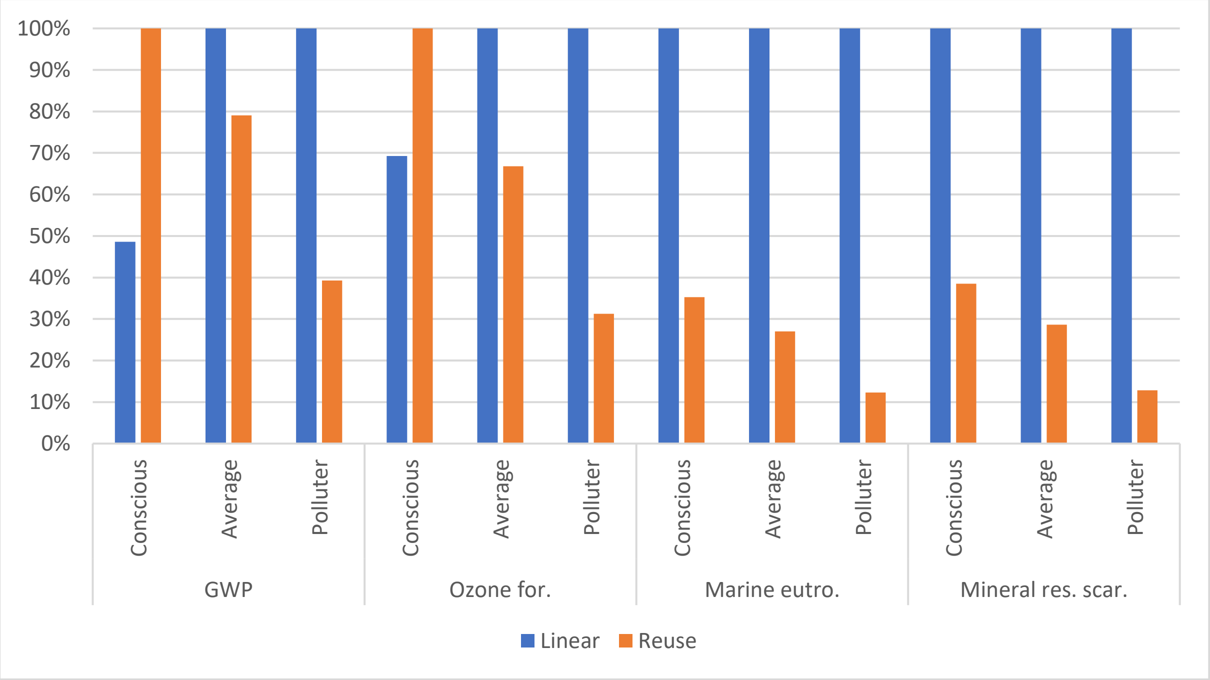

Figure 20: Results of the linear and reuse consumer scenario comparison when applying the second user's perspective of economic allocation

See figure 21 for a visual representation of the comparisons between the allocation methods for each consumer scenario. The use of the second user's perspective economic allocation had an impact on the results, as it differed from system expansion in terms of the magnitude of avoided impacts. In the conscious scenario, the second user's perspective economic allocation led to fewer avoided impacts in most impact categories compared to system expansion. However, in the average and polluter scenarios, the second user’s perspective of economic allocation resulted in a higher magnitude of avoided impacts. These differences in avoided impacts between the allocation methods can be attributed to the value retention factor and the consumer profiles utilized in the reuse consumer scenarios, which represent the total use phase when employing an allocation method (as discussed in section 6.5.1.1). Under the second user's perspective of economic allocation, the secondary average consumer profile determined the total use phase, as the primary use phase was excluded (refer to Figure 17). This led to a different representation of the total use phase of the reuse system compared to system expansion, contributing to the disparities in avoided impacts between the allocation methods. Although the low-value retention factor did not outweigh the impacts due to profile differences in the conscious reuse scenario, it did contribute to lower impacts for the reuse system resulting in higher avoided impacts compared to system expansion in the average and polluter scenario.

Again, it can be concluded that the method of allocation significantly influenced the results but that by applying the second user’s perspective economic allocation reuse is not environmentally beneficial in all consumer scenarios. Similar to the study’s outcome, buying a new phone is more beneficial in the conscious scenario.

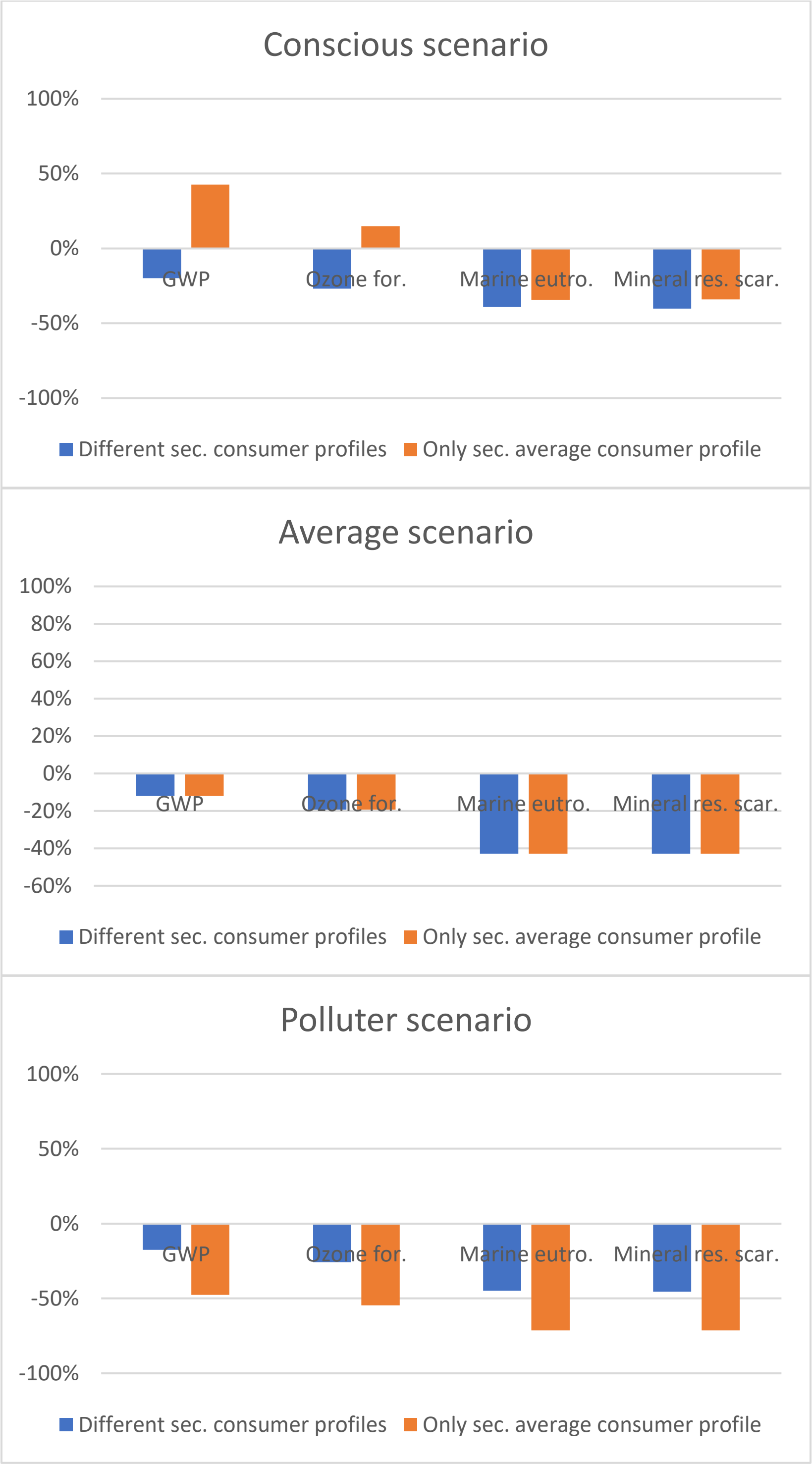

Figure 21: Differences in magnitudes of avoided impacts per scenario between applying the second user's perspective economic allocation and system expansion. A negative percentage shows that impacts are avoided due to reuse. A positive percentage shows that reuse does not lead to avoided impacts.

6.5.1.3 Economic allocation: first user’s perspective versus second user’s perspective

From a methodological standpoint, it was intriguing to observe the differences in avoided impacts when employing system expansion and economic allocation. Furthermore, it is also valuable to examine the disparities in impacts between the first and second user's perspectives of economic allocation. Consequently, a comparison was made between the results obtained from these two perspectives.

Table 32 provides the magnitude of avoided impacts per consumer scenario when applying either the first or second user’s perspective of economic allocation (see Appendix 10.10.3.1 10.10.3.1 Magnitude of avoided impacts between first and second user’s perspectivefor the magnitudes in all impact categories). The absolute values of avoided impacts (per FU) of the first and second user’s perspective of economic allocation for the different consumer scenarios in all impact categories can be found in Appendix 10.10.3.2.

Referring to table 32, it became apparent that the magnitude of avoided impacts for the average scenario from the first and second user's perspectives were relatively close to each other, with the second user's perspective yielding slightly higher avoided impacts. However, in the conscious scenario, the first user's perspective had a higher magnitude of avoided impacts across most impact categories. Conversely, in the polluter scenario, the second user's perspective generated more avoided impacts. The differences in avoided impacts per scenario between the two perspectives primarily stem from the differences in consumer profiles employed in their reuse systems to represent part of their total use phase. This was already explained in more detail in section 6.5.1.1. In summary, selling an iPhone (i.e. first user’s perspective) led to a reduction of impacts in every consumer scenario. While buying an iPhone only led to a reduction of impacts in the average and polluter consumer scenario and not in the conscious consumer scenario.

These findings emphasized the importance of considering different perspectives in economic allocation when analyzing the impacts associated with reuse consumer scenarios. Above all, it emphasized the impact on the results when applying a different allocation method.

Table 32: Magnitude of avoided impacts (per FU) per consumer scenario when applying either first or second user’s perspective economic allocation. A negative percentage shows that impacts are avoided due to reuse. A positive percentage shows that reuse does not lead to avoided impacts.

Impact category	Perspective	Conscious	Average	Polluter
Global warming	1st user	-31.36%	-17.22%	-31.46%
	2nd user	105.78%	-20.94%	-60.73%
Ozone formation	1st user	-41.44%	-27.14%	-45.28%
	2nd user	44.45%	-33.17%	-68.77%
Marine eutrophication	1st user	-59.28%	-59.44%	-77.89%
	2nd user	-64.71%	-73.02%	-87.72%
Mineral resource scarcity	1st user	-59.65%	-58.55%	-76.96%
	2nd user	-61.48%	-71.38%	-87.17%

6.5.2 Excluding network usage from the use phase

A sensitivity analysis was conducted to assess the robustness of the results by examining the network usage during the use phase. The network usage per consumer profile was based on the estimation from Cordella et al. (2021). Based on the data quality indicators used, the electricity consumption due to network usage can be seen as a process that has a high contribution to the total impacts and at the same time poor data quality (see Appendix 10.1.2.310.10.3 Excluding network usage). This made it necessary to evaluate the impact of excluding or altering the network usage as LCI input.

Previous studies on smartphones, including Güvendik (2014) and Sánchez et al. (2022) on Fairphone, did not account for the impacts of network usage in the use phase. This decision was made due to the complexities involved in boundary selection for ICT products. Instead, they focused solely on the impact of recharging the phone. Additionally, Cordella et al. (2021) presented their results both with and without network usage impacts. Hence, it was checked whether eliminating network usage from the LCI had a significant impact on the outcomes.

The sensitivity analysis revealed that excluding network usage had a substantial impact on the results. In all consumer scenarios, excluding network usage resulted in a higher magnitude of avoided impacts in every impact category (see figure 22). By excluding network usage, the use was not the largest contributor to the total impacts anymore. The production phase is then responsible for most impacts. For the absolute values of the avoided impacts for the various consumer scenarios when network usage was excluded, please refer to Appendix 10.10.3.210.10.3 Excluding network usage. The changes in avoided impacts all relate to the consumer profiles that were employed in a consumer scenario and the lower total impacts in the linear system.

The changes in avoided impacts in the conscious scenario can be attributed to network usage in the secondary average profile, which influenced the impacts of the reuse system's total use phase. The higher network usage in the secondary average profile led to higher impacts. Therefore, excluding network usage resulted in more avoided impacts and a higher magnitude of avoided impacts in the conscious consumer scenario (see figure 22).

In the average consumer scenario, the absolute values of avoided impacts did not change because the network usage of the primary and secondary average profiles in the reuse system was identical (refer to Appendix 10.10.3.2). However, the magnitude of avoided impacts increased. This is because excluding network usage also reduced impacts in the linear system, making the avoided impacts a larger proportion of the total impacts which resulted in a higher magnitude of avoided impacts.

In the polluter consumer scenario, lower absolute values of avoided impacts were observed (refer to Appendix 10.10.3.2). This is because the total use phase of the reuse system was influenced by the secondary average profile, which has lower network usage compared to the polluter profile. Consequently, excluding network usage led to lower avoided impacts in the polluter consumer scenario. However, the magnitude of avoided impacts was higher when network usage was excluded (see figure 22) because the avoided impacts constituted a larger proportion of the total impacts of the reference linear system.

Based on this sensitivity analysis it can be concluded that excluding network usage significantly influenced the results and that by excluding it, reuse is environmentally beneficial in all consumer scenarios.

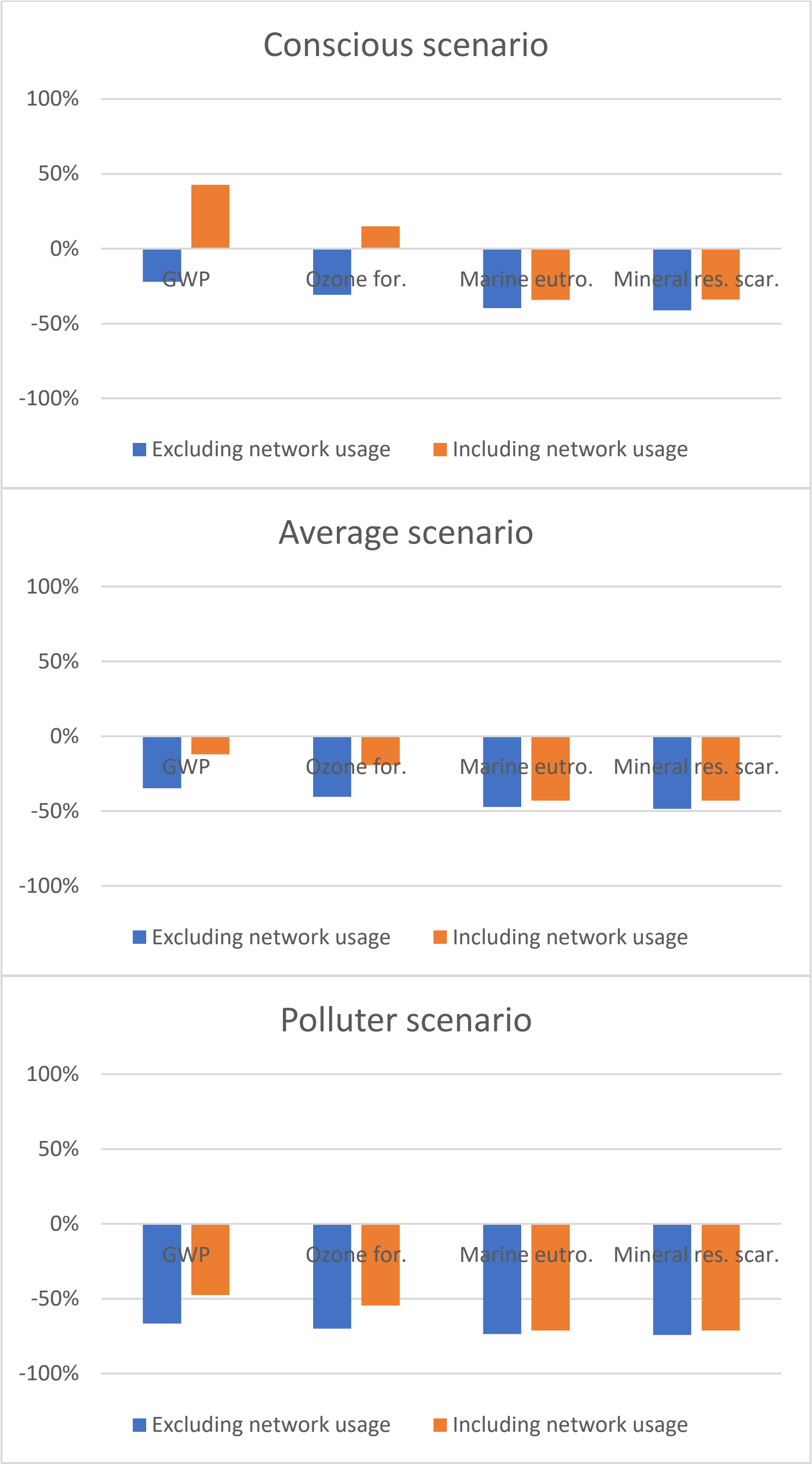

Figure 22: Results of the sensitivity analysis showing the magnitude of avoided impacts per consumer scenario between excluding and including network usage from the LCI. A negative percentage indicates avoided impacts due to reuse. A positive percentage indicates that impacts are not avoided due to reuse.

