A comparative life cycle assessment of the informal and formal recycling procedures of mobile phones

A case study of Ghana and Closing the Loop

Based on ISO 14040:2006 and ISO 14044:2006

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30th June, 2020

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Abstract

The increasing global demand for electronic goods, in particular mobile phones, has led to an unprecedented amount of electronic waste, otherwise known as e-waste. Every year thousands of tonnes of e-waste is exported to vulnerable regions in Africa where it ends up in landfill or is processed in the informal recycling sector. Improper recycling techniques used in the informal sector lead to an uncontrollable release of harmful substances posing a severe threat to the environment and human health. In order to address these issues, a Dutch enterprise named Closing the Loop (CTL) aims to provide a service in which end of life mobile phones are recycled in a safe and responsible manner. This paper aims to address the environmental impact of the recycling procedures of phones through a comparative analysis of the formal sector (CTL) and the informal sector in Ghana. A life cycle assessment was utilised to quantify the environmental impact of both sectors and compared various impact indicators. It was found that the informal recycling procedures were damaging to ecosystems, human health and resources. The release of GHGs such as carbon dioxide and methane alongside soil pollution from metals such as copper and bromine were the biggest contributors towards this negative environmental impact. Contrastingly, it was found that damage was avoided through formal processes utilising appropriate recycling practices. This is due to a higher recovery rate of raw materials and a positive net balance of energy consumption from the formal recycling procedures. Results indicate there is large potential for sustainable recycling processes within the electronics sector by recovering valuable resources in an efficient way and by recycling devices in a safe and responsible manner.

Key words
Electronic waste, end of life phones, life cycle analysis, environmental impact, formal recycling sector, informal recycling sector

Abbreviation

CML - Centrum voor Milieuwetenschappen (Faculty of Science Institute of Environmental Sciences)

CML-IA - Centrum voor Milieuwetenschappen Impact Assessment

CO2 - Carbon Dioxide

CO2-eq - CO2 equivalent

CTL - Closing the Loop

DALY - Disability adjusted life years

EOL - End of Life

E-waste - Electronic waste (discarded electrical and electronic devices)

GHG - Greenhouse gases

GWP - Global Warming Potential

ICT - Information and communications technology

LCA - Life Cycle Assessment

PCB - Printed Circuit Board

PGM - Precious Gold Metals

PM10 - Particulate Matter of 10 micrometers or less in diameter

1. Introduction and framing of study

An estimated 20 to 50 million tonnes of e-waste is generated yearly on a global level (UNEP, 2019). This is a result of the decreasing costs of electronic equipment, shorter electronic lifespans and the rising demand for electronic products. Increased production of electronic products has led to the increasing issue of e-waste, which is already considered to be the fastest growing waste stream in the world, with an estimated growth rate of 3 up to 5% per year (Cuchiella et al., 2015). E-waste, which is a term for discarded electronic devices, can be recycled safely. Nevertheless, only 20% of e-waste is recycled on a global level with the remainder either stored, reused, exported, sent to landfill or incinerated (Cobbing, 2008).

Developing nations with emerging economies such as India, China and several countries in Africa import an increasing amount of new electronic products as secondhand products or waste from other countries (UNEP, 2009). Due to a lack of proper disposal options, most obsolete electronic equipment is either stored away or given to informal collectors (Amoyaw-Osei, 2011). The largest share of e-waste ends up in landfills due to a lack of legislation, a shortage of proper recycling facilities and an underdeveloped environmental awareness for recycling e-waste (Schluep et al., 2009).

Consequently, these factors lead to practices such as the burning of cables and the incinerating of electronic equipment to retrieve valuable metals (Robinson, 2009). These informal procedures can lead to negative impacts on the environment and the health of communities. Thus environmental degradation, which is caused by the disposal of hazardous waste, could result in an uncontrolled release of toxic substances, such as lead and copper, contained in e-waste into air, water, soil and food.

Almost 50% of current e-waste generated by developed countries is illegally transferred to developing countries such as Ghana and Nigeria (Cucchiella, 2015). These countries import new, used or even broken electronic devices such as laptops, computers and cell phones. These devices, and in particular mobile phones, are recycled at a low rate and lead to a loss of materials and precious critical metals. Furthermore, a lack of appropriate recycling infrastructure leads to a growing network of informal recycling where practices such as the burning of cables and manually dismantling phones take place (see figure 1). As a result, local human health and the environment are at risk. These informal recycling techniques expose the direct environment to a range of hazardous substances.

Figure 1: Left - Electronic waste is burned in Agbogbloshie (Ghana) to melt plastics and other invaluable materials to recover valuable metals such as copper (Minter, 2019). Right - Worker is manual dismantling electronic devices to recover printed circuit boards (Vaccari et al., 2020).

Various companies have aimed to mitigate these risks, while increasing circularity in the electronics industry. Closing the Loop (CTL) is one of these companies that aims to tackle the e-waste problem and with this mission it aims to contribute to the sustainable development goal 12: responsible consumption and production. The social enterprise, founded in 2011, aims to compensate waste from phones using a one-for-one principle. For every new device that has been bought with CTL's service, an end of life phone in a developing country that lacks safe recycling systems is bought, collected and responsibly recycled in a certified recycling facility in Europe.

The aim is to increase circularity by safely recycling devices for their valuable and reusable resources, such as gold and silver, while providing a financial incentive to recycling networks in developing countries to become more sustainable. Additionally, a stream from e-waste is developed where end-of-life electronic devices are collected by local service providers, while waste is turned into reusable materials. This not only creates additional job opportunities in developing countries, but it is also increasing circularity in the electronics sector.

1.1 Framing of the study

The toxic substances contained in e-waste pose high risks to human health and the environment if it is improperly managed. There is a growing body of literature that recognizes the importance of protecting human health and the environment against the negative effects of hazardous electronic waste (Wilder et al., 2005; Perkins et al., 2014). Most of these studies have focused on the potential risks of improper recycling, but only a few studies have addressed the environmental impact of the procedures in a quantitative manner.

There is a need to quantify and analyze e-waste treatment processes in a systematic manner (Perkins et al., 2014). Thus, this study focused on the environmental impact of recycling procedures on e-waste by using a life cycle assessment (LCA). This tool can help organisations to identify and quantify processes or products that are contributing to environmental impacts

(ISO 14040:2006). An LCA study includes the collection of energy and materials that are used during a process and includes a calculation on the cumulative emissions to the environment. In order to make a comparison between various e-waste management scenarios, a comparative analysis was carried out on the formal and the informal recycling procedures. It is important to know that an LCA is not suitable to assess risks on a local level due to different local circumstances. Various factors, such as the health of workers and the condition of the environment in which recycling practices take place, are not taken in an LCA into account. However, the emissions and potential environmental impacts from various recycling management scenarios can be analysed and compared with each other.

A case study provided by CTL was used in this study. The formal recycling procedures entails the collection of end of life phones by CTL and the recycling of these devices by a certified recycle facility in Europe. While, the informal recycling procedures include the improper recycling techniques in Ghana. See section 6.3 for the details of these two procedures.

This paper has been divided into six parts. The first part deals with the issues of e-waste in developing countries and the recycling procedures observed in the formal and informal sector. The second part examines impacts of recycling e-waste on resources, environment and human health. The third part focuses on scientific literature surrounding the quantification of the environmental impact of e-waste. The fourth part is a description of the methodology used in this study. The fifth part shows the results of this LCA between the formal and informal recycling procedures. And the paper closes it off with a discussion of the results and a conclusion.

1.2 Problem definition

Electronic waste is a pressing environmental issue and is considered to be one of the fastest growing waste streams in the world (UNEP, 2009). Not only is this stream increasing, but it is also spreading around the globe. Large quantities of e-waste is shipped from developing countries to vulnerable regions in the world where it is often dumped and incinerated on site (UNEP, 2009). E-waste is often manually dismantled and recycled to recover precious metals, such as gold, silver and palladium (Prakash et al., 2010; Fornalczyk et al., 2013). However, these metals are often recovered in an inefficient way due to a lack of environmental regulations and a lack of proper recycling facilities (Prakash et al., 2010). This can lead to an uncontrollable release of emissions in the soil, water and atmosphere which poses great risks for the economy, environment and human health (Cucchiella et al., 2015)

The adverse risks of improper recycling of e-waste can be reduced by using proper waste management. The company Closing the loop (CTL) actively plays a role in the recycling sector by organizing the collection of end of life phones and the transportation of these devices to proper recycling facilities. The end of life phones are collected by a collection network in developing countries and sold to CTL. These devices are transported to multiple certified recycling facilities in Europe to recover valuable materials in a safe and responsible manner. This creates not only an economic incentive for collection networks in developing countries, as they get a financial incentive to collect phones, but can also be beneficial for local human health and the environment (Wang et al., 2012; Bates and Osibanjo, 2019). Numerous studies have assessed the environmental impact of e-waste in various ways (see section 4), but a specific study on CTL and her impacts is lacking. Moreover, there is a lack of studies concerning the environmental impact of recycling phones in the informal sector.

This study aims to assess the environmental impact of recycling end of life phones in the formal sector in comparison with the informal sector. The quantification and assessment of the environmental impact is carried out using a life cycle assessment. This tool is used to evaluate the environmental impact of a product or a process throughout its life cycle, from the cradle to the grave. The LCA can provide key insights on emissions and recycling processes that are harmful for the environment and aims to quantify the environmental impact of recycling end of life phones in the formal and informal sector. The formal recycling procedures are focused on CTL's process, while the informal recycling procedures are focused on circumstances in Ghana. This country is used as a case study, because it is the first country that CTL has entered and operated in ever since. This study aims to address the following research question:

What is the environmental impact of Closing the Loop's recycling procedure of phones in comparison to the business as usual scenario in Ghana using a life cycle assessment?

In order to answer this main question, the following sub questions are used:

1. What are the formal and informal recycling procedures on mobile phones in Ghana?
2. What materials and environmental impacts should be compared with each other?
3. How does the informal and formal recycling procedure compare with each other in terms of environmental impacts?
4. What key processes or emissions are contributing to these environmental impacts?

2. E-waste

All electrical and electronic equipment such as laptops, printers, refrigerators and mobile phones that are discarded and no longer used can be considered as electronic waste or *e-waste* (Step Initiative, 2014). According to the Basel Convention, e-waste is classified as hazardous waste due to its presence of harmful materials such as lead, brominated flame and mercury. These materials and other hazardous toxic waste are not allowed to be transferred between countries who have signed this international treaty (Kummer, 1999). If these materials are not managed or recycled properly, it poses a threat for human health and the environment (UNEP, 2009)

2.1 Drivers of e-waste

Decreasing costs of electronic devices coupled with the rising demand for such products has led to e-waste becoming a prominent global environmental issue. An estimated 20 to 50 million tonnes of e-waste is generated globally each year with this figure expected to grow 3 to 5% annually (UNEP, 2019). If this trend continues then the amount of e-waste that is recovered, recycled or disposed will double by 2050 in comparison with 2019. While the number of people that own multiple electronic devices have increased, many of these devices tend to be replaced every few years. Thus the replacement rate of electronic devices has decreased overtime (Balde et al., 2017).

The increasing issue of e-waste is a problem for both developed and developing economies worldwide. The largest share of e-waste is generated in Asia (41%), Europe (28%) and America (25%) while Africa was responsible for a mere 5% of the global total in 2016. Nevertheless, Africa has become one of the most prominent global dumping grounds for e-waste originating from developed countries and imported as second-hand products or ‘humanitarian aid’ (Cuchiella et al., 2015). Notably, Ghana has become a country which acquires a considerable amount of the developed world’s e-waste, importing large quantities of used and broken equipment ranging from washing machines to laptops, tablets and mobile phones (Balde et al., 2017).

In 2009 approximately 215,000 tons of e-waste was imported into Ghana, with this figure expected to double in 2020 (Daum et al., 2017; Amoyaw-Osei et al., 2011). An estimated 30 percent of imported electronic products is new, while the remaining 70% is used (Amoyaw-Osei et al., 2011). Problematically, most imported second hand products are old or damaged and thus, an estimated 15%, cannot be repaired or re-sold (Kuper & Hosjik, 2008). In addition to the issue of broken imported products, e-waste in Ghana is increasingly being generated from domestic consumption due to a rising middle class and increased demand for electronic goods (Grant et al., 2019; Sovacool, 2019). An accumulation of imported and self-generated e-waste has thus led to Ghana becoming one of the largest e-waste dumping sites in the world (Sovacool, 2019). Furthermore, the lack of regulation and government enforcement within Ghana has led to the country becoming a prime destination for informal recycling procedures which are damaging both to surrounding ecosystems and human health (Amouaw-Osei et al., 2011).

2.2 Recycling e-waste

The recycling rate of e-waste is estimated to be 20% across the globe (Balde et al., 2017). Europe has the highest rate, recycling 35% of their e-waste on average through formal procedures (Balde et al., 2017). Comparatively Africa recycles less than 1% through formal recycling take back programs (Balde et al., 2017). Consequently, e-waste is often untreated or recycled in an environmentally harmful way due to a lack of awareness, sub-optimal recycling infrastructures and weak enforcement of environmental regulations (Balde et al., 2015). These circumstances can lead to an uncontrollable release of toxic chemicals into the environment which are harmful both to human health and the surrounding ecosystems. To mitigate these risks, UNEP (2019) urges that e-waste must be managed appropriately, further emphasising the need to salvage valuable metals contained within electronics that would otherwise be lost. The increasing demand for electronic goods has put significant pressure on scarce metals such as gold, silver, palladium and copper which are supplied through the mining of natural resources (Schluep et al., 2009). The global stock of precious metals is scarce and depleting. Therefore, the importance of recycling e-waste in an effective and environmentally sound way in order to meet global demand for metals and increase circularity in the economy is increasingly urgent (Schluep et al., 2009).

2.3 Recycling of mobile phones

In recent years the lifespan of an average phone has decreased significantly due to declining costs and increasing production on a global level (Balde et al., 2017; Kumar et al., 2014). Additionally, the short lifespan is driven by a number of other factors, such as fashion trends and rapid technology advancements for improved models. (Panambunan-Ferse and Breiter, 2013). The average rate in which phones are replaced is less than 3 year in developing countries and less than 2 years in developed countries (Sarath et al., 2015). Moreover, Balde et al. (2015) estimated mobile phone ownership increased ten times over ten years to nearly 5 billion in 2011 with consumption forecasted to continually increase.

While the global demand for new devices continues to accelerate, so has the amount of generated e-waste continued to grow (UNEP, 2019). Even though the recycling rate for e-waste has slightly improved over the years, the recycling rate remains relatively low (Coalition, 2014). Estimates suggest that only 2-16% of mobile phones are collected and recycled for material recovery on a global level (Navazo et al., 2014). Consequently, the remaining obsolete devices are either stored at home, traded, exported or thrown away meaning a loss of valuable metals that could be recycled (OECD, 2010; Navazo et al., 2014). Resultantly, there is an opportunity to recover these metals from obsolete devices in such a way that can lead to economic benefits, while concurrently reducing risks to the environment and human health (Kumar et al., 2014).

