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Investigating the potential circularity of a phone using Life Cycle Assessment

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1 Introduction

The humble telephone has evolved into a complex, compact and lightweight smartphone that continues to grow in functionality and capability. In essence, the smartphone has replaced the need for numerous other products such as a separate camera, calculator, messenger or emailer and can even perform many functions previously handled by high performance computers. It is this functionality that has made the smartphone one of the most sought after and indispensable products of the developed world.

In 2019 there were 3.2 billion smartphone users globally, which is expected to grow to 3.8 billion users by 2021[1]. The embodied materials within these phones, including precious and rare earth metals, are therefore considerable. For example, it is estimated that 41 handsets contain 1g of gold, which is comparable to 1 tonne of gold ore[2]. These materials have both economic and environmental significance, but currently the circularity of these materials is extremely limited. Only 20% of 2016's e-waste is documented to have been collected and recycled despite rich deposits of gold, silver, copper, platinum, palladium, and other high-value recoverable materials (Balde et al. 2017).

This report presents research on utilising life cycle assessment (LCA) to understand the life cycle environmental impacts of a smartphone in order to incorporate this information into a circular economy model (CE-model). The CE-model is a general equilibrium model that analyses how market actors and outcomes (i.e. raw material extraction, material flows and emissions) react to changes in policy instruments along the product lifecycle (Hennlock, et al., 2020).

The overall aim of the POLICIA project is to combine these models into an integrated assessment that will be able to address market failures and quantify policy effects of circular responses along the entire life-cycle of a product, from raw material extraction, production, consumption and waste management to recycling, reuse and remanufacturing.

The aim of the LCA work was therefore to enable the information and knowledge obtained through the assessment of a smartphone, to be incorporated into the CE-model, so that environmental impacts of policies can be directly modelled and optimised. This report serves as additional information to the main deliveries of the Policia project.

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[1] https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/

[2] http://www.bbc.com/news/blogs-magazine-monitor-28802646

1.1 About this report

The research presented in this report focuses on the first part of POLICIA project's research task, namely, to perform an LCA with the aim of incorporating the results into a CE model.

The work and report begin with a literature review to introduce previous work on LCA and circular economy of smartphones, see chapter 1.4.3. The report then proceeds to chapter 3 where the LCA methodology, both for the base line LCA as well the business model assessment, and CE-model integration are described.

The study is based on a representative smartphone (the Sony X5) to identify hotspots of environmental impact, with results presented in chapter 4. Based on the results of the base case LCA the specific flows and activities with highest contribution to the total impact were identified and possible improvements identified. Based on this, several business models were assessed in terms of their potential to realise the identified improvement potential. The studied business models include increased modularity and cloud offloading. From the business model assessment conclusions were drawn about how different set-ups could influence important variables in the environmental impact.

The LCA methodology and assumptions are presented in the main report so that they are accessible to non-LCA practitioners, but the report also contains several appendices that will deepen the knowledge of the modelling choices, data collection and boundaries of the LCA. The information in the appendix is mainly targeted towards LCA practitioners and included for the purpose of review, reproducibility and transparency of data.

The intended audience of this report is practitioners and researchers within the fields of LCA, circular economy modelling and sustainability assessments. The study and results are focused on the task of integrating LCA and circular economy modelling, as well as assessing circular economy solutions in terms of LCA.

The results are not a footprint of an actual Sony smartphone, as the data collection and methodology behind the study aimed to fulfil the specific research goals related to circular economy, rather than perform a full inventory of the phone. For such results see Ercan et al (Life Cycle Assessment of a Smartphone, 2016).

1.2 What is Life cycle assessment - LCA?

Life cycle assessment (LCA) investigates the environmental impacts related to a product or a system during its whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including; material production, manufacturing, use and maintenance, and end-of-life.

LCA is a widely used and accepted method for studies of environmental performance of various products and systems, for more details on how an LCA is performed and what parts it contains, see Appendix A.

The LCA in this report is performed in accordance with ISO 14040:2006 (European Committee for Standardization, 2006) and ISO 14044:2006 standards (European Committee for Standardization, 2006).

1.3 Goal and objectives

As noted in the introduction, the overall project aim of the POLICIA project is to combine LCA and CE-modelling into an integrated assessment that will be able to address market failures and quantify policy effects of efficient combinations along the entire life-cycle of a certain product, from raw material extraction, production, consumption and waste management to recycling, reuse and remanufacturing.

The aim of the LCA work was therefore to enable the information and knowledge obtained through an LCA of a smartphone, to be incorporated into the POLICIA CE-model, so that environmental impacts of policies can be directly modelled and optimised. The full project is presented in a final report to Naturvårdsverket (Hennlock et al. 2021a).

The objectives were to:

1. Identify the environmental hotspots throughout the life cycle of a case study smartphone
2. Model and quantify environmental impacts based on changes (scenarios) in the smartphone's components and hotspots,
3. Develop ways to incorporate environmental impact data into the CE-model (presented in separate paper (Hennlock et al. 2021b)).

The LCA therefore consists of three main components:

1. Baseline LCA – first a baseline LCA of a Sony Z5 smartphone and an exploratory approach of how knowledge from identifying the hotspots could be utilized with an economic based model, called the CE-model.
2. LCA modelling of circular scenario changes and business models –
3. Development of integration of LCA and CE-Model (Hennlock et al. 2021b)

Each of these are explained in the following sections.

1.3.1 LCA Goal and scope

The goal of the LCA performed in this study is to find the most important environmental hotspots in the life cycle. Based on these identified hotspots, scenarios are investigated to assess what opportunities there are to improve on the environmental impact of these hotspots, and which parameters that influence this improvement.

The results from the LCA – which finds the impact from different stages – and the scenario analysis – which finds the parameters that control potential improvements –were transformed into equations that represent the life cycle impacts. The results from the LCA are incorporated as constant impacts, and the improvement potential is included as variables that correspond to the identified parameters.

The scope of the LCA and the scenario analysis is limited to the assessment of one model of phone, the Sony X5. Although exact component composition may vary between brands, most smartphones have similar material composition and share the same base-line electronic components. For this reason, including only one phone in the scope still gives results that will be indicative of most modern phones.

The LCA does not cover the supporting infrastructure needed to assure the full function of the phone in use. This means leaving out of scope things like network, servers, content creation etc. Only the physical phone, its accessories (like charger) and its production is included. In the use phase it is only the electricity used for charging that is included.

End of life handling of the phones is included in the scope. Several alternative end of life fates are modelled, including formal electronic scrap recycling, informal recycling in the developing world, disposal as well as municipal recycling. These options ensure that both controlled and uncontrolled scrap handling is included in the scope.

A detailed description of the LCA modelling choices, limitations and cut-offs can be found in Appendix B.

1.3.2 Target product and component abbreviations

The assessment uses data from a Sony X5. The inventory is divided between components. Table 1 lists the included components in order of decreasing weight. For each component the material content, production energy and end of life handing is included.

Table 1: The components of the phone are listed in the table in order of decreasing weight. In the report abbreviations are used for some of the electronics components, and these are also listed in the table.

Component	Abbreviation
Battery	
Charger	
Display	
USB cable	
Key Panel	
Cover	
Headset	
Other mech parts	
Printed circuit board	PCB
Shields	
Antennas	
Speakers	
Connectors	
Other components	
Cameras	
Integrated circuit	IC
Printed board area	PBA
Vibrator	
Microphone	
Light emitting diode	LED

Functional unit

A functional unit is used to relate the result to a fixed factor, to enable comparison of different cases based on the prerequisites of a certain function. The desired function is to provide a user with the function having of a physical phone, for the time period of one year.

Chosen functional unit: 1 phone per 1 year

The amount of material needed, weight, durability and use phase details all relate to being able to perform this function. The results are also normalized per year.

This study has chosen to view the function of the phone as linked to its physical existence. Assessments of for example displacements potential from other technical systems are not included. An example of this would have been to look at the environmental benefits of having the phone replace computers, cameras etc.

Selected impact categories

The selection of impact categories was based on both the wishes of the project commissioner and an iterative analysis of the results, where we identified categories that showed significant differences in the results. More detailed information on the categories can be found in Appendix A.

A category looking at climate change was desired by the commissioners, and additionally proves to be representative of most of the impact categories that relate to air emissions like acidification, eutrophication, particulate matter and photochemical ozone formation. In this study the CML method *Climate change midpoint, excl biogenic carbon (v1.09)* was used. It measured the climate change impact in terms of CO_2-equivalents.

The project commissioners also requested a focus on toxicity and for this reason the USEtox category was included. USEtox is a standardised environmental model to evaluate impacts of chemicals on human health and organisms (http://www.usetox.org) (Rosenbaum, o.a., 2008). USEtox uses CTU= comparative toxic units (CTU) per kg of emission, a unit that estimates the increase in morbidity caused by the emission. Toxicity is based on fate, exposure and effects, which is difficult to determine from a LCA inventory. Therefore, the results will have a degree of uncertainty and should not be directly compared to other LCAs but are adequate for the project purpose of comparing the scenarios generated in the project.

Mobile phones are electronic devices, and as such require several rare metals in their electronic parts. For this reason, it was relevant to include a category to assess the risk of material depletion. The chosen category was the CML method *Resource depletion, mineral, fossils and renewables, midpoint (v1.09)*. The method uses a reference flow of antinomy as a unit (similar to how CO2 is the reference unit for climate change). Each materials score is calculated based on the annual production in relation to the total amount of material in the Earth's crust, and the score is set in relation to antimony (van Oers, Guinée, & Heijungs, 2020).

As a complement to these impact categories a monetary valuation method was used, both to evaluate all emissions with one method, but also to have a result in a unit that fits more closely with the economic CE modelling. The chosen method was the Environmental Priority strategy (EPS), a monetary valuation method measured in ELU, a unit that corresponds to € (Steen, 2015).

Table 2: Included environmental impact categories and monetary valuation method

Impact category	Category indicator	Reference
Global warming potential (GWP)	kg CO2 equivalents	CML2001 - April 2015
Resource depletion potential (EP)	kg Sb equivalents	CML2001 - April 2015
Human toxicity potential (AP)	CTUh	USEtox
EPS	ELU (€)	CML2001 - April 2015

1.3.3 Data gaps and limitations

Based on the scope of the study, the inventory analysis did not deep dive into the detailed material content or production specification of the phone. Somewhat aggregated data from Sony was used as input, and instead focus was put on the integration with the CE-model. This does however imply that there are data gaps in the life cycle model.

This implies that the results are not suitable as footprints of a smartphone but should be viewed as inputs for a CE-model. The results can also be used to highlight potentials of different business models, but the numerical results and magnitude of improvements can be misleading if used out of context.

Supporting materials in production, like chemical, are not included. Production electricity is detailed for the most important components only, based on Sony’s own LCA. It is also likely that the actual material content may be more detailed in terms of specific alloys and special materials than what is stated in the bill of materials that this study is based on. None of these factors in concluded to have any impact on the results and conclusions in this study, although it does influence the potential to draw more overarching conclusions from the study.

2 Background and Literature Review

2.1 Introduction - the Smartphone

Environmental impacts of all products, including, smartphones generally occur at each stage of the life cycle from extraction of raw materials, production through to use and disposal. This section focuses on studies related to the life cycle environmental impacts of smartphones.

Sales of smartphones continue to grow with over 1.5 billion sold in 2017 (Gartner 2018) and a similar number of phones reach the end of first use, and are either discarded, stored or reused. A typical smartphone weights around 200g and consists of 25% metals, 30-50% plastics and the remainder consists of glass, epoxy and ceramics (Geyer, 2010). There is therefore a significant flow of metals and other materials associated with the smartphone market and disposal. The PCB for instance is composed of precious metals meaning that approximately 267.3 tonnes of gold and 7 275 tonnes of silver are consumed annually for manufacturing mobile phones and other electronics (Vats and Singh, 2015). Currently only about 15% of these are recovered with the remainder either in storage or landfills (Vats and Singh, 2015).

2.2 Environmental Impact of Smartphones - State of the Art

2.2.1 Past studies

Recognition of the importance of mobile phones began over twenty years ago. They were singled out from the electronics material stream for research by European policy makers in the mid-nineties (Clift R, 1997). Industry led research by the European Trade Organisation for the Telecommunications and Professional Electronics Industry (ECTEL) produced a series of publications in late 1990's (Geyer 2010). These were life cycle based and covered energy and cost assessments, focussing in particular on end of life management. McLaren et al (1999) noted that the take back and recycling of phones was environmental beneficial, and the magnitude of this benefit depended on choices of EoL management. Consistent with CE thinking, they highlight that component recovery is significantly more preferable than metals recovery, but that this is increasingly difficult to pursue due to rapid technological changes. Further research, from Guide et al, (2003) and Skerlos et al. (2003) examined mobile phone remanufacturing and provided economic and environmental assessments. Skerlos et al. (2003) speculated that remanufacturing could add to the net environmental burden of the telecom industry but did not perform a LCA analysis.

More comprehensive LCA's were subsequently published in 2004 by McLaren and Piukkula (2004) and Malmodin (2004) who focussed on the 3G network. Huisman (2004) also used LCA to examine the environmental and economic consequences of the WEEE Directive on mobile phones. They compared the current situation of sending EoL handsets entirely to a Boliden copper smelter to the WEEE requirements (WEEE Directive Annex II) of selective treatment of printed circuit boards with manual dismantling. The study found that the very high costs of manual dismantling were not balanced by improvements in environmental performance.

Meanwhile, Scharnhorst et al. (2006) looked at the environmental effects of the EoL of a phone network and the consequences of upgrading from 2G to 3G. They found that material recycling would help lower the environmental impact of production by 50%.

LCA's have already led to major improvements. For example, early LCA's including those by Nokia (2005a) identified that the standby power consumption of the charger accounted for a major portion of environmental impact. They also found that:

- The production and the use phase are the most important phases in the life of a mobile phone.
- The recovery of metals, especially precious, is crucial to reduce EoL impacts. Recovery of plastics does not result in much reduction of environmental impact.
- Components in order of importance for environmental impact are PWBs, ICs and LCD. Solder paste was also important for one impact category.
- Bromine compounds are responsible for most of the toxicity of the phone as well as lead compounds.
- Air transport of components represents almost all the impacts from the transport phase.

Similarly, Yu et al. (2010) found that 50% of energy consumption across a mobile phone's life cycle occurs in manufacturing, whilst only 20% occurs during in the use phase. However, together with supporting infrastructure, mobile phones account for a 0.17% of Chinese energy. Ercan et al. (2016) produced similar results for an LCA of a smartphone, showing that with an operating life of 3 years, production accounted for 84% of the life cycle Global Warming Potential of 57 kg CO_2e. The integrated circuit alone accounted for 58% of GWP. Meanwhile, the use stage accounted for only 7 kg CO_2e. This suggests that efficiency improvements have significantly reduced the energy use of the mobile phone and shifted the majority of environmental impact onto the production stage. Here too there have been significant improvements due to Moore's Law, but increasing demands for increased processor (or IC) performance have reduced the corresponding energy reduction of production. This will be further discussed in the next section.

Research on the environmental impacts of mobile phones has risen in parallel with the large increase in the use of mobile and smart devices. Hence, a recent literature review of waste management and recycling trends for mobile phones from 1999 to 2015 found that most research has been performed relatively recently (Sarath et al. 2015). The major topics of literature were found to be material recovery and review of waste management options. Sarath et al. (2015) proposed that economically and environmentally beneficial refurbishing or recycling is clearly possible from the literature.

2.2.2 The Integrated Circuit

Other work relevant to this study has focussed on chips and their environmental impact (Boyd 2009, Williams, 2002; Villard, 2015). Williams et al. (2002) focused on material flow in their paper landmark paper titled "the 1.7-kilogram microchip". It highlighted that despite the increasing efficiency of the microchip and its decreasing size the associated material flows, and waste remained high.

However, it has been noted in the literature that in general the current state of art for LCA's of microchips is insufficient (Villard 2015). In addition, the current eco-invent dataset for wafer IC's was suggested as obsolete for showing large differences with other deeper studies (Schmidt et al. 2011).

This was a similarly reported in 2002 by Williams et al. (2002), who noted that there was little consensus on the impact of the semiconductor industry, and whilst companies might know publicly available data is scarce. By 2009, Boyd (2009) also notes that LCI data for the energy used and emissions from semiconductor chemicals production are not available. This situation was still noted by Villard (2015).

Keeping up with the fast-paced electronics development is a key challenge for LCA and other forms of analysis. The semiconductor industry is still complying with Moore's Law which states that the number of transistors that can be placed on an IC doubles every two years (Villard, 2015). This is environmentally beneficially because there are more transistor devices per wafer area, meaning a smaller wafer is needed for a given function and smaller devices require less energy.

However, more transistors mean more computational power for small devices in phones, which also allows more capabilities (such as word processing, gaming and high quality photos) which can typically result in a need for more memory and storage. Hence the overall benefits are difficult to determine without deeper consumer behaviour studies.

Nonetheless Villard (2015) concludes that life cycle thinking is immature in the semi-conductor industry and there is a need for reporting standards on chip performance. Recent LCA's of electronics (Higgs et al. 2009 and Boyd et al. 2010) suggest that for memories and processing the largest impacts were in the use phase, although Schmidt et al. (2011) found that manufacturing accounted for between 15 to 98% of the value chain impacts using IMPACT2002+[3].

The available literature therefore shows the dominance of the production phase to the life cycle GHG emissions (Suckling and Lee, 2015). However, since smartphones are increasingly reliant on the internet for numerous functions a few studies have also considered the associated impact. Ercan et al. (2016) found that the network (which included mobile networks and data networks (data centres, transmissions and IP core networks) accounted for a further 43 kgCO_2e. Meanwhile Suckling and Lee (2015) estimated that a server increased the use phase impact from 8.5 to 18.0 kg CO2-eq, whereas inclusion of the network increases the use phase by another 24.7 kg CO2-eq.