6.5.3 Employing different secondary use phase profiles

In this particular study, only one consumer profile was utilized for the secondary use phase. However, it can be argued that employing a single consumer profile might not adequately represent the second use phase. Notably, the secondary consumer profile appeared to be the primary factor contributing to the relatively low avoided impacts in the conscious scenario and the high avoided impacts in the polluter scenario. To address this concern, a sensitivity analysis was conducted specifically targeting the second use phase.

For this sensitivity analysis, the secondary user was assumed to have the same profile as the primary consumer, albeit with a battery condition of 80%. Based on this battery condition, the electricity consumption resulting from recharging was calculated. Table 33 presents the characteristics and LCI inputs per consumer profile for the sensitivity analysis.

Table 33: Characteristics and data of the consumer profiles where all primary profiles represent the first use phase (battery condition 100%) and the secondary profiles the second use phase (battery condition 80%)

	Primary			**Secondary**		
Consumer profile	Polluter	Average	Conscious	Polluter	Average	Conscious
Functional lifetime (years)	1	3	4	1	3	3
Intensity of use (hours/day)	7	4	1	7	4	1
Battery condition	100%	100%	100%	80%	80%	80%
Recharging cycles per year	478.15	273.75	65.70	502.95	287.40	71.85
Electricity usage per recharging cycle (kWh)	0.01	0.01	0.01	0.01	0.01	0.01
Recharge electricity usage per year (kWh)	6.96	3.98	0.96	7.32	4.18	1.05
Network usage per year (kWh)	55.70	31.89	7.96	55.70	31.89	7.96
Total electricity consumption per year (kWh)	62.66	35.87	8.92	63.02	36.07	9.01

In each reuse scenario, both the first and second use phases now involve the same consumer profile, differing only in the electricity consumption for recharge due to varying battery conditions. However, the utilization of different secondary consumer profiles resulted in distinct inventory inputs per FU across the reuse scenarios. See table 34 for the specific inventory inputs used for this sensitivity analysis. It is important to note that the inventory inputs for the reuse consumer scenarios differ due to the varying durations of use during the second use phase. However, since the maximum functional lifetime in the study was 7 years (conscious reuse scenario), this was also used as the maximum lifetime in this sensitivity analysis. Hence, in the conscious reuse scenario, the functional lifetime is not 8, but 7 years. The inventory inputs for the linear consumer scenarios remained unchanged and are not presented in this section. For detailed information regarding the linear scenarios' LCI input, please refer to section 5.6.

Table 34: LCI input (per FU) for the sensitivity analysis on the second use phase in which the second use phase has the same profile (except for its electricity consumption due to recharge) as in its primary use phase

	Conscious	**Average**	**Polluter**
Production (#)	1/7	1/6	½
Distribution (#)	1/7	1/6	½
First use phase (years)	4/7	1/2	½
Mobimarket (#)	1/7	1/6	½
Second use phase (years)	3/7	1/2	½

Through a comparison of each linear and reuse consumer scenario, the avoided impacts were determined. Appendix 10.10.4.2 provides the absolute values of the impacts for each consumer scenario per impact category. The magnitude of these avoided impacts was compared to the magnitude of avoided impacts previously derived in this study, where solely the secondary average profile was employed to represent the second use phase in the reuse systems.

Figure 23 illustrates the comparisons between the magnitude of avoided impacts. The figure revealed that the changes in the magnitude of avoided impacts occurred specifically in the conscious and polluter scenarios, while no changes occurred in the average consumer scenario due to the unchanged inventory input employed for the average consumer scenario comparison.

The sensitivity analysis for the polluter scenario demonstrated that utilizing a secondary polluter profile resulted in a lower magnitude of avoided impacts than when the secondary average profile was employed (see figure 23). The secondary average profile was responsible for the low impacts observed in the reuse system in the polluter reuse scenario. Therefore, replacing it with the secondary polluter profile created more impacts in the reuse system and resulted in lower avoided impacts.

This sensitivity analysis showed positive absolute values for the avoided impacts for all impact categories in the conscious scenario (see Appendix 10.10.4.2) and a higher magnitude of avoided impacts (see figure 23). Therefore, it was discovered that in the conscious scenario comparison employing a secondary conscious profile in the reuse system led to higher avoided impacts compared to using the secondary average profile. The absolute value of the reuse conscious scenario is 5.11 kg CO_2/year, which is the lowest amount of GHG emissions found in this study. This led to the conclusion that reuse is beneficial in all consumer scenarios and that the best consumer scenario is the reuse conscious scenario that has both in its primary and secondary use phase a conscious consumer type.

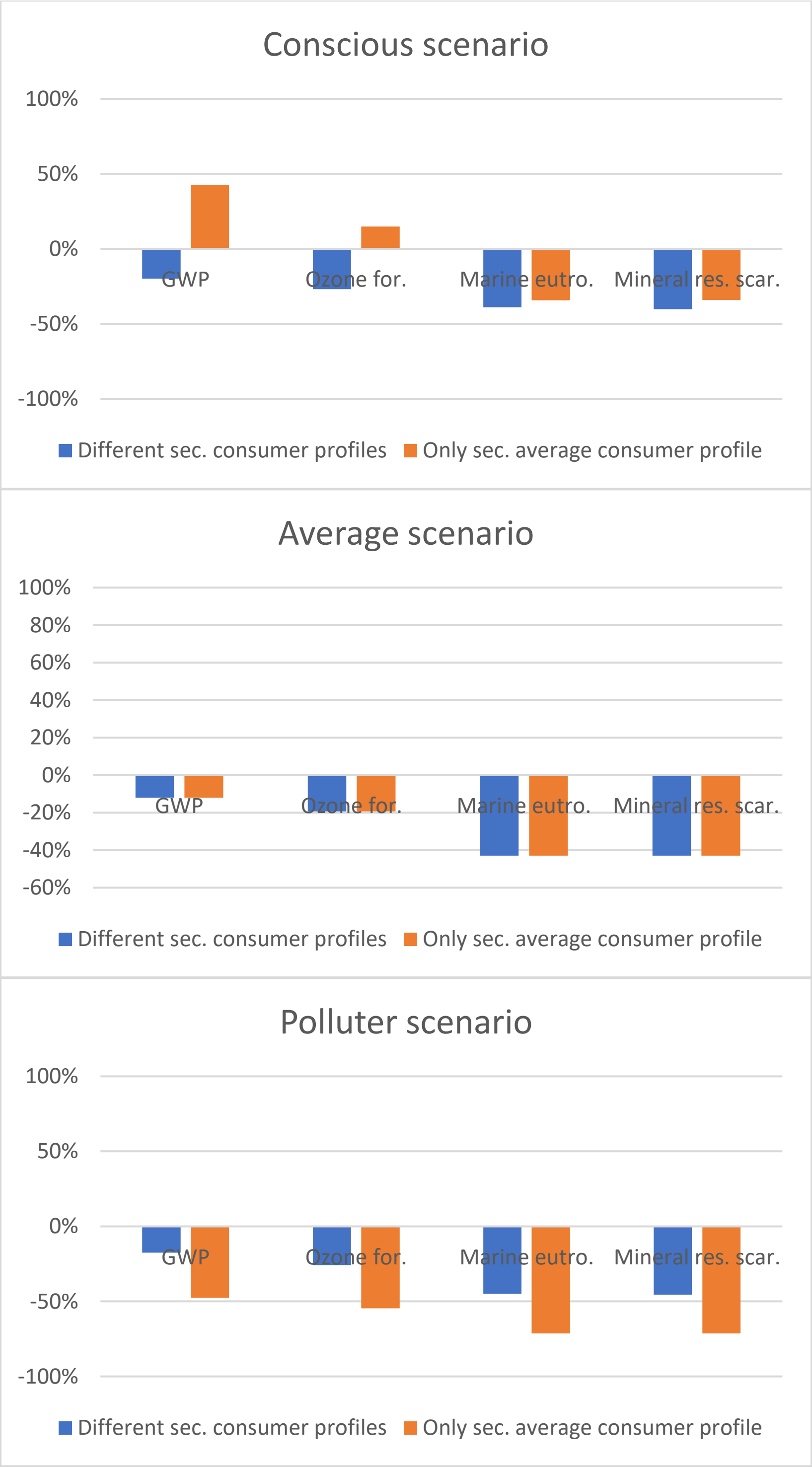

Figure 23: Results of the sensitivity analysis showing the magnitude of avoided impacts between the results of using only the secondary average consumer profile and using different secondary consumer profiles (conscious, average, polluter) to represent the second use phase. A negative percentage indicates avoided impacts due to reuse. A positive percentage indicates that impacts are not avoided due to reuse.

6.5.4 Shorter functional lifetime during the second use phase

In this particular study, the secondary use phase was based on a single consumer profile, namely the secondary average profile, with an assumed functional lifetime of 3 years. Consequently, all scenarios included a 3-year duration for the second use phase. However, it is worth considering that this 3-year duration may not always be applicable for a phone's second life, especially when the phone has already been extensively used during its primary life. Therefore, a sensitivity analysis was conducted to assess the robustness of the results by changing the functional lifetime of the second use phase.

Similar to the main study, the secondary average profile was utilized to represent the second use phase in the sensitivity analysis. However, this profile was modified to incorporate a functional lifetime of 1 year. Consequently, this adjustment led to changes in the LCI inputs for the reuse consumer scenarios, reflecting the altered functional lifetime.

6.5.4.1 Second use phase: one year of use

In the sensitivity analysis, a functional lifetime of 1 year in the second use phase was assumed. Based on this functional lifetime the LCI input for the reuse scenarios was adjusted (see table 35). The inventory input for the linear consumer scenarios remained the same (see section 5.6).

Table 35: LCI input (per FU) and assumed lifetime for the sensitivity analysis on the second use phase in which the second use phase has a shorter functional lifetime (1 year) but only the secondary average profile represents the second use phase

	Conscious	**Average**	**Polluter**
Production (#)	1/5	¼	½
Distribution (#)	1/5	¼	½
First use phase (years)	4/5	¾	½
Mobimarket (#)	1/5	¼	½
Second use phase (years)	1/5	1/4	1/2
Total assumed lifetime (years)	5	4	2

In Appendix 10.10.5.2, the absolute values of impacts per impact category are presented when the second use phase consists of 1 year of use. Figure 24 exhibits the difference in the magnitude of avoided impacts between the functional lifetime previously used in the study (3 years) compared to the sensitivity analysis (1 year).

The figure shows that the change in functional lifetime influences the results in all consumer scenarios. In all scenarios, it was observed that a shorter functional lifetime significantly influenced the impacts categories (marine eutrophication and mineral resource scarcity) that relate to the production phase. The longer a phone is used the higher the magnitude of avoided impacts in these impact categories because the production of a new phone is then avoided.

For the conscious scenario, impacts were not avoided through reuse in most impact categories but the positive magnitudes were lower in most impact categories (see Appendix 10.10.5.1). This means reuse led to fewer impacts when a phone is used in its second use phase for 1 year than when the phone is used in its second use phase for 3 years. This difference in avoided impacts in the conscious scenario can be attributed to the high contribution of impacts of the secondary average profile in its reuse system. This contribution of impacts became less when it is used shorter in its second use phase.

One year of second use resulted in a lower magnitude of avoided impacts for the average and polluter consumer scenarios. Therefore, it is environmentally beneficial when the phone is used longer in its second use phase in the average and polluter scenario. However, in the conscious scenario, it is environmentally beneficial to use the phone shorter in its second life or it is even better to buy a new phone instead of reusing it. Overall, it shows that reuse is not beneficial in the conscious scenario.

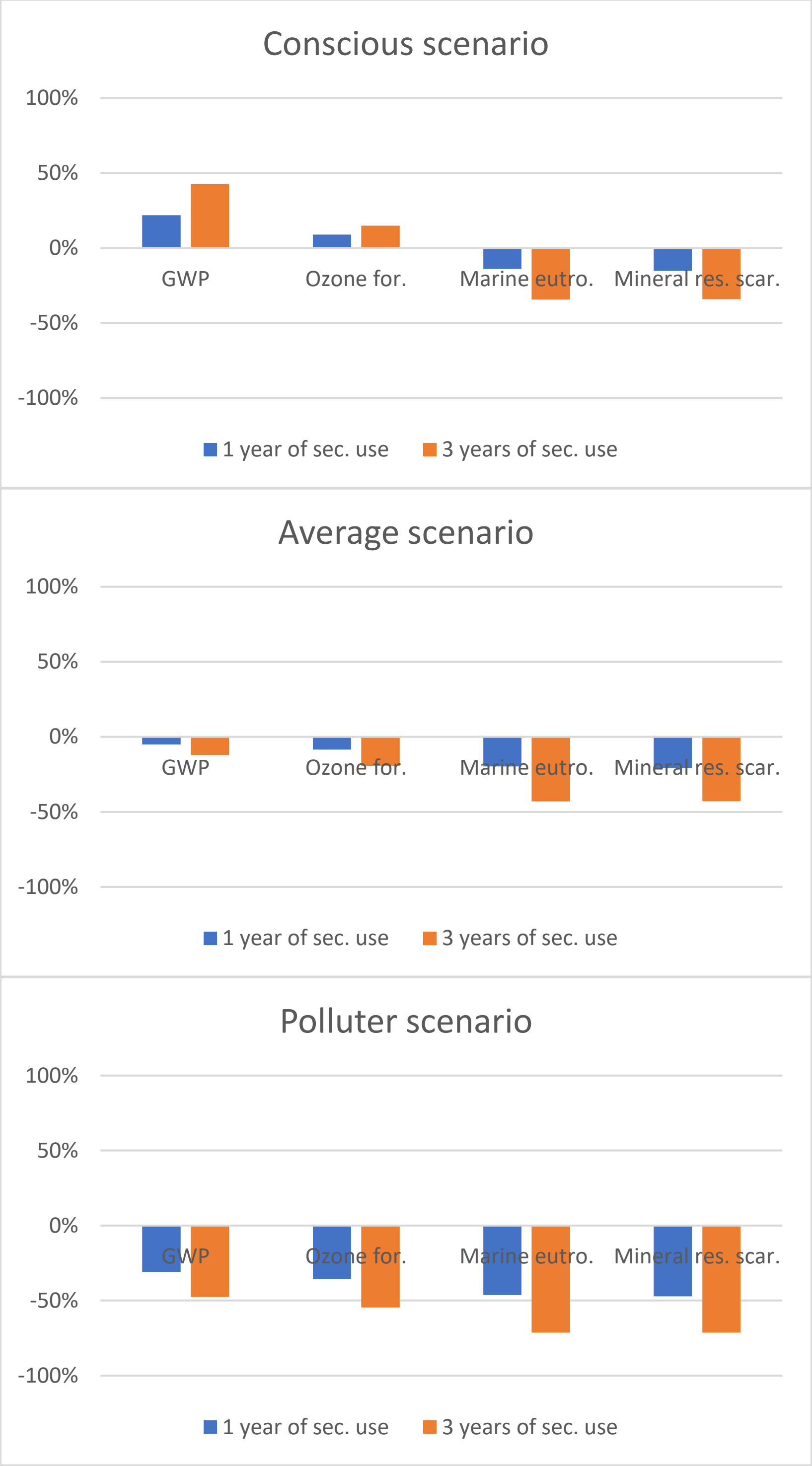

Figure 24: Results of the sensitivity analysis showing the change in magnitude of avoided impacts between using 3 years of secondary use and 1 year of secondary use. A positive percentage indicates avoided impacts due to reuse. A negative percentage indicates that impacts are not avoided due to reuse.

7. Discussion

The discussion is organized into three distinct sections. Firstly, an in-depth examination and comparison of the study's findings with existing literature will be conducted. Secondly, a comprehensive analysis of the advantages and disadvantages associated with various allocation methods will be undertaken. And thirdly, noteworthy limitations of the study will be emphasized.

7.1 Results

This study highlights the presence of LCAs that compare smartphone reuse to a linear reference scenario in the literature. However, most of these studies focus on a single impact category, primarily "global warming potential" (Cordella et al., 2021; Canetta et al., 2018; Suckling et al., 2015), with one study also considering "non-renewable, cumulative energy demand" (Hischier et al., 2021). Although these categories provide insight into electricity and heat usage throughout the life cycle stages, they do not encompass impacts from other environmental processes. Consequently, the interpretation of these studies' results remains robust but challenging to compare across different impact categories. For instance, in this study, the production phase significantly contributes to marine eutrophication and mineral resource scarcity (Figures 5, 10, and 12). The substantial impacts of the production phase in these categories stem from the iPhone's component manufacturing, causing nutrient pollution and depleting non-renewable minerals. This demonstrates that considering multiple impact categories offers a comprehensive understanding of life cycle stage impacts. However, a minimal deviation is expected to be found with the other studies as the components responsible for the significant impacts are present in most smartphones.