2.4 Informal e-waste recycling procedures

As discussed in section 2.1 Ghana imports large quantities of second hand and low cost electronic goods mainly from Europe, North America and Asia (Amoyaw-Osei et al., 2011) Imported devices are often damaged, with 10% not functioning at all and only 20% able to be repaired (Amoyaw-Osei et al., 2011). Consequently, many of these electronic devices are refurbished for their materials or repaired in the informal recycling sector (Ilankoon, 2018). Notably, Ghana has a particularly high collection rate of 95% with nearly all of the collected materials being processed in the informal recycling sector (Bates and Osibanjo, 2019). Most informal collectors and recyclers do not wear protective equipment during the sorting or manual dismantling of electronic waste leading to high health risks through exposure to toxic contaminants (Sovacool, 2019). Moreover, these informal workers are often living under extremely poor conditions meaning they are constantly exposed to occupational hazards linked to improper disposal of e-waste (Oteng-Ababio, 2012). A ban on these recycling practices is considered ineffective, since many individuals are economically and socially reliant on the informal system (Chi et al, 2011).

In the informal sector, e-waste is recycled for valuable materials such as gold and copper often found in printed circuit boards (PCB) from mobile phones (Oteng-Ababio, 2012). PCBs are manually dismantled from plastic casings and other fractions that do not have any economic value either remain uncollected, dumped onsite or openly incinerated (Oteng-Ababio, 2012). The PCBs are heated over a coal fired grill to dismantle electrical components or leached in acid baths. The latter method involves the usage of a toxic substance known as aqua regia, a mixture of nitric and hydrochloric acid, which is often dumped into the ground or nearby stream after usage (Robinson, 2009). However, leaching is not commonly practiced in Ghana, due to a lack of technical knowledge on recovering gold (Oteng-Ababio, 2012). Instead, PCBs are mostly collected in a huge pile, grinded into a fine powder and exported from Ghana to Asian countries such as China and India (Oteng-Ababio, 2012). Unsalvageable materials are either dumped or burned in open fields that lead to an uncontrolled release of toxic substances.

The following practices are observed in the informal sector:

- Collecting and scavenging of electrical components at dumpsites without adequate protection. [1]
- Manual dismantling of waste to recover materials for refurbishment. [2]
- Disposal of unsalvageable and hazardous waste at dumpsites. [1]
- Open burning of unwanted materials (using rubber vehicle tyres or refrigerator foams) to reduce the amount of waste. [3]
- Burning plastic casings from wires in order to recover copper. [2]
- Open burning of circuit boards over coal fired grills to melt lead solders. [2]
- Leaching metals using aqua regia in an open acid pit baths to recover gold and other metals. [4]

[1] Eduljee and Harisson, 2019;
[2] Annamalai, 2015
[3] Atiemo et al., 2016; Caravanos et al., 2011.
[4] Oteng-Ababio, 2012

In addition to informal practices being highly dangerous, the yield rates of metals is found to be low. The maximum recovery rate of gold and other metals is estimated to be 25% in the informal sector, whereas up to 99% of the metals can be recovered in the formal sector (Hageluken, 2007). It is important to recycle materials as effectively and efficiently as possible in order to decrease the need for scarce natural resources (UNEP, 2009).

2.5 Formal e-waste recycling procedures

Scholars argue that the informal sector should be incorporated into formal e-waste recycling systems (Bates and Osibanjo, 2019). By doing so, it can benefit the livelihoods of individuals who are working in the informal sector while it concurrently has the potential to minimize negative impact on the environment and human health. This idea has contributed to the development of the Best of Two Worlds model (Bo2W) (Wang et al., 2012).

The Bo2W model recognises the importance of the informal and the formal recycling sectors and provides a framework for e-waste treatment in emerging economies. This framework suggests a division of tasks between developed and developing countries. While developing countries can focus on pre-processing activities, such as collection and manual dismantling, developed countries can focus on the end of process recycling. The preprocessing activities can be conducted more efficiently and at a lower cost in developing countries and can thus provide incentive for individuals to improve working and environmental conditions (Chi et al. 2011). Moreover, the end-of-life treatment processes, held in developed countries, could lead to a better disposal of hazardous substances and a higher recovery of valuable materials due to proper recycling facilities (Bates and Osibanjo, 2019; Wang et al., 2012). Such formal recycling facilities are rarely found in developing countries due to the high costs of construction and operation (Ilankoon et al., 2018). Thus, linking the formal and informal sectors can be socially and economically beneficial for communities in developing countries whilst concurrently reducing risks to the environment and human health (Wang et al., 2012).

CTL is a company that aims to link these two worlds together by organising the collection in developing countries and recycling of mobile phone waste in developed countries. For example, end of life phones are collected in countries, such as Ghana and Nigeria, and subsequently exported to certified recycling facilities such as Umicore in Belgium. This recycling plant holds strict recycling standards and can recover 80% upto 99% of precious metals found in e-waste (Navazo et al., 2014). The internal processes are designed in an eco-efficient way in order to utilize waste streams as effectively and efficiently as possible. For instance, released heat from combusted plastics are used for internal recycling processes; slag fractions are used in the construction industry and dioxins and furans are captured and separately treated to mitigate environmental risks (Hageluken, 2006).

In general, the formal recycling procedures consists of several main steps (Schleup et al., 2009):

- *Collection*: Electronic devices are collected and allocated to a recycling facility. Prior to recycling, it is important to maintain the material composition as much as possible in order to recover more valuable materials [5].

- *Sorting and physical separation:* Electronic devices are dismantled and are physically shredded into electronic scrap. The scrap gets sorted based on their size and material content [5].

- *End processing*: The fractions are treated in complex recycling processes such as pyrometallurgy, where scrap is smelted and further refined, and hydrometallurgy, where aqueous solutions are used to recover metals [6]. Both processes lead to a high yield of metals. These processes are done in a controlled environment where emissions and hazardous substances are treated in special operations in order to minimize impact on the environment.

If electronic devices are safely disposed then the benefits are twofold: more valuable materials can be recovered in proper recycling facilities and hazardous waste is safely disposed thus minimizing risks to human health and environment.

2.6 Closing the loop

Closing the loop (CTL) is a Dutch social enterprise founded in 2011 which aims to solve the issue of e-waste. CTL organises the collection of devices in developing countries and consequently exports them back to Europe for responsible and environmentally sound formal recycling processes. As of May 2020, CTL has collected more than 2.5 million end of life phones and is active in multiple African countries, such as Ghana and Nigeria.

To effectively tackle the issue of e-waste, CTL additionally set up a '*one-for-one'* initiative. The enterprise has contracts with European telecommunication companies who offer to their consumers the option to pay an additional fee towards the cost of a new phone to compensate for the waste of another phone. The collected funds are used to buy end of life phones from recycling networks in a number of African countries that lack safe recycling systems. These devices are collected, exported to Europe and recycled in a safe and responsible manner. Thus, phones are safely recycled for their valuable resources and it offers a financial incentive to recycling networks in developing countries to become more sustainable.

CTL is an Approved Collector for TCO Development which is an independent organization that offers sustainability certification for IT products. The non-profit organization launched an

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[5] Schleup et al., 2009
[6] Navazo et al. 2014

additional program called E-waste Compensated for which CTL is the first Approved Collector. The program uses third party verification schemes to make sure participants conform to regulations to ensure safe and responsible recycling practices.

3. Impacts of recycling

3.1 Impacts on resources

The increasing demand for electronic goods has an effect on primary production of precious metals such as palladium, silver and gold (UNEP, 2019). The rate in which these stocks of precious metals are mined has increased over time and has resulted in a further depletion of finite natural resources (Heacock et al., 2016). According to Golev et al., (2016) there is a global shortage of precious metals and it is thereby essential to recover these valuable resources by recycling e-waste. This provides an opportunity for *urban mining* where rare metals contained in e-waste can be recovered through recycling procedures (Nanjyo, 1988).

Urban mining has economic benefits, since extracting resources from e-waste can outweigh the costs of extracting metal ores from the ground (Golev et al., 2016). The concentration of metals found in electronic waste is higher than primary ores found in the ground (Pharino, 2017). For example, 5 gram of primary gold can be found in every ton of soil in a typical gold mine, while up to 300-350 gram of secondary gold can be extracted from one ton of mobile phones (Pharino, 2017). Nonetheless, the quantity of secondary metals that are recovered through recycling e-waste is limited so far and thus urban mining could provide a large potential for economic opportunities (Schleup et al., 2019).

In the context of mobile phones, approximately 80% of its materials can be recycled effectively (Molto et al., 2011). Baldé et al., (2017) estimated that the overall resource potential for secondary raw materials of end of life phones is worth 9.4 billion euro (Baldé et al., 2017). This potential value of recovered materials could differ due to economic factors such as market prices of materials, the yield costs and the requirement of complex recycling processes for effective and efficient recycling (Schluep et al., 2009). Additionally, phones are usually recycled when the economic benefits outweigh the costs. These devices are mainly recycled for the metal content which is mostly concentrated in a printed circuit board of a phone (Hageluken, 2008). The recovery of metals has to be done in an efficient way in order to prevent a significant loss of valuable and rare materials (UNEP, 2019). A further depletion of natural resources could lead to increasing marginal prices for the extraction of raw ores (Zeng et al., 2018).

Phones contain valuable materials, such as gold, silver and palladium, and a proper management of e-waste is needed to reduce the scarcity issue of metals (UNEP, 2019). Urban mining could provide a solution to recover these rare metals and other materials that are finite and depleting (Kumar et al., 2017).

3.2 Impacts on the environment

E-waste contains components that are toxic and non-biodegradable thus necessitating a proper recycling technique to mitigate potential effects on the environment (Kumar et al., 2014). Processes such as incineration, open burning, disposal on landfill and even recycling of e-waste generate emissions which directly or indirectly impact the environment (Hong et al., 2015).

In the formal recycling sector, treatment of e-waste is restricted to environmental regulations and high technological standards (Perkins et al. 2014). Moreover, there are recycling facilities that are designed to utilize waste streams as effectively and efficiently as possible in order to mitigate the amount of emissions which enter the environment (Navazo et al., 2014). In contrast, the informal recycling sector in developing countries is characterised as poor and inefficient (Robinson, 2009). Informal practices are predominantly unregulated and uncontrolled due to a lack of inadequate recycling infrastructure and a lack of environmental regulations (Robinson, 2009). Consequently, e-waste is often untreated or poorly recycled leading to an uncontrollable release of emissions and toxic substances into the environment (Robinson, 2009).

This risk of environmental degradation is increased when chemicals residing in e-waste accumulate in the environment. For instance, a typical mobile phone contains over 40 elements including heavy metals such as antimony, copper and lead. Various complex recycling processes are needed to properly dispose or recycle these components (Schluep et al., 2009). Thus, a lack of standards or recycling infrastructure could lead to a higher environmental pollution which could reduce biodiversity and limit habitats of species (Heacock et al., 2016).

The concentration of heavy metals and toxic pollutants found at disposal sites depend on factors such as the type of e-waste that is recycled and the practices that have been taken to mitigate emissions (Atiemo et al. 2012). In the informal sector e-waste it is often compiled and incinerated in an open fire in combination with unorthodox burning fuels such as vehicle tyres and refrigerator foams (Atiemo et al., 2016). In Ghana, Atiemo et al. (2012) found that the concentration of heavy metals, such as zinc, copper, lead and cadmium, found at burning sites are alarmingly high. While the long term effects of e-waste are still unknown (Perkins et al., 2014), studies illustrate that when e-waste is not properly managed such substances can have a substantially negative impact on the atmosphere, water and soil in the environment (UNEP, 2019).

3.2.1 Atmosphere

In the informal sector, e-waste is often dumped and burned onsite without any proper ventilation leading to greenhouse gases, toxic pollutants, dust loaded with heavy metals and flying ash particles in the atmosphere (Annamalai, 2015). This atmospheric pollution can lead to an increased uptake of emissions by plants and other living organisms near recycling sites and by bioaccumulation it could potentially reach the food chain over time (Annamalai, 2015).

Moreover, the incineration of electronic waste can result in an incomplete combustion of waste and a release of persistent organic pollutants such as dioxins, furans and polychlorinated biphenyls (PCB) in the atmosphere (Cogut, 2015). These are highly toxic chemicals that are created as by-products from incomplete burning of e-waste and thus proper treatment is needed to reduce the amount of these emissions entering the environment (Brusselaers et al., 2005).

3.2.2 Water

E-waste that is not properly disposed of, can lead to an accumulation of metals and toxic substances in soil and water bodies. This accumulation of metals can lead to leachates processes in soil and high contamination levels in the environment. For example, high concentrations of copper, cadmium, lead, iron and nickel in various water sources was found across the e-waste dumpsite Agbogbloshie located in Ghana (Daum et al., 2017). This is linked to informal recycling practices such as open burning and acid leaching of metals from PCBs where acid is often dumped into the ground or a nearby stream (Robinson, 2009). The variety of informal practices leads to several discharge points of toxic substances in the environment and could lead to a high environmental contamination in and around water bodies (Oteng-Ababio, 2012). Toxins that seep into the soil and water can negatively affect the health of living organisms (Annamalai, 2015).

3.2.3 Soil

E-waste that is disposed of in fields can break down and lead to the accumulation and leaching of toxic substances such as lead, arsenic, copper and cadmium into soil (Palmiere et al., 2013). Plants and trees can absorb these toxic chemicals and as result enter the food chain (Annamalai, 2015). In Ghana, it has been found that soil contamination is alarmingly high due to recycling activities in the informal sector (Atiemo et al., 2012). For example, the total median toxic levels found in soil after open burning is approximately seven times higher than what is considered as a safe level (Tue et al., 2016).

3.3 Impacts on human health

Harmful elements and chemicals found in e-waste are not only harmful to ecosystems, but equally to people who are living within and near recycling areas (Heacock et al., 2016). Table 1 shows an overview of chemical elements contained in phones that are a threat to human health.

Table 1: Potential health impacts from various chemical elements contained in phones

Elements	Source of components	Potential health impacts
Lead	Printed circuit boards	Damage to blood systems or kidney, affects brain development in children[7]
Mercury	Batteries, LCD displays	Chronic brain damage, skin disorders, damage to kidney and liver[5]
Cadmium	Printed circuit boards, batteries	Weakens bones, lung damage, damages nerves system[8]
Arsenic	Printed circuit boards	Diabetes, diseased related to cancer[9]
Dioxins	Incomplete burning of plastic case	Diseases related to cancer, damage to immune and nervous system[7]
Chromium	Steel case	Damage to lungs[7]
Bromine	Brominated Fire Retardants (BFR) in plastics	Liver problems, impaired development of the nervous system[10]

The exposure of toxins, ash, fumes and persistent chemicals from e-waste recycling is increased when no adequate protective measures are taken. Informal recycling practices, such as the burning and leaching of electronic components, can lead to chemical compounds in the environment. These chemicals can be inhaled, absorbed through skin or even ingested through atmospheric particulates (Ohanjinwa, 2018). Moreover, these chemicals can be absorbed by both plants and animals and can thus accumulate in the human food chain (Annamalai, 2015). Once these chemicals are absorbed toxins can accumulate in human tissue and bodily fluid (Daum et al., 2017). Consequently, these toxins can lead to human health related problems such as respiratory issues, skin diseases, carcinogenic diseases, weaker immune systems, heart problems and a shorter lifespan (Kumar et al., 2014).