2.3 End of life

This section focusses on the end-of-life management of the smartphone, a critical stage for circularity, and what is known. There is sparse data available for what happens to smartphones at the end of their useful life, and a number of uncertainties. However, it appears that collection rates are very low (Riisgaard, 2016) even though there have been over 100 documented collection schemes in the UK alone (Ongondo and Williams, 2011). These originate from various sources such as manufacturers, retailers, mobile network service operators, charities and by mobile phone, reuse, recycling and refurbishing companies (Ongondo and Williams, 2011). The low collection rates are a significant barrier to circular flow and mobile phones have been found to be hibernated longer than they are used (Wilson et al, 2017). More recently, a study by Gartner (2015) found that 7% of phones go to recycling programmes and 64% get a second life (used by another consumer, typically a family member or 41% sold privately or traded). Another study suggested that 15% of phones are collected in Europe (EMF, 2012).

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[3] IMPACT2002+: Impact assessment methodology originally developed at the Swiss Federal Institute of Technology – Lausanne - http://www.impactmodeling.net/

A distinction needs to be drawn between mobile phones and smartphones as their fate is not necessarily the same. Nonetheless, it appears that for both, take-back is generally ineffective and more prompt return of phones into the refurbishment or recycling system could result in reduced impacts through further reuse and reductions in toxic emissions through undesirable disposal routes (Suckling and Lee, 2015). Currently, it appears that reuse is more common than effective recycling (Geyer, 2010). But for smartphones the literature points to increasing opportunities for repair of smartphones and a willingness for consumers to pay (Riisgaard, 2016). The market for refurbished phones sold to end users was predicted to reach 120 million units by 2017 with a wholesale revenue of approximately $14 billion (Gartner, 2015).

The typical smartphone consists of many components, including the battery which is removed for a separate recycling process (and from which cobalt is mainly recovered). For the remainder, the material composition is roughly 25% metals, 30-50% plastics and the remainder consists of glass, epoxy and ceramics (Geyer, 2010). Most of the metal mass consists of copper, with aluminium and steel making up the remainder (Geyer, 2010; Ercan et al. 2016). There are also precious metals such as silver, gold and platinum. Studies suggest that in theory at least with current technology, it is possible to recovery close to 100% of the metals (Geyer 2010; Baka et al, 2016; Bigum et al, 2012). However, it seems that most critical metals are currently not recycled from electronics and 25% has been suggested as a realistic recovery rate for metals in Nordic countries due to losses occurred in the pre-treatment chain (Baka et al. 2016).

However, the ease of recycling metals is subject to several conditions, especially the mix of metals, the product structural design and whether physical separation can first occur for some metals (van Schaik and Reuter, 2016). In light of this, Fairphone investigated three options for recycling their smartphones (Fairphone, 2017):

1. Smelting and metal refining - feeding whole Fairphones into a high-temperature metallurgical furnace, recovering mainly metals, alloys, inorganic compounds and energy. This gave the lowest material recovery by weight (14% metal recycling, 25% total material recycling and 36% recovery (= recycling + energy recovery) for all materials)
2. Dismantling - Separating Fairphone 2 modules and putting them through the most suitable metallurgical and plastic recovery processes. This gave better material recovery and the widest variety of materials weight (19% metal recycling, 28% total material recycling and 31% recycling/recovery).
3. Shredding and sorting - Removing the battery and feeding the rest of the phone through a cutting mill. The resulting scrap is then separated into the relevant processing streams (metallurgy, refining and plastic recovery). This gave the highest material recovery (22% metal recycling, 30% total material recycling and 31% recycling and recovery) but less variety of materials than route 2 could be recovered.

The study also concluded that (Fairphone, 2017):

- High recovery (80% to 98%) rates for gold, copper, silver, cobalt, nickel, palladium, platinum, gallium, indium and zinc and modularity promotes their recovery.
- Recovery depends on recycling method. For example, the recovery of magnesium is 0% ins route 1 as it completely oxidizes in the furnace. However, route 3 (where magnesium is liberated and sorted from the other materials into a high quality recyclate), can recover 92% or route 2 can recover 90% but with less CO2 emissions.
- Separation and separate processing are required for Tungsten and tantalum (offering an argument to even extend modularity).
- Plastic recovery improves with upfront physical separation (another advantage of modular design).

Where recycling is not performed, final disposal of smartphones is either via landfill, incineration or illegal dumping. The metals contained in smartphones can be extremely damaging to human health or the environment if disposed of inappropriately. In absence of adequate recycling Uryu et al. (2008) showed that disposal to landfill was preferable to incineration when considering emissions of gallium and arsenic.

The informal recycling sector, sometimes referred to as illegal recycling, continues to undergo strong growth (Chi et al. 2011). Some studies estimate that of the 64% of waste ICTG was handled by informal recycling, 19% formal recycling and 17% landfill (Liebmann (2015); although there may be large uncertainties with this study).

2.3.1 Informal recycling

There has been a strong growth in the informal recycling sector for WEEE in developing countries due to a high demand for second-hand electronic appliances, gaps in environmental management enforcement and because selling e-waste to individual collectors is standard (Chi et al. 2011)

However, informal recycling has potentially major environmental and health impacts due to the primitive techniques used for recovery of materials and disposal. For instance, PC boards are commonly heated until the connecting solder is melted. Heating is normally done using coal grills, propane torches, kerosene burners or similar devices (SEPA, 2011). Chips are sorted into those for resale and those to be treated by acid separation techniques, collected solder is sold, and PC boards are further burnt, or acid digested to recover the metals (SEPA, 2011).

In acid digestion PC boards and other components are dissolved in strong acid solution which is then heated over open fires and stirred for hours to precipitate the metals. The metals are recovered whilst the waste acids and sludge are often dumped on open ground or in nearby water bodies (BAN & SVTC 2002). Studies of land utilised for informal recycling have indicated high levels of contamination at sites in the Philippines, with Au, Ag, Pb and Sb (Terazono 2016).

The formation and emission of pollutants is favoured in such conditions due to the poor and variable combustion conditions (Evans & Dellinger 2003, Gullett et al 2007). In particular, Gullett et al. [2007] detected very high emissions of PCDD/Fs and PBDD/Fs, especially in the open burning of insulated wires (around 12 000 ng TEQ/kg of wire). Meanwhile, high PBDD/F emissions resulted from the combustion of PC-boards (Gullett et al. 2007; Leung et al. 2006).

Plastics are usually shredded, separated by colour or density and then further grinded, often by children (SEPA, 2011). The plastics may then be melted and extruded for new applications in rooms that have insufficient ventilation and workers have no respiratory protection (Brigden et al 2005, BAN & SVTC, 2002). However, due to impurities and unmatched colours many e-waste plastics are considered unusable and are dumped or burnt on open fires BAN & SVTC 2002.

Addressing informal recycling with suitable policy is challenging for several reasons. Chi et al (2011) note that simply prohibiting or competing with the informal collectors and informal recyclers is not an effective solution. In that case they suggest, that recycling systems should be designed to incorporate informal recyclers with supporting policies to improve recycling rates, working conditions and the efficiency of informal recycling. This is reinforced by other studies (e.g. Sepúlveda et al. 2010) that recognise that the informal sector needs to be incorporated into formal WEEE recycling because many livelihoods depend on it.

2.4 Past Eco-efficiency improvements

Since mobile phones first emerged in the 1980's there have been enormous technological advances in materials and components. This has resulted in a reduction in weight from 10 kg to less than 100 grams, whilst standby and time has increased dramatically (See Figure 1). Hence there have been major improvements in energy efficiency of electrical and electronic components, software development and change in battery chemistry (Nokia, 2005a). Batteries for instance have evolved from lead to NiCD, NiMH, Li-ion through to Li-polymer. These changes, as well as greatly improving energy use have led to the reduction of toxicity effects from the phase of lead and cadmium from the batteries.

Another related effect of smartphones is that they have to some extent replaced the need for many other products that perform functions including: alarm clock, games, internet, music player, radio, camera, GPS, health monitor, reading documents, video conferencing, banking, public transport payment, and an expanding list of other functions (see for example Judl et al. 2012).

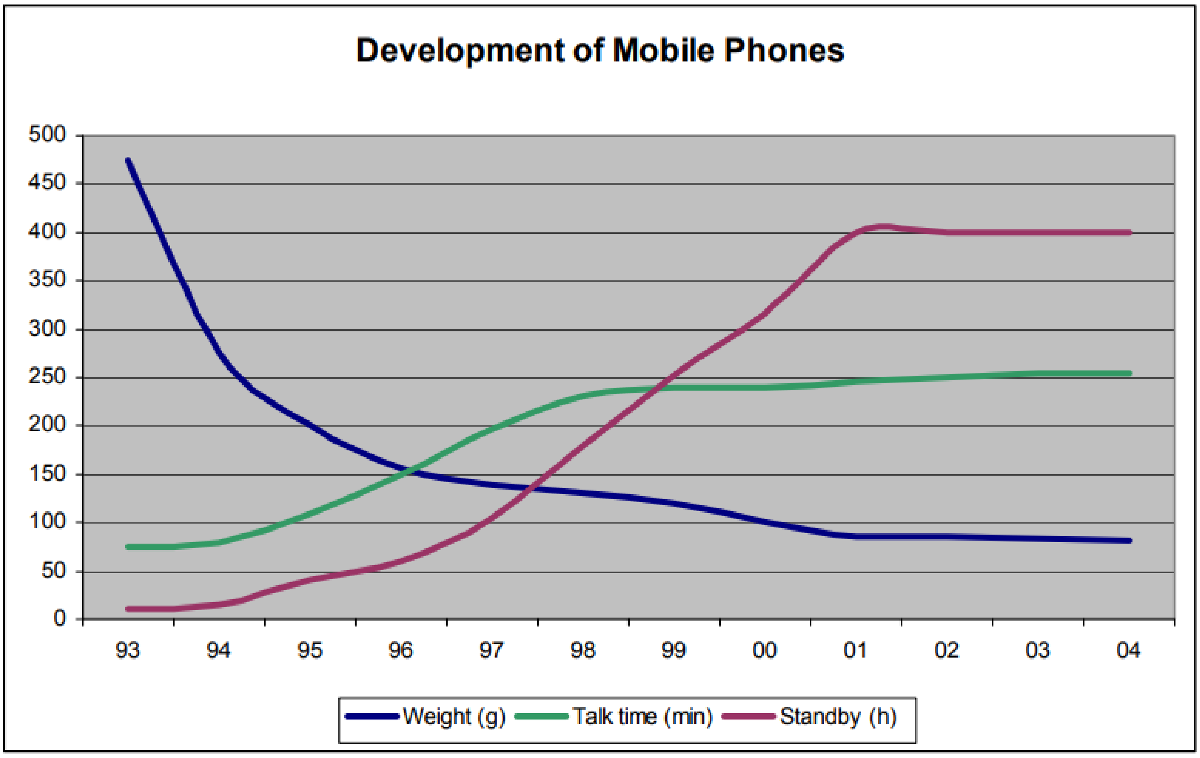


Figure 1: Changes in phones characteristics from the early nineties to 2004 (Source: Nokia, 2005a)

Nokia (2005a) note that for both the Printed Wiring Board (PWB) and the Integrated Circuit the raw material processing and manufacturing are the most significant phases. The presence of gold in the finish of the PWB or the wires and substrates of the IC packaging accounts for most of the impacts from the raw material acquisition. The energy consumption during the manufacturing is the primary environmental impact of manufacturing. They also found that the life cycle environmental impacts of the:

- PWB is proportional to its surface area, number of layers and amount of gold
- IC are proportional to the area of the fabricated die in the IC, the number of mask steps during fabrication of the ide and the amount of gold.

In addition, IC is also energy intensive because the internal manufacturing environment must be extremely clean (Villard 2015). Significant energy is therefore used for heating, ventilation and air conditioning.

2.5 Business Models

2.5.1 Introduction

Circular business models have received increasing attention since the promotion of CE by the Ellen MacArthur Foundation (EMF, 2013). As Osterwalder and Pigneur (2010) state: "A business model describes the rationale of how an organization creates, delivers, and captures value." They define how a company develops value in its business (Magretta, 2002) and are strongly connected to innovation capability (Teece, 2010; Chesbrough, 2009; Yunus, et al 2010). There are nine basic elements or building blocks to a business model: Customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships and cost structure (Osterwalder and Pigneur, 2010).

The choice of business model determines the architecture and potential expansion paths of the business but changing business models is challenging for companies once one is established (Teece 2010). Variations of business models applied to a technology or product innovations will yield different economic outcomes (Teece 2010).

The term "circular business model" has only recently begun to be utilised in academic research (Oghazi and Mostaghel, 2018) rising from 1 mention in the literature in 2013 to 19 in 2016 (Mostaghel et al. 2017). Even so, related practices such as leasing, and renting are well established and product service systems have gained increasing attention over the last twenty years.

CBM's by description are intended to "provide significant economic benefits in addition to new ways of forming partnerships with suppliers and connecting with customers" whilst they "generate essential environmental benefits as a result of the improved resource productivity they offer" (Guldman, 2016). CBM's have been successfully applied in a range of business sectors and for different size companies, but it is critical that they are tailored to each company (Guldman, 2016). However, a CBM represents a radical change, requiring a new approach and new business processes (Bocken et al, 2016).

The types of business models have been categorised in different ways, but in principle involve creating value within the inner loops of the CE model, extending the life or cascading the use. These aspects were highlighted by the Ellen MacArthur Foundation (2013) and Nguyen, Stuchtey and Zils (2014) who pointed to four distinct methods for value creation: power of the inner circle, power of circling longer, power of cascaded use and power of pure circles. Similarly, from a review of 120 CE case studies Accenture highlight five business models (Accenture, 2014):

- Circular supplies – which includes renewable energy, bio-based or fully recyclable input material to replace single lifecycle inputs
- Resource Recovery – recover useful resources/energy from disposed products or by-products

- Product Life Extension – extend working lifecycle of products and components by repairing, upgrading and reselling.
- Sharing platform – enable increased utilisation rate of products by making possible shared.
- Product as a service – offer product access and retain ownership to internalise benefits of circular resource productivity.

Guldman (2016) combined these to show how different business models incorporate different methods of value creation. For example, product as a service typically involves "circling for longer" as well as the "inner circle", but not pure circles or cascaded use. There is also a need to address the challenges of applying CBM's, particularly the need for customers to understand and accept the new models and services (Guldman 2016).

2.5.2 Circular design strategies

For many companies a move towards the circular economy essentially involves addressing both changes in design and changes in business models (Bocken et al. 2016). Circular business models can be distinguished from circular design strategies, which include "design for" (Sauerwien et al. 2017):

- Attachment and Trust
- Standardisation and compatibility
- Reliability and durability
- Upgradability and adaptability
- Recyclability
- Ease of Maintenance and Repair
- Dis- and Reassembly.

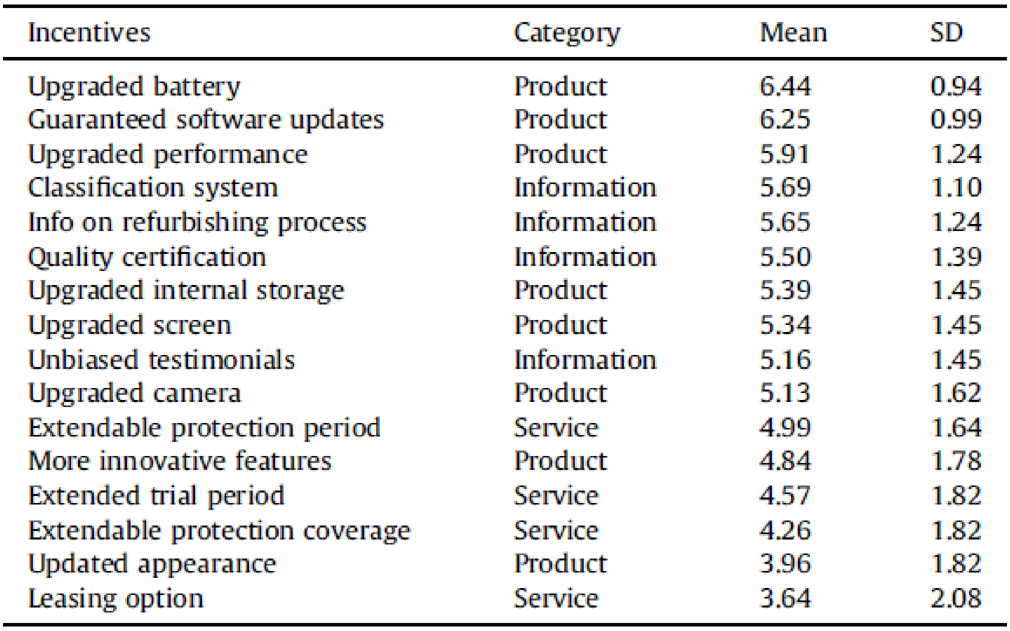
However, as EMF (2017) highlight in their report on CBM's in the built environment, successful CBM's will require action from a range of stakeholders including suppliers, service produces, contractors, end of life companies, in addition to designers. New business models can potentially foster: greater control of resource streams to capture value, innovation in the supply chain where new businesses develop to utilise resources, to refurbish and reverse logistics; enhanced collaboration of stakeholders in the supply chain; and services that capture value in products and resources (EMF, 2017). Bocken et al. (2016) highlights that although one of the circular strategies is durability and longer life, this approach may not be circular from a material flow perspective.

2.5.3 Circular Business Models for the Phone

Business models for phones need to consider both the acceptability from the phone stakeholders and aspects such as whether refurbished phones cannibalise new product sales (Geyer, 2010; Guide 2010). Environmental aspects must also be integrated. For example, the displacement rate (i.e. actual materials not needed to be extracted) has been argued as the single most important factor by Geyer et al (2010) and Zink and Geyer (2017).