Previous LCAs on smartphones have suggested that the production phase is the primary contributor to overall impacts (Sánchez et al., 2022; Güvendik, 2014). However, these studies did not consider network usage during the use phase. In contrast, studies that account for network usage reveal that the use phase plays a significant role (Cordella et al., 2021; Suckling et al., 2015; Ecran et al., 2016). Based on the contribution analysis, this study confirms the dominance of the use phase in most impact categories (six out of nine) based on overall life cycle impacts (figures 5, 10, and 12). Network usage is the primary driver during the use phase (figure 8).

Based on the GHG emissions of all linear and reuse consumer scenarios analyzed, a ranking was established in this study. Refer to table 36 for the ranking based on absolute GHG emission values per consumer scenario. This summary of consumer scenarios demonstrates the consumer scenario with the least and greatest environmental impact in the global warming impact category, revealing that certain changes in parameters result in different absolute values of GHG emissions. Notably, when network usage was excluded from the LCI, the lowest GHG emission values were observed. This finding aligns with existing literature (Cordella et al., 2021; Suckling et al., 2015; Ecran et al., 2016), which also indicates that network usage is a significant contributor to the overall global warming impacts. Therefore, excluding it from the LCI allowed for the identification of scenarios with the lowest GHG emissions.

In the baseline scenario (i.e. linear average), the total impacts found in the global warming impact category was 16.77 kg CO_2-eq/yr, which aligns with Cordella et al.'s (2021) study that found 18.97 kg CO_2-eq/yr. However, Suckling et al. (2015) reported nearly twice the impacts (30 kg CO_2-eq/yr), while Ecran et al. (2016) showed nearly four times higher impacts (60 kg CO_2-eq/yr) compared to the baseline scenario. Suckling's study, representing heavy users, can be compared to this study's linear polluter scenario (34.83 kg CO_2-eq/yr), as they have similar impacts. Ecran et al.'s (2016) total impacts do not correspond to any of this study's consumer scenarios due to higher network usage assumptions for its average scenario and a larger contribution from the production phase (almost 50%), with nearly 70% of its production impacts attributed to Integrated Circuit production. In contrast, this study attributes around 20% of its production impacts to Integrated Circuit production and employs different modeling approaches such as using ecoinvent datasets, diverging from Ecran's use of GaBi datasets. Studies using similar datasets, such as Cordella (2021) and Güvendik (2014), report similar impacts regarding IC production. Therefore, it is important to consider that absolute results may vary across studies due to design characteristics, user behavior, system aspects, modeling approaches, assumptions, and data sources utilized.

The production phase significantly influences the total life cycle impact, particularly when network usage is not considered. In this study, the production phase's global warming potential ranges from 2.98 to 11.92 kg CO_2-eq/yr, depending on the consumer scenario (conscious, average, or polluter). Comparing impacts across studies is challenging due to variations in smartphone characteristics, quantities, scopes, and methodologies used. Nonetheless, this study's findings can be considered as falling within the range reported in the literature (3.7 to 18.96 kg CO_2-eq/yr) (Güvendik, 2014; Cordella et al., 2021; Sánchez et al., 2022; Suckling et al., 2015; Ecran et al., 2016; Apple, 2019b), indicating a reasonable level of certainty.

An examination of the components responsible for the majority of emissions in the production phase revealed that the manufacturing of the printed wiring board, display, and integrated circuit plays a significant role (see figure 7). These findings align with previous studies (Cordella et al., 2021; Sánchez et al., 2022; Güvendik, 2014; Ecran et al., 2016), which consistently highlight the printed wiring boards and integrated circuits as major contributors. The impact of the display varies since different smartphone models use different screen types, resulting in varying emissions.

Studies on smartphone reuse did not consider different consumer scenarios corresponding to various types of smartphone users. Instead, these studies used average values to address the use phase in the LCA. Without comparable studies examining the effects of smartphone reuse across different consumer scenarios, it is challenging to assess the avoided impacts for each scenario. However, some LCAs on the overall product life cycle of smartphones, from production to disposal (linear system), did incorporate different consumer scenarios. This allows for a comparison of the impacts among different consumer types in a linear system. This study revealed that, in terms of the global warming category, the conscious scenario generates the lowest emissions, followed by the average and polluter scenarios. However, the distribution of emissions across the life cycle stages varies depending on the scenario. Ecran et al. (2016) and Sánchez et al. (2022) present similar findings, with the consumer characterized by the longest functional lifetime and lowest usage intensity having the lowest impacts, followed by the representative (average) and high (polluter) usage scenarios. Sánchez et al. (2022) visually represent the impacts per year of use for different life cycle stages in each consumer scenario within the global warming category. While the production, transport, and EoL impacts change according to the consumer scenario's functional lifetime, the impacts of the use phase remain the same in all scenarios. This is because Sánchez et al. (2022) do not vary the usage intensity per scenario, only the functional lifetime. Based on these observations, it can be concluded that increasing the functional lifetime reduces total impacts in a linear system. However, drawing further conclusions is challenging due to the inability to directly compare the results and the lack of LCAs that include consumer scenarios in a reuse system.

Table 36: Ranking of all consumer scenarios considered in this study based on their total GHG emissions." –" = no parameter change was applied. In all consumer scenarios, system expansion was applied unless it says "economic allocation" as the parameter of change.

Ranking	**Consumer scenario**			**GHG emissions (kg CO2-eq/yr)**	**Parameter of change**
	Primary profile	Secondary profile	Linear/reuse		
1	Conscious	Average	Reuse	2.83	Network usage excluded from LCI
2	Conscious	-	Linear	3.64	Network usage excluded from LCI
3	Average	Average	Reuse	3.77	Network usage excluded from LCI
4	Conscious	Average	Reuse	4.38	Economic allocation - 1st user perspective
5	Conscious	Average	Reuse	5.11	Second use phase 1 year
6	Conscious	Conscious	Reuse	5.11	Same secondary consumer profile as primary profile
7	Polluter	Average	Reuse	5.23	Network usage excluded from LCI
8	Average	-	Linear	5.79	Network usage excluded from LCI
9	Conscious	-	Linear	6.38	-
10	Conscious	Average	Reuse	9.11	-
11	Conscious	Average	Reuse	13.14	Economic allocation - 2nd user perspective
12	Average	Average	Reuse	13.26	Economic allocation - second user
13	Polluter	Average	Reuse	13.68	Economic allocation - second user
14	Average	Average	Reuse	13.88	Economic allocation - 1st user perspective
15	Average	Average	Reuse	14.75	Second use phase 1 year
16	Average	Average	Reuse	14.75	-
17	Polluter	-	Linear	15.65	Network usage excluded from LCI
18	Average	-	Linear	16.77	-
19	Polluter	Average	Reuse	18.26	-
20	Polluter	Average	Reuse	23.87	Economic allocation - 1st user perspective
21	Polluter	Average	Reuse	28.74	Second use phase 1 year
22	Polluter	Polluter	Reuse	28.74	Same secondary consumer profile as primary profile
23	Polluter	-	Linear	34.83	-

7.2 Allocation

The LCA methodology was initially designed to assess product system impacts from cradle to grave. However, as circularity gains prominence, defining absolute cradle and grave boundaries becomes less clear. To deal with the sharing of burdens and credits between first and second use, LCA guidelines recommend using system expansion to prevent allocation. This approach considers the entire system, evaluating if extending product lifetimes outweighs additional processing impacts. Results provide insights into potential impact savings or additions, informing decisions on supporting reuse.

This study deals with primary and secondary consumers. An individual that sells the phone and one that buys the phone. Based on the goal of this study, both need to be informed about the impacts that can be saved by choosing to sell or buy a second-hand phone. As used in this study, system expansion sets the system boundaries from cradle to grave and determines the impacts on multiple consumers. Although it enables to inform both consumers (primary and secondary) about the environmental benefit of reuse, it does not tell the personal footprint of buying a new phone and then selling it or buying a second-hand phone. When a distinction between the multiple lives of a product is wanted, different system boundaries have to be set, which creates difficulty in allocation. Still, it could be argued that it properly informs the different consumers on saved impacts. The different ways of dealing with the multiple lives in an absolute cradle-to-grave setting mean different FUs have to be used. For example, how should the impacts of the production phase be allocated when a distinction is made between the first and second users?

Economic allocation based on value retention after the first life can be considered as an allocation method to take the first and second user's perspectives determining the impacts of two users (seller and buyer). The value of an iPhone diminishes based on its perceived second-hand quality and time of primary use, which differs per individual. This makes it difficult to determine the value retention. Hence it can be debated whether economic allocation best represents the relation between the first and second life of an iPhone. Whether system expansion or value retention is used, the way the shared burdens are allocated between the different consumers will always be influential for the results.

When employing economic allocation, the avoided impacts per consumer scenario differ significantly depending on the user's perspective taken. Hence, a seller can be informed that giving his/her phone a second life is environmentally beneficial, while for the buyer that purchases this phone, it could result in no avoided impacts compared to buying a new phone. For example, from the seller's perspective impacts are always avoided in a conscious scenario. However, from the buyer's perspective buying the phone from a conscious person leads to more impacts than when buying a new phone because the phone is used for a long duration which outweighs the impacts considered from reuse. In other words, taking different perspectives could be tampered with to make reuse always look good from the different perspectives. The study chose system expansion to avoid allocating impacts based on a perceived secondhand quality and prevent only looking at the most favorable outcomes. System expansion provides Twig, the most "fair" view of the whole system (for both perspectives) on avoided impacts due to reuse. The strength of this study lies in the aggregation and averaging at the product level to inform Twig's customers about avoided impacts due to reuse. System expansion provides this aggregated view of the first and second product life cycles.

7.3 Limitations

In executing this study, it is important to acknowledge that multiple limitations were encountered. First of all, this research encounters some limitations in modeling the production of the iPhone. In this particular study, the LCI data for the production phase is based on secondary data obtained from other LCAs and from various smartphone brands since Apple does not disclose this information. This reliance on external data sources can introduce several potential limitations to the study. Within the production phase of smartphones, there is variability in production processes and materials or components used. Each smartphone brand may employ unique production processes, components, technologies, and supply chains. Relying on secondary data from other studies and brands might not accurately capture the specific production practices and materials or resources utilized associated with iPhone production. As a result, the LCI data used for the production phase may not precisely represent the actual environmental impacts of iPhone production.

Secondly, the study does not account for social impacts related to human well-being, labor conditions, community engagement, and other social dimensions as it focuses on environmental impacts. The production of iPhones involves complex global supply chains that often span multiple countries. This can lead to concerns regarding fair wages, working hours, worker health and safety, and labor rights. Neglecting to address these social aspects may overlook potential human rights abuses and worker exploitation that can occur within the iPhone's life cycle. Also, inadequate iPhone disposal can result in issues that affect the health and well-being of people, especially in regions with inadequate infrastructure for e-waste management.

Thirdly, the study encounters some limitations regarding the modeling of consumer behavior. Although the study attempts to take into account different types of consumers, the consumer scenarios are based on secondary data rather than primary data and do not account for shares of the population and purchase intentions towards second-hand iPhones, which can impact the accuracy and relevancy of the findings. By obtaining primary data on consumer behavior, such as surveys or interviews, the study can capture the actual shares of the population representing different consumer types. Also, behaviors such as leaving the charger plugged in without a phone attached, which leads to an environmental impact, could be assessed and included. This allows for a more accurate representation of the diverse range of consumers and their preferences towards reusing iPhones. Understanding the distribution of consumer profiles can provide insights into the potential adoption rates of second-hand phones, influencing the overall LCA results. Within the study, some data points that relate to consumer behavior, such as the functional lifetime and network usage, were more uncertain than others. These data points influence the results which could lead to different conclusions. To deal with this uncertainty a sensitivity analysis was conducted to find out the impact of these data points. Based on the sensitivity analysis a more certain interpretation of the results was provided. Furthermore, including data on consumers' willingness to purchase used iPhones can significantly impact the LCA results. Consumer attitudes, motivations, and perceived benefits or barriers associated with second-hand purchases can influence the demand for reused devices and subsequently affect the environmental implications of producing new phones. Also, rebound effects could be a consequence of the purchase of a second-hand phone causing less environmental benefits due to reuse than expected. By understanding consumer preferences for second-hand devices and potential rebound effects, the LCA can capture more accurately the potential environmental benefits associated with extending the device's life and minimizing electronic waste generation.

8. Conclusion

The study looked into the question *what is the environmental impact of reusing an iPhone through Twig's business model*? The study showed that reusing iPhones through Twig's business model can indeed mitigate an iPhone's environmental footprint, but the magnitude of this reduction depends on the specific consumer scenarios considered. Different consumer scenarios were analyzed, taking into account the various impacts during the use phase, particularly those stemming from network usage and recharging. Additionally, the duration of phone use varied across scenarios. Essentially, when an iPhone is reused, it diminishes the need for the production of new iPhones, which can quickly offset the additional impacts associated with processing for its second life. However, the extent of this offsetting effect hinges on the types of consumers involved in both the primary and secondary use phases.

Employing system expansion analysis, it was observed from the life cycle impact assessment (in section 6.4) that in the "conscious" consumer scenario reuse creates 42.64% more GHG emissions than its reference linear scenario in the global warming impact category. The "average" scenario showed that reuse results in 12.02% less GHG emissions compared to its linear reference scenario, while in the "polluter" scenario reuse led to 47.57% less GHG emissions compared to its linear reference scenario. The outcome for the conscious scenario was primarily driven by the assumption that in the reuse system, an average consumer type uses the phone in the second use phase instead of a conscious consumer type. Since the average consumer consumes significantly more electricity in terms of network usage, no avoided impacts for reuse were observed.

Theoretically, a conscious consumer should not resell their iPhone unless it is also used by a conscious consumer in its second use phase or used for only one year in its second use phase as can be learned from the sensitivity analyzes (in section 6.5.3 and 6.5.4). If it is resold to a conscious consumer or only used for one year in the second use phase, it is the ideal combination of consumer types (when system expansion is employed and network usage is included) because the lowest absolute values of GHG emissions were found for these consumer scenarios compared to all other scenarios (see table 36). However, practically this is not possible. The individual that sells the phone cannot decide to whom to sell the phone and it remains uncertain how the second user will use the phone. Therefore, for a conscious individual, it makes more sense to buy a new phone and use it for as long as possible instead of engaging in second-hand apps. For an average and polluter individual, it is recommended to always sell their phone for second use because this leads to lower GHG emissions than buying a new phone (see table 36).

When a phone is reused by the same consumer type in its second use phase as in its primary use phase, impacts are also avoided in the conscious consumer scenario. This underscores the significant impact of employing different consumer types in the second use phase of a phone. Furthermore, from the results of the sensitivity analysis (in section 6.5.4.1), it was learned that the shorter the duration of the iPhone's second use phase, the lower the avoided impacts across all impact categories. To increase the duration of use, measures such as making phones more modular, which facilitates component replacement can be undertaken. This also reduces the actions needed to give a phone a second life which leads to lower environmental impacts (see figure 13).

Within this study, it is important to acknowledge the significant influence of the production phase as well. The materials and manufacturing processes of a few components play a crucial role in the overall impacts during production leading to the production phase creating a majority of the impacts in freshwater eutrophication, marine eutrophication, and mineral resource scarcity (see section 6.1.1). Reusing iPhones requires less production, resulting in reduced impacts from production within these categories and therefore contributes to the stark difference in impacts between the linear and reuse systems within these impact categories. As a phone undergoes multiple cycles of reuse, the need for production decreases further, consequently amplifying the avoided impacts in these categories. To mitigate the impacts stemming from the production phase, one potential strategy is to incorporate reused or recycled materials in the manufacturing of components and accessories. By adopting such practices, the overall impacts originating from production can be diminished.

The findings of this study emphasize the substantial influence of the use phase on the environmental impacts associated with smartphone reuse, primarily driven by the duration of use and consumer-specific electricity consumption patterns (see section 6.3). Consequently, it highlights the criticality of comprehending consumer behavior, as it can significantly shape the outcomes of such analyses. Therefore, a comprehensive consumer study encompassing a large sample size becomes imperative. For this consumer study, it is of particular importance to focus on capturing the network usage of consumers since this significantly influences LCA results. It is also crucial to better understand how intensive and how long consumers use their smartphones, as well as how consumer behavior evolves in relation to smartphone reuse, as this may influence consumer demands and preferences. Exploring these dynamics and capturing differences in consumer behavior will enhance the understanding and inform the development of strategies and policies that promote sustainable consumption patterns and maximize the benefits of product reuse.

In societal terms, the findings of this study are useful to raise awareness about the environmental benefits of reuse. It helps individuals understand the positive impact of their actions and encourages responsible consumer behavior. By highlighting the environmental advantages of reusing smartphones, society can be motivated to participate in reuse programs, extend product lifespans, and reduce electronic waste generation. Governments and regulatory bodies can use the data to establish standards, incentives, and frameworks that encourage and incentivize reuse practices. Additionally, the study raises awareness of the significant impacts associated with smartphone usage. The electricity consumed during network usage plays a substantial role in the overall environmental footprint of a smartphone. By increasing consciousness about these effects, smartphone usage patterns can be potentially altered. From a policy standpoint, this data holds the potential to incentivize or discourage specific behaviors and ultimately decrease electricity consumption associated with network usage.