There is a lack of detailed studies on the impact of toxic elements on human health from recycling sites (Srigboh et al., 2016). Due to the complex chemical composition of electronics and unorganised management of e-waste, it is difficult to estimate how long the toxins remain in the environment and what the long term effects are (Daum et al., 2016). However, studies suggest that individuals who are exposed to a contaminated environment due to informal practices have a higher risk of sustaining damage to their health (Annamalai, 2015). This risk is increased if individuals do not wear any form of protective equipment during recycling (Sovacool, 2019). In a study conducted by Srigboh et al. (2016) informal recyclers in Ghana were constantly exposed to toxic elements and the researchers found a high amount of cadmium, lead and arsenic in their blood samples.

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[7] Annamalai, 2015
[8] Sethi et al., 2006
[9] Abernathy et al, 2003
[10] Birnbaum et al., 2004

Not only workers from informal e-waste recycling areas are exposed to these toxic substances, but children too. Bridgen (2008) noted that children who live within or near e-waste recycling areas in Agbogbloshie (Ghana) are one of the most vulnerable groups exposed to the health risks related to e-waste. A link was found between the contaminated environment and the underdevelopment of childrens' brains due to a presence of lead that was found in dust particles around recycling areas (Bridgen, 2008).

It is important to know that these local effects on human health differ depending on the context at hand. This LCA study does not take these different local circumstances into account, but looks at the overall effect on the environment.

4. Literature review on LCA studies

Limited LCA studies have investigated the recycling of mobile phones. Studies which have been conducted predominantly focus on the environmental impact of the production and usage phase (Proske et al., 2016), with only a few addressing the impact of the end of life stage (Bian et al., 2016; Hong et al., 2015; Sarath et al., 2015). Additionally, these assessments were mostly done on industrial processes or activities held in the formal sector (Hong et al., 2014; Navazo et al., 2014; Soo et al, 2014), with minimal studies evaluating the informal sector (Song et al., 2013; Yadav et al., 2014).

Furthermore, LCA studies regarding the recycling processes of mobile phones have been conducted in a variety of countries such as China, India, Australia and Malaysia (Ashwahti, 2013; Soo et al., 2014; Song et al., 2013). However, a quantitative assessment of the informal recycling sector of end of life phones in Ghana is lacking. Daum et al. (2016) argue that this is caused by a lack of reliable data and the unpredictability of e-waste management practices taken in the informal sector. In order to assess the environmental impact of recycling phones for the formal and the informal sector, various studies are combined. The next section is a study on the environmental impact between the formal and informal sector of recycling end of life phones using a life cycle assessment.

5. Analytical framework

5.1 Basic methodology

There is a need for assessing the environmental impact of the formal and informal recycling process of e-waste in a systematic approach (Kiddee et al., 2013). Moreover, Hong et al., (2015) argue that an environmental analysis on the recycling processes is highly complex due to its variety and interlinkages of processes, activities and materials. However, a widely used tool for assessing environmental performance is a life cycle assessment (LCA). This is an appropriate methodology towards quantifying and evaluating different alternatives of e-waste recycling (Kiddee et al., 2013). An LCA can help organizations to identify and quantify processes or products that are contributing to emissions over its entire lifecycle (ISO

14040:2006). Furthermore, it quantifies how a product or process is affecting specific environmental indicators such as climate change, non-renewable resources and human toxicity.

The International Organization for Standardization (ISO) defines LCA as a method which:

“...addresses the environmental aspects and potential environmental impacts throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal.” (ISO 2006)

The structure of an LCA is set to ISO standards also known as the ISO 14040-series. These series define how systems and reporting on environmental management systems are carried out. Thus, this research is conducted in accordance with ISO 14040 which specifies the principles and frameworks to conduct an appropriate LCA (ISO, 2006). Furthermore, the study complies with ISO 14044 norm which specifies the requirements and guidelines to carry out an LCA.

The software scientific tool CMLCA v6.1 was used in this LCA study and it is developed by the Institute of Environmental Sciences (CML) from Leiden University. This LCA study followed the generic framework taken from ISO14040 and ISO14044. Furthermore, the database of EcoInvent 2.2 was imported in this tool. All other relevant data found in literature were manually inserted in the tool. The full list of data that were used in this study can be found in section 10.1 (informal) and section 10.2 (formal).

5.2 Structure LCA study

The LCA framework (figure 2) is defined in the following four seperate, but related phases (ISO, 2006). A brief overview on these phases in the following section, and a more detailed section of the phases are described in section 6 of this study.

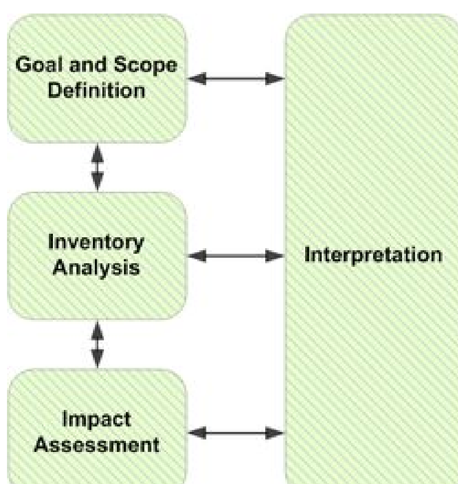

Figure 2: LCA framework derived from ISO:14044

(1.) Goal and scope

The goal defines the intended applications of the study, while the scope defines the outlines of the study such as system boundaries and assumptions. Moreover, a functional unit is also defined in this phase and it is a measurable function to connect various inputs and outputs (e.g. materials and energy) of processes and the relation between them. A comparison between various systems is only fair, if the functional unit for all environmental management systems are the same. The quantitative input and output data (e.g. emissions and physical goods) are all calculated in relation to this functional unit.

(2.) Inventory analysis

In the second phase, all relevant data are collected regarding environmental inputs and outputs of a product or service. These data include the extraction of raw materials or resources, the production of energy and emission to air, land or water. These flows are differentiated in economic and environmental goods and they are compiled in a life cycle inventory. Moreover, this list is accompanied with a flow diagram that shows how the processes within the LCA model are related.

(3.) Impact assessment

In this third phase the environmental impacts of the chosen systems are evaluated based on a chosen impact category group (see section 5.2 for more info). Multiple emissions are assigned to a unique characterization factor which shows the relative contribution of an emission towards an environmental impact. These emissions are multiplied with their own characterization factor and thereafter aggregated and assigned to various impact categories such as ecosystem quality, human health and resource scarcity. The potential contributions of selected impact categories are obtained and analysed

(4.) Interpretation.

The evaluation of the results on the aforementioned phases is conducted in the last phase of the LCA research. The results of the impact categories are interpreted and discussed on consistency and completeness. All data are evaluated on their completeness and consistent within the goal and scope of the study.

5.3 Impact calculation method

The above mentioned phases describe the basic outlines of an LCA study. In the impact assessment phase, the procedures are analysed based on a chosen impact calculation method. Each emission is multiplied with a factor and converted into a specific environmental impact indicator. Each impact calculation method has their own unique characterisation factors, conversion rates and impact indicators. It is important to know that there are several impact calculation methods and based on the chosen calculation method, the end results might differ.

For this study, processes and their related emissions were imported in the software tool CMLCA followed by a ReCiPe calculation method. The emissions were calculated and converted from emissions to impacts based on this method. The ReCiPe method is built on the work of LCA impact assessment methods such as CML-IA and Eco-Indicator 99 (CML, 2006; Goedkoop et al., 2009). While CML-IA focusses on a midpoint approach and Eco-Indicator 99 focuses on the endpoint approach, the ReCiPe method provides a framework where both midpoint and endpoint indicators can be used (figure 3)

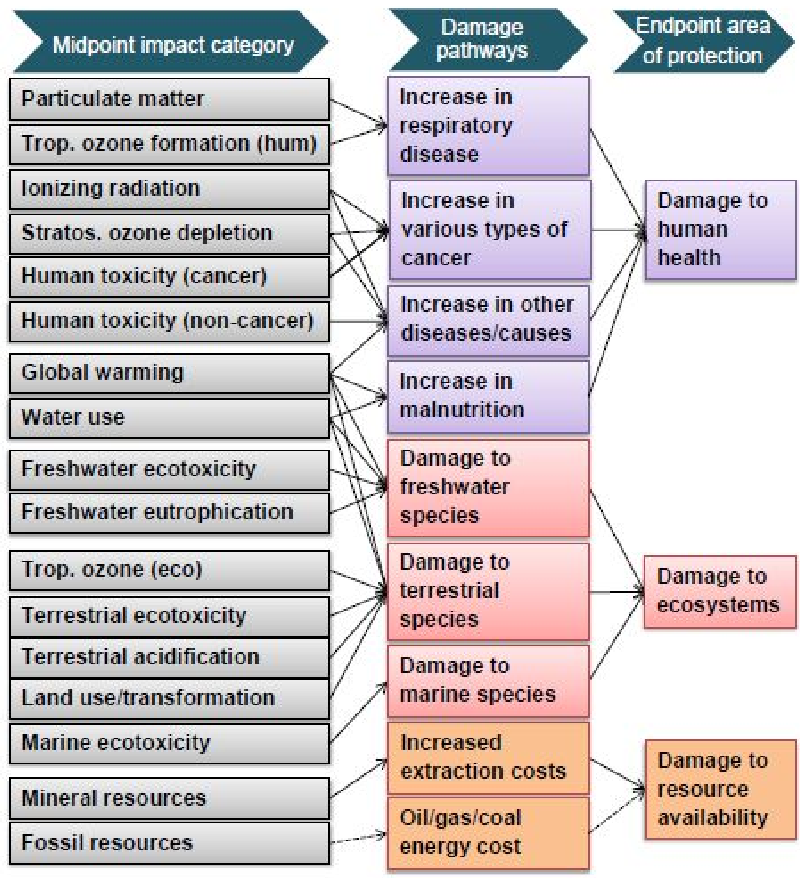

Figure 3: The figure shows the relations between 18 midpoint indicators (left) and 3 endpoint indicators (right). Source: ReCiPe 2016

The method calculates the environmental impacts related to the resources that are consumed and to emissions that are released during recycling (Goedkoop et al., 2009). Based on the chosen method, emissions are multiplied with characterization factors and assigned to a midpoint or an endpoint category. The midpoints indicate the impact (e.g. Climate change impact in CO2-equivalent) between the emission and endpoint and the endpoints indicate the environmental impact on aggregated levels of areas that need protection (e.g. human health). The connection between the midpoint and endpoint categories is based on a chosen cultural perspective. There are three perspectives (i.e. individualist, hierarchist and egalitarian) that represent a set of choices on timeframe (respectively short, medium and long term) or technology that can avoid damage in the future (respectively high, medium and low avoidance). The hierarchist perspective (H) is chosen in this study in order to simplify the wide range of values from midpoint categories. This perspective is widely used in scientific models and is based on the most common policy principles related to time-frame (Goedkoop et al., 2008).

The midpoint and endpoint indicators (figure 3) were reported in points, as a common unit, to analyse their relative contribution to environmental impact, however this brings uncertainties in the results. The link between mid and endpoint categories was based on a weighting set that is inherently subjective (Schmidt and Sullivan, 2002). In order to increase the quality of this analysis, all mid and endpoint indicators were converted from one common unit (i.e. points) to endpoint units (i.e. DALY, $ and loss of species). This conversion was done by deriving the characterizing factors between midpoint and endpoint categories for the hierarchist perspective (Goedkoop et al., 2008). See section 10.5 for the quantitative connection between these categories.

Table 1: Three areas of protection and description. Source: ReCiPe 2008

Area of protection	Endpoint category	Description	Unit
Human health	Damage to human health	Disability adjusted loss of life years	DALY
Natural environment	Damage to ecosystem quality	Loss of species over time	Species * year
Resource scarcity	Damage to resource availability	Surplus costs caused by extraction of mineral and fossil resources	$

The endpoint categories are expressed in their own unique units (table 1). Human health is expressed in disability-adjusted loss of life years (DALYs) which indicates the amount of years that are lost due to a disease or burden. Natural environment is expressed in local species that are lost over time (loss of species) and resource scarcity is expressed in surplus costs for extraction of mineral and fossil resources ($) (Goedkoop et al., 2009). It is important to know that these units can not be used as absolute numbers, since there are huge uncertainties regarding the conversion of midpoint categories into endpoint categories. However, the endpoint categories can indicate the relevance of the impact between categories.

Furthermore, these endpoint categories can further be simplified in one unit (referred to as points) after an equal weighting set is employed. This implies that all normalised results of each environmental impact category are multiplied with an equal weighting factor. The results can be aggregated into one unit for the environmental impact. However, this is not recommended since the weighting set itself was developed subjectively and local variations are found across environments (Schmidt and Sullivan, 2002). Nevertheless, in order to find out which impacts are relevant in this analysis a weighting set is employed, followed by an interpretation of the results. Thus, in the next sections the results are first reported in points and further split into endpoint indicators (e.g. DALYs) in another section.

6. Results

6.1 Goal and scope

In this section the intended applications and the outlines of this study are described.

6.1.1 Goal

The goal of this study is to make a comparison on the environmental impact of recycling end of life phones through formal and informal recycling procedures using an LCA. While the formal recycling procedures are based on the processes of recycling facility Umicore in Belgium, the informal recycling procedures are based on the recycling practices held in Ghana.

The targeted audience for this study are environmental authorities who want to reduce electronic waste, mainly end of life mobile phones, and/ or those who want to promote sustainability in the IT sector. This study is developed under supervision of the expert reviewers Dr. Reinout Heijungs from Vrije University and Reinhardt Smit from Closing the Loop.

6.1.2 Scope

The scope describes the choices that are taken in this study.

<u>Scenarios</u>

For this study two scenarios (informal and formal) are used in order to the environmental impact of phone waste recycling.

For this report, the process of Umicore, in Belgium was used, as the most information was publicly available about their process. However, CTL works with different recycling companies in different European countries. Though they all work with similar methods for recycling and extracting precious metals, their methods might differ slightly. For consistency, it has therefore also been assumed that all shipments go from Ghana to Antwerp. This can be seen as valid as Closing the Loop has in the past also had phones recycled by Umicore, even though at the time of writing, no recycling of phones was done at Umicore for Closing the Loop. For shipments to other countries, the figures would differ slightly.