Business models also need to be considered in tandem with potential design changes and requirements depending on the aim of the business model (e.g. increased recyclability or longer life) (Bocken et al. 2016). In addition, there needs to be consideration of what is currently possible and most likely be repaired or refurbished. Mugge et al. (2017) highlight 16 potential different options for phone refurbishment and found that upgraded batteries, guaranteed software updates and upgraded performance offered the biggest incentives for the intention of purchase. Refurbishment of phones is increasingly recognised as a viable business concept (Mugge et al, 2017; Guide and Van Wassenhove, 2001; Linton, 2008)

Table 3: Proposed incentives of refurbished phones arranged with the greatest incentive for the intention of purchase at the top (source: Mugge et al. 2017)



Incentives	Category	Mean	SD
Upgraded battery	Product	6.44	0.94
Guaranteed software updates	Product	6.25	0.99
Upgraded performance	Product	5.91	1.24
Classification system	Information	5.69	1.10
Info on refurbishing process	Information	5.65	1.24
Quality certification	Information	5.50	1.39
Upgraded internal storage	Product	5.39	1.45
Upgraded screen	Product	5.34	1.45
Unbiased testimonials	Information	5.16	1.45
Upgraded camera	Product	5.13	1.62
Extendable protection period	Service	4.99	1.64
More innovative features	Product	4.84	1.78
Extended trial period	Service	4.57	1.82
Extendable protection coverage	Service	4.26	1.82
Updated appearance	Product	3.96	1.82
Leasing option	Service	3.64	2.08

The literature points to increasing opportunities for repair of smartphones and a willingness for consumers to pay (Riisgaard, 2016). More than 10% of consumers require screen repairs or other damages each year due to the fragility of smartphones (Politiken, 2012). Repair and maintenance across the life cycle of smartphones therefore presents a viable business opportunity that is being exploited by entrepreneurs (Riisgaard, 2016).

A further crucial factor that influences the environmental impact is what users do at the end-of-use of the phone. Riisgaard (2016) highlights that collection rates for phones are very low. This is a significant barrier to circular flow and mobile phones have been found to be hibernated longer than they are used (Wilson et al, 2017).

Green Alliance (2015) propose six business models suitable to increase the circularity: Software longevity, better reuse, minor modularity, cloud offloading, parts harvesting and remanufacturing and DIY repair. Each of the business models requires different combination of three main elements: hardware, software and the business model (Green Alliance 2015). For example, minor modularity can help address common repairs such as replacing the phone or the screen. Cloud offloading however takes a different approach, utilising the cloud for computing power for core tasks. The cloud has continued to develop over the last decade and for the smartphone has the potential to alleviate battery consumption, offload computation and backing up data (Barbera et al. 2013). Cloud offloading bundles cloud access, smartphone and performance, rather than selling them separately (Green Alliance, 2015). Smartphones could for example calculate the most efficient or fastest option and judge whether to task offload or not (Altamimi et al. 2015). This has been shown to have the potential to reduce overall energy consumption (Said et al. 2017).

3 Methodology and life cycle inventory

This section presents the methodology used in the LCA work, both to model the life cycle environmental impacts of a smartphone (section 3.1), and the method to evaluate key parameters for improvement in circular business models (section 3.2).

For more details on the underlying LCA methodology, see Appendix B. All datasets used are listed in Appendix D.

3.1 Baseline LCA model

The baseline LCA focuses on one phone, a Sony X5. All life cycle inventory data, including material composition, manufacturing data, use, maintenance and end-of-life handling are based on this model. The baseline LCA also aims at representing the current linear life of the product. A list of the components in the inventory can be found in Table 1 in section 1.4.2.

3.1.1 Material extraction and processing

The downstream data for raw material extraction, refining and distribution was taken from GaBi datasets, while the information on material content was taken from previous work by Sony. The bill of materials used to represent the material content of the phone results in the material composition shown in Figure 2 (Ercan, Malmodin, Bergmark, Kimfalk, & Nilsson, 2016).

An assumption was made that the material content of the phone was a good approximation of the material inflow into production. This assumption is based on personal communication with Jens Malmodin at Ericson, suggesting that the majority of the production losses are recirculated back into the production, thus causing insignificant net losses.

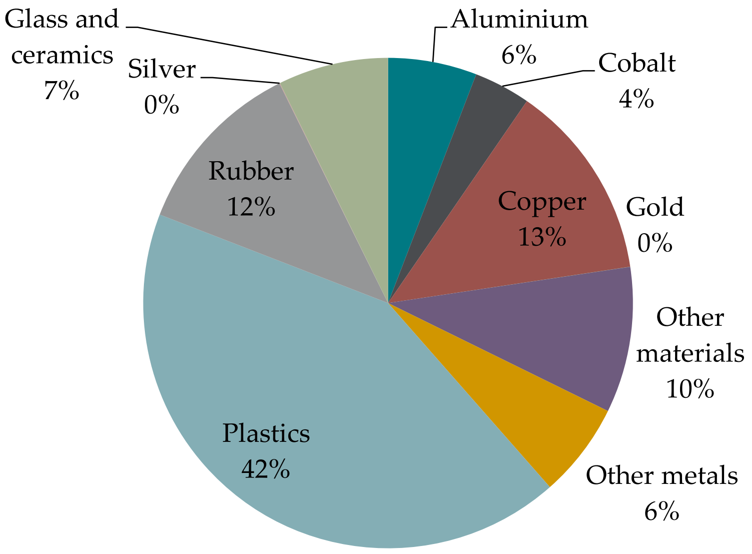


Figure 2: Material composition of the assessed mobile phone.

3.1.2 Manufacturing and transport

Product data was included in the follow stages:

1. Transport of parts to assembly, with truck.
2. Component production stage requiring electricity, and a fossil energy mix, including transportation via airplane.
3. Complete phone assembly stage requiring electricity, diesel and natural gas.

The transport was assumed to be done in 34t EU5 trucks and the total transport was 10tonkm. The distance was based on previous LCA results indicating 0.45kg CO_2-eq. emissions from diesel-based transport (Ercan, Malmodin, Bergmark, Kimfalk, & Nilsson, 2016).

For the component production, information on electricity consumption is again taken from Sony and modelled to be East Asian electricity mix, in total 50,2 kWh electricity for all components.

The component production additionally requires some other energy sources, mainly heat from natural gas (40%) and oil/diesel (40%), in total 12,5 kg fuel for all components. The data used in the assessment additionally includes kerosene in the mix of other energy sources. Kerosene is used to model the jet fuel consumed when transporting components via airplane, a factor that was included in the reference LCA by Sony and therefore also included in the scope of this study.

The base case for the assembly was that it required 1.7 kWh of South Asia electricity mix, to represent the current production conditions.

3.1.3 Use phase and maintenance

The use phase of one phone consists of one first life and a fraction of second and third lives. These fractions depend on the average amount of phones being reused one or several times. The first use is assumed to be in Sweden, using 4kWh/year. In the base case the life length of the first use is 2 years, with 3 years total use. The base case for the scenario assessment focuses only on the first use, and thus is set to 2 years.

If the phone is collected and reused the second and third users have the same energy consumption per year (4kWh/year), but of course the total energy use depends on how long the phones are used and how many that have a second and/or third use. This in turn depends on the quality and the number of phones that are collected for reuse. This is discussed further in the following section on collection and reuse.

Maintenance data for the base case was based on assumption on typical replacement parts. There are few studies detailing the actual maintenance of phones today, and the cases chosen in this study aims to exemplify the importance of maintenance rather than claiming to accurately model it. The maintenance stage of this study for this reason includes:

- Display (base case: 1/3 average replacement per phone over the entire life).
- Battery (base case: 0,1 average replacement per phone over the entire life).
- Charger (base case: 0,1 average replacement per phone over the entire life).

3.1.4 Collection and reuse

The number of phones that end up being reused, recycled and disposed is approximated based on statistics of electronics waste. This data is one of the most uncertain inputs to the assessment, but also highly interesting as variable parameters, allowing the project to investigate the impact of increased collection, higher quality etc. An estimate for the base case was made based on available statistics. The parameters were then varied in the scenario assessment detailed in the next section.

According to a mapping done by Nokia (Tanskanen, 2012):

- Thrown in landfills = 4%
- Fully recycled = 3%
- Sent to emerging markets for reselling = 16%
- Passed on to families or friends = 25%
- Kept in drawers at homes = 44%
- Other = 8%

For the purpose of this study, passing on the phone to family and friends is just seen as prolonging the first life. Assuming that 44% is what is lost to drawers and storage, the remaining phones are handled either in landfills, recycled or sent for reselling. Table 4 shows how the statistics above are converted to represent the fate of the phones without the reuse within families included. In other words, this is base case assumption of what happens to phones when they reach the end of their Swedish lives.

Table 4: The percentages of phones meeting different end of life fates are detailed in the table. The table shows both the original data for Nokia where reuse by family was viewed as an event of its own. It also shows our adaptation of the data so that the actual end of life fates represents 100% and family reuse is excluded.

Handling	Nokia report distribution	Distributed of the phones disregarding family reuse
Landfill/municipal incineration	4%	=4/(4+3+16)*56 ≈ 10%
Electronics recycling Sweden	3%	=3/(4+3+16)*56 ≈ 7%
Emerging markets (assumed via collecting companies)	16%	=16/(4+3+16)*56 ≈ 39%
Stored	44%	44%
Family reuse	33%	0%

For the second and third uses it is the 39% going to collection companies that are important to consider. Of these it is assumed that 5% go to recycling due to a too poor quality. Of those exported, 60% go to European countries (modelled as East Europe), while 40% go outside of EU (in this work estimated to be to regions with poor formal recycling systems) (Hemström, Stenmarck, Sörme, & Carlsson, 2012).

Of the phones that end up in EU, an assumption has to be made of how many that are once again reused in a third life compared to being handled as waste. For this study, this figure was assumed to be 30%. The remaining 70% are handled according to waste statistics for eastern Europe; 20% is formally recycled, 40% is informally recycled and 40% is sent to landfill (Liebmann, 2015).

Based on these figures the total flow of phones to second life in Eastern EU are:

(39% to collection companies) * (95% sold on) * (60% sold to EU) = **22% of all phones**

For the rest of the world the flows are:

(39% to collection companies) * (95% sold on) * (40% sold to RoW) + (22% to EU) * (30% sold on to rest of world) = 15% + 7% = **22% of all phones**

Similar to the data presented in Table 4 the assessment must also contain information on how waste phones are handled in the second and third hand markets (Eastern EU and regions with poor formal recycling systems). Estimates of these flows are presented in Table 5.

Table 5: The split between different waste handling pathways for phones in different regions is presented in the table.

Handling	Eastern EU (2nd user)	Region with poor formal recycling (final user)
Landfill/municipal incineration	28%	10%
Formal recycling EU	14%	0%
Informal recycling	28%	90%
Sold to third use	30%	n/a

Based on these statistics Figure 3 shows all the flows associated with second and third life, as well as waste handling (see next section for modelling details for this last stage). These are the base case flows. In the scenarios these relations are varied, and in the integration with the CE model the flows are left numerically undefined so that they can be influenced by policies.

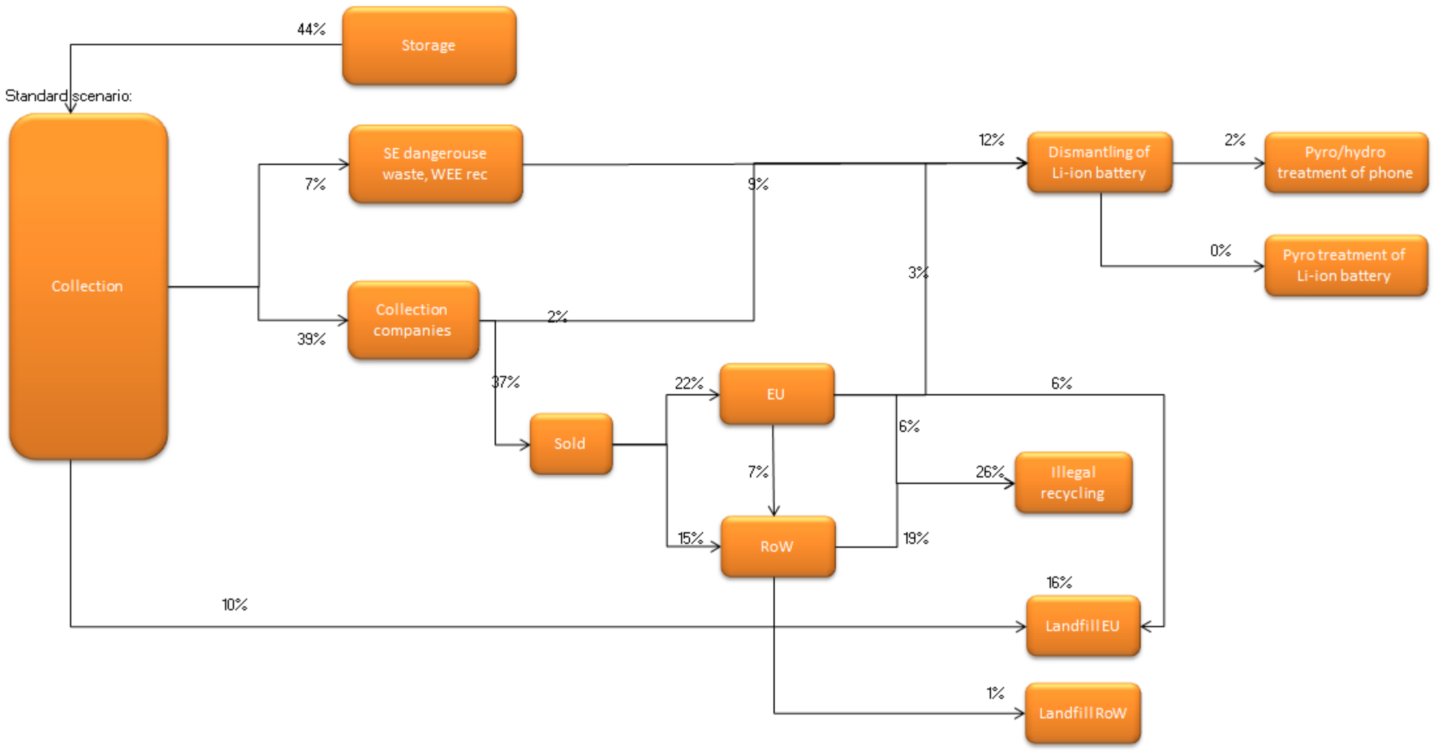


Figure 3: All the end of life flows of the baseline LCA are shown in the figure. The distribution to different areas after collection are best on adapted data from Nokia, estimates of phone second-hand market and statistics on waste handling in different regions.

The collection and reuse stages are in this assessment not assumed to have any significant added impacts in themselves. An added transport of 2 000 km truck was included to represent moving the phones between markets.

3.1.5 End of life handling

In this study, several different End-of-life fates are modelled for the phones. The number of phones ending up in the different streams depends on the collection rates discussed on the previous section. Table 6 shows how large part of the studied phones that on average ends up in each waste fraction, the table also highlights how these fractions are modelled in the LCA.

Table 6: The distribution of phones between different waste handling pathways is given in the table. The distribution depends on both on how the phones disperse over different regions (see previous section) and on how these regions handle their waste.

Handling	% of phones in the base case	Data reference for modelling
Formal recycling EU	12%	Pyrometallurgical treatment of the phone without battery from Fairphone LCA (Grüvendik, 2014). Pyrometallurgical treatment of battery from ecoinvent 3.3.
Informal recycling*	26%	The waste is split into three types of handling; open air burning of cables to retrieve copper (Gullet, o.a., 2007), chemical acid treatment of electronics containing valuable metals (Terazono, Oguchi, Yoshida, Medina, & Ballesteros, 2017), and dumping.
Landfill	17%	Modelled as plastic waste on landfill
Municipal incineration	0%	Modelled as average municipal incineration. Not included in base case but included in the CE integration.

**) Informal recycling might in the end be a process including both material extraction and landfilling of residue.*

For the formal recycling, the choice of pyrometallurgical treatment represents a case that is both a common handling of electronics but can also be viewed as a worst case for future handling. It is deemed a worst case since less of the materials can be retrieved from a process that includes incineration.

The availably of data for the information recycling is poor. Most reports give an outline of potential methods of handling, but without giving LCI data for the stages. Data for two different types of handling was however available; one was a from an assessment of emissions from open air burning of cables (a proxy for the conditions informal recycling occurs in) (Gullet, o.a., 2007) and the other was a dataset for the leaching of valuable metals in electronics with the help of a heated acid bath (Terazono, Oguchi, Yoshida, Medina, & Ballesteros, 2017). Especially the toxicity category is deemed to be impacted by this lacking inventory data as it is sensitive to changes in flows of metals to water and ground.

The end of life is modelled with the cut-off method. System expansion was avoided in the LCA in line with the goal of the project to deliver input for an economic model. The effects on a larger system are instead included in the circular economy model.

The full inventory for the end of life processes can be found in Appendix C.

3.2 LCA modelling of circular changes and business models

Based on the results of the baseline LCA of the smartphone the environmental impacts of key changes were investigated and quantified. This was divided into two parts:

1) Firstly, scenario analysis was performed. In this, the major hotspots, such as life cycle, stages, lifespan and the phones components were changed individually in order to quantify the effects on the life cycle environmental impact.
2) Based on the baseline LCA and scenario analysis two key business models were identified and an LCA was performed on a smartphone within each business model.

Several potential business models were highlighted in section 2.5 that can potentially be implemented to reduce the environmental impact of smartphones. These were reviewed in terms of how they could be modelled within the LCA model, for example in terms of extended life, use of components etc. Most of the business models in fact result in similar changes and so modelling all the business models was unnecessary. The following two business models were therefore selected, representing quite different approaches, and together representing all the potential changes to the important parameters:

1. Cloud offloading
2. Modularity

Table 7 shows the main gains and associated actions envisaged by the implementing of these business models.

Table 7: Implied changes to the smartphone life cycle from the two business models; cloud offloading and increased modularity, are detailed in the table. The effects of the business model that lead to environmental gains are listed.