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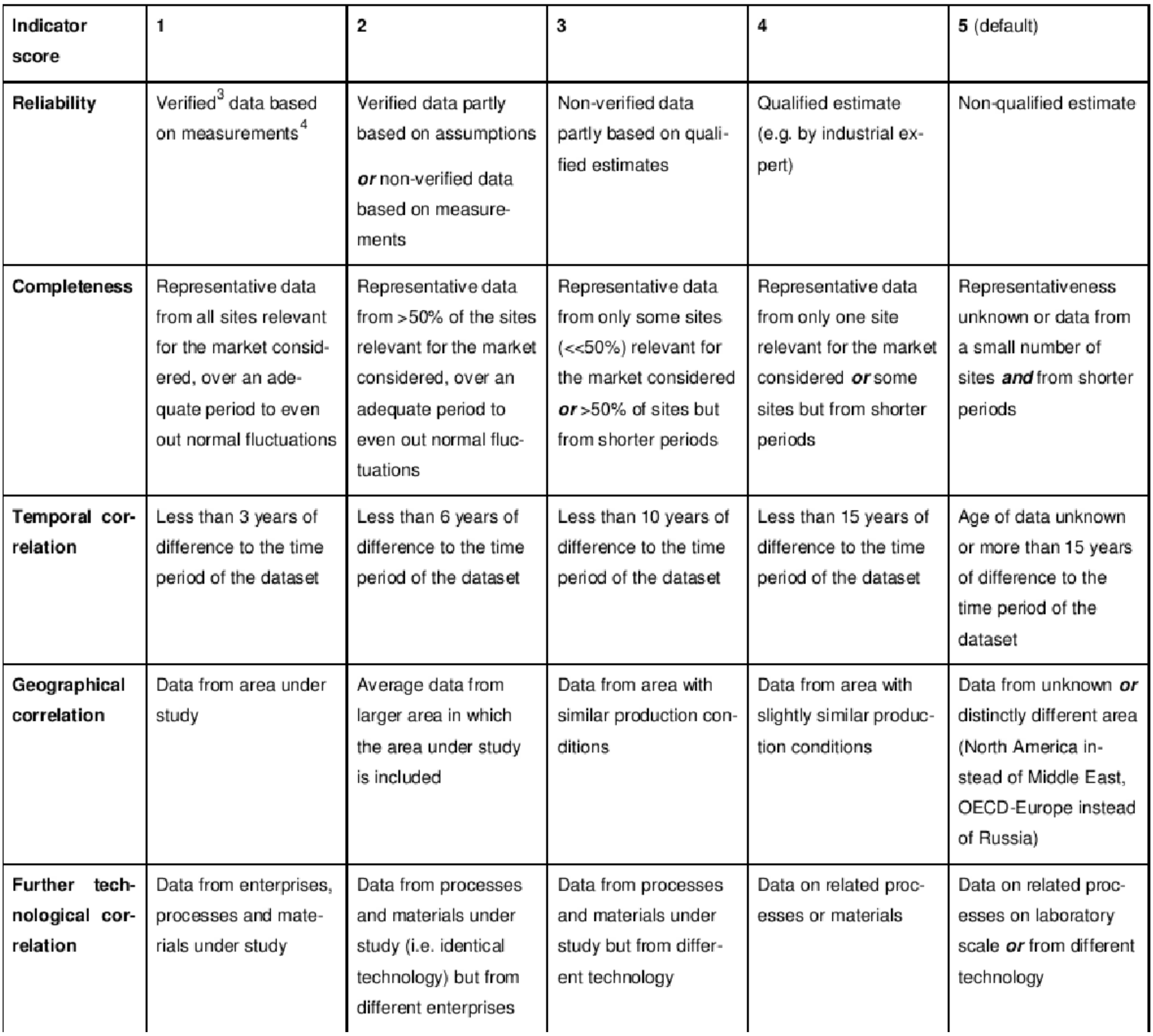
10.Appendix

10.1 Data quality indicators

10.1.1 Pedigree matrix

The table below shows the pedigree matrix that is used to assign a score on the different aspects to check how well the data used represents the different processes in the life cycle stages. Source for pedigree matrix: Ciroth et al. (2016)



Indicator score	**1**	**2**	**3**	**4**	**5** (default)
Reliability	Verified[3] data based on measurements[4]	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods	Representativeness unknown or data from a small number of sites ***and*** from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

10.1.2 Data quality indicators per life cycle stage

Based on the Pedigree matrix, data quality indicators are assigned to the different processes in a life cycle stage to show to what extent the data represents the modeled process. The indicators show the reliability, completeness, temporal correlation, geographical correlation and technological correlation in order to spot processes that have high environmental impacts and poor data quality.

10.1.2.1 Production phase

Per process taking place in the production phase, the tables below show the data quality indicators for the data used to represent these processes.

Manufacturing of components

No.	Main component	Sub-components	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation	Average indicator
1	Liquid Crystal Display (LCD)	1.1 Flexible printed Circuit	4	4	3	2	2	3
		1.2 Flexible Printed circuit	4	4	3	2	2	3
		1.3 LCD screen (LED Backlit)	4	4	3	2	2	3
		1.4 Plastic	4	4	3	2	2	3
		1.5 Shell	4	3	3	2	4	3.2
		1.6 (White) LEDs	4	4	3	2	2	3
		1.7 IC	4	4	3	2	2	3
2	Battery	2.1 Li-ion Battery	2	3	3	2	2	2.4
3	Casing	3.1 Shell/frame	4	3	3	2	4	3.2
		3.2 Front housing	4	3	3	2	4	3.2
		3.3 Back housing	4	3	3	2	4	3.2
4	Camera, vibrator, speaker & microphone	4.1 Front camera	4	5	3	5	4	4.2
		4.2 Vibration motor	4	5	3	5	4	4.2
		4.3 Camera	4	5	3	5	4	4.2
		4.4 Speaker	4	5	3	5	4	4.2
		4.5 Microphone	4	5	3	5	4	4.2

5	Printed circuit boards	5.1 Mainboard	4	4	3	2	2	3
		5.2 Daughter board	4	4	3	2	2	3
6	Integrated Circuits	6.1 IC, memory	4	4	3	2	2	3
		6.2 IC, logic	4	4	3	2	2	3
7	Capacitors, Diodes, Varistors & Transistors	7.1 Diodes	4	4	3	2	2	3
		7.2 Varistors	4	4	3	2	2	3
		7.3 Transistors	4	4	3	2	2	3
		7.4 Capacitor	4	4	3	2	2	3
		7.5 Tantalum capacitor	4	4	3	2	2	3
		7.6 Surface acoustic wave (S.A.W.)	4	4	3	2	2	3
8	Others	8.1 Battery Cap	4	4	3	2	2	3
		8.2 PCB Covers	4	4	3	2	2	3
		8.3 Simcard Holder	4	4	3	2	2	3
		8.4 CT oils	4	4	3	2	2	3
		8.5 Magnetic bead	4	4	3	2	2	3
		8.6 Unspecified	4	5	3	5	4	4.2
		8.7 Cable	4	4	3	2	2	3
		8.8 Screws	4	3	3	2	4	3.2
		8.9 Copper coil	4	4	3	2	2	3
		8.10 Connectors	4	4		2	2	2.4
		8.11 Thin film	4	4	3	2	2	3
		8.12 Plastic tape	4	4	3	2	2	3
		8.13 Net	4	4	3	2	2	3
		8.14 Plastic pieces	4	4	3	2	2	3
		8.15 Sensors: Face ID,	4	5	3	5	4	4.2

	proximity, barometer, three-axis gyroscope, ultra-wideband chip

Manufacturing of accessories

	Rigid box	Plastic (protective film)	Charging cable	Sim ejector tool
Reliability	2	3	3	3
Completeness	2	3	4	4
Temporal correlation	3	3	3	3
Geographical correlation	2	2	2	2
Technological correlation	1	2	2	2
Average data quality indicator	2	2.6	2.8	2.8

Transport and packaging of sub-components and accessories from manufacturing facility to assembly facility

	iPhone sub-components	Rigid box	Plastic (protective) film	Charging cable	Sim ejector tool
Reliability	3	3	3	3	3
Completeness	4	4	4	4	4
Temporal correlation	3	3	3	3	3
Geographical correlation	3	2	2	2	2
Technological correlation	2	2	2	2	2
Average data quality indicator	3	2.8	2.8	2.8	2.8

Assembly

	Assembly
Reliability	3
Completeness	4
Temporal correlation	3
Geographical correlation	3
Technological correlation	2
Average data quality indicator	3

10.1.2.2 Distribution

The table shows the data quality indicators for the data used that represents the distribution of the iPhone.

	Distribution
Reliability	3
Completeness	4
Temporal correlation	3
Geographical correlation	2
Technological correlation	2
Average data quality indicator	2.8

10.1.2.3 Use phases: primary and secondary consumers

The table shows the data quality indicators for the data used that represents the processes during the use phase per consumer profile.

	Primary polluter		**Primary average**		**Primary conscious**		**Secondary average**	
	Network usage	Recharge	Network usage	Recharge	Network usage	Recharge	Network usage	Recharge
Reliability	4	2	4	2	4	2	4	2
Completeness	4	2	4	2	4	2	4	2
Temporal correlation	3	3	3	3	3	3	3	3
Geographical correlation	2	2	2	2	2	2	2	2
Technological correlation	4	1	4	1	4	1	4	1
Average data quality indicator	3.4	2	3.4	2	3.4	2	3.4	2

10.1.2.4 Processing for secondary life

The table shows the data quality indicators for the data used to represent a circular strategy applied by Twig.

	Directly resold	**Value-add**	**Repair**	**Remanufactured**
Reliability	2	2	3	3
Completeness	1	1	3	3
Temporal correlation	3	3	3	3
Geographical correlation	1	1	3	3
Technological correlation	1	1	4	4
Average data quality indicator	1.6	1.6	3.2	3.2

10.1.2.5 End-of-life management

The table shows the data quality indicators for how the EoL of the different components is modeled.

No.	**Main component**	**Sub-components**	**Reliability**	**Completeness**	**Temporal correlation**	**Geographical correlation**	**Technological correlation**	**Average data quality indicator**
1	Liquid Crystal Display (LCD)	1.1 Flexible printed Circuit	5	4	3	2	3	3.4
		1.2 Flexible Printed circuit	5	4	3	2	3	3.4
		1.3 LCD screen (LED Backlit)	5	4	3	2	3	3.4
		1.4 Plastic	2	4	3	2	2	2.6
		1.5 Shell	2	4	3	2	2	2.6
		1.6 (White) LEDs	5	4	3	2	3	3.4
		1.7 IC	5	4	3	2	3	3.4
2	Battery	2.1 Li-ion Battery	4	4	3	2	2	3
3	Casing	3.1 Shell/frame	2	4	3	2	2	2.6
		3.2 Front housing	2	4	3	2	2	2.6
		3.3 Back housing	2	4	3	2	2	2.6
4	Camera. vibrator. speaker & microphone	4.1 Front camera	5	4	3	2	3	3.4
		4.2 Vibration motor	5	4	3	2	3	3.4
		4.3 Camera	5	4	3	2	3	3.4
		4.4 Speaker	5	4	3	2	3	3.4
		4.5 Microphone	5	4	3	2	3	3.4
5	Printed circuit boards	5.1 Mainboard	5	4	3	2	3	3.4
		5.2 Daughter board	5	4	3	2	3	3.4

6	Integrated Circuits	6.1 IC. memory	5	4	3	2	3	3.4
		6.2 IC. logic	5	4	3	2	3	3.4
7	Capacitors, Diodes, Varistors & Transistors	7.1 Diodes	5	4	3	2	3	3.4
		7.2 Varistors	5	4	3	2	3	3.4
		7.3 Transistors	5	4	3	2	3	3.4
		7.4 Capacitor	5	4	3	2	3	3.4
		7.5 Tantalum capacitor	5	4	3	2	3	3.4
		7.6 Surface acoustic wave (S.A.W.)	5	4	3	2	3	3.4
8	Others	8.1 Battery Cap	2	4	3	2	2	2.6
		8.2 PCB Covers	2	4	3	2	2	2.6
		8.3 Simcard Holder	2	4	3	2	2	2.6
		8.4 CT oils	5	4	3	2	3	3.4
		8.5 Magnetic bead	2	4	3	2	2	2.6
		8.6 Unspecified	5	4	3	2	3	3.4
		8.7 Cable	5	4	3	2	3	3.4
		8.8 Screws	2	4	3	2	2	2.6
		8.9 Copper coil	2	4	3	2	2	2.6
		8.10 Connectors	5	4	3	2	3	3.4
		8.11 Thin film	2	4	3	2	2	2.6
		8.12 Plastic tape	2	4	3	2	2	2.6
		8.13 Net	5	4	3	2	3	3.4
		8.14 Plastic pieces	2	4	3	2	2	2.6
		8.15 Sensors: Face ID, proximity, barometer, three-axis gyroscope, ultra-wideband chip	5	4	3	2	3	3.4

10.2 Material densities for known materials of iPhone sub-components

Material densities of the corrected sub-components (*ASM Material Data Sheet*, n.d.; Omnexus, n.d.; Matweb, n.d.; Amesweb, n.d.). The table shows the material density of the iPhone components of which the material is known compared to the material densities of the respective components in the Fairphone (Güvendik, 2014).

Sub-component	iPhone material	Fairphone Material	iPhone material density (g/cm3)	Fairphone material density (g/cm3)
1.5 Shell	Aluminum	Stainless steel	2.81	7.93
3.1 Shell/frame	Aluminum	Stainless steel	2.81	7.93
3.2 Front housing	Gorilla glass	Polycarbonate	2.4	1.2
3.3 Back housing	Gorilla glass	Polycarbonate	2.4	1.2
8.8 Screws	Stainless steel	Copper	8.96	8.96

10.3 iPhone's bill of components: steps and adjustments to determine the weight per sub-component

See the Excel file (tab 10.3).

The table (see tab 10.3) shows all steps and adjustments per column that were made to create the bill of components and respective weights for the iPhone 11. The columns highlighted in light orange are cells filled with data from Güvendik (2014). The empty cells in the "material (Güvendik)" column show that the materials are the same as in the iPhone 11. The empty cells in the "percentage of weight (Güvendik)" are the ones of the LCD screen and battery, which are the only components of which the weight was known. First, the weight of the iPhone's components was determined by the percentage of the weight of that component in Güvendik's (2014) study. Next, the weight was corrected for the components of which a quantity and/or material was known. This resulted in the most right column which shows the assumed total weight per sub-component

10.4 Mobimarket: transport and packaging calculations for all inbound and internal processes

See the Excel file (tab 10.4). (**confidential**)

Calculations were made to assess all transport and packaging used for Mobimarket's inbound and internal processes. The blue columns show all transport and packaging from the seller to Mobimarket, the yellow columns show transport and packaging from Mobimarket to Company X, the green columns show transport and packaging for Company X to Mobimarket and the grey columns show the total packaging and transport that took place. These totals were used as LCI input for the "processing for secondary life" stage of the LCA.