Scenario 1 - Informal recycling procedures

This baseline scenario takes place in Ghana and assumes that end of life phones are recycled in the informal sector. Phones with a total weight of 1000 kg are collected in Agbogbloshie (Ghana) and recycled onsite for their precious materials. Printed circuit boards (PCB) are manually dismantled due to the high content of gold and the rest of the phone is discarded at dumpsites. This remainder, including non degradable plastic, contains no valuable materials for informal recyclers and is completely incinerated in an open fire to reduce the volume of electronic waste. On the other hand, PCBs are manually dismantled and stored locally. These PCBs are not treated in Ghana, because there is a lack of technical knowledge to recover gold

(Oteng-Ababio, 2012). Instead, these PCbs are exported to other countries such as China. For this scenario Guiyu (China) is chosen as the final destination of PCBs, because this town is considered one of the biggest e-waste dumpsites in the world (Shi et al., 2016). In this town PCBs are leached using a chemical acid called aqua regia (mixture of nitric and hydrochloric acid). This recycling process is considered inefficient and harmful for the environment, as the recovery rate of metal is low (i.e. maximum recovery rate of gold is 25%) and the acid laden solution filled with heavy and toxic metals are often dumped in the soil or a nearby stream.

Scenario 2 - Formal recycling procedures

In this scenario CTL aims to reduce the amount of localized e-waste in Ghana due to a lack of proper recycling infrastructure. The aim of CTL is to compensate waste from end of life phones in a responsible way while providing financial incentives to local communities in Ghana. In this example, 1000 kg of end of life phones are collected in Ghana and exported to recycling facility in Hoboken (Belgium) where they are safely recycled for their precious materials. Phones go through various recycling phases, including shredding, smelting, converting and electrical refining processes, to recover valuable metals and safely dispose of e-waste. The recycling process is designed in order to recycle materials as efficiently and effectively as possible. Precious metals, such as copper, silver, gold and palladium, are recovered with recovery rates ranging between 80 and 99%. The by-products of end of life phones are either combusted for heat that can be used for internal processes or recycled in a responsible manner.

Both scenarios are modelled in this analysis and the processes are described in section 6. Both scenarios begin with the collection of end of life phones, followed by various logistical and recycling processes, before materials are recovered or waste residues are treated. Only emissions related to transportation and recycling processes of phones are included in this LCA study. Moreover, every process leads to the creation of one or more physical products. These products are also known as flows and they can be divided between physical goods and waste streams. Goods are products that can be offered from the producer (i.e. recycling facility) to the market, while waste is an unsold good and it requires energy or additional costs to the producer to process it or dispose of it.

<u>Geographical boundary</u>

The collection of phones takes place in Agbogbloshie (Ghana). Depending on the scenario these phones are either exported to recycling facility Umicore in Hoboken (Belgium) in the formal sector or they are exported to Shantou (China) in the informal sector. The process of Umicore was used as the most information on their recycling processes was publicly available. Shantou is chosen in this case study, since it is the closest harbour city to the town Guiyu which is considered one of the largest e-waste sites in the world.

Boundaries in respect to natural systems

Both scenarios start with the collection of end of life phones and go through various transport and recycling processes. These processes need various energy sources and material resources as inputs in order to do the transportation and separation of valuable metals from electronic scrap. While the environmental impact of the transportation and recycling phase are included, the impact from collection phase, production phase, usage phase and final treatment of materials are excluded. See figure 4 for a framework to see which processes are included and excluded in this study.

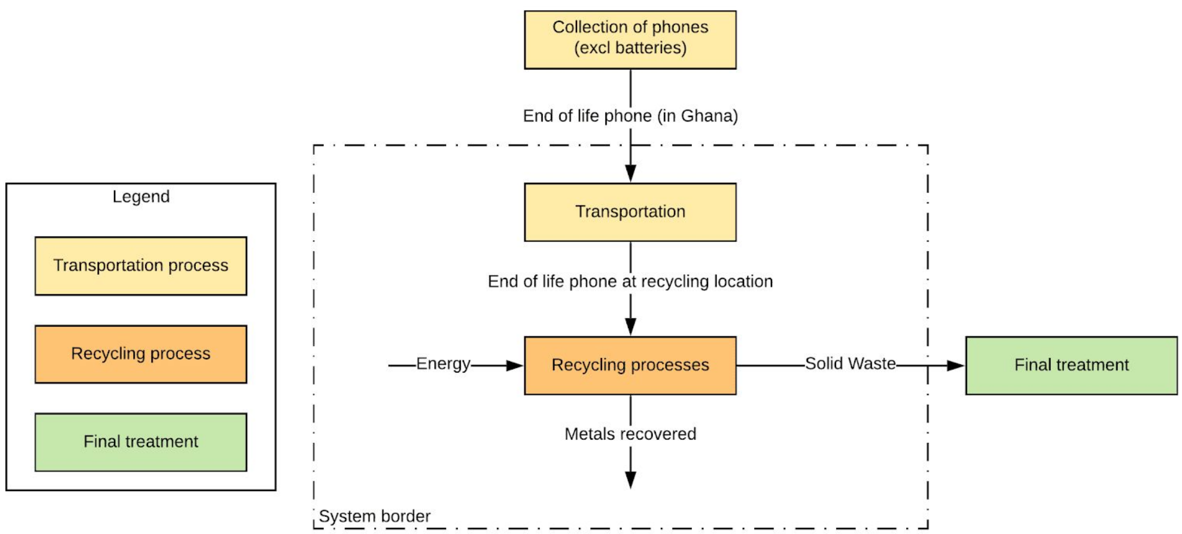

Figure 4: Flowchart of processes that are included and excluded in this study

Functional unit

In order to make a comparison between several scenarios a functional unit has to be defined. This unit is a reference unit to connect all relevant inputs and outputs of product systems and allows for a comparison between systems. The results are referred to this unit and in this study the following functional unit is chosen:

Treatment of 1000 kg of collected end of life phones (excluding batteries)

This functional unit is chosen, because several other LCA studies related to recycling mobile phones have used this unit as well (Navazo et al., 2014; Hong et al., 2015; Molto et al., 2014). It makes a comparison between systems more accessible and relevant. The end of life phone is based on the model used in Navazo et al., (2014). Batteries are excluded from the functional unit, since they are hardly exported to other countries because of the Basel Convention.

Data quality requirements

Data that are used in this LCA study should be relevant to the functional unit as well as the transportation or recycling processes. The data (environmental and economic flows) were collected from various sources such as conducted LCA studies on mobile phone recycling and studies on released emissions during combustion. Closing the Loop supplied additional information on their internal processes (i.e. transportation and recycling processes). All of the collected data were linked to database EcoInvent 2.2. All of the data inputs were chosen to match the process and location of activity as much as possible. See section 10.1 Appendix for a comprehensive list of data that are used in this study.

Limitations and assumptions

The quality of this study depends on relevant data that can be found in studies and existing databases. The data should be transparent enough so it could be available and accessible for the public. Only emission data that are related to phone recycling are manually inserted to new processes in the CMLCA tool and these data are derived from various LCA reports. It is assumed that all functional units within these reports are identical or convertable to the functional unit that is used in this study (Hageluken, 2007; Navazo et al., 2014; Molto et al., 2014). Furthermore, EcoInvent 2.2 consists of an extensive database and some processes of this database are used based on their relevance and match to this study. No additional emissions are manually added to existing processes contained in EcoInvent.

It is assumed that in the formal and informal scenario, no phones are lost during the process and that all major parts of a phone is either completely recycled or is finally disposed of. In the informal sector it is assumed that uncontrolled emissions are directly released into the environment during recycling that leads to emissions into the air, leachates into the groundwater and residue on the soil. In the formal sector it is assumed that released emissions are captured and treated that would lead to a lower amount of emissions into the environment.

It is important to know that this LCA study does not cover the entire environmental impact related to recycling phones. This LCA aims to assess the environmental impact in a broad sense meaning that this impact is calculated based on all living beings. It does not take various local circumstances, such as duration of exposure, timeframe and location in which recycling practice takes place and health of individuals, into account. The impact is calculated and it is equal for all species regardless of human health, age and sex groups.

In this LCA study an avoided impact burden approach is used to allocate environmental burden in the context of recycling. Both formal and informal recycling processes lead to a recovery of metals. However, it is expected that the formal procedures lead to a higher recovery rate in comparison with the informal procedures. Metals that are recovered do not have to be produced elsewhere again and thus leads to a reduction of production of metals and its related environmental impact. In other words, as the recovery rate of recycled metals increases, so will the avoided environmental impact caused by producing metals increase. Note that the use of this avoided burden approach may yield *negative* emissions or impacts, when more impact is saved than created.

6.2 Inventory analysis

In the inventory analysis phase, all relevant data, such as energy consumption, materials and emissions, were identified, collected and quantified for all resources for the transportation and recycling processes. Moreover, all relevant substances that are released in the environment during these processes were collected and quantified. The processes are described for both the informal and the formal recycling route in this section. The full list of data can be found in section 10.1 for the informal scenario and section 10.2 for the formal scenario.

6.2.1 Scenario 1 - Informal

In this scenario (figure 5) phones are used until they become obsolete; they are often stored away or discarded on a landfill. These end of life phones, with a total weight of 1000 kg, are collected in Ghana and go through various recycling processes in the informal sector that pose a high risk to the environment.

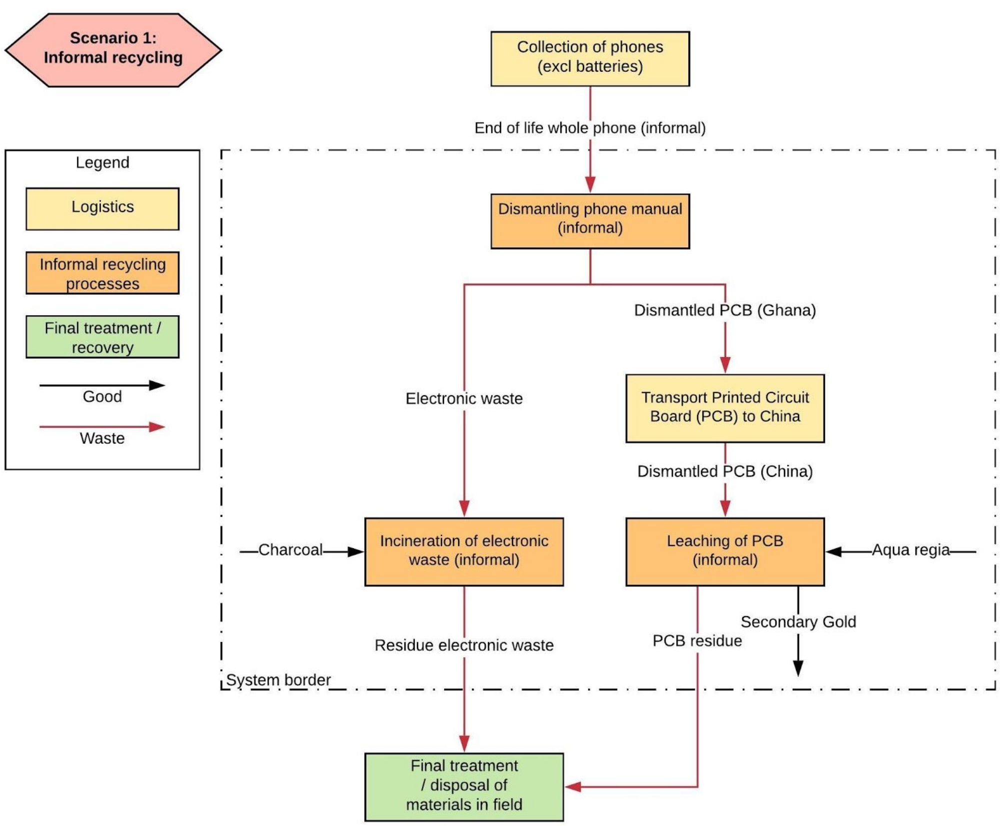

Figure 5: Flowchart for informal recycling procedures

Dismantling phone manual (informal)

Phones are manually dismantled in order to separate valuable from invaluable components. PCBs are recovered for their high concentration of gold, while the rest of the phone is discarded (Schluep et al. 2009). An average PCB weighs 20 gram and an average phone (excluding battery) weighs 90 gram (OECD, 2010). If these values are normalized to the functional unit (1000 kg phones), then a total of 219 kg is allocated to PCB, while the remainder with a total weight of 781 kg is allocated as electronic waste. The remainder consists of plastic scrap, metal scrap, LCD screen and other small electronic components. The physical separation of a phone is done manually and no additional emissions are allocated to this process.

Incineration of electronic waste

The electronic scrap is a mixture of plastic scrap, metal scrap and LCD screens. This scrap contains no valuable materials for informal recyclers and is discarded on a dumpsite (Oteng-Ababio, 2012). The scrap is often compiled with other electronic waste and is incinerated at open burning sites in order to reduce the volume of waste. The open burning of waste releases a great amount of GHG, toxic pollutants and fumes in the environment.

It is assumed that all of this electronic scrap is completely incinerated in an open fire that leads to emissions into the air, water and soil. Often vehicle tyres are used as fuel sources to combust waste (Atiemo et al., 2016), however no emission values could be found for this fuel and charcoals are used in this analysis instead. Charcoal has been chosen, because it sustains combustion and matches observed practices (Gullet et al., 2007). In this study it was found that 6.96 MJ of heat was needed to combust one kg of mobile phone. A total of 6960 MJ is allocated for the incineration of 1000 kg phones.

Furthermore, emissions for water and soil are derived from a study conducted by Gullet et al. (2007) that calculated the leaching and residual ash emissions from an uncontrolled combustion of electronic waste. Additionally, air emissions are released during combustion and these emission values are retrieved from a study conducted Molto et al. (2012). They detected high values of toxic compounds, such as dioxins, and greenhouse gases, such as carbon dioxide and methane from incinerating electrical phone waste.

Transport printed circuit boards to China

Phones are dismantled to recover PCBs and they are collected in Ghana and shipped in a container ship to China (Oteng-Ababio, 2012). For this process it assumed that PCBs are transported between Accra (Ghana) and Shantou (China) by a container freight ship over an average distance of 17840 km (Searates, n.d.).

Leaching of PCB

The dismantled PCBs are imported in China where they are further treated to recover valuable metals (Robinson, 2009). However, due to a lack of environmental regulations and proper recycling facilities in the informal sector, these PCBs are often treated in an open acid bath. During this process aqua regia is used to leach gold from PCBs. The solution is often dumped on the soil or a nearby stream and releases an uncontrollable amount of emissions into the environment.

Aqua regia, a mixture of three parts hydrochloric and one part nitric acid, is used as a solution for the leaching process (Rubin, 2014; Sheng and Etsel, 2007). However, limited amounts of data on released emissions could be found for this leaching process. These emission values were mostly described in compounds such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) and these emissions were not found in the EcoInvent database. Therefore, emissions derived from Gullet et al. (2007) and Molto et al. (2012) were used as environmental outflows for this process. During this leaching process, it was assumed that only 25% of gold contained in PCBs or 90 gram gold per 1 ton of PCB were recovered, while the remainder was incinerated (Hageluken, 2007).