Business model	Added components	Gain
Cloud offloading	More charging Design update by exchanged case	Longer life (5 years) Less integrated circuit (IC)
Modularity	**Light External:** Increased exchange of display, Added exchange of casing Added exchange of battery **Light Internal:** More connectors Increased exchange of display Added exchange of battery Update of camera Exchange of processing components (IC, PBA, PCB)* **High:** More connectors Increased exchange of display Added exchange of charger Added exchange of casing Added exchange of battery Update of camera Exchange of processing components (IC, PBA, PCB)*	**Light external:** Longer life (5 years) **Light Internal:** Longer life (5 years) **High:** Longer life (10 years)

*PCB=Printed cicuit board, PBA=printed board area, IC=integrated cicuit
See Table 1 for details on components

The gains and actions identified in Table 7 also need to be included in the LCA. In Table 8 the changes in the input data for the LCA can be found. The numerical variations are set to represent the changes and gains identified for each business model. The input that is left identical to the baseline is not included in the table. No infrastructure is included in this assessment.

Table 8: The table highlights how the LCI was varied to represent the investigated business models. Three different cases of modularity targeting different components are included, along with a case representing cloud offloading.

	Unit	Base case	Light modularity, external	Light modularity, internal	High modularity	Cloud offloading
Connectors (1 cable)	g	2.7	2.7	4.0	4.0	2.7
Connector Production energy	*kWh*	0.5	0.5	0.75	0.75	0.5
ICs	g	1.2	1.2	1.2	1.2	0.6
IC Production energy	*kWh*	40	40	40	40	20
IC fossil energy	*kg*	11	11	11	11	5.5
Maintenance display	pieces	0.1	0.5	0.5	2	0.1
Maintenance charger	pieces	0	0	0	0.33	0
Maintenance casing	pieces	0	1	0	1	1
Maintenance battery	pieces	0	1	2	3	0
Maintenance camera	pieces	0	0	2	3	0
Maintenance processing (IC, PBA, PCB)	pieces	0	0	1	2	0
Charging	kWh /a	4	4	4	4	6
Years in use	years	3	5	5	10	5

In short, the business case of modularity explores the life cycle effects of being able to exchange components and achieve a longer total life for the phone. The different cases within this model look at different degrees of exchange, and different target components for the exchange. The cases for cloud offloading instead explore the benefits of avoiding processing components in each phone in favour of having a centralized storage server.

4 Results

Life cycle impact assessment implies taking the inventory results for all flows (material, energy and emissions) and evaluating each material and emission's impact on different impact categories. This LCA uses the following impact categories:

- Global warming potential
- Human toxicity
- Abiotic depletion of non-renewable resources

As well as using the following monetary valuation method:

- EPS

The results in these categories/methods are presented below, with focus on the most impactful components and stages (hotspots).

4.1 Base case results and environmental hotspots

An overarching conclusion from the base case is that the majority of the impact over the life cycle occurs in the raw materials and production stage. The impact in the use phase is very small, which can be explained by the large share low-carbon electricity in the first use country (Sweden).

Even though informal recycling can happen under dismal circumstances, the effects are highly local, and do not give significant contributions to the global impact categories assessed. In addition, the inventory results for this stage had a high degree of uncertainty and data gaps, specifically for the toxicity category.

4.1.1 Climate change hotspots

In the base case the single largest life cycle impact comes from the production of the electricity used to produce the integrated circuit (IC). The production of the IC has a high energy consumption, especially considering its relatively low weight. In the base case the electricity used in component production is assumed to be South Asian electricity mix. This mix has a high part fossil-based sources and thus the potential to impact the results of the climate change category. The combination high electricity use in production and an impactful electricity mix results in the high production impact for the component production stage, specifically for the integrated circuit (IC) that can be seen in Figure 4.

The result in the climate change category is indicative also of the results in several other environmental impact categories. These impacts have in common that they relate to air emissions. Examples of impact categories with similar profiles include particle matter, acidification, eutrophication and photochemical ozone formation.

While climate change mainly is impacted by CO2-emissions these categories relate to other emissions like particles, NOx and SO2 PM, but regardless of this they share a similar impact profile, with similar hotspots.

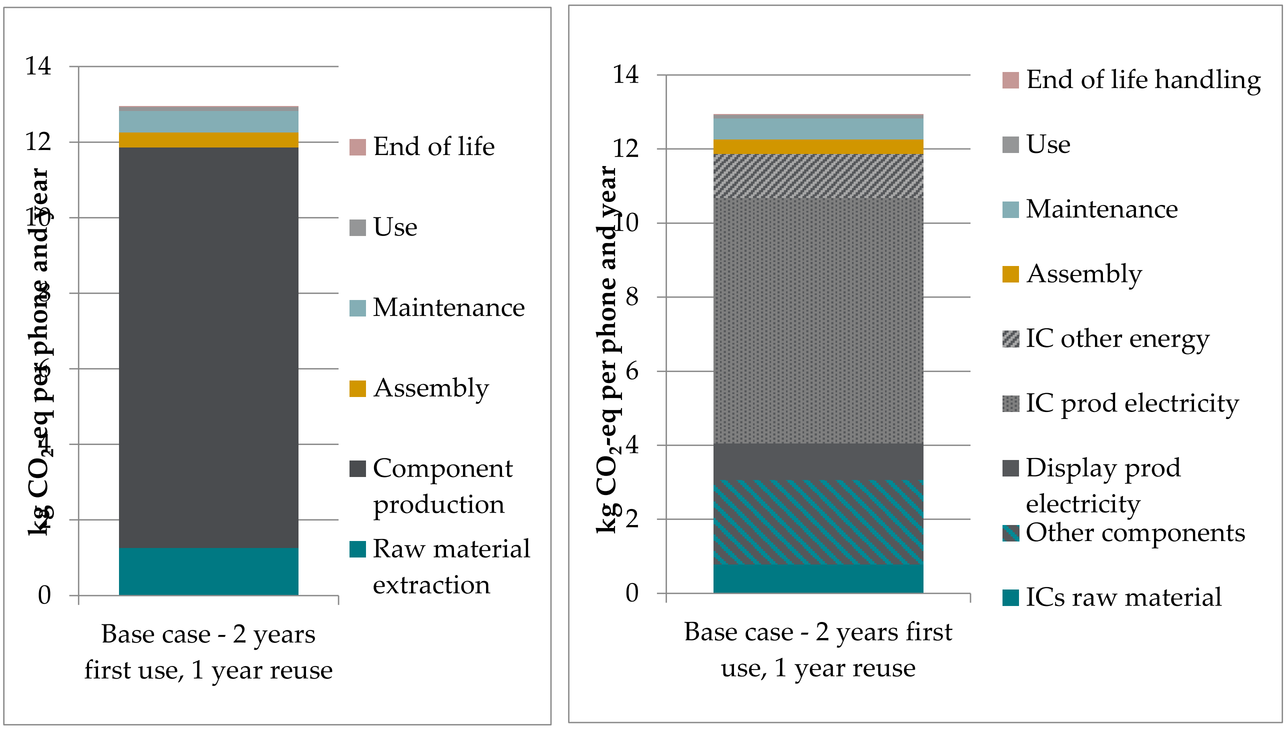


Figure 4: The climate impact of the base case phone LCA is shown in the figure. When considering the life cycle stages the component production stands out due to the use of fossil-based electricity. Important components like the IC ad display are shown separately in the right-hand figure as they represent the major part of the total impact. Specifically, the electricity used to produce the IC is impactful.

In order to further break down the results presented in Figure 4, the top eight most impactful parts of the life cycle are shown in Table 9. All life cycle stages, including use and end of life recycling are included in the assessment, but it is only the components and their production energy that show up as hotspots.

For all the hotspots the basis for the emissions of greenhouse gases is from burning fossil resources, either directly for heat or indirectly via the production and use of electricity. Since the production is assumed to be in Asia, and the Asian electricity mix has a high part fossil-based energy the electricity becomes an important hot-spot. When a component appears as hotspots it is due to the use of materials that require impactful extraction and processing, for example precious metals in electronic components.

Table 9: The top 8 most impactful components in the climate change category are listed. The use of energy from fossil sources, either directly or via electricity, stand for a large part of the production impact.

Part/stage	%contribution
IC production electricity	52%
IC other production energy	10%
Display production electricity	8%
IC materials	6%
PBA production electricity	3%
PCB production electricity	3%
Battery production electricity	2%
Assembly electricity	2%

Table 9 indicates that it is the components and their production that has the highest impact on climate change, but it also helps us determine which components that are hotspots. The integrated circuit, the display and the battery are important along with the printed circuit board and the printed board assembly.

4.1.2 Human toxicity hotspots

The result from the assessment of toxicity shows a very different distribution of impact compared to the climate change category. Although it is still the components that dominate, toxicity is dominated by the mining of metals rather than electricity use in production. The impact is also more evenly spread between different components, which can be seen in Figure 5.

The materials that most significantly influence the results in the toxicity category are gold and copper, both materials with high relevance for electronics. The danger to human health comes mainly from the emissions of heavy metals to water. Additionally, some highly processed material, like the anode and cathode in the battery impact this category.

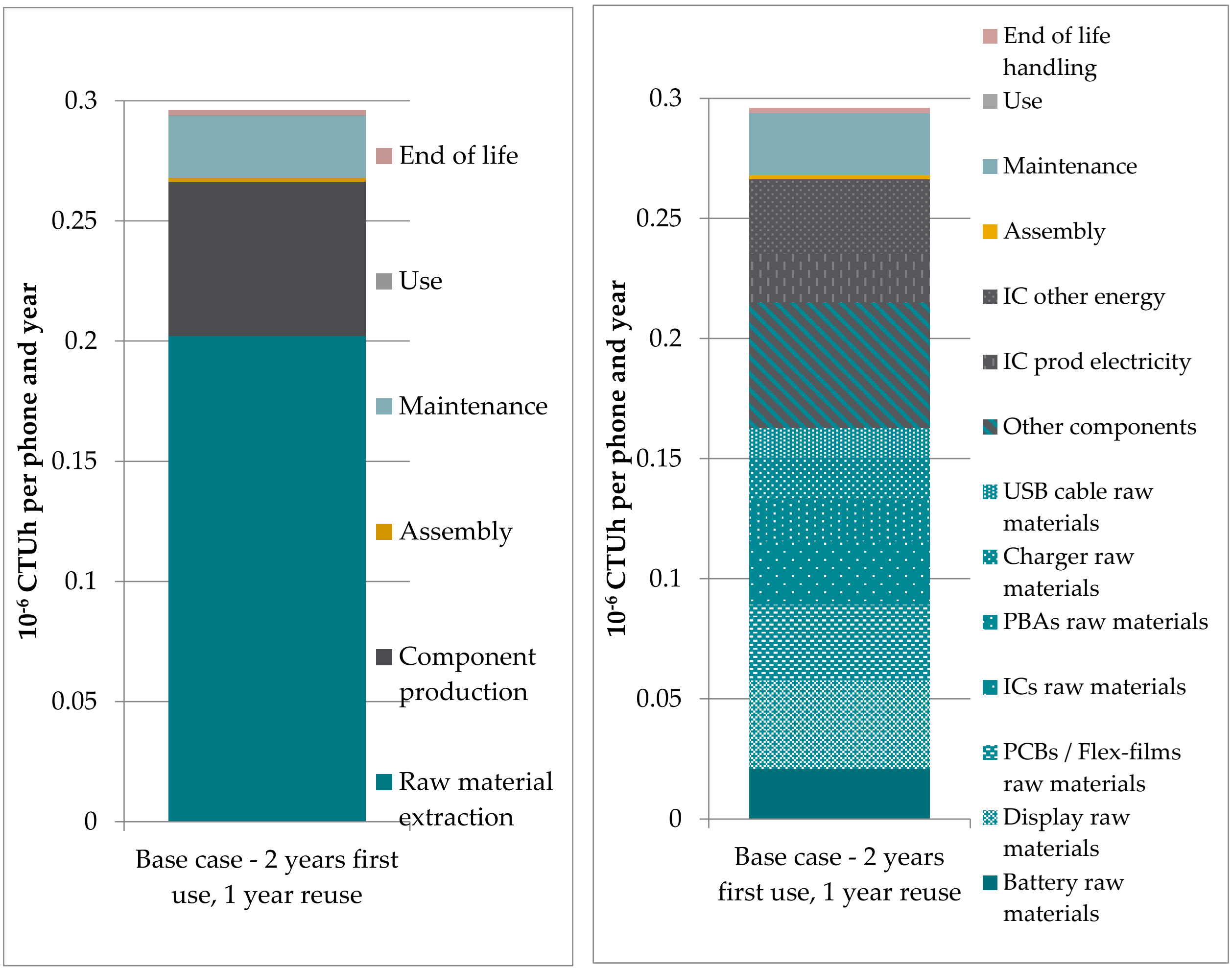


Figure 5: The figure shows the toxicity impact per life cycle stages, as well as a further division of the production stage per component. Several of the copper rich and precious metal rich component contribute impact.

Table 10 shows the top ten components that impact the toxicity results. As in the graphical representation the spread between components is more even, compared to the climate change category.

Interesting to note is that the production energy for the IC makes an appearance alongside the material-dominated impacts. This due to the high percentage of coal-based electricity, where the mining of coal is harmful to human health due to emissions of heavy metals to air and water.

Table 10: The table lists the top ten most impactful components for the toxicity category. Electronic components with metals like gold stand out, along with components with copper. The impact is more evenly spread over components than the climate change impact.

Part/stage	%contribution
Display	13%
PCBs / Flex-films	12%
ICs	10%
IC other production energy	%
Battery	8%
PBAs	7%
Charger	6 %
IC production electricity	6%
USB cable	5%
Headset	3%

Even though there is a wider spread of impact, the toxicity category highlights similar components as hotspots, compared to the climate change category. Again, it is the display, IC and battery that stand out, together with the electronic assemblies in the printed circuit board and printed board assembly.

4.1.3 Resource depletion hotspots

The impact category of abiotic depletion potential (ADP) as defined by CML comprises the depletion of environmental resources. The model defined in the ADP is a function of the annual extraction rate and geological reserve of a resource. Depletion of a resource means that its presence on Earth is reduced which refers to nature stocks (van Oers, Guinée, & Heijungs, 2020).

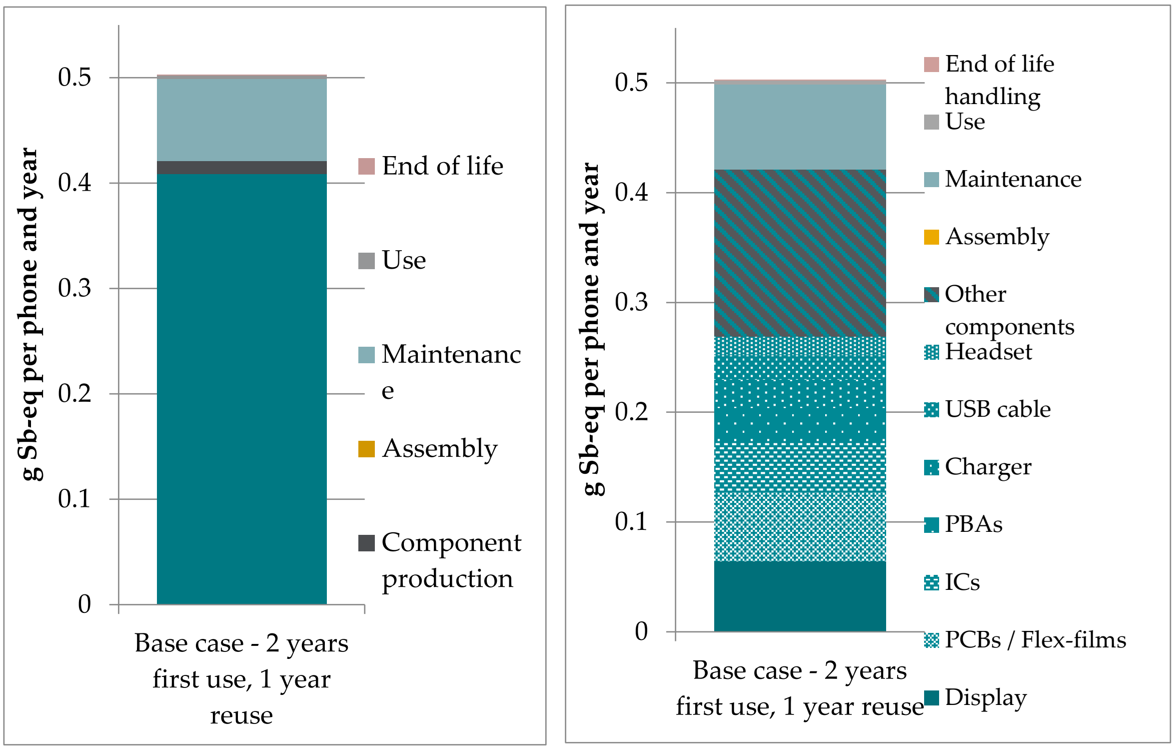


Figure 6: The resource depletion of elements is shown in the graph. Electronic components containing precious metals stand for significant impact. Some impact is also found in the use of copper.

As expected, the abiotic resource depletion is strongly linked to the use of relatively uncommon metals in the phone's components. This gives similar results to the toxicity category, as this environmental impact also relates to the extraction of metals.

The main difference compared to the toxicity case is that copper decreases in importance while gold increases in importance. Materials that are important for toxicity due to their high level of processing (coal powered electricity) also decrease in importance when looking at resource depletion.

For resource depletion we can find the display, IC, PCBs as hot-spot components. The display and battery further increase in importance when exchanged in the maintenance stage, see Table 11 for a list of the most impactful components.

Table 11: The table shows the most impactful components in the resource depletion category. The battery and display are important, especially if they are exchanged in the maintenance stage (not included in numbers below).