10.5 DEFRA UK waste statistics

Packaging waste and recycling/recovery, split by material in the UK in 2020 (thousand tonnes and % rate) (*UK Statistics on Waste*, 2022)

Material	Packaging waste arising	Total recovered / recycled	Achieved recovery / recycling rate
Metal	754	594	78.8%
Paper and cardboard	5,25	3,628	69.1%
Glass	2,481	1,841	74.2%
Plastic	2,491	1,174	47.2%
Wood	1,416	600	42.4%
Other* materials	23	0	0.0%
Total (for recycling)	12,415	7,838	63.1%
Energy from Waste	z	639	5.1%
Total (for recycling and recovery)	12,415	8,477	68.3%

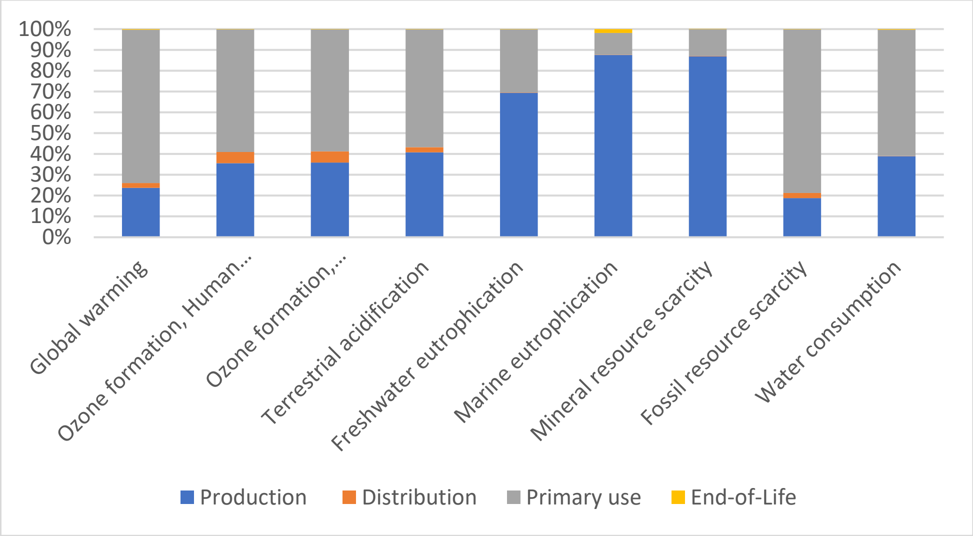
All waste at final treatment, split by method, England, 2016-18 (million tonnes) (*UK Statistics on Waste*, 2022)

Method	2016	2018
Recycling and other recovery	92.4	96.5
Incineration with energy recovery (R1)*	6.2	7.4
Incineration (excl. R1)	5.4	7.0
Backfilling	13.3	11.1
Landfill	44.7	44.1
Land treatment and release into water bodies	17.9	16.8
Total	179.9	182.8

10.6: Results: contribution analysis

10.6.1 Visualization of impacts per life cycle stage

Share of environmental impacts per impact category for every life cycle stage of the baseline scenario with respect to the total impacts of the baseline scenario



10.6.2 Absolute values of impacts per life cycle stage

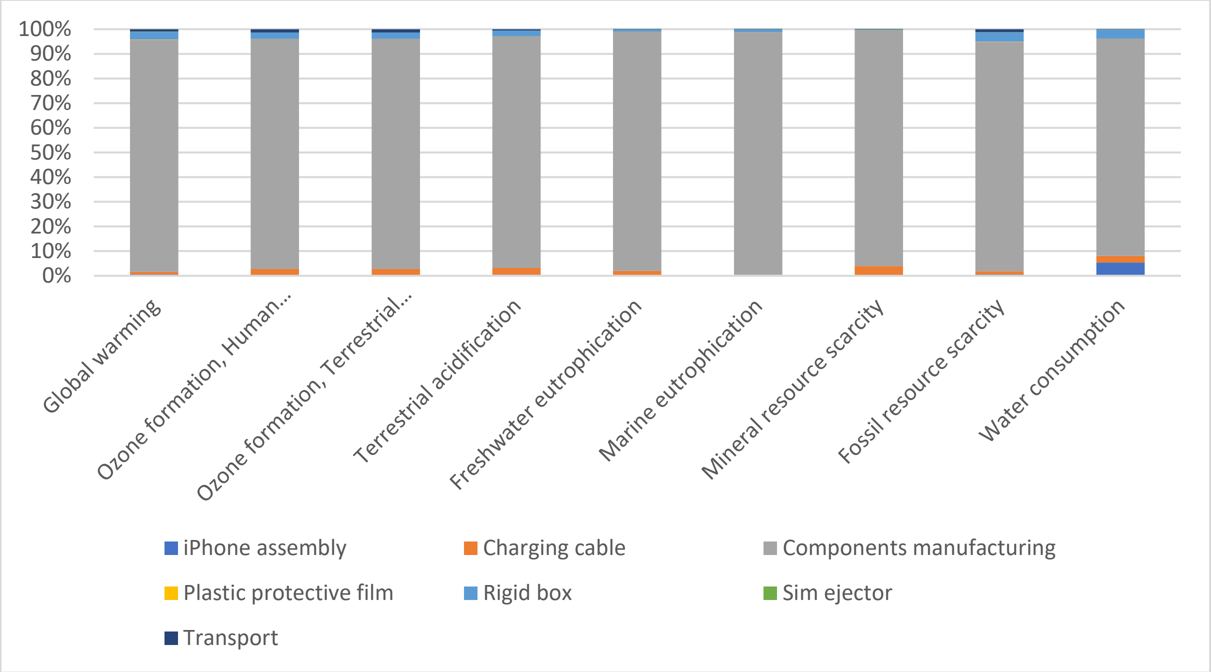
Absolute values (per FU) of the impacts of the life cycle stages of the baseline scenario.

Impact category	Unit	Total	Production	Distribution	Primary use	End-of-Life
Global warming	kg CO2 eq	16.77	3.97	0.39	12.35	0.05
Ozone formation, Human health	kg NOx eq	0.04	0.01	1.97E-03	0.02	6.01E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.04	0.01	1.98E-03	0.02	6.08E-05
Terrestrial acidification	kg SO2 eq	0.05	0.02	1.17E-03	0.03	9.82E-05
Freshwater eutrophication	kg P eq	9.69E-04	6.73E-04	6.38E-07	2.94E-04	9.84E-07
Marine eutrophication	kg N eq	5.76E-04	5.05E-04	1.99E-07	6.02E-05	1.11E-05
Mineral resource scarcity	kg Cu eq	0.22	0.19	0.00	0.03	7.69E-05
Fossil resource scarcity	kg oil eq	5.39	1.02	0.13	4.24	0.01
Water consumption	m3	0.10	0.04	0.00	0.06	2.66E-04

10.6.3 Production phase

10.6.3.1 Visualization of the impacts of the production of the components and accessories

Share of environmental impacts per impact category for the different (manufacturing) processes in the production phase with respect to the total impacts in the production phase



10.6.3.2 Absolute values of the impacts of the production of the components and accessories

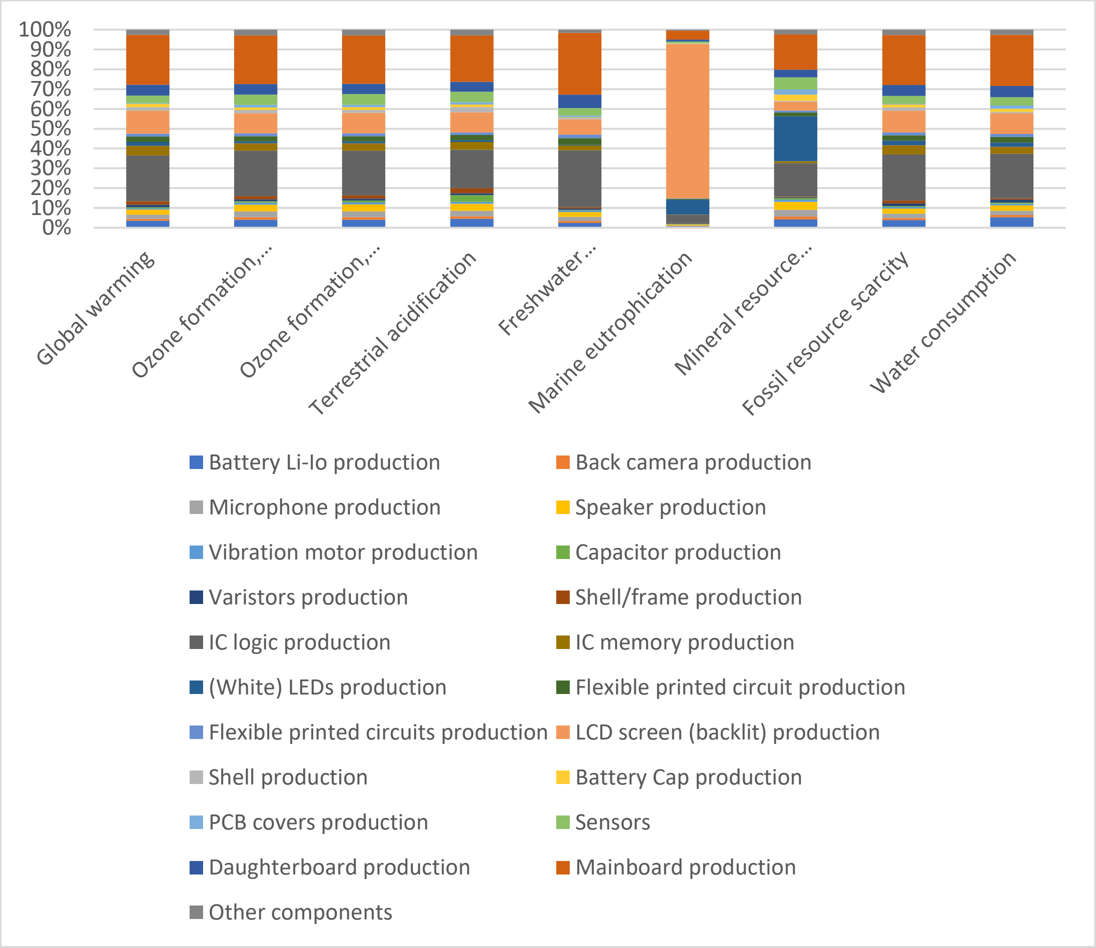
Absolute values (per FU) of the impacts of the manufacturing of iPhone accessories/components and other processes during the production phase.

Impact category	**Unit**	**Total**	**iPhone assembly**	**Charging cable**	**Components manufacturing**	**Plastic protective film**	**Rigid box**	**Sim ejector**	**Transport**
Global warming	kg CO2 eq	3.97	0.02	0.04	3.74	1.43E-03	0.13	1.94E-03	0.04
Ozone formation, Human health	kg NOx eq	0.01	4.48E-05	3.15E-04	0.01	2.92E-06	3.27E-04	4.60E-06	1.76E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.01	4.54E-05	3.22E-04	0.01	3.05E-06	3.34E-04	4.73E-06	1.78E-04
Terrestrial acidification	kg SO2 eq	0.02	7.93E-05	5.28E-04	0.02	3.98E-06	4.26E-04	6.63E-06	1.09E-04
Freshwater eutrophication	kg P eq	6.73E-04	2.24E-06	1.13E-05	6.53E-04	2.82E-08	6.06E-06	5.50E-08	1.16E-07

Marine eutrophication	kg N eq	5.05E-04	2.45E-07	1.72E-06	4.97E-04	8.02E-08	5.79E-06	9.76E-08	2.73E-08
Mineral resource scarcity	kg Cu eq	0.19	8.11E-05	0.01	0.19	2.39E-06	3.20E-04	9.76E-05	1.88E-05
Fossil resource scarcity	kg oil eq	1.02	0.01	0.01	0.95	6.39E-04	0.04	6.18E-04	0.01
Water consumption	m3	0.04	2.20E-03	1.08E-03	0.04	2.02E-05	0.00	1.94E-05	2.53E-05

10.6.3.3 Visualization of the impacts of the production of the different components

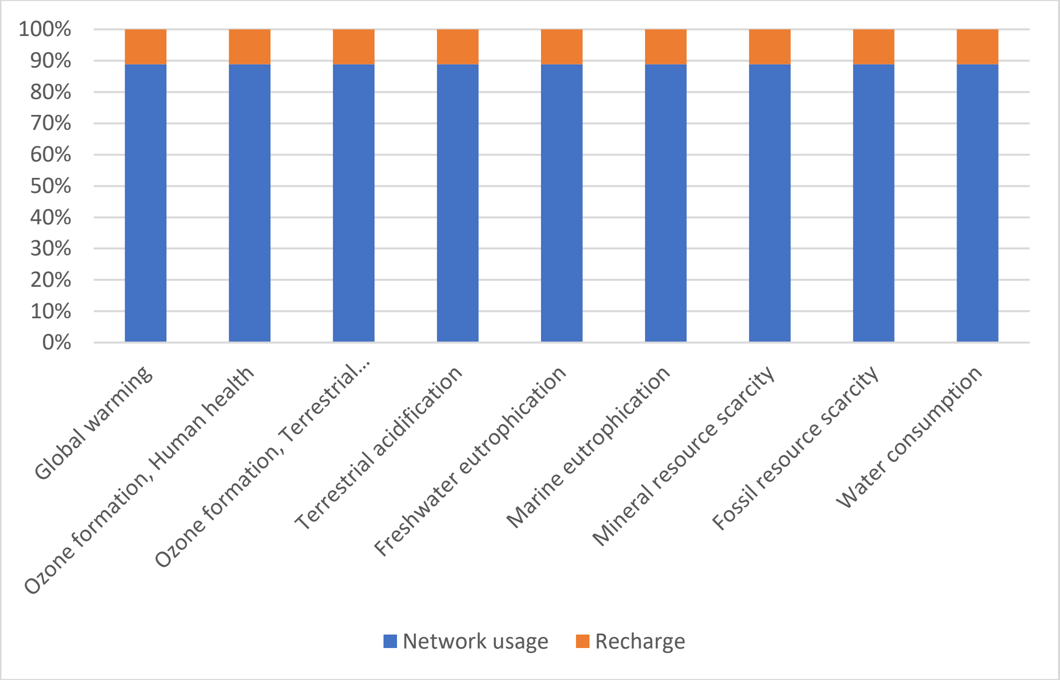
Share of environmental impacts per impact category for the different iPhone's sub-components with respect to the total impacts in the manufacturing of the iPhone's components process



10.6.4 Use phase

10.6.4.1 Visualization of impacts in the use phase

Share of environmental impacts per impact category for network usage and recharge in the baseline scenario with respect to the total impacts in the use phase



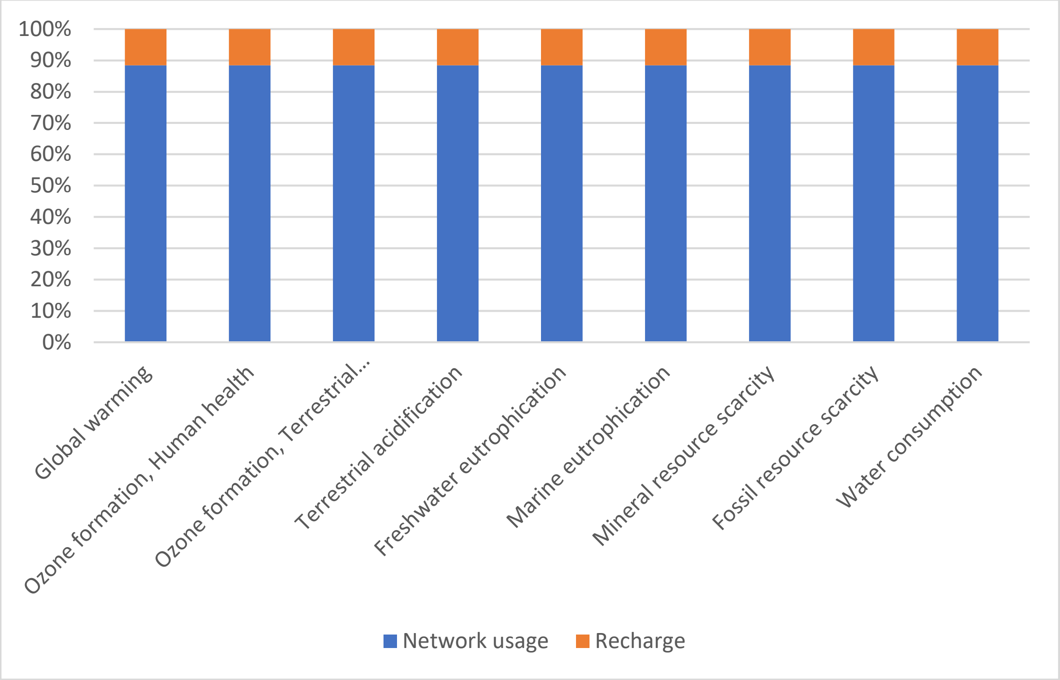
10.6.4.2 Absolute values of impacts in the use phase

Absolute values (per FU) of the impacts of network usage and recharge during the use phase of the baseline scenario.

Impact category	**Unit**	**Total**	**Network usage**	**Recharge**
Global warming	kg CO2 eq	12.35	10.98	1.37
Ozone formation, Human health	kg NOx eq	0.02	0.02	2.40E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.02	0.02	2.42E-03
Terrestrial acidification	kg SO2 eq	0.03	0.02	2.96E-03
Freshwater eutrophication	kg P eq	2.56E-03	2.27E-03	2.84E-04
Marine eutrophication	kg N eq	2.97E-04	2.64E-04	3.30E-05
Mineral resource scarcity	kg Cu eq	0.03	0.03	3.21E-03
Fossil resource scarcity	kg oil eq	4.24	3.77	0.47
Water consumption	m3	0.06	0.06	0.01

10.6.4.3 Visualization of impacts of the secondary average profile

Share of environmental impacts per impact category for network usage and recharge for the secondary average profile with respect to the total impacts in the use phase



10.6.4.4 Absolute values of impacts of the different consumer profiles

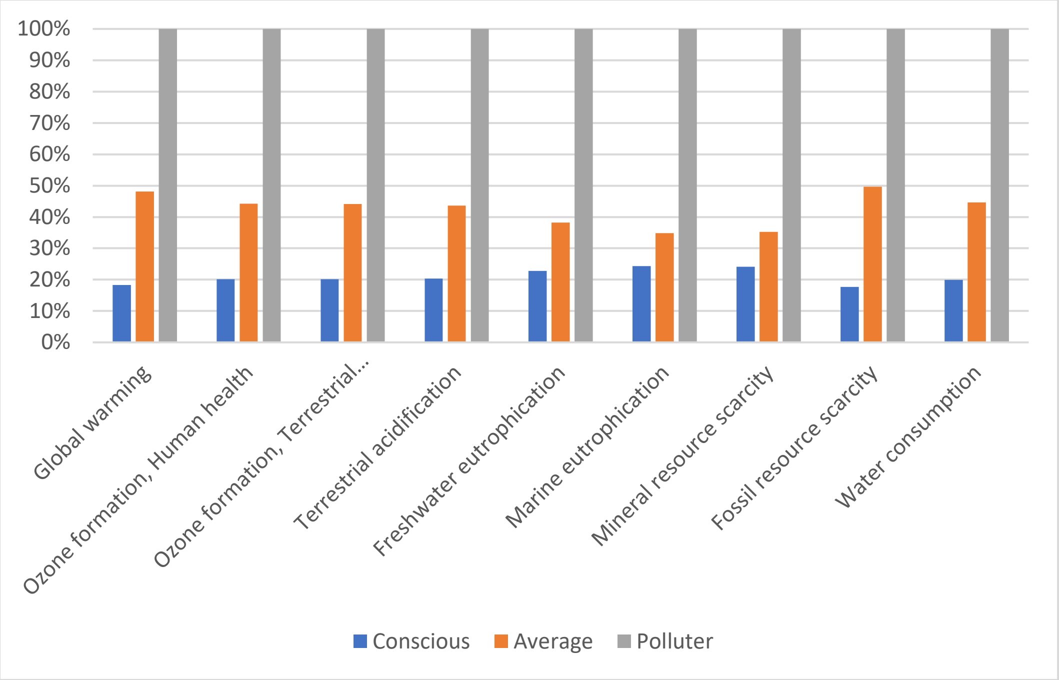
Absolute values (per FU) of the use phase impacts per consumer profile.