6.3.2 Scenario 2 - Formal

In this scenario (figure 6) end of life phones are collected in Ghana and exported to Belgium, where these devices go through various formal recycling procedures for proper recycling. The main processes include shredding, smelting and converting of e-waste, followed by a series of refining processes to recover valuable metals. These processes and their related emissions are mainly derived from a material flow analysis conducted by Navazo et al. (2013) and they are briefly explained in the following sections.

<u>Transport over sea from from Accra (Ghana) to Antwerp (Belgium)</u>
End of life phones with a total weight of 1000 kilogram are collected in Accra and shipped from the local port Tema in a container freight ship to Antwerp. The average distance between these two cities is 3978 nautical miles or 7367 km (Sea distances, n.d.).

<u>Transport over land from Antwerp (Belgium) to Hoboken (Belgium)</u>
After the phones are transported over sea, they are transported on a vehicle from Antwerp to the recycle facility Umicore in Hoboken (Belgium). The shipment to Umicore is used as an example. It is assumed that the collected phones are transferred on a lorry (capacity more than 16 ton) over a distance of 19.4 km (Google, n.d.).

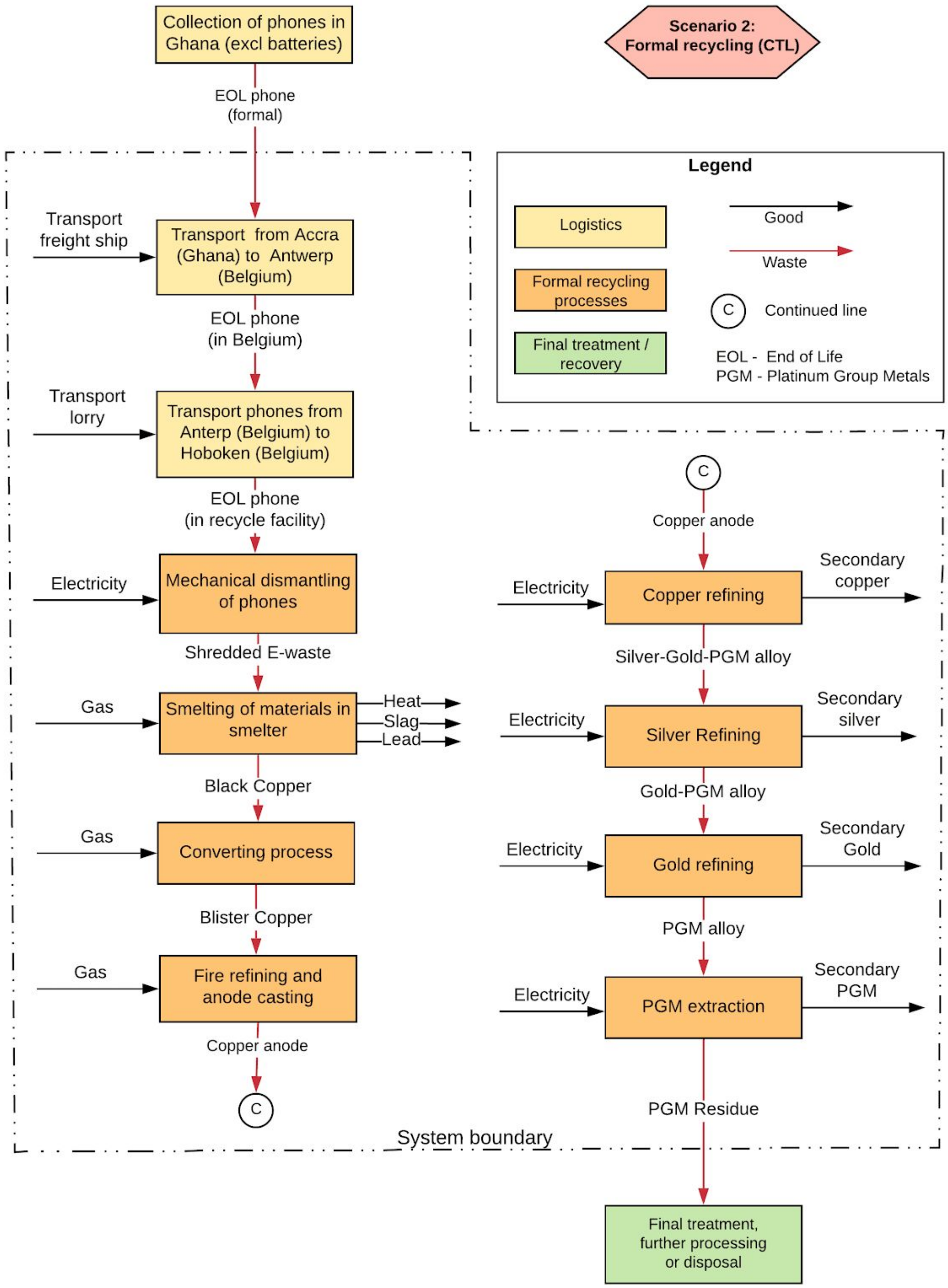

Figure 6: Flowchart for formal recycling procedures

Dismantling of phone mechanically at plant

In the recycling facility phones are mechanically shredded and turned into shredded e-waste. According to Hischier (2007) this step involves the shredding of 1 ton e-waste and requires an energy input of 137 MJ per ton e-waste. The average energy input from Belgium is used for this process.

Smelting of materials in smelter

The shredded e-waste is fed in a copper smelter, where copper and precious metals are separated from the rest of the smelting mix. In order to smelt 1000 kg of e-waste it requires an additional energy of 1393 MJ (Alvarao et al., 2002). However, plastic from phones are simultaneously smelted and this releases an excessive heat which can be recovered for internal use. Subsequently, more energy is being produced then consumed during the smelting process. According to Navazo et al. (2014) the plastics contained in 1 ton mobile phones represents 10,652 MJ worth of energy. This energy is captured and recovered for additional recycling processes. This smelting process results in 147 kg of black copper (including precious metals and copper), 396 kg of slag (including silica, iron and aluminum oxide) and 17 kg of lead slag (including lead, tin and antimony) (Navazo et al., 2014). During smelting approximately 440 kg of plastic is combusted and this releases energy, fumes and gases in the air. The air particles are treated in a cleaning installation where Polychlorinated dioxins (PCDD) and furans are removed that are contained in plastics and as a result low emissions are released in the air (Brusselaers et al., 2005). The monitored emissions are used as emissions output in this model.

Converting process

During this process an air-oxygen mixture is blown on the black copper to oxidize the remaining iron and impurities (lead, tin, zinc, arsenic and antimony) and as a result 147 kg blister copper is produced. According to Navazo et al., (2014) this step requires an average energy usage of 2.6 MJ per kg of refined copper. Using this value the total required energy for this step is 369.2 MJ.

Fire refining and Anode furnace

The blister copper is placed in an anode furnace where natural gas is blown in order to remove the remaining oxygen (Navazo et al., 2014). Almost 90% of AS and 70% of Sb are removed during this process. This fire refining process requires an energy input of 958 MJ for 1 ton of mobile phones (Reuter et al., 2005). Resultantly, 147 kg blister copper is casted on thin anode plates for refining precious metals.

Copper refining

The anode plates are placed in a bath filled with sulfuric acid that dissolves impurities. As a result 128 kg of copper is deposited on cathode plates, while the impurities (including precious metals) accumulate on the bottom. This electrolysis step requires an average energy input of 2791 kWh per ton of refined copper (Navazo et al., 2014); a total of 1424 MJ is allocated for the power consumption.

Silver refining

The impurities are melted and casted to alloy anodes. These anodes are submerged in a nitric acid bath, where silver is extracted using electrolysis resulting in impurities that are left on the bodem. In order to refine 1 kg silver an energy input of 485 MJ is needed. One ton of mobile phone contains 3.63 kg of silver and a total of 1761 MJ for energy consumption is allocated to this process (Navazo et al., 2014). Emissions from the production of secondary silver derived from EcoInvent were used.

Gold refining

The residue on the bodem is melted and casted into a Gold-PGM alloy. This alloy goes through an electrolysis process and leaves anode slimes on the bottom of the bath. Gold is recovered from cathodes plates and as result secondary gold is produced. The electrolysis step requires an average energy consumption of 186 MJ per kg of refined gold (Navazo et al., 2014). One ton of mobile phones contains approximately 350 gram of gold and the total energy consumption for this process is estimated to be 65.1 MJ.

PGM extraction

The platinum group metals (PGM) are refined and recovered using an extraction technique that separates the ions from a solution (Navazo et al., 2014). During this process 150 gram of PGM is recovered and a total energy consumption of 1000 MJ is needed (Navazo et al., 2014). The remaining wastewater is neutralized and treated in a purification system before it is discharged back in the environment.

Table 2 shows an overview of the resources that are used for both the informal and formal processes.

Table 2: Overview of economic inputs and outputs used in this study

Property	Informal	Formal
Input	1000 kg of collected phones	
Additional resources needed	Aqua regia, coals	Electricity and heat
Total energy needed	6960 MJ needed for incineration of phones	137 MJ for shredding process 1393 MJ for smelting process 1327.2 MJ for converting process 4250.1 MJ for refining processes ________________ 7107.3 MJ needed in total
Metals recovered	90 gram gold	369 kg slag, 17 kg of lead, 128 kg of copper, 3.63 kg of silver, 350 gram gold and 150 gram platinum,
Recovery rate	Max 25% for gold	80-99% for precious metals
Additional information	-	10,652 MJ heat is captured and reused for internal processes

6.3 Impact categories results

6.3.1 Midpoint impact categories

The ReCiPe calculation method was employed on both models and the full results can be seen in section 10.4. The midpoint indicators show that not all impact categories were evenly presented, since some of the categories were hardly impacted by the formal or the informal recycling processes. Due to the goal and scope of this study, not all 18 impact categories were analysed. In order to simplify the analysis only the midpoint categories that contributed the most towards the overall environmental impact were considered in this study. Only the selected impact categories of top 99% of the total environmental impact were used and all other categories were not analysed.

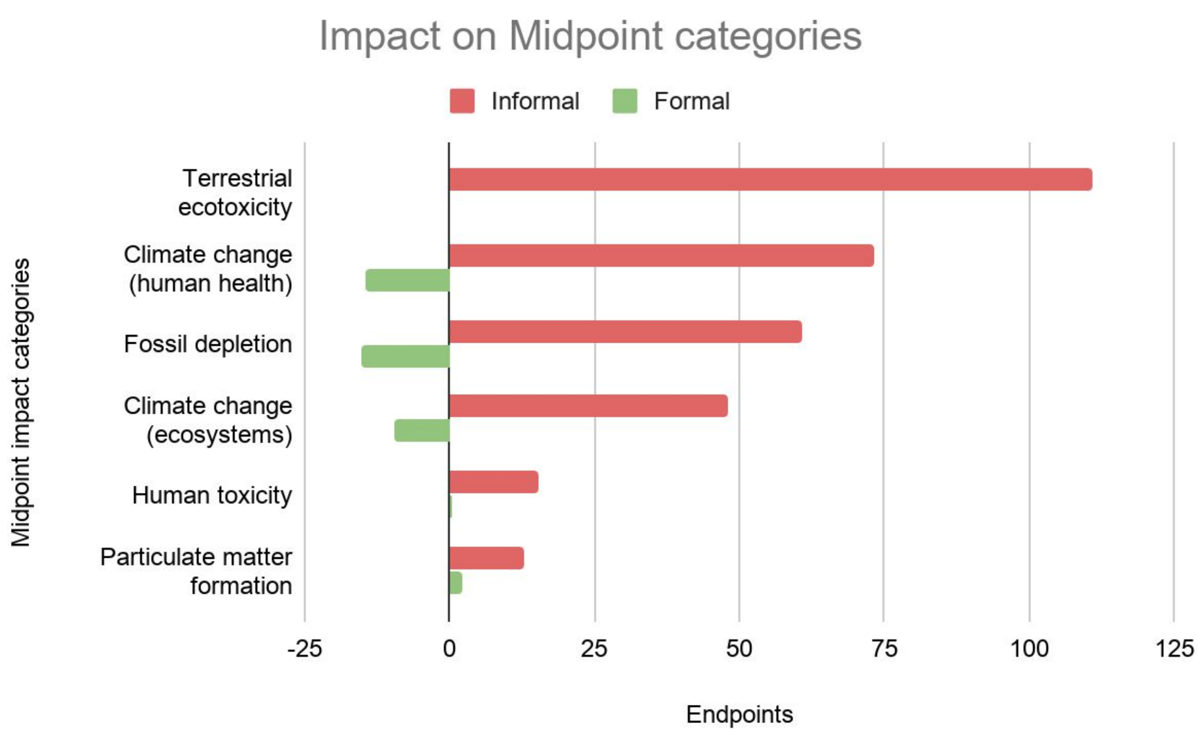

Figure 7: Comparison of midpoint impact categories between formal and informal recycling procedures. Note that an impact category is considered positive when it is damaging to the environment and negative when it is avoiding a burden.

Six out of eighteen midpoint categories were analysed in this study as they accumulate over 99% of the overall environmental impact (figure 7). The results from various impact categories differ greatly between the formal from the informal sector. The informal recycling procedures were damaging on all midpoint categories, while the formal recycling procedures mostly avoided damage on certain categories. The results show that the informal recycling procedures (total

324 points) had a higher environmental impact in comparison with the formal recycling procedures (total -36.6 points) across all midpoint indicators. The biggest contributors towards this environmental impact in the informal scenario were the following indicators *terrestrial ecotoxicity (34.3%), human health (22.6%), fossil depletion (18.8%), climate change on ecosystems (14.8%) and human toxicity (4.8%)*. On the other side, a burden on certain impact categories were avoided in the formal scenario, namely *fossil depletion (-41.3%), human health (-32.8%) and ecosystems (-25.9%).* However, *human toxicity (1%)* and *particulate matter formation (5.7%)* seemed to be the only categories that were positive (damaging) for the formal sector.