Part/stage	%contribution
Battery materials	21%
Display materials	13%
PCBs materials	12%
ICs materials	9%
PBAs materials	6%
Charger materials	5%
USB cable materials	4%

4.1.4 Environmental damage cost – EPS method

To show environmental impacts not on the level of impact categories but aggregated in a single value ("single score"), a methodological weighting of environmental impacts against each other is necessary. How important is for example acidification compared to global warming?

In comparison to the results of impact categories, which are based on scientific models, it is important to understand that "single-score"-methods always rely on societal values. Results are therefore depended on subjective preferences integrated in the respective method and should be understood as representative only under the valued conditions.

The Environmental Priority Strategy (EPS) (Steen, 2015) method strives to minimize the subjectivity by introducing it only in the last stage (Steen, 2015). Only the monetary valuation is value-based. The harm (for example lives lost) caused by different environmental impacts is taken from scientific studies, implying that the harm is not evaluated subjectively, only the value of the harm. Compare evaluating the value/cost of human lives lost due to CO2 (EPS case) and evaluating the cost of CO2 emissions directly.

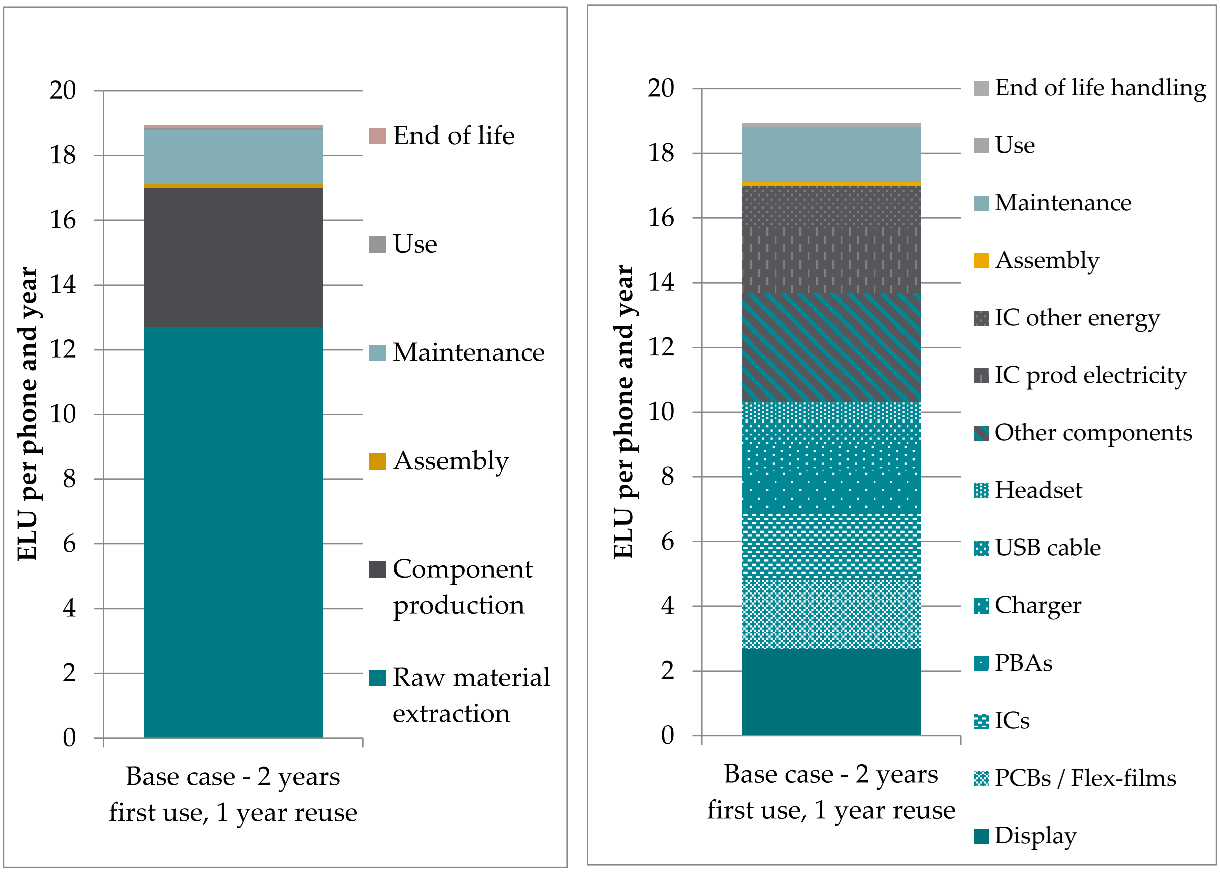


Figure 7: The EPS results are shown in the graph. Use of scarce resources is an important aspect that influence the results, showing components with electronics as hotspots. Additionally, the use of fossil resources and emissions of CO2 from production gives a noticeable contribution for the IC.

The EPS method values all environmental impacts in terms of long-term damage cost. It places a high value on scarce materials, as the cost of extracting without deposits is very high. Therefore, the results in the EPS category follows the same trends as the results of resource depletion, but with higher importance given to components with precious metals like gold and platinum (electronics) compared to components including more copper

In addition, which differs from the resource category, emissions of CO2 and use of fossil resources also contribute to EPS. This means that we see impact also from the production stage of components with high energy use in that stage, specifically from the IC. The most impactful stages and components are listed in Table 12.

Table 12: In this table the most impactful components and stages are lsited for the EPS assessment. The results highlight the relatively even spread of impact between many different components.

Part/stage	%contribution
Display materials	14%
PCBs materials	11%
ICs materials	11%
IC production electricity	11%
IC production fossil energy	7%
PBAs materials	7%
Battery materials	6%
Charger materials	5%

4.2 Hotspots identified in the linear base case

The hotspots of the different impact categories had one main thing in common – they were all related to the components. This fact leads to the conclusion that the components are important for all impact categories, although the underlying pathways leading to the impact of course varies between categories. For climate change and EPS, the high-fossil electricity plays in, while for the toxicity and resource depletion the materials are in focus. Table 13 shows how the hotspots play into the different categories.

Table 13: The table shows the hotspots that were identified in the linear base case LCA. X marks which hotspots that are relevant for each impact category. Looking at the complete life cycle it is clear that the hotspots are focused in the production stage of the life cycle, with materials and production electricity giving the highest impact.

Hotspot	Climate change	Human toxicity	Resource depletion	EPS
IC energy for production	X	X		X
IC material	X	X	X	X
Display energy for production	X			
Display materials		X	X	X
PCB energy for production	X			
PCB materials		X	X	X
Battery energy for production	X			
Battery materials		X	X	X

One general conclusion, valid for all impacts, is that long life and high utilization of the components is important because all the hotspots relate to the production. By achieving this, more function can be extracted from the same components so that the impact per function is smaller. In this study we look at the impact per phone and year, where the normalization by year is a way to capture the value of increasing life.

These conclusions about component utilization lead us to the first major improvement potential:

Prolonged life of phone and/or hotspot components.

A straightforward approach to reduce the impact from components is to have less of them, therefor an additional improvement connected to the component hotspots can be to:

Reduce the need for hotspot components.

Looking specifically at the results in the climate change and EPS categories highlights the electricity mix used in production as an important aspect, in addition to the materials. Especially the integrated circuit is impacted by the choice of electricity production path as it consumes the highest amount of electricity.

When it comes to the electricity impact, there are several options for improvements that can be explored. The first is to simply reduce the amount of electricity needed. For the IC this alternative is not technically feasible, as the required energy large is an effect of the material properties of the electronics.

The second option is to instead improve the environmental impact of the electricity. This can be done either by installing renewable electricity production at the manufacturing site, by encouraging more green energy production in the grid by buying "green electricity" or by producing in a location that already has a high-renewable electricity mix.

This hot spot in the climate change category leads to our second improvement area:

More renewable electricity in component production

This action has the integrated circuit as top priority, but also other components could benefit from an improved electricity mix. Lowering the need for electricity could be an alternative improvement but was not deemed as technically possible with current production paths.

The next step is to evaluate these potential improvements to the hotspots in a scenario assessment. To ensure that the scenarios are relevant for the circular economy application that the LCA results will feed into, they are based on circular business models.

4.3 Scenario assessment based on circular business models

In the previous section we identified the parameters in the base case that has the most potential to improve the environmental performance of the phone life cycle. In this section we look at how different circular business models can contribute to the improvement of life cycle impact, based on the identified parameters. The results are presented in the climate change and EPS categories, as toxicity and resource depletion follow similar trends as EPS.

Two different types of circular business models are included in the LCA:

- Minor modularity - The components are modular and thus more easily exchangeable
- Cloud offloading – the phones share a common storage in the form of cloud server

In short, the business case of modularity explores the life cycle effects of being able to exchange components and achieve a longer total life for the phone. Cloud offloading instead explores the benefits of reducing the need for electronic components in the phone in favour of central server storage.

In the assessment presented in this section the effect of rebound is disregarded. The scope is limited to the life cycle of one phone and does not consider broader system effects. When the results are incorporated into the circular economy model, such effects could, however, appear and need to be handled.

The scenarios only consider the first life, so that the base case life length is 2 years (compared to the 3-year life when including second use). This is because the circular business models are assumed to affect the first use, and the impact on this use is what is investigated.

4.3.1 Climate change effect of the business models

The results of the different business model life cycles are presented in Figure 8, as well as the results for a production case using green electricity. The results are normalized to represent one phone for one year. This means that one year of use is included and the production is normalized by the total years used in order to split the production impact between the years of use. Presenting the results in this way highlights the impact per performed function and not per physical phone.

A first conclusion is that both examples of circular business models have the potential to significantly reduce the emissions of greenhouse gases. A second conclusion is that we also can create situations where more emissions are generated per delivered function (inner exchange case).

It is unlikely that a significant proportion of the IC production will convert to low carbon energy sources in the near future, but the case is included in the results as reference. Instead, a decrease of IC in the phones is a promising option. In addition to using less IC the cloud offloading can potentially lower the phones vulnerability to become outdated in terms of storage and processing power. However, it would have limited functionality outside areas with a good internet connection. In the cloud offloading cases in Figure 8 we therefore assume a five-year life length instead of the base two years. We also include more charging electricity, but since the Swedish mix is relatively carbon neutral the effect of this is small.

The benefit of the cloud offloading model is that the phone needs less IC, an identified hotspot in the base case assessment. The cloud offloading case thus has dual potential to reduce the impact – less IC and longer life, giving the potential to reduce the impact by 60%. Just reducing the amount of IC with 50%, without making assumptions of increased life would lower the total impact with around 30% for the climate change category.

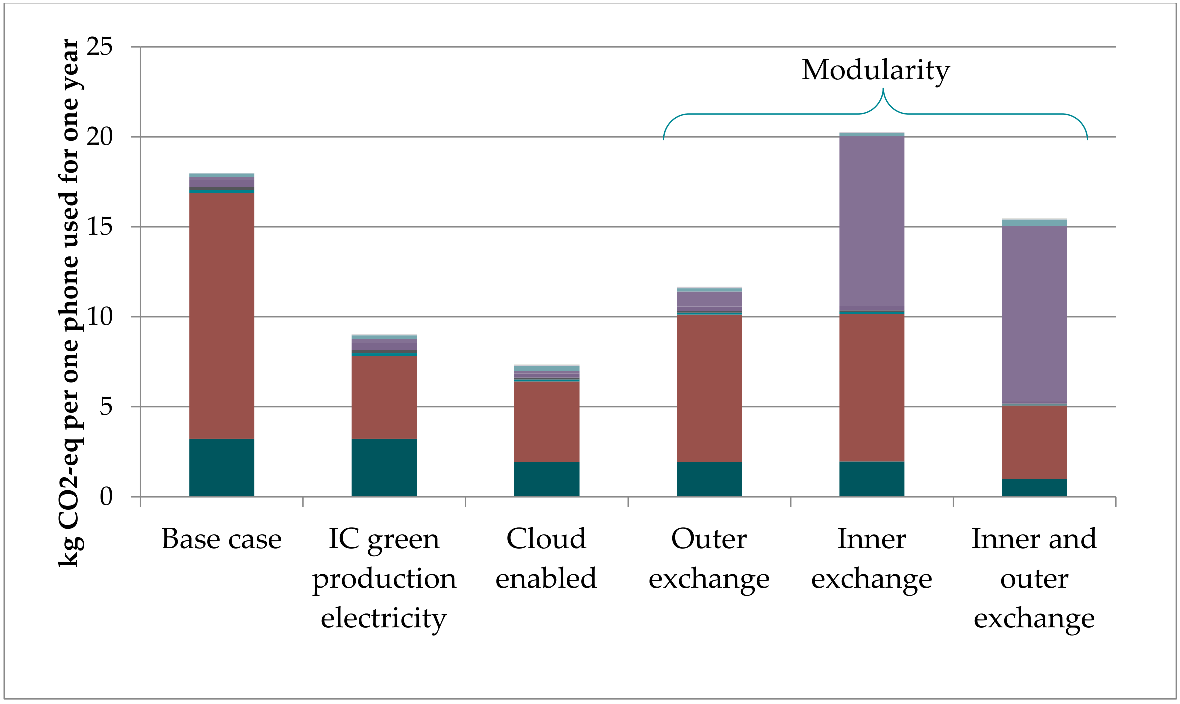


Figure 8: The figure shows the climate impact of the scenarios, normalized per year. The benefits of reducing the amount of impactful IC can be seen in the cloud offloading case. The modularity cases highlight that benefits can be found if the increase in life length is greater that the impact of the added components.

Looking further at the three cases related to modularity the improvement potential is not as straight forward as it is for decreased IC use. The reason is that the main impact of the base case - the IC production - still remains in the life cycle. The benefits of this business model instead come from increasing the life of the phone and thus utilizing the IC more to achieve more function.

The three cases for modularity assume a life length of five, five and ten years respectively. It is of course difficult to correctly assess how replacement of components increases the life length of the phone, but these cases can highlight the most important aspects to consider.

To start with, in the first modularity case "Outer exchange" we assume that we achieve a five-year life length by replacing the casing of the phone and updating the battery. This does not require a high level of modularity, as the battery and casing are not as integrated as for example the electronic components. It is assumed that the display is replaced as often as in the base case.

This approach gives the best result of the three modularity cases, since it increases life length without adding a lot of new production impact. With just the impact from the casing and battery we can utilize the hotspot IC two years more implying less impact per function.

For each specific product and production route the breakeven between adding new components and increasing life will vary. It will depend on how large the impact from the exchanged component is and what added function it gives, compared to the impact and function of a new phone. If the focus is on exchanging the low-impact components in exchange for longer life, the improvement to the life cycle impacts will be the greatest.

The second modularity case further highlights the other side of this point. In this case it is assumed that a larger renovation is performed by replacing both the outer components and electronics in order to increase the life-length of the phone and hence reduce the impact. However, the impact is larger even though the life length is longer, due to the footprint of the replaced components.

For the exchange of a high impact component (like the IC) to be beneficial you need to achieve a significant increase in life length, as exemplified in the third modularity case.

In conclusion, if there is a component that has a large share of the impact (such as the IC), then this should be the focus of actions aimed at reducing impact. If this is not possible it is important to utilize the component as much as possible, for example by prolonging the life by exchanging other less impactful components. Using renewable electricity is an important step towards making the products less impactful in terms of climate impact, although it is not a design choice.

4.3.2 Business model effect of environmental damage cost – EPS

The climate change impact category is not only a result on its own, it is also an indicative proxy for other emission related impacts like particles, acidification and eutrophication. In this section, the results of the business model scenario assessment are presented for the EPS category, see Figure 9 , giving a representation of how the linear base case could change for categories that are impacted by the raw materials, like EPS, resource depletion and toxicity.

The similarity to the climate change category is that it still is the production phase that dominates. The difference is that it no longer is the IC alone that is in focus, but instead the impact is spread between several of the electronic components including the display, IC, PCBs and PBAs. The impact from the carbon intense electricity is less dominating, which is also highlighted by the fact that green production electricity gives a smaller improvement in the EPS case compared to climate change.

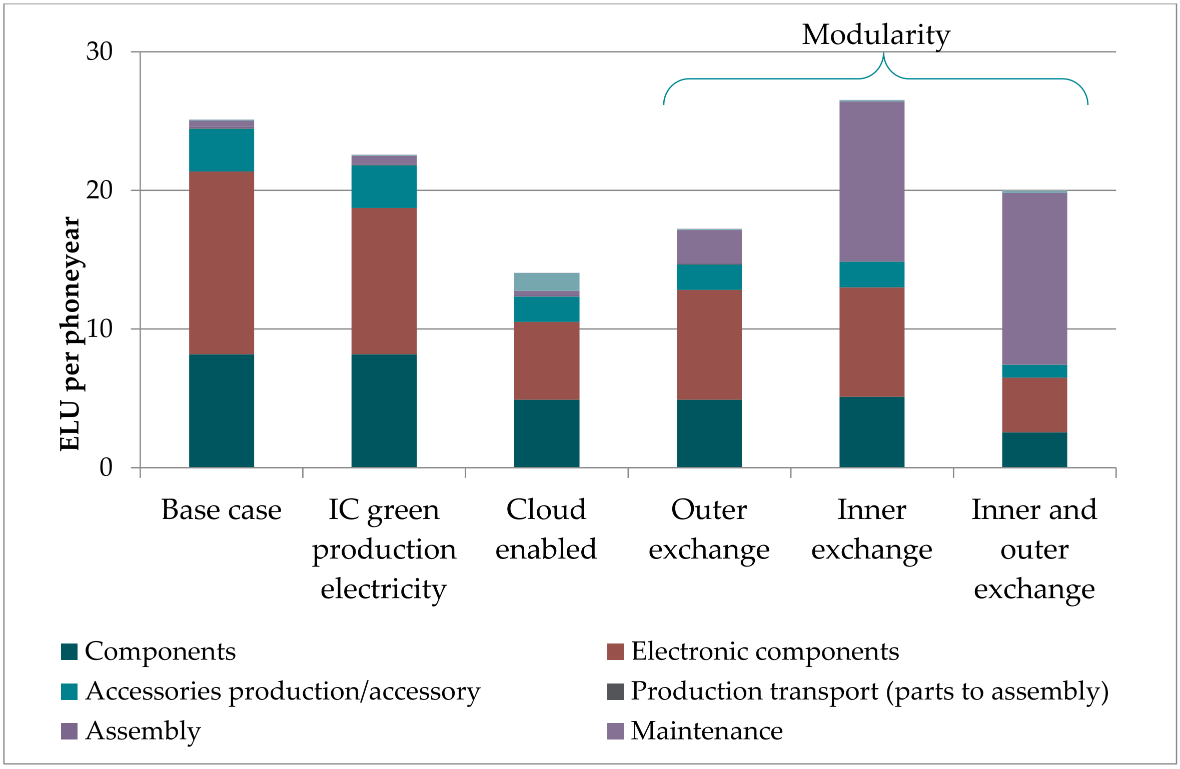


Figure 9: The results of the business model scenarios are shown for the EPS category. All business models hold potential to lower the environmental impact.