Impact category	**Unit**	**Primary average profile**	**Primary consciou s profile**	**Primary polluter profile**	**Secondary average profile**
Global warming	kg CO2 eq	12.35	3.07	21.58	12.42
Ozone formation, Human health	kg NOx eq	0.02	0.01	0.04	0.02
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.02	0.01	0.04	0.02
Terrestrial acidification	kg SO2 eq	0.03	0.01	0.05	0.03
Freshwater eutrophication	kg P eq	2.94E-04	7.31E-05	5.14E-04	2.96E-04
Marine eutrophication	kg N eq	6.02E-05	1.50E-05	1.05E-04	6.05E-05
Mineral resource scarcity	kg Cu eq	0.03	0.01	0.05	0.03
Fossil resource scarcity	kg oil eq	4.24	1.05	7.41	4.27
Water consumption	m3	0.06	0.02	0.11	0.06

10.7 Results: comparison of linear consumer scenarios

10.7.1 Visualization of total impacts per impact category

Comparison of the environmental impacts of the different linear consumer scenarios with respect to the total impacts of the linear polluter scenario



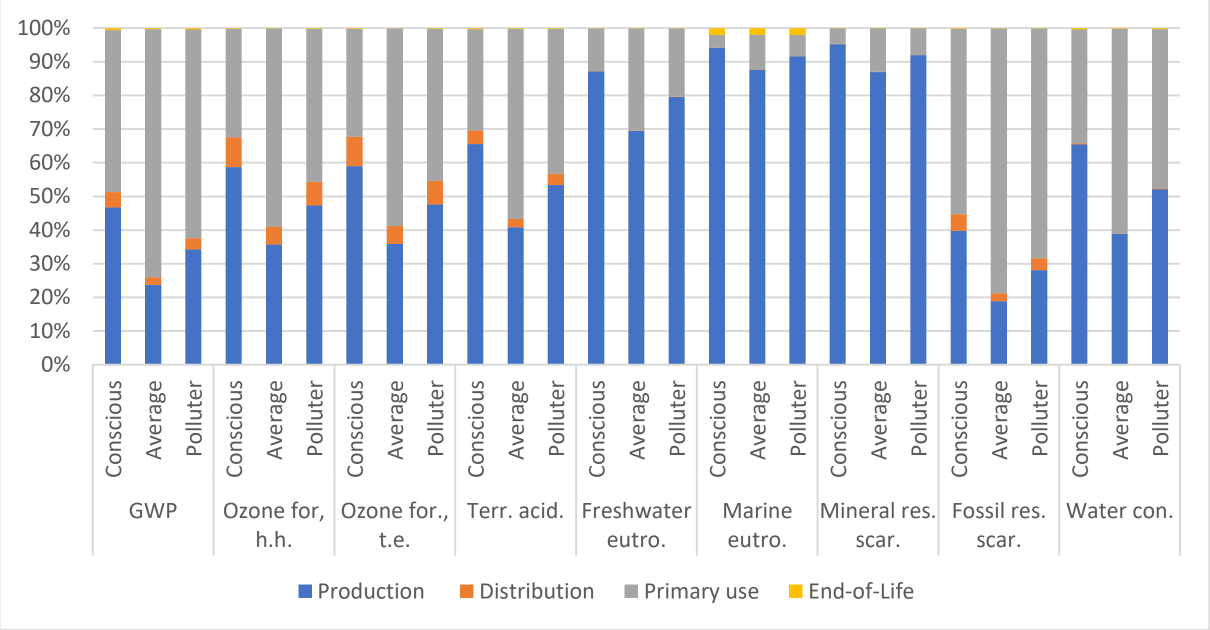
10.7.2 Absolute values of total impacts per impact category

Absolute values (per FU) of the total impacts for every linear consumer scenario per impact category.

Impact category	Unit	Conscious	Average	Polluter
Global warming	kg CO2 eq	6.38	16.77	34.83
Ozone formation, Human health	kg NOx eq	0.02	0.04	0.08
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.02	0.04	0.08
Terrestrial acidification	kg SO2 eq	0.02	0.05	0.11
Freshwater eutrophication	kg P eq	5.79E-04	9.69E-04	2.54E-03
Marine eutrophication	kg N eq	4.02E-04	5.76E-04	1.65E-03
Mineral resource scarcity	kg Cu eq	0.15	0.22	0.63
Fossil resource scarcity	kg oil eq	1.92	5.39	10.86
Water consumption	m3	0.05	0.10	0.23

10.7.3 Visualization of impacts per life cycle stage

Share of environmental impacts of the life cycle stages of the linear consumer scenarios per impact category with respect to the total impacts in their full life cycles.



10.7.4 Absolute values of impacts per life cycle stage

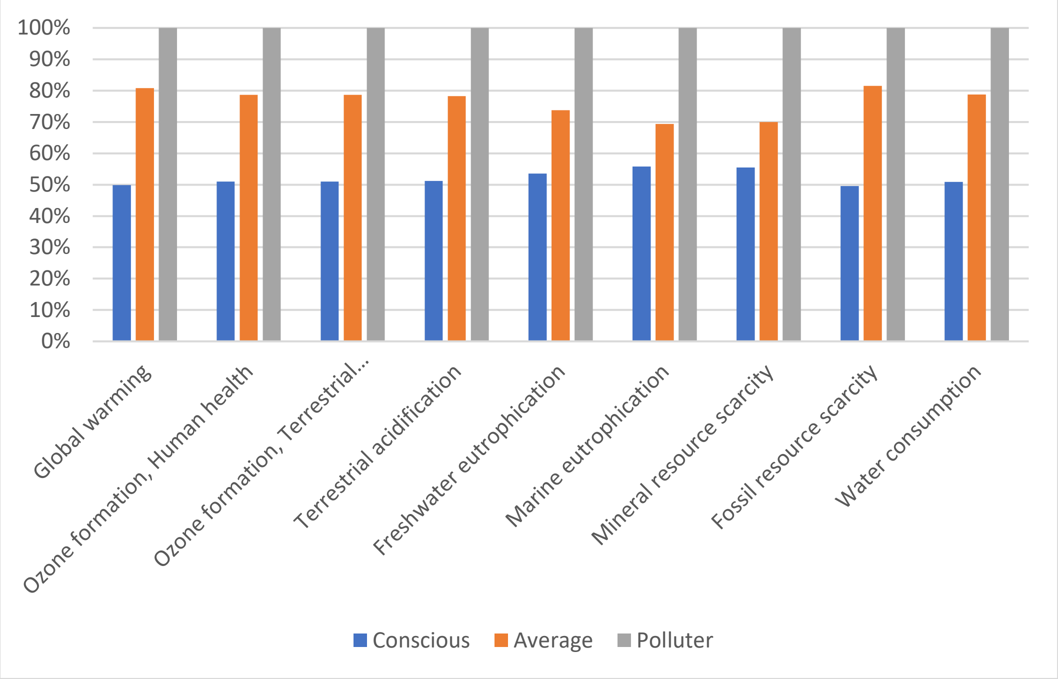
Results (per FU) of the linear system comparison which shows the absolute values of impacts in the different life cycle stages of every scenario per impact category

Impact category		Production	Distribution	Primary use	End-of-Life	Totals
GWP (kg CO2 eq)	Conscious	2.98	0.29	3.07	0.04	6.38
	Average	3.97	0.39	12.35	0.05	16.77
	Polluter	11.92	1.17	21.58	0.16	34.83
Ozone for, h.h. (kg NOx eq)	Conscious	0.01	1.48E-03	0.01	4.50E-05	0.02
	Average	0.01	1.97E-03	0.02	6.01E-05	0.04
	Polluter	0.04	0.01	0.04	1.80E-04	0.08
Ozone for., t.e. (kg NOx eq)	Conscious	0.01	1.49E-03	0.01	4.56E-05	0.02
	Average	0.01	1.98E-03	0.02	6.08E-05	0.04
	Polluter	0.04	0.01	0.04	1.83E-04	0.08
Terr. acid. (kg SO2 eq)	Conscious	0.01	0.00	0.01	7.36E-05	0.02
	Average	0.02	0.00	0.03	9.82E-05	0.05
	Polluter	0.06	0.00	0.05	2.94E-04	0.11
Freshwater eutro. (kg P eq)	Conscious	5.05E-04	4.78E-07	7.31E-05	7.38E-07	5.79E-04
	Average	6.73E-04	6.38E-07	2.94E-04	9.84E-07	9.69E-04
	Polluter	2.02E-03	1.91E-06	5.14E-04	2.95E-06	2.54E-03
Marine eutro. (kg N eq)	Conscious	3.79E-04	1.49E-07	1.50E-05	8.30E-06	4.02E-04
	Average	5.05E-04	1.99E-07	6.02E-05	1.11E-05	5.76E-04
	Polluter	1.51E-03	5.96E-07	1.05E-04	3.32E-05	1.65E-03
Mineral res. scar. (kg Cu eq)	Conscious	0.15	0.00	0.01	5.76E-05	0.15
	Average	0.19	0.00	0.03	7.69E-05	0.22
	Polluter	0.58	0.00	0.05	2.31E-04	0.63
Fossil res. scar. (kg oil eq)	Conscious	0.76	0.10	1.05	3.87E-03	1.92
	Average	1.02	0.13	4.24	0.01	5.39
	Polluter	3.05	0.38	7.41	0.02	10.86
Water con. (m3)	Conscious	0.03	0.00	0.02	1.99E-04	0.05
	Average	0.04	0.00	0.06	2.66E-04	0.10
	Polluter	0.12	0.00	0.11	7.98E-04	0.23

10.8 Results: comparison reuse consumer scenarios

10.8.1 Visualization of total impacts per impact category

Comparison of the environmental impacts of the reuse consumer scenarios with respect to the total impacts of the reuse polluter scenario



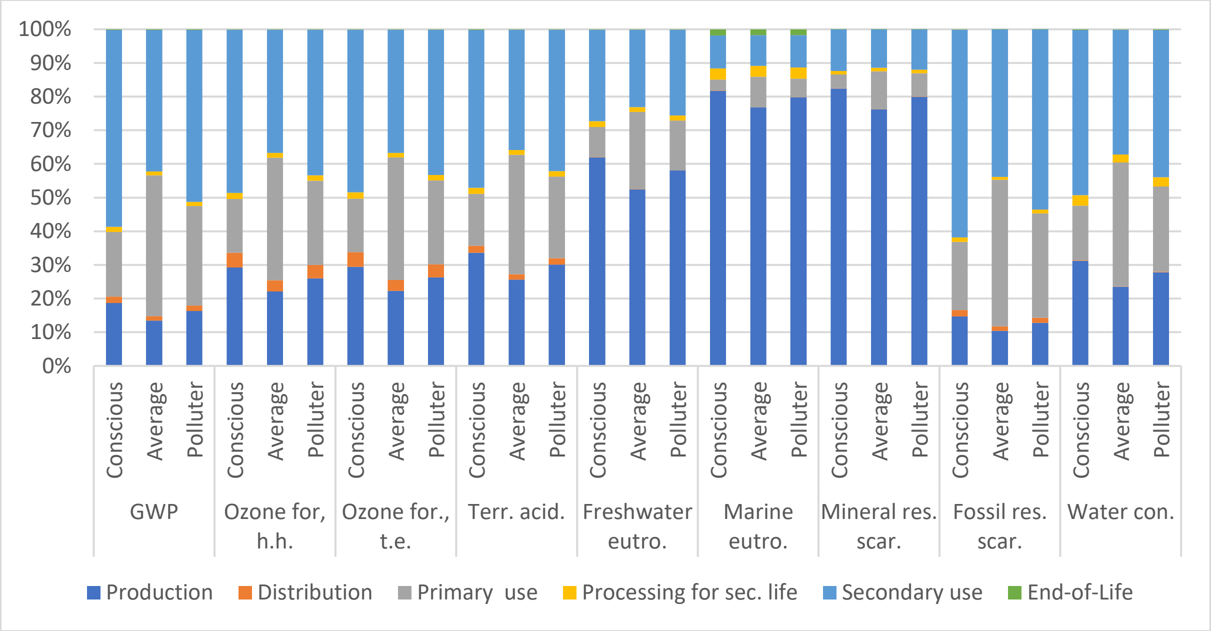
10.8.2 Absolute values of total impacts per impact category

Absolute values (per FU) of the total impacts for every reuse system per impact category.

Impact category	Unit	Conscious	Average	Polluter
Global warming	kg CO2 eq	9.11	14.75	18.26
Ozone formation, Human health	kg NOx eq	0.02	0.03	0.04
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.02	0.03	0.04
Terrestrial acidification	kg SO2 eq	0.02	0.04	0.05
Freshwater eutrophication	kg P eq	4.65E-04	6.41E-04	8.70E-04
Marine eutrophication	kg N eq	2.65E-04	3.29E-04	4.75E-04
Mineral resource scarcity	kg Cu eq	0.10	0.13	0.18
Fossil resource scarcity	kg oil eq	2.96	4.87	5.98
Water consumption	m3	0.06	0.09	0.11

10.8.3 Visualization of total impacts per life cycle stage

Share of environmental impacts of the life cycle stages of the reuse scenarios per impact category.



10.8.4 Absolute values of total impacts per life cycle stage

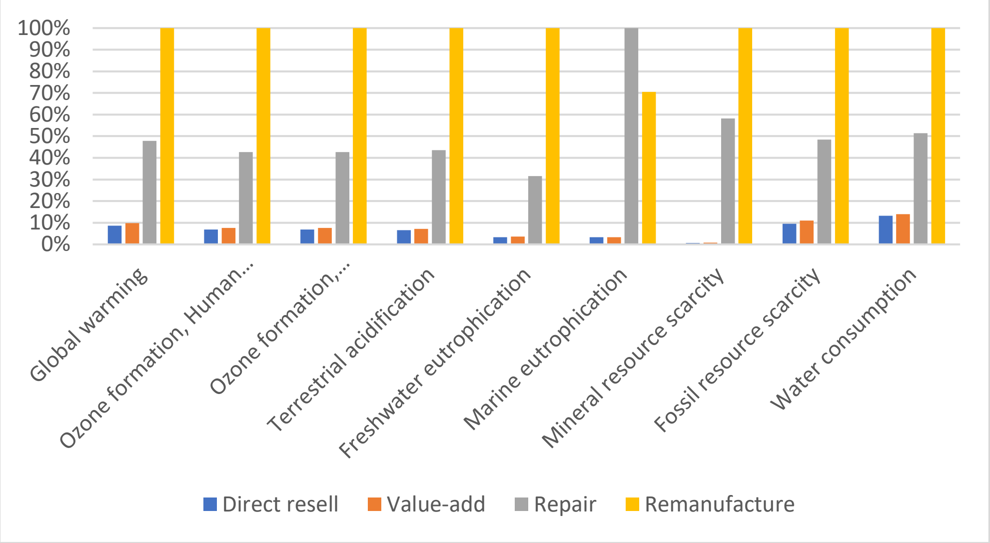
Results (per FU) of the reuse system comparison which shows the absolute values of impacts in the different life cycle stages of every scenario per impact category

Impact category		**Production**	**Distribution**	**Primary use**	**Processing for sec. life**	**Secondary use**	**End-of-Life**
GWP (kg CO2 eq)	Conscious	1.70	0.17	1.76	0.13	5.32	0.02
	Average	1.99	0.20	6.18	0.16	6.21	0.03
	Polluter	2.98	0.29	5.39	0.23	9.32	0.04
Ozone for, h.h. (kg NOx eq)	Conscious	0.01	8.43E-04	3.07E-03	3.48E-04	0.01	2.97E-05
	Average	0.01	9.84E-04	0.01	4.06E-04	0.01	3.47E-05
	Polluter	0.01	1.48E-03	0.01	6.09E-04	0.02	5.20E-05
Ozone for., t.e. (kg NOx eq)	Conscious	0.01	8.50E-04	3.10E-03	3.55E-04	0.01	3.01E-05
	Average	0.01	9.92E-04	0.01	4.15E-04	0.01	3.51E-05
	Polluter	0.01	1.49E-03	0.01	6.22E-04	0.02	5.27E-05
Terr. acid. (kg SO2 eq)	Conscious	0.01	5.02E-04	3.79E-03	4.44E-04	0.01	4.52E-05
	Average	0.01	5.86E-04	0.01	5.18E-04	0.01	5.27E-05