6.3.2 Endpoint impact categories

These midpoint categories were categorized into the following endpoint categories: human health, resources and ecosystem quality. Figure 8 shows the contribution from each endpoint category towards the environmental impact of recycling. The area of protection that is damaged most in the informal scenario is *ecosystem (49.7%),* followed by *human health (31.5%)* and *resources (18.8%).* In the formal scenario the area that is avoided most is on *resources (41.3%),* followed by *human health (32.8%)* and *ecosystem (25.9%).*

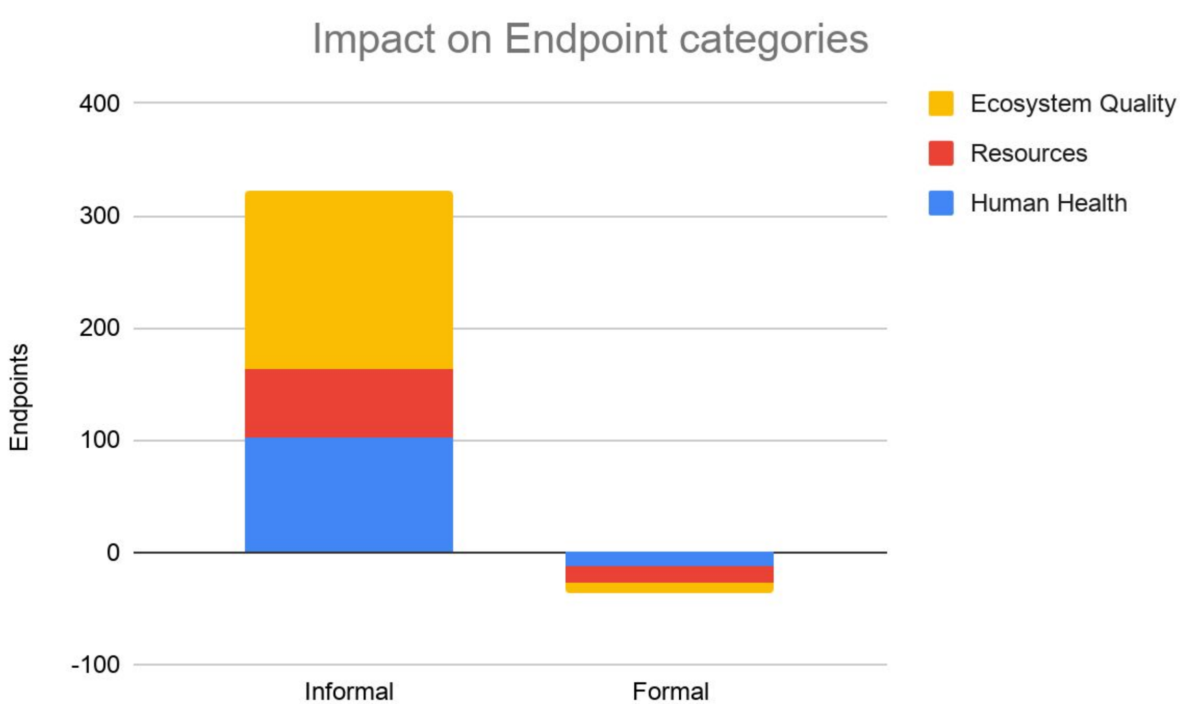

Figure 8: Comparison of total environmental impact between formal and informal recycling procedures

6.4. Interpretation

6.4.1 Contribution analysis

Each relevant midpoint category can be analyzed based on the contributions of emissions and processes.

Terrestrial Ecotoxicity

This impact category indicates the potential damage that is caused by emissions of toxic substances to soil. In the informal sector, the impact towards this terrestrial ecotoxicity is mostly caused by copper (62%), followed by bromine (36%). These substances are released when phones are incompletely incinerated and the remains are left on the soil. As a result, this impact indicator is contributing 34.3% towards the total environmental impact in the informal sector. The impact in the formal sector is negligible, since it is assumed that no substances are discarded on the soil due to proper recycling treatments.

Climate Change (Human health & Ecosystem)

The results show that for every 1000 kg of phones that are recycled 3160 kg of CO2-equivalent emissions are emitted into the environment in the informal sector, while 528 kg of CO2-eq emissions are avoided in the formal sector. The biggest contributors towards this impact category are CO2 (62%), followed by dinitrogen monoxide (13%) and methane (11%) in the informal sector. The release of these GHG emissions (mainly CO2 and methane) are almost 68% caused by incinerating electronic waste using coal as a fuel, while the release of dinitrogen monoxide is entirely caused by recycling PCBs where the chemical aqua regia is being used to leach gold. Notably, when all the GHG emissions are aggregated in the formal sector, it provides a net negative amount of CO2-eq emissions (-528 kg), which suggests that these emissions are avoided. This is highly linked to the eco-efficient recycling procedure, where heat from melted phones (mostly plastic) is captured and reused for internal recycling processes. The energy that is released during smelting is higher than the energy that is required to heat the recycling processes, leading to a net positive energy consumption in the formal sector.

Moreover, the contribution analysis shows that for the transportation of phones from Ghana to the recycling facility in Belgium, a total of 74.2 kg of CO2-eq is allocated for the transportation through the formal route. Additionally, 58.6 kg of CO2-eq is allocated for transportation over sea, while the remainder 15.6 kg of CO2-eq is allocated for transportation over land. For the informal route, a total of 47 kg CO2-eq is allocated to the transportation of PCBs from Ghana to China. Even though the total distance between Ghana and China is almost 2,5 times more in comparison with the distance between Ghana and Belgium, a lower amount of emitted CO2-eq is allocated to the informal process. This is because the CO2-eq impact for transportation depends on the weight of the cargo in relation with the weight of the transportation mode (Spielmann et al., 2007). In this LCA, 219 kg of PCBs are transported in the informal side, while 1000 kg of phones are transported in the formal side. This difference in weight leads to a lower amount of CO2-eq that is emitted during the transportation process in the informal sector .

Fossil Depletion

The impact on fossil depletion is damaging in the informal sector, while impact on fossil resources is avoided in the formal sector. A total of 804 kg of oil-equivalent is needed for the formal recycling procedures, while a total of 144 kg of oil-equivalent is avoided when 1 ton of phones are recycled through the formal route. This avoidance is likely caused because there is a much higher recovery efficiency in the formal sector leading to a high recovery of materials. The production of new materials is therefore being avoided.

Human toxicity

This impact category is measured in the amount of kg of 1,4-dichlorobenzene (1,4-DCB) equivalent which describes the toxicity of toxic substances (e.g. heavy metals) that have an impact on human health. Figure 9 shows that the impact on human health in the informal side is mostly caused by manganese (29%), followed by dioxins (19%), mercury (7%) and antimony (6%). A further analysis shows that the release of manganese in water is not directly linked to informal recycling procedures, but it is rather caused by the disposal of material waste from coal mining. A possible explanation for the high value of manganese was found in the model, where the heat of coals was used as an input for the incineration of mobile phones. Coals were chosen as a fuel replacement instead of vehicle tyres, since the latter one was not available in the database. The effect of manganese in the formal sector, seems to be minimal since no coals were directly used in the model. However various fuel sources, mainly heat and electricity from the grid, were used in the formal sector.

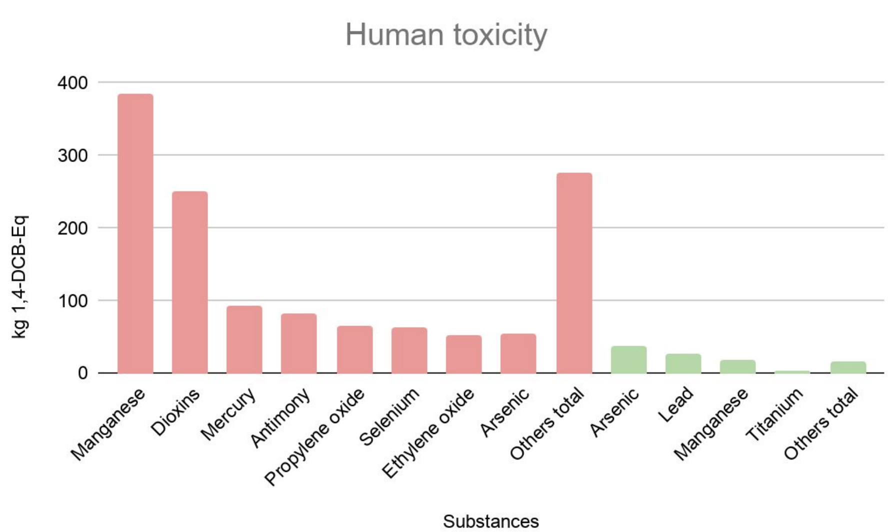

Figure 9: Released toxic substances in the environment for the informal sector (red) and the formal sector (green)

Furthermore, it is noticeable that a high amount of dioxins are produced during the leaching and the incineration process. This is presumably caused when plastic contained in electrical waste is incinerated in an open fire leading to a release of dioxins into the environment. In the formal sector the impact on human toxicity is mostly caused by arsenic, lead and manganese during formal recycling procedures. These substances were mostly released during the processes of smelting and anode casting. Nevertheless, the total impact on human toxicity during the formal recycling procedures (96.4 kg 1,4-DCB) is more than a factor of 13 smaller in comparison with the informal recycling procedures (1320 kg 1,4-DCB).

Particulate matter formation

This impact category indicates the amount of primary and secondary aerosols caused by air pollution in the atmosphere that can have a negative impact on human health when inhaled. The indicator is indicated in particulate matter of 10 µm equivalents (PM10-eq) which are coarse aerosols particles. Based on the results, both formal and informal sectors cause harm to this indicator, however the informal sector (3.09 kg PM10-eq) is approximately 7 times more harmful than the formal sector (0.451 Pm10-eq). The higher value in the informal sector is mostly contributed by sulfur dioxide (45%), followed by nitrogen oxides (27%) and particulates (18%). Due to cleaner technology and higher standards in the formal sector, the amount of particles in the atmosphere is decreased leading to a reduction in air pollution.

6.4.2 Endpoint results

The midpoint categories (section 6.4.1) were expressed in midpoint units (i.e. CO2-eq and 10PM-eq) and converted into one endpoint unit (i.e. points). However, these points are difficult to interpret and should be converted into several appropriate indicators that correspond with the three endpoint impact categories. Appendix 10.5 shows the conversion rates from midpoint categories which were expressed in midpoint units into endpoint categories expressed in multiple endpoint units. Thus, in order to express the endpoint categories in multiple units instead of one unit, the midpoint categories were multiplied with the conversion rates. Table 3 shows the results of this conversion and the endpoint categories are split into three separate indicators.

Table 3: Overview of endpoint categories between formal and informal recycling procedures

	Unit	Informal	Formal	Ratio I/F ▲
Resources	$	948	-23.6	-40.2
Human health	DALY	6.37E-03	-5.46E-04	-11.7
Ecosystem quality	Species loss per year	258	-27	-9.6

The results seem paradoxical, however the positive number in the informal sector indicates that damage is caused to a specific endpoint category, while a negative number in the formal sector indicates that damage is avoided. Table 3 shows that every 1000 kg phones that are recycled through the informal route the diversity of species group would potentially lead to a decrease of 258 species. This does not mean that 258 species are lost during the process, but it indicates that there is a reduction in the quality of ecosystems. In contrast, there would be an increase in ecosystem quality if the devices are recycled through the formal route.

In terms of damage to human health, the processes would lead to a loss of 6.37E-03 DALY for the formal route and an increase of -5.46E-04 DALY for the informal route. The DALY indicates the disability-adjusted life years which is a metric that reports the years that are lost for all ages. In other words, on a population of 1 million people 6730 life years would be lost in the informal route, while 546 life years would be gained in the formal route.

In the endpoint category resources, it was found that more resources would be extracted in the informal route, while the extraction of resources would be avoided in the formal route. The total cost to society due to extraction of resources is expressed in $ and indicates the marginal cost increase per kilogram of a resource due to an extraction or yield multiplied with the annual consumption. A higher extraction of a resource, would cause an increase in price and consequently damage to resources. It was found that the marginal costs for extraction of resources would increase by $ 948 for the informal sector, while $ 23.60 would decrease for the formal sector. All of the endpoint categories and the comparison between the two sectors are shown in figure 9. The figure indicates that informal procedures were damaging to all endpoint categories, while formal procedures were avoiding damage. The damage caused by informal procedures in comparison with formal procedures were 9.6 higher in the ecosystem quality, 11.7 higher for human health and 40.2 higher for resources.

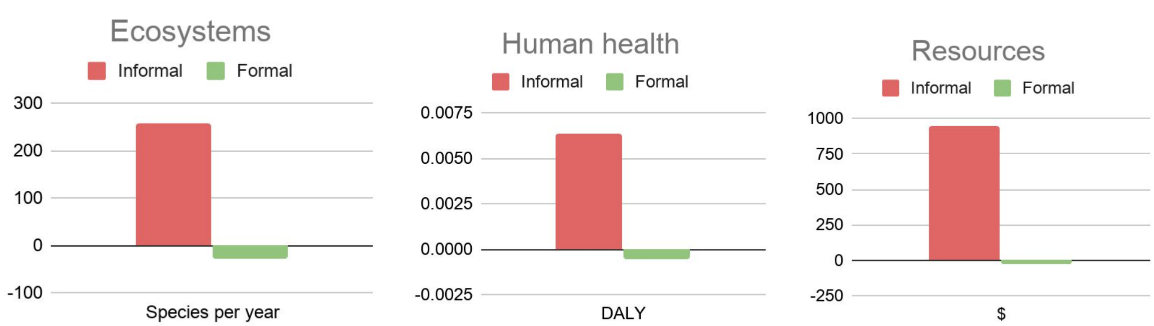

Figure 9: Comparison of formal and informal recycling procedures across endpoint categories

7. Discussion

The aim of this study was to conduct a comparative analysis on the environmental impact of the recycling procedures of e-waste. In this LCA study a case study provided by CTL was used in order to make a comparison between two scenarios where end of life phones are recycled through the informal (i.e. incineration and leaching) and the formal route (i.e. certified recycle facility).

7.1 Summary of findings

This study found that recycling end of life phones through the informal route causes an impact on several areas of protection including: ecosystems, human health and resources. In particular, it was found that 6 out of the 18 midpoint categories contribute 99 percent of the total environmental impact through informal recycling procedures. These 6 midpoint categories were used to compare and analyse the formal recycling procedures with the informal recycling procedures. It was found that a high amount of GHGs (including carbon dioxide and methane) and metals (including copper and bromine) contribute most to these impact indicators. Contrastingly, it was found that negative impact was avoided when phones were recycled through the formal route. Specifically, the results show that for every 1000 kg phones that are collected and recycled through the informal procedure 3160 kg of CO2-eq emissions are emitted in the atmosphere, while 528 kg of CO2-eq would be avoided in the formal sector. The transportation of phones would lead to 74.2 kg of CO2-eq in the formal sector and 47 kg of CO2-eq in the informal sector. Additionally, it was found that recycling 1000 kg of phones in the informal sector would lead to a loss of 6.37E-03 DALY or in other words in a population of 1 million people 6370 life years would be lost. Finally, it was found that informal recycling procedures are almost 9.6 times more damaging on ecosystems, 11.7 times more damaging on human health and 40 times more damaging on resources in comparison with formal recycling procedures.