Since the production still dominates, many of the conclusions from the climate change assessment hold. This means that a prolonged life is very beneficial since it implies longer utilization of the "invested" production impact. However, the balance between component exchange an increased life becomes less clear cut in the EPS assessment. Since the impact is more evenly distributed among the different components it is more likely that an exchange of component that leads to longer life is beneficial, compared to climate change where it is unlikely that an exchange of IC will be efficient.

On the other hand, sine the impact is more distributed it is more difficult to make business models that target the hotspot problem and achieve very large improvements. This can for example be seen in the cloud offloading business model. It targets the climate change hotspot IC and makes a large improvement for climate change (30% reduction from IC), but for EPS the improvement from less IC is 14% and the majority of the improvement is instead from the prolonged life.

For material use and its correlating environmental impacts we can conclude that business models that give potential to prolong the function of electronic components with high precious metal content will be most beneficial. Among these components there is no clear hotspot to target.

In a system perspective the potential benefits that material recycling has for resource depletion could also be considered. This LCA uses the cut-off approach for the end of life modelling, but in the project the CE-model takes the system into consideration (Hennlock, et al., 2020).

5 Conclusions and recommendations

The most important conclusions from the LCA presented in this report relate to the identification of hotspots, improvement potentials and business model results. From this we were able to develop a set of equations that represented the impacts of the phone's life cycle for input into the LCA-CE model.

The linear base case assessment identified the following conclusions in relation to the investigated impact categories:

Climate change:

- The IC (materials and production energy) accounts for around 70% of the total life cycle impact.
- The climate intensity of the production electricity is an important factor.
- Other components mainly add impact based on the use of carbon-intense electricity.

EPS, resource depletion and human toxicity:

- The impact in these categories are more evenly distributed compared with the climate impact. The three most contributing components are the display, IC, the battery and the PCB
- The important components (typically electronics) have the use of special metals in common, for example gold and copper
- Copper and gold are critical (hotspot) materials

An overarching conclusion from the base case is that the majority of the impact over the life cycle occurs in the raw materials and production stage. Impacts from the use phase are very small, aided by the low-carbon electricity in the first use country (Sweden).

The end of life, with informal recycling in developing countries, represents a key area of concern that could not be fully covered in the scope of this project. The main reason for this is that the impact of informal recycling is not well understood or quantified, and therefore not characterised within LCA databases. The impacts are primarily local and will likely have a detrimental effect on human and ecosystem health.

Equipped with the knowledge of the life cycle environmental hotspots, the next part of the study focused on finding how circular business models could influence the total results by aiming to improve or influence parameters relating to the hotspots. The two business models chosen to highlight the changes were cloud offloading (reduced amount of IC) and modularity (longer life).

Cloud offloading has clear potential to reduce the impact, specifically for the climate change category, but also for the other categories EPS, resource depletion and toxicity. In the climate change category, the combined effects of using less IC and gaining a longer life shows a potential to reduce the impact by 60%. The added impact from more charging electricity gives little effect as the use phase electricity has a low carbon footprint. For the resource categories the benefits of cloud offloading lie in the longer life of the phone, implying that more function is achieved with the same components.

An additional improvement, outside the scope of the chosen business models, is to ensure that the IC is produced with renewable electricity, an improvement that will benefit all categories, but hugely reduce the impact on climate change. For climate change the improvement could be around 50%

The modularity case highlighted a very interesting trade-off, with conclusions that can be extrapolated to any product. The benefit of modularity is that it increases the life of the product, implying that the same materials and components can be used to get more function. The trade-off is that the life is extended by exchanging certain components, either to update cosmetical aspects (as exemplified in the outer exchange case) or functionality (exchanging electronics). If the components that are exchanged give higher impact than the value of the longer life, then modularity does not benefit the environmental impact and vice versa.

From the base case and scenario assessment several variables were identified to represent the most important hotspots of the LCA. By looking at the linear as well as the circular business model results conclusions were drawn on how these variables impact the results, and this was in turn converted into equations for the CE-LCA integration.

These equations were the goal of this study and the inventory and result assessment were performed with this goal in mind. The conclusions are therefore valid for integration and are not a footprint of existing circular business models or phone hardware. The main outcome is the relation between different life cycle stages and components and how this knowledge can be used to create input to a CE-model.

The results are also valid for highlighting important parameters and differences in future circular business models. The importance of considering certain components and life length are key take-aways, while the numerical results and magnitude of improvements can be misleading if used out of context.

5.1 Recommendations for future work

There is a very high rate of technological innovation for smartphones, e.g. with recent advances in foldable and curved screens, as well as increasing processor speeds. This means that increasing the circularity of phones through business models that focus on extending length of use, is extremely challenging and has limitations. One route could be to increase the second life of phones by increasing the export of used phones to developing countries. This needs further investigation into both the system wide environmental impacts and the international (global) socio-economic consequences.

Recommendations for further work therefore include.

- Investigation of the system-wide consequences of second life phones for developing countries, which would include research on the socio-economic consequences and the implications for environmental impact.
- Increased research on end-of-life fate of phones at the end-of-life, possibly with the addition of other methodology than LCA which does not cover the highly local and social effects of informal recycling.
- Further studies on informal recycling, including quantities of smartphones that reach informal recycling and quantified impacts of informal recycling and development of LCA sets.
- Business models to increase take back of smartphones, increased modularity and repairability.

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Appendix A. Brief introduction to LCA

Environmental life cycle assessment (LCA) is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO 14040:2006 and 14044:2006).

Environmental inputs and outputs refer to demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transports used at/needed for raw material extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment (figure 1).

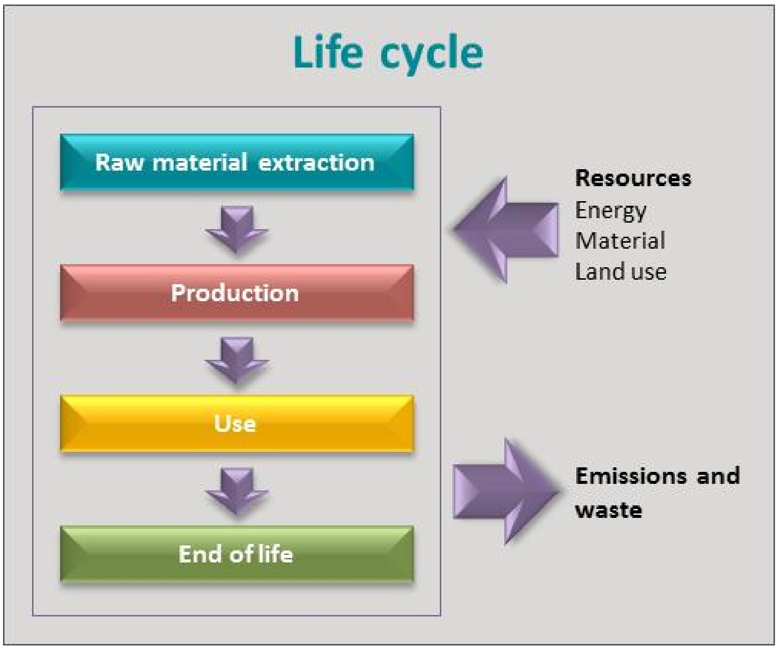

Figure 1: Illustration of the LCA system.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation (figure 2).

An LCA can be used in many different ways, depending on how the goal and scope are defined. Product development, decision making, indicator identification and marketing are examples of areas where the information retrieved from an LCA may be valuable.

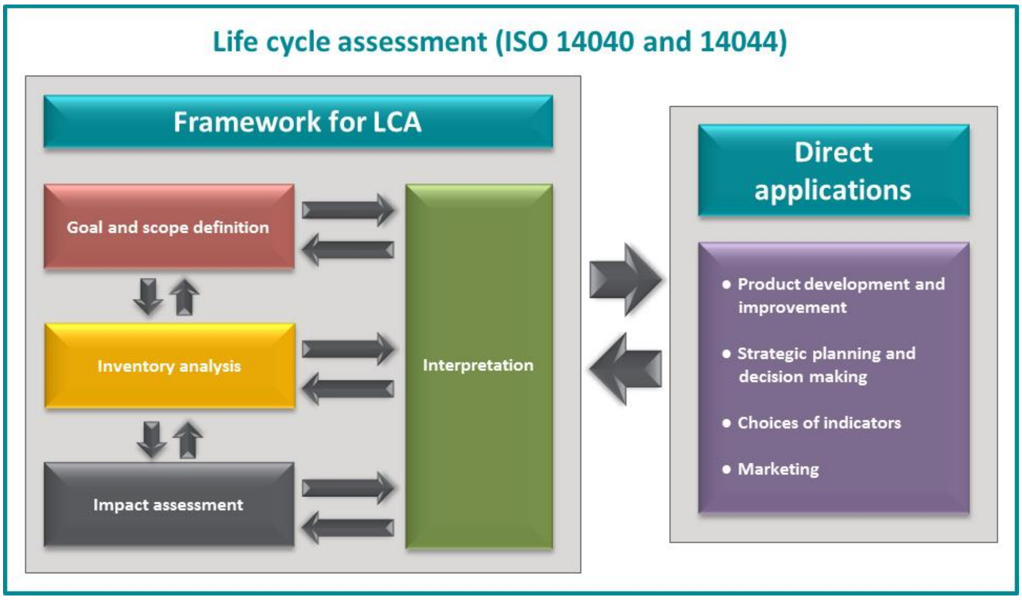

Figure 2: Illustration of the phases of an LCA.

Goal and Scope

In the first phase the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study. Furthermore, the scope of the study is described. This includes a description of the limitations of the study, the functions of the systems investigated, the functional unit, the systems investigated, the system boundaries, the allocation approaches, the data requirements and data quality requirements, the key assumptions, the impact assessment method, the interpretation method, and the type of reporting.

Inventory analysis

In the inventory analysis, data are collected and interpreted, calculations are made, and the inventory results are calculated and presented. Mass flows and environmental inputs and outputs are calculated and presented.

Impact assessment

In the life cycle impact assessment (LCIA), the production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase.

For comparative assertions, there are four mandatory elements of LCIA:

1. Selection of impact categories, category indicators and models,
2. Assignment of the LCIA results (classification),
3. Calculation of category indicator results (characterization) and
4. Data quality analysis.

The following elements are optional:

- Calculating the magnitude of category indicator results relative to a reference value (normalization),
- Grouping and
- Weighting.

Interpretation

The interpretation is the phase where the results are analysed in relation to the goal and scope definition, where conclusions are reached, the limitations of the results are presented and where recommendations are provided based on the findings of the preceding phases of the LCA.

An LCA is generally an iterative process. The impact assessment helps increasing the knowledge about what environmental inputs and outputs are important. This knowledge can be used in the collection of better data for those inputs and outputs in order to improve the inventory analysis.

The conclusions of the LCA should be compatible to the goals and quality of the study.

Details description of the chosen impact categories

Global warming

A global climate change is a problem for many reasons. One is that a higher average temperature in the seawater results in flooding of low-lying, often densely populated coastal areas. This effect is aggravated if part of the glacial ice cap in the Antarctic melts. Global warming is likely to result in changes in the weather pattern on a regional scale. These can include increased or reduced precipitation and/or increased frequency of storms. Such changes can have severe effects on natural ecosystems as well as for the food production.

Global warming is caused by increases in the atmospheric concentration of chemical substances that absorb infrared radiation. These substances reduce the energy flow from Earth in a way that is similar to the radiative functions of a glass greenhouse. The category indicator is the degree to which the substances emitted from the system investigated contribute to the increased radiative forcing. The characterisation factor stands for the extent to which an emitted mass unit of a given substance can absorb infrared radiation compared to a mass unit of CO_2. As the degree of persistence of these substances is different, their global warming potential (GWP) will depend on the time horizon considered, such as 20, 100 and 500 years. In this study, a time horizon of 100 years has been applied. The time scale 100 years is often chosen as a "surveyable" period in LCAs and discussions regarding global warming.

The characterisation of this environmental impact takes into account the substances that contribute directly to the greenhouse effect. The total contribution to the global warming potential from the life cycle is calculated as:

$$\mathrm{GWP} = \sum \mathrm{GWP}_j \cdot \mathrm{E}_j$$

where E_j is the amount of the output j and GWP_j the characterisation factor for this output. The characterisation factor is measured *in g CO_2 equivalents per g of the emitted substance*, and thus, the unit of the category indicator is *g CO_2 equivalents (g CO_2 eq.)*.

Human toxicity

USEtox is a standardised environmental model to evaluate impacts of chemicals on human health and organisms (http://www.usetox.org) (Rosenbaum, o.a., 2008). Toxicity in particular is dependent on a lot of complex, specific factors – the local environment, the status of the receiving ecosystem health of flora and fauna etc. E.g. an ecosystem in a healthy state should cope better than one already suffering.
USEtox uses CTU= comparative toxic units (CTU) per kg of emission, a unit that estimates the increase in morbidity caused by the emission.
The impact is expressed at a mid-point level – meaning actual consequences are not calculated, e.g. greenhouse gas emissions are expressed as CO2-eqivalent, but the consequences are Endpoint – which could be expressed as biodiversity loss, temperature gain etc.

Resource depletion

The chosen category for assessing resource depletion in this project was the CML method *Resource depletion, mineral, fossils and renewables, midpoint (v1.09)* was used. The indicator is based on a global scale and is on the concentration reserves and rate of deaccumulation. Abiotic (non-living materials) Depletion Potential (ADP) of a resource is defined as the ratio of the annual production and the square of the ultimate (crustal content based) reserve for the resource divided by the same ratio for a reference resource (antimony (Sb)).

The indicator is expressed as kg Sb-eq/uni, which measures the depletion of a particular resource as a ratio of the scarcity of Sb (antimony).

EPS- Environmental Priority strategy

One common way to present LCA results is by looking at the life cycle impact in different impact categories. This implies looking at how much each resource use or emission contributes to for example acidification, global warming or ozone depletion. These impacts are measured in a standard unit, and all emissions are translated into this unit. One such unit is CO_2 equivalents, used for measuring global warming potential. CO_2 is of course then worth 1 CO_2 equivalent, while other greenhouse gases are worth more or less, depending on if they impact global warming more or less than carbon dioxide.

To show environmental impacts not on the level of impact categories but aggregated in a single value ("single score"), a methodological weighting of environmental impacts against each other is necessary. How important is for example acidification compared to global warming? This is often helpful for non-LCA practitioners, as it gives one result to consider and not several.

In comparison to the results of impact categories, which are based on scientific models, it is important to understand that "single-score"-methods always rely on subjective value choices. Results are therefore depended on subjective preferences integrated in the respective method and should be understood as representative only under the valued conditions.

The Environmental Priority Strategy (EPS) (Steen, 2015) method strives to minimize the subjectivity by introducing it only in the last stage (Steen, 2015). Only the monetary valuation is subjective. The harm (for example lives lost) caused by different environmental impacts is taken from scientific studies, implying that the harm is not evaluated subjectively, only the value of the harm. Compare this to evaluating the value/cost of human lives lost due to CO_2 (EPS case) and evaluating the cost of CO_2 emissions directly.

EPS 2000d is value based, meaning it aims to assess actual real-life impacts and their financial implications. In this method the environmental impacts evaluated and expressed in terms of "willingness to pay" to hinder the damage of five safeguard subjects: human health, biological diversity, eco-system production, natural resources and aesthetic values. The calculation is based on an average OECD citizen (Steen, 2015).

As a guide for non-LCA practitioners it can be commented that the calculation of environmental impact in terms of cost is a way to both highlight the effect of emissions on future generations, but also a way to highlight what cost can be expected due to environmental legislation in the near or long term future.

Appendix B. Goal and scope details

System boundaries

The LCA includes all processes contributing significantly to the environmental impacts of the system investigated.

Boundary towards nature

For inputs of fuels, electricity and raw materials the cradle of the life cycle is nature. The boundary between nature and the product life cycle is crossed when the natural resources (e.g. crude oil or uranium) are extracted from the ground. The "grave" of the life cycle is the air (e.g. emissions from combustion of fuels) or water (e.g. water emissions from wastewater treatment).

Boundary in the technical system

The technical system is limited to the phone and its supporting components. The larger system containing for example servers and towers is not included. No auxiliary impact from the producing company was included in the study, for example office spaces or business travel.

For materials that are recovered at the end of life of the phone, the life cycle is cut-off at the point of entry into a new product system. No credit or allocation is given. Based on the same boundaries, any secondary material that enters into the system is free of upstream burden.

Temporal boundaries

The study considers current conditions, although some stages like recycling may occur in the future this is not modelled in the study.

Geographical boundaries

The study aims to incorporate the geographical spread of the phone as it moves through its life cycle, with the first use located in Sweden. Where available, geographically specific datasets were chosen for the first life in Sweden, second life in EU and third life in southern Africa. Where these were not available EU averages were chosen for EU and Sweden, and global average was a last choice. For the production of the phone, data for China or east Asia were preferred.