	Polluter	0.01	8.78E-04	0.01	7.77E-04	0.02	7.91E-05
Freshwater eutro. (kg P eq)	Conscious	2.88E-04	2.73E-07	4.18E-05	7.79E-06	1.27E-04	4.36E-07
	Average	3.36E-04	3.19E-07	1.47E-04	9.09E-06	1.48E-04	5.09E-07
	Polluter	5.05E-04	4.78E-07	1.28E-04	1.36E-05	2.22E-04	7.63E-07
Marine eutro. (kg N eq)	Conscious	2.16E-04	8.51E-08	8.55E-06	8.98E-06	2.59E-05	4.78E-06
	Average	2.52E-04	9.93E-08	3.01E-05	1.05E-05	3.03E-05	5.57E-06
	Polluter	3.79E-04	1.49E-07	2.63E-05	1.57E-05	4.54E-05	8.36E-06
Mineral res. scar. (kg Cu eq)	Conscious	0.08	4.98E-05	4.11E-03	1.10E-03	0.01	3.51E-05
	Average	0.10	5.81E-05	0.01	1.28E-03	0.01	4.09E-05
	Polluter	0.15	8.71E-05	0.01	1.92E-03	0.02	6.14E-05
Fossil res. scar. (kg oil eq)	Conscious	0.44	0.05	0.60	0.04	1.83	2.52E-03
	Average	0.51	0.06	2.12	0.05	2.13	2.94E-03
	Polluter	0.76	0.10	1.85	0.07	3.20	4.41E-03
Water con. (m3)	Conscious	0.02	6.83E-05	0.01	1.75E-03	0.03	1.18E-04
	Average	0.02	7.97E-05	0.03	2.04E-03	0.03	1.37E-04
	Polluter	0.03	1.20E-04	0.03	3.06E-03	0.05	2.06E-04

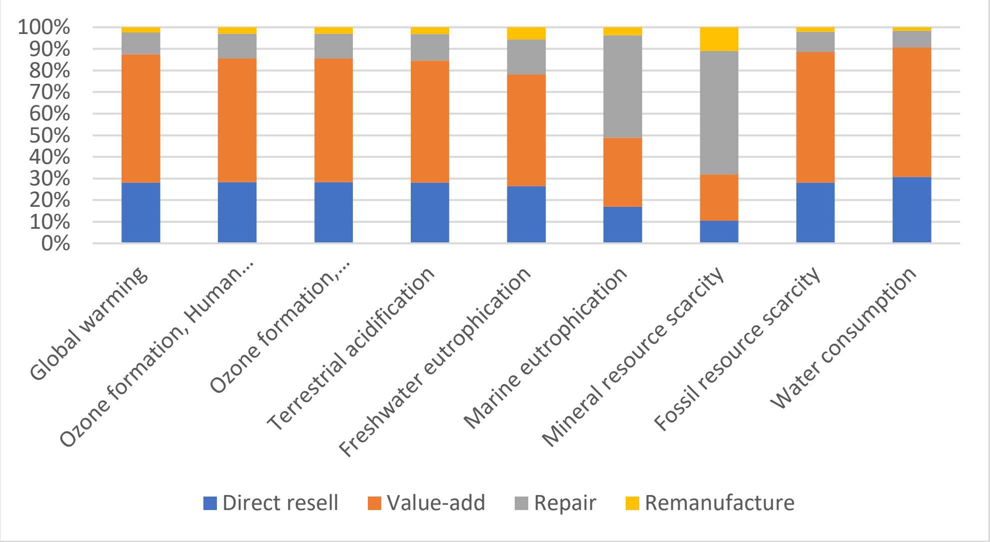
10.8.5 Comparison of Twig's circular strategies

Comparison of the environmental impacts of the different circular strategies per phone processed (not per FU)



10.8.6 Share of impacts of Twig's different circular strategies

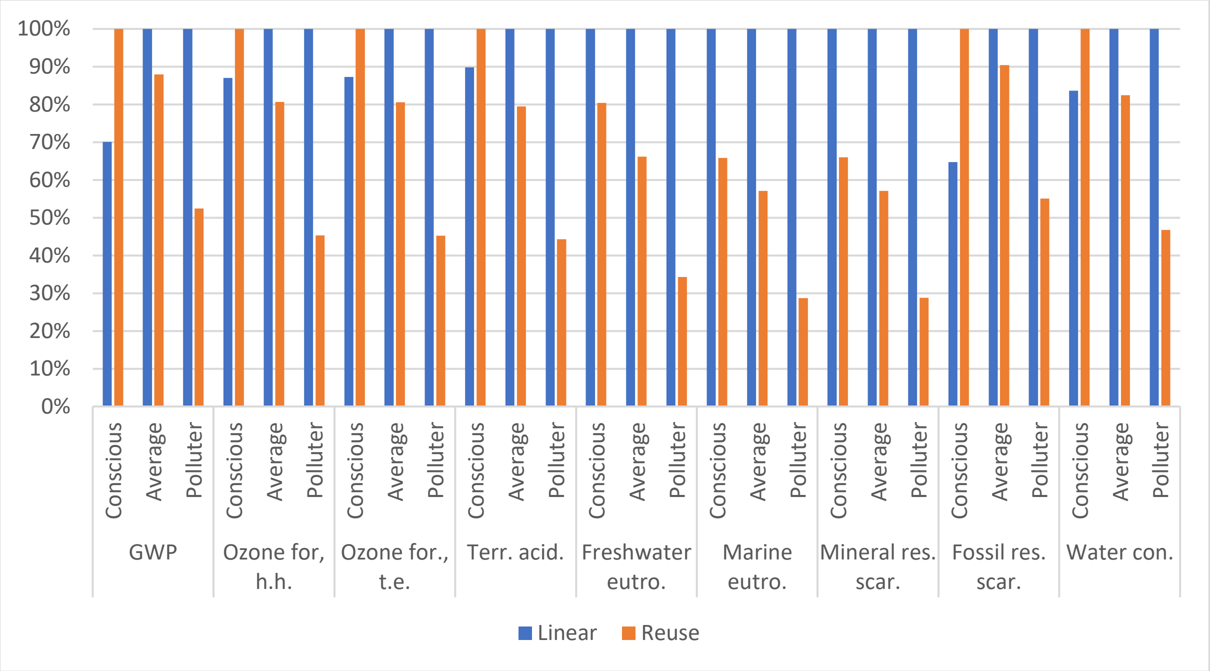
Share of environmental impacts of the different circular strategies per impact category (per FU) with respect to the total impacts of the processing for the secondary life phase



10.9 Results: linear versus reuse scenarios

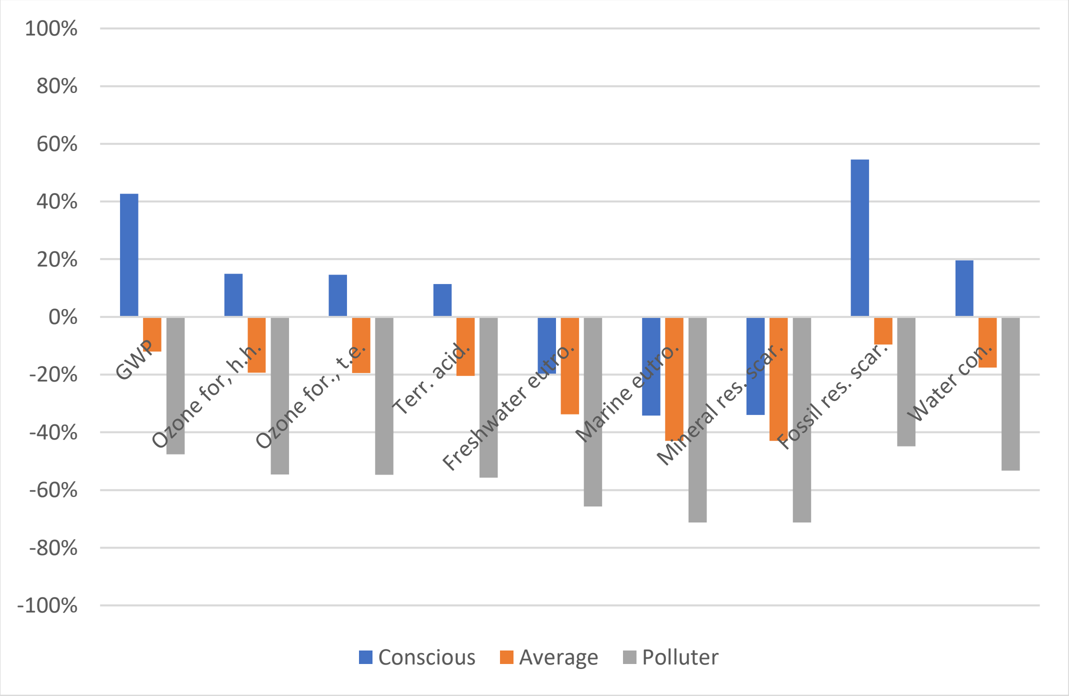
10.9.1 Visualization of total impacts of linear versus reuse consumer scenarios

Environmental impacts per impact category of the comparison between the linear and reuse consumer scenarios with respect to their total impacts per comparison



10.9.2 Visualization of the magnitude of avoided impacts between consumer scenarios

The magnitude of avoided impacts between the different consumer scenarios per impacts categories. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.



10.9 Magnitude of avoided impacts between consumer scenarios in all impacts categories

The magnitude of avoided impacts between the different consumer scenarios per impacts category. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Conscious	Average	Polluter
Global warming	42.64%	-12.02%	-47.57%
Ozone formation, Human health	14.96%	-19.30%	-54.65%
Ozone formation, Terrestrial ecosystems	14.63%	-19.41%	-54.74%
Terrestrial acidification	11.35%	-20.48%	-55.68%
Freshwater eutrophication	-19.62%	-33.79%	-65.72%
Marine eutrophication	-34.17%	-42.93%	-71.30%
Mineral resource scarcity	-33.99%	-42.91%	-71.25%
Fossil resource scarcity	54.58%	-9.58%	-44.90%
Water consumption	19.61%	-17.52%	-53.24%

10.9.4 Absolute values of total impacts and avoided impacts

Total impacts and avoided impacts (linear minus reuse) of the different scenarios per impact category (per FU). Avoided impacts = linear – reuse.

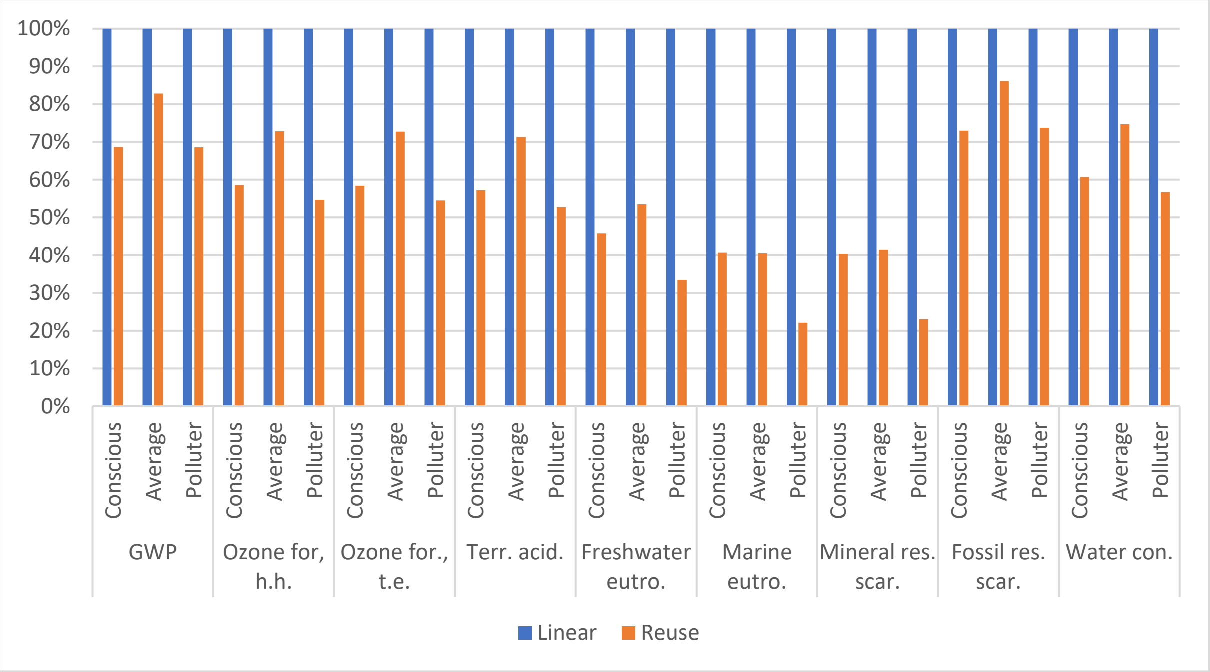
Impact category	Scenario	Linear	Reuse	Avoided impacts
Global warming (kg CO2 eq)	Conscious	6.38	9.11	-2.72
	Average	16.77	14.75	2.02
	Polluter	34.83	18.26	16.57
Ozone formation, Human health (kg NOx eq)	Conscious	0.02	0.02	-2.50E-03
	Average	0.04	0.03	0.01
	Polluter	0.08	0.04	0.05
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.02	0.02	-2.49E-03
	Average	0.04	0.03	0.01
	Polluter	0.08	0.04	0.05
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.02	-2.50E-03
	Average	0.05	0.04	0.01
	Polluter	0.11	0.05	0.06
Freshwater eutrophication (kg P eq)	Conscious	5.79E-04	4.65E-04	1.14E-04
	Average	9.69E-04	6.41E-04	3.27E-04
	Polluter	2.54E-03	8.70E-04	1.67E-03
Marine eutrophication (kg N eq)	Conscious	4.02E-04	2.65E-04	1.37E-04
	Average	5.76E-04	3.29E-04	2.47E-04
	Polluter	1.65E-03	4.75E-04	1.18E-03
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.10	0.05
	Average	0.22	0.13	0.10
	Polluter	0.63	0.18	0.45
Fossil resource scarcity (kg oil eq)	Conscious	1.92	2.96	-1.05
	Average	5.39	4.87	0.52
	Polluter	10.86	5.98	4.87
Water consumption (m3)	Conscious	0.05	0.06	-0.01
	Average	0.10	0.09	0.02
	Polluter	0.23	0.11	0.12

10.10 Sensitivity analysis

10.10.1 First user perspective – economic allocation

10.10.1.1 Visualization of linear and reuse scenario comparison

Results of the linear and reuse scenario comparison when applying the first user’s perspective of economic allocation.



10.10.1.2 Magnitude of avoided impacts between consumer scenarios in all impact categories

The magnitude of avoided impacts when applying the first user’s perspective of economic allocation. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Conscious	Average	Polluter
Global warming	-31.36%	-17.22%	-31.46%
Ozone formation, Human health	-41.44%	-27.14%	-45.28%
Ozone formation, Terrestrial ecosystems	-41.56%	-27.29%	-45.47%
Terrestrial acidification	-42.78%	-28.73%	-47.26%
Freshwater eutrophication	-54.24%	-46.53%	-66.52%
Marine eutrophication	-59.28%	-59.44%	-77.89%
Mineral resource scarcity	-59.65%	-58.55%	-76.96%
Fossil resource scarcity	-27.03%	-13.88%	-26.21%
Water consumption	-39.28%	-25.33%	-43.29%

10.10.1.3 Absolute values of total impacts and avoided impacts

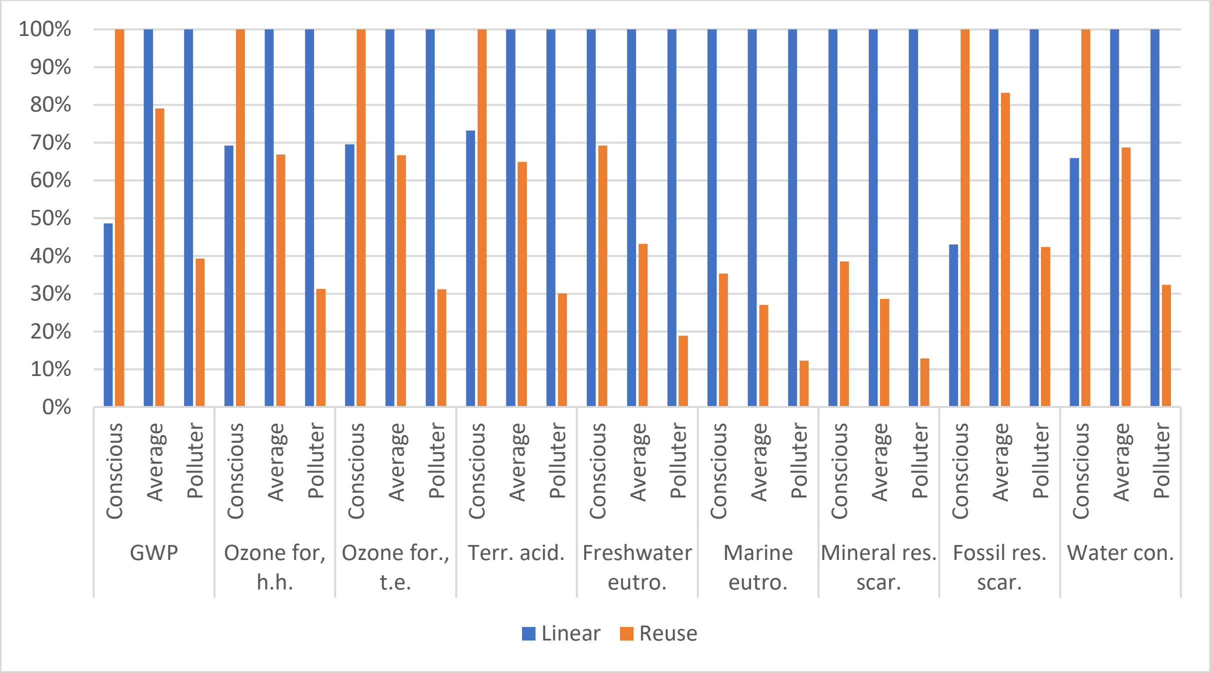
Absolute values of total impacts and avoided impacts (per FU) of the different scenarios per impact category when the first user's perspective of economic allocation is applied. Avoided impacts = linear – reuse.