7.2 Transition from results to interpretation

These results indicate that proper recycling of phones could bring about large environmental benefits, including the high recovery rate of materials and mitigated emissions, which would be incurred through informal procedures. The environmental impact as a result of formal recycling procedures is almost 10 times lower in comparison with the informal recycling route. This suggests that informal recycling of e-waste, in particular the recycling of mobile phones, can be highly damaging on the environment. Moreover, the calculated damage to the environment caused by the informal recycling procedures is an underestimation. The local circumstances in which these informal recycling practices take place, were not considered in the LCA study. For instance, these informal practices are highly linked to extremely poor working conditions where often no adequate safety measures are being taken (Oteng-Ababio, 2012). E-waste is often burned onsite without any proper ventilation or the accumulation of toxic substances can lead to high contamination levels that exceed health standards (Annamalai, 2015). Due to the unorganised manner in which these practices are held, it is difficult to estimate the actual impact of informal recycling to human health and environment (Daum et al., 2016). These and other local factors were not taken into account in this LCA study and thus the actual environmental impact of recycling is expected to be higher.

Many studies reach the same conclusion, further contending that e-waste should be properly collected and materials should be safely recovered (UNEP, 2009; Perkins et al., 2010). In this study, it has been found that formal recycling has significantly lower impact on areas such as terrestrial ecotoxicity and climate change, followed by human health and resources than informal processes. Furthermore, formal recycling leads to a high avoidance of soil emissions, such as copper and bromine, and GHG, such as carbon dioxide and methane. These findings were also found by Hong et al. (2015) that suggest that the highest environmental impact is caused by improper waste treatment, such as incineration and disposal on land, that leads to high pollution in soil and air.

7.3 Approach of the study

7.3.1 Consistency of functional unit

In order to compare various scenarios in an LCA study, choices were made to be as consistent as possible within analysis (Weidema, 2018). For example, the same functional unit was used in the formal and the informal recycling scenario. This functional unit is chosen in this study, because it allows for comparison with other studies that used a similar functional unit (Navazo et al., 2014; Hageluken 2007; Molto, 2012). However, it is important to know that every LCA study is carried out with different system boundaries and assumptions. These assumptions were not always aligned nor well documented, thus it is difficult to compare various LCA studies with each other. For example, the mobile phones that were analysed in previous LCA studies were not identical to each other and most likely different mobile phone models were used. Different models would lead to different chemical compositions and possibly a change in the end results. Nevertheless, all LCA studies have their own system boundaries and all functional units across LCA studies were considered to be equal in size, model and chemical composition.

7.3.2 Consistency of choice of data

The emission data was carefully chosen based on availability and relevance to the recycling procedures. Pre-calculated processes and their related emissions were extracted from the database EcoInvent. However, not all processes, in particular the informal recycling processes, are covered in this database and thus additional information from various sources had to be retrieved. Consequently, a combination of studies were used including Navazo et al.'s (2014) data on emissions from the formal recycling procedures. This study focused on the material flows between processes rather on the released emissions per process. The processes and physical material flows were derived from this study, while the emissions were derived from closely related processes within EcoInvent. Only data that matched the actual recycling procedures of phones as close as possible were used. Furthermore, emission data for the informal recycling procedures was lacking in the database. Several studies were used in order to fill this data gap. The emissions that are linked to the incineration of phones were derived from a study from Molto et al., (2012) who assessed the released air emissions from combusting different parts of a mobile phone. Moreover, dust and soil emissions were derived from a study conducted by Gullet et al. (2007). All of the emission data from various sources were retrieved and modified to the functional flow in this study in order to be as consistent as possible.

7.3.3 Conflicting results

The results indicate that not all environmental impact categories were relevant and only 6 out of 18 categories were impacted by the formal and informal recycling procedures. Notably, the metal depletion impact category was shown not to be of importance in this study. One of the primary reasons to recycle a phone is to recover valuable metals such as gold and silver. The recovery of these metals would avoid a burden of production of virgin materials. A higher recovery of metals would lead to a higher avoided impact, however this was not observed in this LCA study and the contribution of metal depletion towards the environmental impact seemed to be rather small (<0.01%). It was assumed that recycling phones would lead to a recovery of secondary metals instead of primary metals. Primary metals are produced from natural ores, while secondary metals are recovered from metal scrap by melting and refining processes. The assumption of using secondary metals instead of primary metals in this study is crucial, since changing the metals that are recovered from recycling would lead to a different conclusion regarding the environmental impact of recycling. A contribution analysis shows that the production of secondary metals leads to a much lower environmental impact than the production of primary metals. For example, the production of 1 kg of primary gold in comparison with the production of 1 kg of secondary gold would lead to approximately 111 times more CO2 (EcoInvent 2.2). The avoided environmental impact on metal depletion was limited due to the relative low environmental impact from the production of secondary metals.

7.4 Limitations

All LCA studies depend on the quality and availability of data, however appropriate available data for this study was limited. Emission data for formal and the informal recycling were not directly obtained from stakeholders, but could only be derived from various reports or from the database EcoInvent. Additionally, most processes and the related emissions were manually inserted in the tool as they could not be found in the database. Several assumptions had to be made in order to conduct this research. For example, it was assumed that all the functional units within the reports were identical, but different system boundaries and assumptions were applied in every study (Molto et al., 2014; Navazo et al., 2014; Gullet et al., 2007). These studies used different mobile phones for their experiments leading to different chemical compositions and emissions. Moreover, no emission data on leaching could be found and thus emissions from the incineration of phones were used instead (Molto et al., 2014). The emissions for the formal recycling procedures were mostly derived from EcoInvent. However, this database might be outdated since it was made before 2010 and most processes were inserted in the database long before this date.

Another limitation to this study is the scope of this LCA research. Not all processes related to recycling e-waste, such as the collection and final disposal of materials, were considered in this study. Moreover, in the depicted scenarios, the recycling processes were simplified where phones are collected on one hand and materials are recovered or disposed of. In reality the processes are more complex and there are more interlinkages within these processes.

7.5 Importance of study

As the global demand for electronic products has significantly increased over the past decades, the environmental impact of e-waste has gained increasing attention by scholars (Widmer et al., 2005; Schleup et al., 2009, UNEP, 2019). Nevertheless, this is the first study that has aimed to quantify the environmental impact of recycling mobile phones through a comparative analysis of the formal route with the informal recycling procedures in Ghana. This study shows that recycling mobile phones has to be done in a responsible manner. In particular, it is necessary that modern recycling technologies are used and high environmental standards are maintained. The higher recovery rate of metals and safe disposal of toxic waste can lead to benefits for the environment and human health. Notably, this study suggests that the environmental benefits are gained most when toxic substances, such as copper, bromine and dioxins, contained in e-waste are mitigated through safe and responsible recycling.

7.6 Recommendations

E-waste is a growing global challenge and it needs to be properly managed in order to improve sustainability in the information and communication technologies (ICT) sector. Thus, it is important to recognise emerging risks, challenges and opportunities arising from e-waste. While it is imperative to limit the amount of e-waste consumption in general, it is equally as important to develop a management system where e-waste can be properly collected and recycled. In the context of mobile phones, it is necessary to continuously develop proper recycling techniques where all components of a mobile phone can be effectively recycled. Additionally, high environmental standards must be maintained to mitigate damage to human health and the environment. In regions where this is unlikely to happen in the short term, a framework for e-waste treatment is needed according to the Best of 2 World (BO2W) principle. This approach recognises the importance of the informal and the formal recycling sector by combining local collection and dismantling activities in developing countries with high technological recycling practices in developed countries.

7.7 Further research

Small IT products, especially mobile phones, are becoming increasingly accessible worldwide. Consequently, there is an increasing need for e-waste management where materials can be recycled in an environmentally friendly manner. While this study focused on a comparative analysis of the formal sector in Belgium and the informal sector in Ghana, e-waste continues to be a global problem. Therefore, more research should be done on other countries and other types of e-waste, such as laptops and tablets. In this study, a recycling facility in Belgium was used as an example, however different recycling facilities and/or techniques in different countries can alternatively be used. The methodology that was used in this study can be applied to other recycling facilities, since many use similar methods for recycling and extracting precious metals. Moreover, this study could be improved if more relevant and recent emission data on e-waste recycling was available, especially regarding the informal sector and their procedures.

8. Conclusion

What is the environmental impact of Closing the Loop's recycling procedure of e-waste in comparison to the business as usual scenario in Ghana using a life cycle assessment?

Recycling e-waste has environmental benefits as the recovery of valuable and rare materials from electronics could save natural resources and reduce environmental pollution. However, it has to be done in a safe and responsible manner where high health standards are maintained and modern recycling techniques are used. In this study formal recycling procedures were compared with informal recycling procedures on the environmental impact of recycling mobile phones. The informal recycling procedures were considered inefficient in the recovery of materials and harmful for the environment. In contrast, the formal recycling procedures would lead to a much higher recovery of materials, while high standards were maintained to mitigate the amount of emissions from recycling.

Based on a life cycle assessment, it can be concluded that the informal recycling procedures have a negative impact on the environment, while the formal recycling procedures would avoid a burden on the environment. It was found that the accumulation of six out of eighteen impact categories were contributing towards 99% of this environmental impact. Key findings of this research show that for every 1000 kg of phones that are recycled through the informal procedure 3160 kg of CO2-equivalent emissions are emitted. Contrastingly, 528 kg of CO2-e would be avoided through recycling the same quantity of mobile phones through formal procedures. Moreover, in this study the informal recycling procedures were found to be almost 9.6 times more damaging on the ecosystem, 11.7 times on human health and 40 times on resources in comparison with the formal recycling procedures.

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10. Appendix

10.1 - CMLCA - Informal processes

Process = [P4088] SC 1 - dismantling phone manual (informal)					
Economic inflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[W4088]	End of life whole phone (informal)	1.00E+03	kg	Collection of phones	-
Economic outflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[W4089]	Dismantled PCB (Ghana)	211	kg	On average a PCBs weighs 19% of a phone weight (90 gram) (OECD, 2010).	(19% * 1000 kg) / 0.09 kg
[W4090]	Electronic Waste	789	kg	Remainder of phone excluding PCBs	1000 kg - (19*1000)/90
Process = [P4089] SC 1 - Incineration of electronic waste (informal)					
Economic inflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[G1296]	heat, hard coal coke, at stove 5-15kW[RER]	6.96E+03	MJ	Coal is used as fuel to incinerate phones. In order to combust phones 6.96 MJ/kg phone is needed (Hageluken, 2007)	6.96 MJ * 1000 kg
[W4090]	Electronic Waste	1.00E+03	kg	Remainder of electronic waste set at 1000 kg instead of 789 kg to normalise environmental emissions	

Economic outflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[W4091]	Electronic Waste residue	1.00E+03	kg	Remainder of electronic waste after incineration	-

Environmental emissions					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[E43]	Carbon monoxide, fossil[air_high population density]	1.05E+02	kg	Release of air emissions during combustion of electronic waste (Molto et al., 2014). In the study, electrical waste was uncontrolled combusted at 850 celsius degrees and air samples were captured and analysed. These values were taken and converted into air emissions (high population), because of high population density in Ghana.	-
[E45]	Carbon dioxide, fossil[air_high population density]	7.44E+02	kg		
[E59]	Methane, fossil[air_high population density]	1.36E+01	kg		
[E69]	Toluene[air_high population density]	6.00E+00	kg		
[E112]	Ethylene oxide[air_high population density]	6.55E+00	kg		
[E114]	Propane[air_high population density]	5.10E-02	kg		
[E125]	Propylene oxide[air_high population density]	1.94E+00	kg		
[E140]	Butene[air_high population density]	2.90E+00	kg		
[E155]	Benzene[air_high population density]	1.59E+01	kg		
[E297]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_high population density]	1.50E-06	kg		
[E298]	Hydrocarbons, aliphatic, alkanes, unspecified[air_high population density]	4.74E+01	kg		
[E311]	Butane[air_high population density]	8.50E-02	kg		
[E312]	Pentane[air_high population density]	3.00E-03	kg		
[E436]	Xylene[air_high population density]	6.34E-01	kg		
[E636]	Ethane[air_high population density]	8.39E-01	kg		

[E795]	Polychlorinated biphenyls[air_high population density]	1.76E-06	kg		
[E1012]	Arsenic[soil_industrial]	1.59E-02	kg	Emissions that were found in the study by Gullet et al. (2007). In the study, residual ash was collected from combusted electrical waste and dust emissions were analysed based on residual ash. In this study, the dust samples were converted into soil emissions.	-
[E1024]	Chloride[soil_industrial]	2.10E-01	kg		
[E1026]	Chromium[soil_industrial]	2.72E-01	kg		
[E1030]	Copper[soil_industrial]	1.39E+01	kg		
[E1038]	Iron[soil_industrial]	6.78E+00	kg		
[E1042]	Magnesium[soil_industrial]	2.95E+00	kg		
[E1044]	Manganese[soil_industrial]	4.53E-02	kg		
[E1060]	Strontium[soil_industrial]	2.00E-01	kg		
[E1067]	Zinc[soil_industrial]	1.80E-01	kg		
[E1346]	Nickel[soil_industrial]	2.79E-01	kg		
[E1347]	Lead[soil_industrial]	3.63E+00	kg		
[E1780]	Selenium[soil_industrial]	4.46E-03	kg		
[E1783]	Tin[soil_industrial]	2.15E+00	kg		
[E1915]	Antimony[soil_industrial]	2.73E-01	kg		
[E3071]	Bromine[soil_industrial]	2.12E+00	kg		
[E1094]	Arsenic, ion[water_ground-, long-term]	6.20E-05	kg	After combustion of electrical waste, the residual bottom was analysed and leaching tests were performed (Gullet et al., 2007). Leaching emissions from Gullet et al. (2007) were converted into waterground emissions on long term.	-
[E1101]	Barium[water_ground-, long-term]	2.33E-03	kg		
[E1123]	Cadmium, ion[water_ground-, long-term]	4.00E-06	kg		
[E1147]	Chromium, ion[water_unspecified]	7.00E-05	kg		
[E1192]	Iron, ion[water_ground-, long-term]	2.00E-01	kg		
[E1196]	Lead[water_ground-, long-term]	8.74E-02	kg		
[E1208]	Mercury[water_ground-, long-term]	6.00E-06	kg		
[E1255]	Selenium[water_ground-, long-term]	9.30E-05	kg		

Process = [P4090] SC 1 - Transport PCB to China					
Economic inflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[G103]	transport, transoceanic freight ship[OCE]	1.83E+04	tkm	Distance between Ghana and Shanzou (China) calculated on Searates (n.d.). Total distance is 18300 km. It was assumed that PCBs were shipped in a transocean freight ship.	-
[W4089]	Dismantled PCB (Ghana)	1.00E+03	kg	Printed circuit boards are transported	-
Economic outflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[W4092]	Dismantled PCB (China)	1.00E+03	kg	PCBs arrive in China	-
Process = [P4091] SC 1 - Leaching of PCB					
Economic inflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[G152]	nitric acid, 50% in H2O, at plant[RER]	755	kg	PCBs are leached using chemical acid aqua regia. This is made of 1 part nitric acid and 3 parts hydrochloric acid (Rubin, 2014). The author employed 2 ml of aqua regia per 1 g of PCB in total. Molecular weight of HNO3 is 1.51 g / cm3 (Sheng and Etsell, 2007)	1000 kg of PCB * (1 part nitric acid / 4 total parts) * 1.51 g * 2 ml
[G2902]	hydrochloric acid from benzene chlorination, at plant[RER]	1.77E+03	kg	Aqua regia is made of 1 part nitric acid and 3 parts hydrochloric acid (Rubin, 2014). The author employed 2 ml of aqua regia per 1 g of	1000 kg of PCB * (3 part hydrochloric acid / 4 total parts) * 1.18 g * 2 ml