Non-elementary inputs and outputs

The production of inputs such as chemicals and auxiliary materials used in a process is excluded from the LCA if the amount is small and if the production is not expected to contribute significantly to any of the studied impact categories.

Valuable material outputs from recycling as well as waste along the production chain and use are not followed to grave.

Data quality

The bill of materials for the phone, used to model the cradle to gate impact of the material production was taken from previous work by Sony. However, the data was aggregated, and small flows were excluded already when the inventory was received. This exclusion was based on results from previous LCAs and was not deemed to impact the results of this study.

The data for energy consumption in the production stage was also taken directly from Sony. Electricity was given in kWh making it possible to vary the source, but other energy sources (for example heat) was aggregated into one flow that was not varied or reported in detail.

In addition to this specific information, generic data was used for the upstream flows. Generic data are defined as data sets mainly based on literature and other publications (sometimes from several data sources). In this study most generic data correspond to:

- production of raw materials (such as metals, plastics etc.)
- energy (production of fuels and electricity) and,
- transportation data (energy use and emissions per ton km) for different transport modes.

Most generic data in this study have been based on data sets from the Gabi Professional database [Gabi] 2018, as well as the ecoinvent version 3.3 database.

Allocation approaches

The following stepwise allocation procedure is required by ISO 14044: 2006:

The first step of the procedure is: "wherever possible, allocation should be avoided by dividing the unit process to be allocated into two or more sub-processes and collecting the environmental data related to these sub-processes, or by expanding the product system to include the additional functions related to the co-products."

The second step of the procedure recommended by ISO 14044: 2006 is: "where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical causal relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products and functions delivered by the system”.

The third and final step of the ISO procedure is: "where physical causal relationships alone cannot be established or used as the basis for the allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products."

Substitution

Substitution was not used in the assessment as it did not align with the aim of the study to provide input for combining LCA and CE-modelling. Any possible substitution will instead be included in the CE-model in the form of inclusion of a wider system perspective.

Allocation

Allocation of production energy, transport and material to one phone was done by Sony and provided to IVL. The baseline data uses economic allocation as a default method. No allocation of recovered material was done at end of life, however, the underlying datasets from ecoinvent include economic allocation and scrap flows.

Key assumptions and limitations

Limits enforced by goal and scope

The main limitation in the study is introduced by the goal and scope definition. The study focuses on the integration of LCA and CE-model, thereby focusing on hot-spot identification, finding how varying certain parameters impact the results and creating equations describing the LCA.

Based on this, several important inputs are based on rough assumptions. Important examples include the number of maintenance components and the life length of the phone.

This implies that the results are not suitable as footprints of a smartphone but should be viewed as inputs for a CE-model. The results can also be used to highlight potentials of different business models, but the numerical results and magnitude of improvements can be misleading if used out of context.

Production location and electricity

One of the most important aspects highlighted in the LCA is the use of carbon-intense electricity in production. The impact from electricity production varies greatly between sources, and in turn the most common energy sources vary between regions.

In this study the base case scenario was that the production of the phone took place in east Asia, with an average electricity mix (equal parts Chinese, Korean, Taiwanese and Thai average electricity mixes). The effects of this key assumption were analysed further in the business model assessment, and there subject to a sensitivity analysis.

Dataset approximations

A detailed list of the datasets used to model the life cycle flows can be found in Appendix D. Some specific flows were difficult to find data for and these rough approximations were used, see list below. Again, the impact of this on the total results is concluded to be small.

Appendix C. Details on data collection

Production, transport and use

All inventory data for these stages was collected through personal correspondence with Sony. A confidential LCI for the components and production can be found in the project documentation.

Transportation as included in the assessment as a fixed distance transport with truck. The distance was approximated from the climate change impact reported by SONY in their LCA but modeled as truck transport to get other impact categories as well. The transport was set to 10 tonkm.

The first user was assumed to be close to the assembly, and transport was omitted, while the transport to second and third users where set to 3 tonkm each. Transport to end of life was omitted, assuming that the handling on average is close to the final user. The simplified assumptions on transport where supported from the iterative processes of extracting results and improving inventory, the transport shows a very small impact.

For the use phase the assessment included three cases; first use in Sweden, second use in Eastern EU and third use in Africa. There cases were modeled with average electricity from Sweden, Romania and South Africa respectively.

Maintenance

Maintenance was for the purpose of this study very roughly assessed. Instead of exact numbers for changes, maintenance was included in the study to highlight what effect different maintenance scenarios could have on the total results. Based on this, it was deemed that estimates serves as good enough input data for this stage.

Table 14: The table shows the assumed maintenance rates. The numbers are examples of possible maintenance and chosen to illustrate the effect of maintenance rather than provide an exact representation of current maintenance practises. The yellow numbers mark changes compared to the base case.

	Unit	Base case	Light modularity, external	Light modularity, internal	High modularity	Cloud offloading
Maintenance display	pieces	0.1	0.5	0.5	2	0.1
Maintenance charger	pieces	0	0	0	0.33	0
Maintenance casing	pieces	0	1	0	1	1
Maintenance battery	pieces	0	1	2	3	0
Maintenance camera	pieces	0	0	2	3	0
Maintenance processing (IC, PBA, PCB)	pieces	0	0	1	2	0

Formal recycling

Formal recycling is modelled based on an LCA performed on a Fairphone (Grüvendik, 2014). The processing is divided in two parts, one handling the battery and one handling the rest of the phone. In the referenced LCA data was collected by MFA for a pyrometallurgical treatment of the phone without battery. The data is of course dependent on the material content of a specific phone, but as many components are very similar between phones, the LCI data collected for the Fairphone is a good approximation for the phone modelled in this work. The data in the LCI has been scaled based on weight to get the inventory for the Sony phone, as well as a general dataset per 1kg of phone.

For the recycling of the battery the ecoinvent 3.3 data set “treatment of used Li-ion battery, pyrometallurgical treatment”. The pyrometallurgical process is chosen to align with the processing of the rest of the phone. It is also a commonly used method for battery treatment.

The phone in this assessment has a battery weight of 5 grams and the amount going to further to formal recycling is 181g.

Table 15: The dataset used for formal recycling of non-battery components is listed in the table. The base is from the Fairphone LCA, but the flows are modified based on the content in our phone.

Formal recycling phone without battery	**Original Fairphone** *(124.85g without battery)*	**Unit**	**Modified input, Sony phone** *(180g without battery)*	**1kg phone**
Economic inflows				
transport, lorry 20-28t, fleet average [CH]	0,14	tonkm	cut-off	cut-off
sodium carbonate from ammonium chloride production, at plant [GLO]	4,99E-05	kg	7,22E-05	0,000305292
lime, hydrated, packed, at plant [CH]	0,000106	kg	0,000153277	0,000648516
electricity, medium voltage, production BE, at grid [BE]	0,257	kWh	0,371624161	1,572346283
transport, freight, rail [BE]	0,0468	tonkm	cut-off	cut-off
Environmental emissions				
Nitrogen oxides [air_high population density]	2,24E-05	kg	3,23906E-05	1,37E-04
Particulates, < 2.5 um[air_high population density]	4,81E-08	kg	6,9553E-08	2,9428E-07
Particulates, > 10 um[air_high population density]	1,50E-08	kg	2,16901E-08	9,17712E-08
Particulates, > 2.5 um, and < 10um[air_high population density]	2,87E-08	kg	4,15004E-08	1,75589E-07
Hydrogen chloride[air_high population density]	4,48E-07	kg	6,47812E-07	2,7409E-06
Hydrogen fluoride[air_high population density]	4,48E-08	kg	6,47812E-08	2,7409E-07
Sulfur dioxide[air_high population density]	4,48E-05	kg	6,47812E-05	0,00027409
Arsenic[air_high population density]	9,36E-10	kg	1,35346E-09	5,72652E-09
Copper[air_high population density]	1,56E-05	kg	2,25577E-05	9,5442E-05
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_high population density]	2,24E-16	kg	3,23906E-16	1,37045E-15
Lead[air_high population density] 3.50E-09 kg	3,50E-09	kg	5,06103E-09	2,14133E-08
Nickel[air_high population density] 5.31E-10 kg	5,31E-10	kg	7,6783E-10	3,2487E-09
Arsenic, ion[water_unspecified] 5.78E-10 kg	5,78E-10	kg	8,35793E-10	3,53625E-09
Cadmium, ion[water_unspecified] 5.08E-10 kg	5,08E-10	kg	7,34572E-10	3,10798E-09
Copper, ion[water_unspecified] 2.23E-08 kg	2,23E-08	kg	3,2246E-08	1,36433E-07
Nickel, ion[water_unspecified] 2.06E-05 kg	2,06E-05	kg	2,97878E-05	0,000126032
Zinc, ion[water_unspecified] 1.20E-08 kg	1,20E-08	kg	1,73521E-08	7,34169E-08

Informal recycling

In the modelling of the informal recycling the components of the phone are split into three groups corresponding to the two available datasets and a "rest" category. The categorization is roughly done by

1. Identifying components that contain electronics and valuable metals and having them in one group
2. Identifying components that are cables or connectors (copper focused parts) and making them the second group
3. Collection the remaining parts and classifying them as parts that are not targeted by material recovery actions.

The table below shows how the components are split into these groups.

	Group 1	Group 2	Group 3
	Leaching of Au (and same as proxy for Ag)	Open air cables	Dumped (disassembled unwanted parts)
	Display	USB cable	Other mech parts
	PBAs, PCB, flex films	Microphone	Key Panel
	Headset	LEDs	Antennas
	Speakers	Shields	Cover
	Cameras	Vibrator	Battery
	ICs	Connectors	
	Other components	Charger	
Total weight	64g	68g	99g
Source	(Terazono, Oguchi, Yoshida, Medina, & Ballesteros, 2017)	(Gullet, o.a., 2007) CO2 emissions from thinkstep dataset "Cable waste in waste incineration plant"	Est dumping with the Al, Cu, Ag, Au remaining in residue being emitted to water. No other emissions

In the following table the amount of gold, silver, copper and aluminium in each group is listed. These flows are used to scale the data used to model handling (group 1 and 2) and to know the potential emissions of metals to water (group 3). The materials marked in bold are used for scaling of group 1 and 2 respectively

Flow	Group 1 - Informal electronics recycling	Group 2 - Informal wire recycling	Group 3 - Residue
Gold	0,02g	0,003g	0g
Silver	0,05g	0,02g	0,02g
Copper	9g	**13g**	8g
Aluminium	0,4g	3g	10g

Group 1 was set to represent informal recovery of gold with leaching. It was hard to determine the potential impact of this, and the effects are likely highly local. The dataset it incomplete in terms of energy use and emissions from this energy. One possibility could be that a wood fire could be used, but this is not modelled. Emissions from this could contribute to the climate impact but considering the magnitude of the emissions from burning group 2 (which is a small part of the total results) the incomplete data will likely not affect the total results.

The dataset used looked at the use of chemicals for informal leaching of gold and silver in the Philippines (Terazono, Oguchi, Yoshida, Medina, & Ballesteros, 2017). The data was scaled from the original input of 989g terminals based on the weight of the materials in Group 1 (64g). In the study used as reference, the gold content of the input components (terminals) was 0,92%. In our components the content was 0,02/64=0,3% gold, but no data could be found on how this could potentially alter the inputs, and scaling was only done on input weight.

Chemical name in source	Flow in GaBi	Amount per kg	Original – per 989g	unit
Au coated terminals	Group 1 components	1	0,989	kg
Borax powder	Borax pentahydrate	0,277	0,274	kg
Pb nugget	Lead secondary	0,231	0,228	kg
Sodium m-nitrobenzene sulfonate	Nitrobenzene	0,065	0,064	kg
Sodium carbonate	Soda	0,011	0,11	kg
Sodium cyanide powder	Sodium cyanide	0,051	0,05	kg
Water	Water	1,769	1,75	kg

Group 2 is modelled as open air burning of cable, adapted from (Gullet, o.a., 2007). The adaptation was done based on copper content. The inclusion of carbon dioxide emissions was done from a thinkstep dataset.

	Our µg/g	Gullet	Factor		
Cu	189 973 (13g copper / 67,6g group 2 components)	352 000	0,5		
			(Factor 0 where the material was not in BOM)		
	Emissions per kg waste, Gullet		Modified to our case		Emission type
Sb	140	mg	0	mg	
Br	171	mg	0	mg	
Cl	785	mg	0	mg	
Cu	106	mg	57	mg	Heavy metals to air
Pb	964	mg	0	mg	
K	25,6	mg	0	mg	
Na	42,9	mg	0	mg	
Sb	3,02	mg	0	mg	
Sn	81,2	mg	0	mg	
Zn	98,2	mg	0	mg	
PM	17,5	g	17,5	g	Particles <2,5 µm to air
CO2	2,18	kg	2,18	kg	Inorganic emissions to air from thinkstep dataset "Cable waste in waste incineration plant"

The residue components that were modelled as being dumped were not processed. However, the assumption was that the metals in these components would in time release to water.

Flow	Group 3 Residue	Emission type
Gold	0g	Heavy metals to water
Silver	0,02g	Heavy metals to water
Copper	8g	Heavy metals to water
Aluminium	10g	Inorganic emission to fresh water
Other material	80g	Not modelled

Appendix D. GaBi data and data creation

The LCA performed in the project was based on data from ecoinvent 3.3, complemented by data from the thinkstep database 2018 version where necessary. In this section only the datasets are presented. For numerical LCI, see Appendix C and Chapter 2.

Life cycle stage	Subprocess	Datasets
Components	Charger	GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RoW: market for aluminium, primary, ingot ecoinvent 3.3
	Headset	GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RoW: polyethylene production, linear low density, granulate ecoinvent 3.3
	USB cable	GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RoW: market for aluminium, primary, ingot ecoinvent 3.3 RoW: polyethylene production, linear low density, granulate ecoinvent 3.3
	Antennas	GLO: market for copper ecoinvent 3.3 GLO: market for iron-nickel-chromium alloy ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3
	Battery	CN: anode production, graphite, for lithium-ion battery ecoinvent 3.3 GLO: aluminium oxide production ecoinvent 3.3 GLO: market for battery separator ecoinvent 3.3 GLO: market for carbon black ecoinvent 3.3 GLO: market for cathode, LiMn2O4, for lithium-ion battery ecoinvent 3.3 GLO: market for cobalt ecoinvent 3.3 GLO: market for copper ecoinvent 3.3 GLO: market for lithium hexafluorophosphate ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RoW: market for aluminium, primary, ingot ecoinvent 3.3

Components	Cameras (2p)	EU-28: Float flat glass ts GLO: market for acrylonitrile-butadiene-styrene copolymer ecoinvent 3.3 GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for neodymium oxide ecoinvent 3.3 GLO: market for praseodymium oxide ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 GLO: permanent magnet production, for electric motor ecoinvent 3.3
	Connectors (1 cable)	GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 RoW: iron-nickel-chromium alloy production ecoinvent 3.3 RoW: polyethylene production, linear low density, granulate ecoinvent 3.3 RoW: tin production ecoinvent 3.3
	Cover	DE: Natural rubber (NR) ts DE: Solvent-based polychloroprene adhesive of good heat resistance (estimation) ts GLO: market for copper ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 RoW: market for aluminium, primary, ingot ecoinvent 3.3
	Display	GLO: aluminium oxide production ecoinvent 3.3 GLO: market for acrylonitrile-butadiene-styrene copolymer ecoinvent 3.3 GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 GLO: market for silica sand ecoinvent 3.3 GLO: market for silver ecoinvent 3.3
	ICs	GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for silver ecoinvent 3.3
	Key panel	GLO: market for polycarbonate ecoinvent 3.3 GLO: market for polyethylene terephthalate, granulate, amorphous ecoinvent 3.3 GLO: market for silica sand ecoinvent 3.3
	LEDs	GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3
	Microphone	GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3

Components	Other components	GLO: market for acrylonitrile-butadiene-styrene copolymer ecoinvent 3.3 GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for polycarbonate ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RER: Epoxy resin PlasticsEurope
	Other mech parts	GLO: market for polycarbonate ecoinvent 3.3
	PBAs	GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for silver ecoinvent 3.3
	PCBs / Flex-films	EU-28: Float flat glass ts GLO: market for copper ecoinvent 3.3 GLO: market for gold ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RER: Epoxy resin PlasticsEurope RoW: cast iron production ecoinvent 3.3 RoW: market for aluminium, primary, ingot ecoinvent 3.3 RoW: tin production ecoinvent 3.3
	Shields	GLO: market for copper ecoinvent 3.3
	Speakers (2p)	CN: Praseodymium ts GLO: market for acrylonitrile-butadiene-styrene copolymer ecoinvent 3.3 GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for neodymium oxide ecoinvent 3.3 GLO: market for praseodymium oxide ecoinvent 3.3 GLO: market for silver ecoinvent 3.3 RoW: nylon 6 production ecoinvent 3.3 RoW: polyethylene production, low density, granulate ecoinvent 3.3
	Vibrator	GLO: market for copper ecoinvent 3.3 GLO: market for gallium, semiconductor-grade ecoinvent 3.3 GLO: market for molybdenum ecoinvent 3.3 GLO: market for neodymium oxide ecoinvent 3.3
Production and transport	Electricity mix - south Asia	CN: Electricity grid mix ts KR: Electricity grid mix ts TH: Electricity grid mix ts TW: Electricity grid mix ts
	Low carbon	CN: Electricity from photovoltaic ts
	Swedish electricity	SE: Electricity grid mix (production mix) ts <LC>
	Fossil energy mix	EU-28: Diesel mix at refinery ts
		EU-28: Natural gas mix ts
		EU-28: Kerosene / Jet A1 at refinery ts
	Truck transport	EU-28: Diesel mix at refinery ts GLO: Truck-trailer, 34-40 t tot weight, MPL 27 t, Euro 5

Use	Electricity	SE: Electricity grid mix ts RO: Electricity grid mix ts ZA: Electricity grid mix ts
End of life	Landfill	EU-28: Plastic waste on landfill ts
	Incineration	EU-28: Municipal waste in waste incineration plant ts <p-agg>
	Formal battery recycling	GLO: treatment of used Li-ion battery, pyrometallurgical treatment ecoinvent 3.3
	Formal recycling phone without battery, see Appendix 0	EU-28: Sodium hydroxide (caustic soda) mix (100%) ts DE: Lime (CaO; finelime) (EN15804 A1-A3) ts Disposal without battery <u-so> EU-28: Electricity grid mix ts
	Informal recycling leaching, see Appendix C4	DE: Nitrobenzene ts DE: Water (desalinated; deionised) ts EU-27: Lead primary and secondary mix ILA EU-28: Soda (Na2CO3) ts GLO: Sodium sulphate ts RER: Hydrogen cyanide (prussic acid) PlasticsEurope
	Informal open air burning of cable, see Appendix C4	No inputs, only elementary outputs
	Informal recycling residue, see Appendix C4	No inputs, only elementary outputs

Appendix E. Equations for the LCA-CE integration

Raw Material supplier

$$\boldsymbol{I_{Material} = I_{other\ material} + I_{other\ materialIC} * IC + I_{secondarygold} * m_{sgold} + I_{primarygold} * m_{pgold} + \cdots} \tag{1}$$

… + the same for silver, tin and copper that are included as outputs from the recycling.