Impact category		**Linear**	**Reuse**	**Avoided impacts**
Global warming (kg CO2 eq)	Conscious	6.38	4.38	2.00
	Average	16.77	13.88	2.89
	Polluter	34.83	23.87	10.96
Ozone formation, Human health (kg NOx eq)	Conscious	0.02	0.01	0.01
	Average	0.04	0.03	0.01
	Polluter	0.08	0.05	0.04
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.02	0.01	0.01
	Average	0.04	0.03	0.01
	Polluter	0.08	0.05	0.04
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.01	0.01
	Average	0.05	0.03	0.01
	Polluter	0.11	0.06	0.05
Freshwater eutrophication (kg P eq)	Conscious	5.79E-04	2.65E-04	3.14E-04
	Average	9.69E-04	5.18E-04	4.51E-04
	Polluter	2.54E-03	8.50E-04	1.69E-03
Marine eutrophication (kg N eq)	Conscious	4.02E-04	1.64E-04	2.38E-04
	Average	5.76E-04	2.34E-04	3.43E-04
	Polluter	1.65E-03	3.66E-04	1.29E-03
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.06	0.09
	Average	0.22	0.09	0.13
	Polluter	0.63	0.15	0.49
Fossil resource scarcity (kg oil eq)	Conscious	1.92	1.40	0.52
	Average	5.39	4.64	0.75
	Polluter	10.86	8.01	2.85
Water consumption (m3)	Conscious	0.05	0.03	0.02
	Average	0.10	0.08	0.03
	Polluter	0.23	0.13	0.10

10.10.2 Second user perspective – economic allocation

10.10.2.1 Visualization of linear and reuse scenario comparison

Results of the linear and reuse scenario comparison when applying the first user's perspective of economic allocation.



10.10.2.2 Magnitude of avoided impacts between consumer scenarios in all impacts categories

The magnitude of avoided impacts when applying the second user's perspective of economic allocation. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Conscious	Average	Polluter
Global warming	105.78%	-20.94%	-60.73%
Ozone formation, Human health	44.45%	-33.17%	-68.77%
Ozone formation, Terrestrial ecosystems	43.70%	-33.34%	-68.87%
Terrestrial acidification	36.58%	-35.10%	-69.92%
Freshwater eutrophication	-30.80%	-56.82%	-81.10%
Marine eutrophication	-64.71%	-73.02%	-87.72%
Mineral resource scarcity	-61.48%	-71.38%	-87.17%
Fossil resource scarcity	132.35%	-16.81%	-57.68%
Water consumption	51.67%	-31.31%	-67.62%

10.10.2.3 Absolute values of total impacts and avoided impacts

Absolute values of total impacts and avoided impacts (per FU) of the different scenarios per impact category when the second user's perspective of economic allocation is applied. Avoided impacts = linear – reuse.

Impact category		**Linear**	**Reuse**	**Avoided impacts**
Global warming (kg CO2 eq)	Conscious	6.38	13.14	-6.75
	Average	16.77	13.26	3.51
	Polluter	34.83	13.68	21.15
Ozone formation, Human health (kg NOx eq)	Conscious	0.02	0.02	-0.01
	Average	0.04	0.02	0.01
	Polluter	0.08	0.03	0.06
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.02	0.02	-0.01
	Average	0.04	0.02	0.01
	Polluter	0.08	0.03	0.06
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.03	-0.01
	Average	0.05	0.03	0.02
	Polluter	0.11	0.03	0.08
Freshwater eutrophication (kg P eq)	Conscious	5.79E-04	4.01E-04	1.78E-04
	Average	9.69E-04	4.18E-04	5.50E-04
	Polluter	2.54E-03	4.80E-04	2.06E-03
Marine eutrophication (kg N eq)	Conscious	4.02E-04	1.42E-04	2.60E-04
	Average	5.76E-04	1.56E-04	4.21E-04
	Polluter	1.65E-03	2.03E-04	1.45E-03
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.06	0.09
	Average	0.22	0.06	0.16
	Polluter	0.63	0.08	0.55
Fossil resource scarcity (kg oil eq)	Conscious	1.92	4.45	-2.54
	Average	5.39	4.48	0.91
	Polluter	10.86	4.59	6.26
Water consumption (m3)	Conscious	0.05	0.07	-0.02
	Average	0.10	0.07	0.03
	Polluter	0.23	0.08	0.16

10.10.3 First user's perspective versus second user's perspective – economic allocation

10.10.3.1 Magnitude of avoided impacts between first and second user's perspective in all impact categories

The magnitude of avoided impacts when applying the first or second user's perspective of economic allocation. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Perspective	**Conscious**	**Average**	**Polluter**
Global warming (kg CO2 eq)	1st user	-31.36%	-17.22%	-31.46%
	2nd user	105.78%	-20.94%	-60.73%
Ozone formation, Human health (kg NOx eq)	1st user	-41.44%	-27.14%	-45.28%
	2nd user	44.45%	-33.17%	-68.77%
Ozone formation, Terrestrial ecosystems (kg NOx eq)	1st user	-41.56%	-27.29%	-45.47%
	2nd user	43.70%	-33.34%	-68.87%
Terrestrial acidification (kg SO2 eq)	1st user	-42.78%	-28.73%	-47.26%
	2nd user	36.58%	-35.10%	-69.92%
Freshwater eutrophication (kg P eq)	1st user	-54.24%	-46.53%	-66.52%
	2nd user	-30.80%	-56.82%	-81.10%
Marine eutrophication (kg N eq)	1st user	-59.28%	-59.44%	-77.89%
	2nd user	-64.71%	-73.02%	-87.72%
Mineral resource scarcity (kg Cu eq)	1st user	-59.65%	-58.55%	-76.96%
	2nd user	-61.48%	-71.38%	-87.17%
Fossil resource scarcity (kg oil eq)	1st user	-27.03%	-13.88%	-26.21%
	2nd user	132.35%	-16.81%	-57.68%
Water consumption (m3)	1st user	-39.28%	-25.33%	-43.29%
	2nd user	51.67%	-31.31%	-67.62%

10.10.3.2 Absolute values of total impacts and avoided impacts of both first and second user's perspective

The absolute values of avoided impacts (per FU) per scenario when taking the first or second user's perspectives of economic allocation. Avoided impacts = linear – reuse.

Impact category	**Perspective**	**Conscious**	**Average**	**Polluter**
Global warming (kg CO2 eq)	1st user	2.00	2.89	10.96
	2nd user	-6.75	3.51	21.15
Ozone formation, Human health (kg NOx eq)	1st user	0.01	0.01	0.04
	2nd user	-0.01	0.01	0.06
Ozone formation, Terrestrial ecosystems (kg NOx eq)	1st user	0.01	0.01	0.04
	2nd user	-0.01	0.01	0.06
Terrestrial acidification (kg SO2 eq)	1st user	0.01	0.01	0.05
	2nd user	-0.01	0.02	0.08
Freshwater eutrophication (kg P eq)	1st user	3.14E-04	4.51E-04	1.69E-03
	2nd user	1.78E-04	5.50E-04	2.06E-03
Marine eutrophication (kg N eq)	1st user	2.38E-04	3.43E-04	1.29E-03
	2nd user	2.60E-04	4.21E-04	1.45E-03
Mineral resource scarcity (kg Cu eq)	1st user	0.09	0.13	0.49
	2nd user	0.09	0.16	0.55
Fossil resource scarcity (kg oil eq)	1st user	0.52	0.75	2.85
	2nd user	-2.54	0.91	6.26
Water consumption (m3)	1st user	0.02	0.03	0.10
	2nd user	-0.02	0.03	0.16

10.10.3 Excluding network usage from the use phase

10.10.3.1 Magnitude of avoided impacts between consumer scenarios in all impact categories

The magnitude of avoided impacts when network usage is excluded from the LCI. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Conscious	Average	Polluter
Global warming	-22.22%	-34.84%	-66.59%
Ozone formation, Human health	-30.85%	-40.47%	-69.94%
Ozone formation, Terrestrial ecosystems	-30.92%	-40.52%	-69.97%
Terrestrial acidification	-31.81%	-41.16%	-70.34%
Freshwater eutrophication	-38.48%	-46.29%	-73.11%
Marine eutrophication	-39.76%	-47.32%	-73.65%
Mineral resource scarcity	-41.12%	-48.50%	-74.24%
Fossil resource scarcity	-17.08%	-31.89%	-64.70%
Water consumption	-27.72%	-38.07%	-68.65%

10.10.3.2 Absolute values of total impacts and avoided impacts

Absolute values of total impacts and avoided impacts (per FU) of the different scenarios per impact category when network usage is excluded from the LCI input. Avoided impacts = linear – reuse.

Impact category		**Linear**	**Reuse**	**Avoided impacts**
Global warming (kg CO2 eq)	Conscious	3.64	2.83	0.81
	Average	5.79	3.77	2.02
	Polluter	15.65	5.23	10.42
Ozone formation, Human health (kg NOx eq)	Conscious	0.01	0.01	3.67E-03
	Average	0.02	0.01	0.01
	Polluter	0.05	0.01	0.03
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.01	0.01	3.76E-03
	Average	0.02	0.01	0.01
	Polluter	0.05	0.02	0.04
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.01	0.01
	Average	0.02	0.01	0.01
	Polluter	0.07	0.02	0.05
Freshwater eutrophication (kg P eq)	Conscious	5.14E-04	3.16E-04	1.98E-04
	Average	7.07E-04	3.80E-04	3.27E-04
	Polluter	2.08E-03	5.60E-04	1.52E-03
Marine eutrophication (kg N eq)	Conscious	3.89E-04	2.34E-04	1.55E-04
	Average	5.23E-04	2.75E-04	2.47E-04
	Polluter	1.56E-03	4.11E-04	1.15E-03
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.09	0.06
	Average	0.20	0.10	0.10
	Polluter	0.59	0.15	0.44
Fossil resource scarcity (kg oil eq)	Conscious	0.98	0.81	0.17
	Average	1.62	1.10	0.52
	Polluter	4.27	1.51	2.76
Water consumption (m3)	Conscious	0.03	0.02	0.01
	Average	0.05	0.03	0.02
	Polluter	0.14	0.04	0.09

10.10.4 Employing different secondary use phase profiles

10.10.4.1 Magnitude of avoided impacts between consumer scenarios in all impact categories

The magnitude of avoided impacts when different consumer profiles are employed for the secondary use phase. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

	Conscious	Average	Polluter
Global warming	-19.91%	-12.02%	-17.49%
Ozone formation, Human health	-26.83%	-19.30%	-25.68%
Ozone formation, Terrestrial ecosystems	-26.91%	-19.41%	-25.78%
Terrestrial acidification	-27.79%	-20.48%	-26.89%
Freshwater eutrophication	-36.04%	-33.79%	-38.74%
Marine eutrophication	-39.00%	-42.93%	-44.90%
Mineral resource scarcity	-40.10%	-42.91%	-45.38%
Fossil resource scarcity	-16.97%	-9.58%	-14.40%
Water consumption	-24.44%	-17.52%	-23.57%

10.10.4.2 Absolute values of total impacts and avoided impacts

Absolute values of total impacts and avoided impacts (per FU) of the different scenarios per impact category when network the same profile is used for the second use phase as in its first use phase. Avoided impacts = linear – reuse.

Impact category	Scenario	Linear	Reuse	Avoided impacts
Global warming (kg CO2 eq)	Conscious	6.38	5.11	1.27
	Average	16.77	14.75	2.02
	Polluter	34.83	28.74	6.09
Ozone formation, Human health (kg NOx eq)	Conscious	0.02	0.01	4.48E-03
	Average	0.04	0.03	0.01
	Polluter	0.08	0.06	0.02
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.02	0.01	4.57E-03
	Average	0.04	0.03	0.01
	Polluter	0.08	0.06	0.02
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.02	0.01
	Average	0.05	0.04	0.01
	Polluter	0.11	0.08	0.03
Freshwater eutrophication (kg P eq)	Conscious	5.79E-04	3.70E-04	2.09E-04
	Average	9.69E-04	6.41E-04	3.27E-04
	Polluter	2.54E-03	1.55E-03	9.83E-04
Marine eutrophication (kg N eq)	Conscious	4.02E-04	2.45E-04	1.57E-04
	Average	5.76E-04	3.29E-04	2.47E-04
	Polluter	1.65E-03	9.11E-04	7.42E-04
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.09	0.06
	Average	0.22	0.13	0.10
	Polluter	0.63	0.35	0.29
Fossil resource scarcity (kg oil eq)	Conscious	1.92	1.59	0.33
	Average	5.39	4.87	0.52
	Polluter	10.86	9.29	1.56
Water consumption (m3)	Conscious	0.05	0.04	0.01
	Average	0.10	0.09	0.02
	Polluter	0.23	0.18	0.06

10.10.5 Employing a functional lifetime of 1 year for the second use phase

10.10.5.1 Magnitude of avoided impacts between consumer scenarios in all impact categories

The magnitude of avoided impacts when 1 year of second use instead of 3 years is employed. The magnitude displays the percentage of change in impacts between the linear and reuse system. A negative percentage indicates that reuse leads to fewer impacts than buying a new iPhone. A positive percentage shows that reuse leads to more impacts than buying a new phone.

Impact category	Conscious	Average	Polluter
Global warming	21.87%	-5.07%	-30.81%
Ozone formation, Human health	8.95%	-8.53%	-35.44%
Ozone formation, Terrestrial ecosystems	8.80%	-8.58%	-35.50%
Terrestrial acidification	7.19%	-9.14%	-36.16%
Freshwater eutrophication	-7.90%	-15.96%	-43.10%
Marine eutrophication	-13.85%	-19.64%	-46.26%
Mineral resource scarcity	-15.19%	-20.88%	-47.10%
Fossil resource scarcity	27.40%	-3.93%	-29.08%
Water consumption	12.66%	-6.81%	-33.75%

10.10.5.2 Absolute values of total impacts and avoided impacts

Absolute values of total impacts and avoided impacts (per FU) of the different scenarios per impact category when a functional lifetime of 1 year is used instead of 3 years for the second use phase. Avoided impacts = linear – reuse.

Impact category		Linear	Reuse	Avoided impacts
Global warming (kg CO2 eq)	Conscious	6.38	7.78	-1.40
	Average	16.77	15.92	0.85
	Polluter	34.83	24.10	10.73
Ozone formation, Human health (kg NOx eq)	Conscious	0.02	0.02	-1.50E-03
	Average	0.04	0.03	3.13E-03
	Polluter	0.08	0.05	0.03
Ozone formation, Terrestrial ecosystems (kg NOx eq)	Conscious	0.02	0.02	-1.50E-03
	Average	0.04	0.03	3.20E-03
	Polluter	0.08	0.05	0.03
Terrestrial acidification (kg SO2 eq)	Conscious	0.02	0.02	-1.58E-03
	Average	0.05	0.04	4.31E-03
	Polluter	0.11	0.07	0.04
Freshwater eutrophication (kg P eq)	Conscious	5.79E-04	5.33E-04	4.57E-05
	Average	9.69E-04	8.14E-04	1.55E-04
	Polluter	2.54E-03	1.44E-03	1.09E-03
Marine eutrophication (kg N eq)	Conscious	4.02E-04	3.46E-04	5.57E-05
	Average	5.76E-04	4.63E-04	1.13E-04
	Polluter	1.65E-03	8.89E-04	7.65E-04
Mineral resource scarcity (kg Cu eq)	Conscious	0.15	0.13	0.02
	Average	0.22	0.18	0.05
	Polluter	0.63	0.34	0.30
Fossil resource scarcity (kg oil eq)	Conscious	1.92	2.44	-0.53
	Average	5.39	5.18	0.21
	Polluter	10.86	7.70	3.16
Water consumption (m3)	Conscious	0.05	0.05	-0.01
	Average	0.10	0.10	0.01
	Polluter	0.23	0.16	0.08