$I_{Material}$
$=$ Impact from the material stage. Mining and post processing in the virgin case and processing in the secondary case
$I_{other\ material} = X\ [Impact\ (GWP, tox\ etc)]$ includes all material (not IC) that are not invstigated further, suggest contant
$I_{other\ material}IC = \ [Impact\ (GWP, tox\ etc)]$ includes all material in ICthat are not invstigated further, suggest contant
$I_{secondarygold} = X\ \left[Impact\ (GWP, tox\ etc)/kg_{gold}\right]$ secondary gold processing
$I_{primarygold} = X\ \left[Impact\ (GWP, tox\ etc)/kg_{gold}\right]$ mining and primary gold processing
$m_{s/p\ gold} = [\mathrm{kg}]$amount of secondary and primary gold

Changes in masses ms and mp imply variations in the recycled shares of gold, silver, copper and tin. These are decisions by the producer, but they affect this stage. The equation is limited by ms+mp being a fixed total, see below **50%<IC<100%**

ms and mp total, including variable IC

The total mass ms+mp is constant for each case of IC. Changing the amount of IC leads to changes in the kg of gold, silver and copper

$$\boldsymbol{m_{scopper} + m_{pcopper} = 0{,}029 + 0{,}0011 * IC\quad [\mathrm{kg}]} \tag{2}$$

IC = the factor [%] that determines how much IC is included compared to base case.
29,2g = copper in other components than IC (constant). 1.13g of copper in the IC base case.

$$\boldsymbol{m_{sgold} + m_{pgold} = 0.0000158 + 0.0000037 * IC\quad [\mathrm{kg}]} \tag{3}$$

IC = the factor [%] that determines how much IC is included compared to base case.
0.0158g = gold in other components than IC (constant). 0.0036g of gold in the IC base case

$$\boldsymbol{m_{ssilve} + m_{psilver} = 0.00007875 + 0.0000075\ * IC\ \ [\mathrm{kg}]} \tag{4}$$

IC = the factor [%] that determines how much IC is included compared to base case.
0.07875g = silver in other components than IC (constant). 0.0075g of silver in the IC base case

Manufacturing

Component supplier

Impact from energy

$$\boldsymbol{I_{subsupplier} = I_{other\ energy} * e_{p\ other} + e_{p\ electric} \sum s_{pi} I_{ei}} \tag{5}$$

$I_{other\ energy} = X\ [Impact\ (GWP, tox\ etc)/kWh]$ includes all non − electricity energy
$e_{p\ other} =$ [kWh] total amount electricity type

$I_e = X\ [Impact\ (GWP, tox\ etc)/kWh]$ impact from a certain electricity type
$e_{p\ electric} =$ [kWh] total amount electricity type

$s_{pi} =$ [%] % of certain electricity type

Changing the amount IC requires change in the amount of total energy sum ep (kWh), both for electricity and other (fossil) energy. Normal value for base case is that IC=1.

$$\boldsymbol{e_{p\ other} = 1.7 + 10.9 * IC \quad [\mathrm{kWh}]} \tag{6}$$

$$\boldsymbol{e_{p\ electric} = 9.7 + 40.5 * IC \quad [\mathrm{kWh}]} \tag{7}$$

9.7 kWh is the electricity consumption for other components than IC. 40.5 kWh is the base case (normal value) electricity consumption of the IC.

$IC =$ the factor [%] that determines how much IC is included compared to base case, and where **50%<IC<100%**

Changing electricity mix

$$\boldsymbol{\sum s_{pi} = 1} \tag{8}$$

For a given IC level, the sum of electricity consumption in kWh is constant.

Phone supplier (assembly)

$$\boldsymbol{I_{Assembly} = I_{transport} + I_{Assembly}} \tag{9}$$

Impact from transport and assembly are constants. The unit is the impact unit (kg Co2-eq, ELU etc).

Consumption including repair

$$\begin{aligned} \boldsymbol{I_{Consumers}} &= \overbrace{\boldsymbol{a_{ic} * n * I_{electricity_i}}}^{Use} + \\ &\underbrace{+ \sum_{\substack{\boldsymbol{Exchanged}\\ \boldsymbol{components}}} (\boldsymbol{m_{component}} * \boldsymbol{I_{component}} + \boldsymbol{m_{component}} * \boldsymbol{I_{Formal\ EoL\ component}}) * \boldsymbol{\#of\ exchanges}}_{Repair} \end{aligned} \tag{10}$$

Use

a_{i_c} = years in use for each user market (i) $[years]$

$n = 4 \left[\frac{kWh}{year}\right]$. Electricity consumption per year during use phase. Suggestion to keep as constant

$\mathrm{I_{electricity_i}}$ = impact from electricity use in market i $\left[\frac{\text{Impact (GWP, tox etc)}}{\text{kWh}}\right]$

Repair

How many times the parts are exchanged can be a variable that impacts the quality factor positively. Exchange of components can also increase the life of the product.

#of exchanges is a factor representing the number of changes
(For reference, in the base case LCA model we assumed #exchanges=0,1 display exchanges/phone during a three-year life)
$m_{component} = mass\ [kg]$ of exchanged components
$m_{battery} = 0{,}05\ [kg]$
$m_{display} = 0{,}029\ [kg]$
$I_{component}$ = Impact from raw material and manufacturing of one new components $\left[\frac{\text{Impact (GWP, tox etc)}}{kg}\right]$

$I_{component} = Modified\ I_{material}\ (Equation\ (11))\ +\ Modified\ I_{subsupplier}\ (Equation\ (12))$

$I_{Formal\ EoL\ compoennt}$ = Impact of formally recycling one (broken screen/battery) component $\left[\frac{\text{Impact (GWP, tox etc)}}{component}\right]$

The equations for the impact of repair are modified from the equations representing production and formal recycling of the whole phone:

Modified material equations

$$\boldsymbol{I_{Material} = I_{other\ material} + I_{secondarygold} * m_{sgold} + I_{primarygold} * m_{pgold}} + \cdots \tag{11}$$

… + the same for silver, tin and copper that are included as outputs from the recycling

Same material impact as in Equation (1) but with other numerical impact from “other material” (see Table 18, row 26 and 27) and other total amounts (m_s+m_P) of copper, gold and silver, see below

	Battery	Screen
Total amount copper [kg]	0,0073	0,0003
Total amount gold [kg]	0	0,000005
Total amount silver [kg]	0,00002	0,000015

For the manufacturing the same mix of electricity as in Equation (5) should be used, only the total amount of electricity changes, in other words $\sum s_{pi} I_{ei}$ is the same as in Equation (5), as is $I_{other\ energy}$

.

$$I_{subsupplier} = I_{other\ energy} + e_p \sum s_{pi} I_{ei} \tag{12}$$

$$e_{pbattery} = 1.7\ [kWh]$$

$$e_{pscreen} = 0{,}006\ [kWh]$$

For the EoL the same formula is used as for the total phone, in equation (14), but with changes in masses, according to Table 17.

$$I_{Formal\ recycling} = (I_{battery} * m_{battery} + I_{restrecycling} * m_{other\ components})^{4} \tag{13}$$

$m_{battery} = 0{,}05$ [kg]
$m_{other\ components} = m_{screen} = 0{,}029\ [kg]$

Table 16: The amount of material is the exchanged components

Output:	Amount from battery	Amount from screen	Unit
copper	7,25*0,95	0,3*0,95	g
gold	0	0,005*0,95	g
silver	0,02*0,95	0,015*0,95	g

(The factor by which the numbers are multiplied is a recovery rate of the process, taken from (Proske, Clemm, & Richter, 2016).)

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[4] For full description of this equation, see section" Formal recycling"

Post-consumer options

The consumer now has the opportunity to:

1. Store in a drawer *f(non-tech factors)*
2. Send to collection companies (via e.g. Telia) *f(non-tech factors, quality, market)*
3. Send to formal Wee recycling (for example via hand-ins at municipality recycling centers) *f(non-tech factors, quality, market)*
4. Sell/reuse without going to a collection company *f(non-tech factors, quality, market) (repeat the consumption stage)*
5. Send to informal recycling – sell/dump it somewhere where it ends up in illegal market *f(non-tech factors, market)*
6. *Incineration e.g. via household waste*
7. Landfill *f(non-tech factors, market)*

q=*f*(durability, exchanged components in the consumer stage, years used)

How reasonable each action is depending on a consumer's perceived quality of the phone and the markets, but these options should be available for consumers on all three markets. In the **base case** we used the following assumption:

SE:	To SE WEE handling	7%
	To Collection companies	39%
	To landfill/incineration	10%
	Storage	44%
	Informal recycling	0%
	P2P reselling not included	
EU (east):	To EU WEE handling	14%
	To illegal recycling	28%
	Sold to RoW	30%
	To landfill	28%
	Collection companies	0%
RoW[5]:	Illegal recycling	90%
	Landfill	10%

Storing at home

Assume no/delayed impact, only that the material does not enter waste handling.

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[5] RoW=rest of world. Here assumed to be African market.

Consumer to consumer sales

Assume no impact from this activity.

Collection companies

Transport to and from collection companies is left out due to its low impact.

The collection companies can

1. Send to formal recycling e.g. Stena, Boliden (if broken) *f(quality, market)*
2. Sell for reuse (SE, EU, 3^{rd}) *f(non-tech factors, quality, market) (repeat consumption stage)*
3. Loose to informal recycling (same impact as consumer case) *f(market, non-tech factors)*
4. Loose to landfill (same impact as consumer case) *f(market, non-tech factors)*

In the base case the following division was used:

Collection company SE:	Recycling	5%
	Sold	95%
	% of sold to EU (east)	60%
	% of sold to RoW	40%

q=*f*(durability, exchanged components in the consumer stage, exchanged components in the collection company stage, years used)

The division should depend on the country in which the collection company operates; in the African market it is uncertain if it even exists, probably not.

Formal recycling (option 2 and 3 consumer and 1 collection companies)

The formal recycling model has two parts; one for battery and one for the rest (therefore also fits the repair situation). They scale with the weight of the parts. For example, using less IC would lower the impact for the "restrecycling".

$$I_{Formal\ recycling} = (I_{battery} * m_{battery} + I_{restrecycling} * m_{other\ components}) \qquad (14)$$

$I_{Formal\ recycling} = \text{Impact of formal recycling [Impact (GWP, tox etc)]}$

$I_{Xrec} = \text{Impact of formally recycling 1kg of X} \left[\frac{\text{Impact (GWP, tox etc)}}{kg_X}\right]$

$m_{battery} = 0{,}05\ [\text{kg}]$

$I_{restrecycling} = \text{Impact of formally recycling 1kg of phone appart from battery} \left[\frac{\text{Impact (GWP, tox etc)}}{kg_{other\ components}}\right]$

$m_{other\ components} = 0{,}179 + 0{,}00115 * IC\ [\text{kg}]$

IC can be varied, see Equation (1).

Output:	Amount	Unit
copper	(29.2+1.13*IC)*0,95	g
gold	(0.0158+0.0037*IC)*0,95	g
silver	(0.07875+0.0075*IC)*0,95	g

(The factor by which the numbers are multiplied is a recovery rate of the process, taken from (Proske, Clemm, & Richter, 2016).)

Informal recycling

For the informal recycling the components are split into groups that are handled differently, just like the formal one, but the division is different. One group is modeled as being treated in a heated acid bath, one is a proxy for open air burning of cables and the rest is just dumped. The groups that are:

Chemical Au (and same as proxy for Ag)	**Open air cables**	**Dumped (disassembled unwanted parts)**
Display (5”, 74 cm2)	USB cable	Other mech parts
ICs	Microphone	Key Panel
PBAs	LEDs	Antennas
PCBs / Flex-films	Shields	Cover
Headset	Vibrator	Battery (2900 mAh)
Other components	Connectors (1 cable)	
Speakers (2p)	Charger (some gold and silver)	
Cameras (2p)		

$$\boldsymbol{I_{Informal\ recycling} = I_{burning\ cables} * m_{cables} + I_{leaching} * m_{leaching} + I_{dumped} * m_{dumped}} \tag{15}$$

$I_{Informal\ recycling}$ = Impact of informal recycling (GWP, EPS, tox etc)
I_X = Impact of informally recycling 1kg of component with each method (GWP, EPS, tox etc per kg of x)

m_{cables} = 0,027 [kg]
$m_{leaching}$ = 0,064+0,00115 $* IC$ [kg]
m_{dumped} = 0,138 [kg]

Output:	**Amount**	**Unit**
copper	7,9+1.13*IC	g
gold	0.0132+0.0037*IC	g
silver	0.044+0.0075*IC	g

(Note: dumping impact does not exactly scale with weight, because it differs depending of which of the dumped components it is that is scaled. It is an acceptable estimate as it mainly is impacted by the battery which is the one that is likely to change).

Incineration in municipal waste handling

$$\boldsymbol{I_{Phone\ Incineration}} = \boldsymbol{I_{Incineration}} * \boldsymbol{m_{phone}} \tag{16}$$

$\boldsymbol{I_{Incineration}}$ = Impact per kg of municipal waste incineration [Impact (GWP,tox etc)/kg waste]

m_{phone} = 0,230 [kg]

Landfill

$$\boldsymbol{I_{Phone\ Landfill}} = \boldsymbol{I_{landfill}} * \boldsymbol{m_{phone}} \tag{17}$$

$\boldsymbol{I_{Landfill}}$ = Impact per kg of landfilled waste [Impact (GWP,tox etc)/kg waste]

m_{phone} = 0,230 [kg]

Constants

In the following table the numerical values for the constants are listed for the four investigated impact categories.

Table 17: Constants listed for the investigated impact categories

1. Raw material supplier		**X=kg CO2-eq**	**X=CTUh**	**X=kg Sb-eq**	**X=ELU**
	Unit	Climate change	Toxicity cancer	Abiotic depletion	EPS
$I_{\text{other material}}$	X	1,7	1,3E-07	0,00041	3,777
$I_{\text{other materialIC}}$	X	3,3	4,2E-10	9,53E-07	4,7E-01
$I_{\text{primary gold}}$	X/kg	15872,1	0,029	49	2216900
$I_{\text{primary silver}}$	X/kg	339,0	0,0001	2	26619
$I_{\text{primary copper}}$	X/kg	4,1	5,2E-06	0	172
$I_{\text{secondaryX}}$	X/kg	Assume no impact			
2. Manufacturing		X=kg CO2-eq	X=CTUh	X=kg Sb-eq	X=ELU
	Unit	GWP	Toxicity	Abiotic depletion	EPS
$I_{\text{other energy}}$	X/kWh	0,4643	1,2E-08	1E-06	0,51924
$I_{\text{south asian mix}}$	X/kWh	0,707	2,2E-09	7E-07	0,21309
$I_{\text{swedish mix}}$	X/kWh	0,0355	6,3E-11	1,8E-06	0,01798
$I_{\text{solar panel electricity}}$	X/kWh	0,0665	1,3E-09	1,6E-05	0,25367
$I_{\text{transport}}$	X	0,511	3,2E-09	1,9E-07	0,15005
I_{assembly}	X	1,2019	3,8E-09	1,2E-06	0,36226
3. Consumption including repair					
		X=kg CO2-eq	X=CTUh	X=kg Sb-eq	X=ELU
Use	Unit	GWP	Toxicity	Abiotic depletion	EPS
$I_{\text{electricitySE}}$	X/kWh	0,0355	6,3E-11	1,8E-06	0,01798
$I_{\text{electricityEUeast}}$	X/kWh	0,4471	4E-10	1,6E-06	0,1312
$I_{\text{electricityAfrica}}$	X/kWh	1,3326	8,4E-10	4,4E-07	0,30473
Repair					
$I_{\text{other material}}$ for battery repair	X	0,3378	5E-08	0,00037	3,02798
$I_{\text{other material}}$ for screen repair	X	0,5027	8,2E-09	6,1E-07	0,0966

4. Post-consumer		X=kg CO2-eq	X=CTUh	X=kg Sb-eq	X=ELU
	Unit	GWP	Toxicity	Abiotic depletion	EPS
Formal recycling					
$I_{battery}$	X/kg	1,462	1,1E-07	0,00011	1,61546
$I_{restrecycling}$	X/kg	0,6606	5,4E-09	3E-06	0,17104
Informal recycling					
$I_{burning\ cables}$	X/kg	2,177	1,1E-06	0	2,42002
$I_{leaching}$	X/kg	0,8943	9,5E-09	0,00015	22,9377
I_{dumped}	X/kg	0	0	0	0
Incineration					
$I_{incineration}$	X/kg	384,7	2,4E-07	2,9E-05	43,4438
Landfill					
$I_{landfill}$	X/kg	0,0703	7,9E-10	4,2E-08	0,02098

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