				PCB in total. Molaculair weight of HCl is 1.18 g / cm3	
[W4092]	Dismantled PCB (China)	1.00E+03	kg	PCBs in China	-
Economic outflows					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[G3417]	gold, secondary, at precious metal refinery[SE]	0.09	kg	25% recovery rate of potential gold (360 g) (Hageluken, 2007)	25% * potential 360 gram gold per 1 ton mobile phones
[W4093]	PCB Residue	999	kg	Remainder after gold has been recovered	1000 kg - 0.09 g
Environmental emissions					
Label	*Name*	*Value*	*Unit*	*Description*	*Calculation*
[E43]	Carbon monoxide, fossil[air_high population density]	3.51E+01	kg	Leaching emissions were not found for this study. Air emissions from Molto et al (2014) from combustion of printed circuit boards were used instead. PCBs were combusted, air samples were captured and analysed. These values were taken and converted into air emissions (high population).	-
[E45]	Carbon dioxide, fossil[air_high population density]	2.50E+02	kg		
[E59]	Methane, fossil[air_high population density]	1.96E+00	kg		
[E69]	Toluene[air_high population density]	2.27E-01	kg		
[E112]	Ethylene oxide[air_high population density]	4.44E-01	kg		
[E114]	Propane[air_high population density]	1.00E-03	kg		
[E125]	Propylene oxide[air_high population density]	1.20E-01	kg		
[E140]	Butene[air_high population density]	7.00E-03	kg		
[E155]	Benzene[air_high population density]	1.29E+00	kg		
[E181]	Butadiene[air_high population density]	5.90E-02	kg		

[E297]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_high population density]	5.95E-06	kg		
[E298]	Hydrocarbons, aliphatic, alkanes, unspecified[air_high population density]	4.33E+00	kg		
[E311]	Butane[air_high population density]	1.03E-01	kg		
[E436]	Xylene[air_high population density]	8.10E-02	kg		
[E636]	Ethane[air_high population density]	4.80E-02	kg		
[E795]	Polychlorinated biphenyls[air_high population density]	7.91E-07	kg		
[E1012]	Arsenic[soil_industrial]	1.59E-02	kg	No data could be found for leaching process, instead dust emissions from printed circuit boards were used. These emissions were found in the study by Gullet et al. (2007). In the study, residual ash was collected from combusted printed circuit boards and dust emissions were analysed based on residual ash. In this study, the dust samples were converted into soil emissions.	-
[E1024]	Chloride[soil_industrial]	2.10E-01	kg		
[E1026]	Chromium[soil_industrial]	2.72E-01	kg		
[E1030]	Copper[soil_industrial]	1.39E+01	kg		
[E1038]	Iron[soil_industrial]	6.78E+00	kg		
[E1042]	Magnesium[soil_industrial]	2.95E+00	kg		
[E1044]	Manganese[soil_industrial]	4.53E-02	kg		
[E1060]	Strontium[soil_industrial]	2.00E-01	kg		
[E1067]	Zinc[soil_industrial]	1.80E-01	kg		
[E1346]	Nickel[soil_industrial]	2.79E-01	kg		
[E1347]	Lead[soil_industrial]	3.63E+00	kg		
[E1780]	Selenium[soil_industrial]	4.65E-03	kg		
[E1783]	Tin[soil_industrial]	2.15E+00	kg		
[E1915]	Antimony[soil_industrial]	2.73E-01	kg		
[E3071]	Bromine[soil_industrial]	2.12E+00	kg		
[E1094]	Arsenic, ion[water_ground-, long-term]	6.20E-05	kg	After combustion of printed circuit board, the residual bottom was analysed and leaching tests were performed (Gullet et al., 2007). Leaching emissions from Gullet et al. (2007) were converted into	-
[E1101]	Barium[water_ground-, long-term]	2.33E-03	kg		
[E1123]	Cadmium, ion[water_ground-, long-term]	4.00E-06	kg		
[E1192]	Iron, ion[water_ground-, long-term]	2.00E-01	kg		
[E1196]	Lead[water_ground-, long-term]	8.74E-02	kg		

[E1208]	Mercury[water_ground-, long-term]	6.00E-06	kg	waterground emissions on long term.	
[E1255]	Selenium[water_ground-, long-term]	9.30E-05	kg		

10.2 - CMLCA - Formal recycling processes

Process = [P4092] SC2 - Transport from Accra (Ghana) to Antwerp (Belgium)					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G103]	transport, transoceanic freight ship[OCE]	7,370	tkm	Distance between Ghana to Antwerp (Searates, n.d.). Total distance is 7370 km	-
[W4094]	End of life phone (formal)	1,000	kg	The collection of 1000 kg of phones in Ghana	-
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[W4095]	End of life phone (in Belgium)	1,000	kg	Arrival of phones in Belgium	-
Process = [P4093] SC2 - Transport phones over land from Antwerp (Belgium) to Hoboken (Belgium)					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G101]	transport, lorry >16t, fleet average[RER]	19	tkm	Distance between Antwerp to Hoboken (Google, n.d.). Total distance is 19.4 km. The phones are assumed to be transferred on a lorry that can carry more than 16 ton	-
[W4095]	End of life phone (in Belgium)	1,000	kg	The collection of phones in Belgium	-
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[W4096]	End of life phone (in recycle facility)	1,000	kg	Arrival of phones in facility	-

Process = [P4094] SC2 - Dismantling of phone, mechanically at plant					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G571]	electricity, medium voltage, at grid[BE]	137	kWh	This step involves the shredding of 1 ton e-waste and requires an energy input of 137 MJ per ton e-waste (Hischier, 2007)	
[W4096]	End of life phone (in recycle facility)	1,000	kg	-	
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[W4097]	Shredded E-waste	1,000	kg	-	
Process = [P4095] SC2 - Smelting of materials in smelter					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G1770]	natural gas, burned in power plant[BE]	1,390	MJ	Energy consumption for smelting process is 1.39 MJ per kg materials (Alvarao et al., 2002)	1.39 MJ * 1000 kg
[W4097]	Shredded E-waste	1,000	kg	Shredded e-waste goes in the smelter	-
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[G145]	heat, natural gas, at industrial furnace >100kW[RER]	9,260	MJ	The plastics contained in 1 ton mobile phones is equal to 10,650 MJ worth of energy (Navazo et al., 2014). This energy is captured and reused for internal processes. Gas that is needed for smelting is deducted from this.	10,650 MJ - 1,390 MJ

[G3412]	lead, secondary, from electronic and electric scrap recycling, at plant[SE]	17	kg	Lead is a co-product from smelted e-waste and value is taken from Navazo et al. (2014)	-
[W4098]	Black Copper	192	kg	Black copper is a co-product from smelted e-waste. Value is taken from Navazo et al. (2014)	-
[W4105]	Slag	396	kg	Slag is a co-product and sold to cement industry. Value is taken from Navazo et al. (2014).	-
Environmental emissions					
Label	Name	Value	Unit	Description	Calculation
[E8]	Heat, waste[air_low population density]	86.8	MJ	All emission values are taken from EcoInvent process "*Metal values from electric waste, in blister-copper, at converter [SE, 2000-2005]".* This process is the closest process that was found in the database. The output of this process is a blister copper. The original emission values were taken from this process and multiplied with 192 in order to match the smelting process	0.452 * 192 kg
[E192]	Nitrogen oxides[air_low population density]	3.59E-03	kg		1.87E-05 * 192 kg
[E221]	Sulfur dioxide[air_low population density]	7.64E-02	kg		3.98E-04 * 192 kg
[E224]	Particulates, < 2.5 um[air_low population density]	7.91E-04	kg		4.12E-06 * 192 kg
[E225]	Cadmium[air_low population density]	6.18E-07	kg		3.22E-09 * 192 kg
[E227]	Copper[air_low population density]	3.86E-05	kg		2.01E-07 * 192 kg
[E229]	Zinc[air_low population density]	3.44E-05	kg		1.79E-07 * 192 kg
[E233]	Lead[air_low population density]	2.65E-04	kg		1.38E-06 * 192 kg
[E314]	Particulates, > 10 um[air_low population density]	2.63E-04	kg		1.37E-06 * 192 kg
[E340]	Particulates, > 2.5 um, and < 10um[air_low population density]	5.28E-04	kg		2.75E-06 * 192 kg

[E553]	Arsenic[air_low population density]	1.72E-08	kg		8.96E-11 * 192 kg
[E607]	Chlorine[air_low population density]	1.31E-03	kg		6.84E-06 * 192 kg
[E634]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_low population density]	2.59E-08	kg		1.35E-10 * 192 kg
[E661]	Fluorine[air_low population density]	1.05E-05	kg		5.48E-08 * 192 kg
[E728]	Mercury[air_low population density]	1.24E-06	kg		6.45E-09 * 192 kg
[E1095]	Arsenic, ion[water_lake]	1.98E-07	kg		1.03E-09 * 192 kg
[E1124]	Cadmium, ion[water_lake]	1.72E-08	kg		8.96E-11 * 192 kg
[E1159]	Copper, ion[water_lake]	6.87E-06	kg		3.58E-08 * 192 kg
[E1197]	Lead[water_lake]	2.40E-06	kg		1.25E-08 * 192 kg
[E1209]	Mercury[water_lake]	5.16E-08	kg		2.69E-10 * 192 kg
[E1318]	Zinc, ion[water_lake]	2.23E-06	kg		1.16E-08 * 192 kg
Process = [P4096] SC2 - Converting process					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G1770]	natural gas, burned in power plant[BE]	500	MJ	The energy consumption for converting black copper to blister copper is 2.6 MJ per kg of refined copper (Navazo et al., 2014).	2.6 MJ * 192 kg blister copper
[W4098]	Black Copper	192	kg	Black copper as result from smelting	
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[W4099]	Blister Copper	192	kg	Blister copper as result from conversion of black copper.	

				Value is taken from Navazo et al. (2014)	
Process = [P4097] SC2 - Fire refining and anode casting					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G1770]	natural gas, burned in power plant[BE]	958	MJ	This fire refining process requires an energy input of 958 MJ for 1 ton of mobile phones (Reuter et al., 2005)	
[W4099]	Blister Copper	192	kg	Blister copper as result from converting (Navazo et al., 2014)	
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[W4100]	Copper anode	192	kg	Copper anode where arsenic and antimony are heavily reduced (Navazo et al., 2014)	
Environmental emissions					
Label	Name	Value	Unit	Description	Calculation
[E224]	Particulates, < 2.5 um[air_low population density]	1.78E-02	kg	All emission values are taken from EcoInvent process "Precious metals from electronic waste, in anode slime, at refinery[SE, 2000-2005]" This process is the closest process that was found in the database. The output of this process is precious metals from electronic waste, in anode slime, at a refinery. The original emission values were taken from this process and multiplied with 192 copper anode in order to match the fire refining process	9.27E-05 * 192
[E227]	Copper[air_low population density]	6.57E-04	kg		3.42E-06 * 192
[E228]	Nickel[air_low population density]	2.46E-04	kg		1.28E-06 * 192
[E233]	Lead[air_low population density]	1.45E-03	kg		7.56E-06 * 192
[E314]	Particulates, > 10 um[air_low population density]	5.93E-03	kg		3.09E-05 * 192
[E340]	Particulates, > 2.5 um, and < 10um[air_low population density]	1.19E-02	kg		6.18E-05 * 192

[E553]	Arsenic[air_low population density]	3.84E-04	kg		2.00E-06 * 192
[E1095]	Arsenic, ion[water_lake]	2.21E-04	kg		1.15E-06 * 192
[E1124]	Cadmium, ion[water_lake]	1.94E-04	kg		1.01E-06 * 192
[E1159]	Copper, ion[water_lake]	8.52E-03	kg		4.44E-05 * 192
[E1197]	Lead[water_lake]	4.59E-04	kg		2.39E-06 * 192
[E1209]	Mercury[water_lake]	2.46E-06	kg		1.28E-08 * 192
[E1220]	Nickel, ion[water_lake]	7.85E-04	kg		4.09E-06 * 192
[E1318]	Zinc, ion[water_lake]	4.59E-04	kg		2.39E-06 * 192
Process = [P4098] SC2 - Copper refining					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G571]	electricity, medium voltage, at grid[BE]	448	kWh	This electrolysis step requires an average energy input of 2791 kWh per ton of refined copper (Navazo et al., 2014).	147 kg * 2791 kwh / 1000 kg
[W4100]	Copper anode	147	kg	Value was taken from Navazo et al. (2014)	
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[G3415]	copper, secondary, from electronic and electric scrap recycling, at refinery[SE]	128	kg	Value was taken from Navazo et al. (2014)	
[W4101]	Silver-Gold-PGM alloy	5.41	kg	Value was taken from Navazo et al. (2014)	

Environmental emissions					
Label	Name	Value	Unit	Description	Calculation
[E8]	Heat, waste[air_low population density]	8.26	MJ	All emission values are taken from EcoInvent process "Copper, secondary, from electronic and electric scrap recycling, at refinery[SE, 2000-2005]" This process is the closest process that was found in the database. The output of this process is secondary copper. The original emission values were taken from this process and multiplied with 128 kg of secondary copper in order to match copper refining process	6.45E-02 * 128
[E224]	Particulates, < 2.5 um[air_low population density]	2.09E-05	kg		1.63E-07 * 128
[E227]	Copper[air_low population density]	7.71E-07	kg		6.02E-09 * 128
[E228]	Nickel[air_low population density]	2.89E-07	kg		2.26E-09 * 128
[E233]	Lead[air_low population density]	1.70E-06	kg		1.33E-08 * 128
[E314]	Particulates, > 10 um[air_low population density]	6.96E-06	kg		5.44E-08 * 128
[E340]	Particulates, > 2.5 um, and < 10um[air_low population density]	1.40E-05	kg		1.09E-07 * 128
[E553]	Arsenic[air_low population density]	4.49E-07	kg		3.51E-09 * 128
[E1095]	Arsenic, ion[water_lake]	2.59E-07	kg		2.02E-09 * 128
[E1124]	Cadmium, ion[water_lake]	2.28E-07	kg		1.78E-09 * 128
[E1159]	Copper, ion[water_lake]	1.00E-05	kg		7.81E-08 * 128
[E1197]	Lead[water_lake]	5.40E-07	kg		4.22E-09 * 128
[E1209]	Mercury[water_lake]	2.89E-09	kg		2.26E-11 * 128
[E1220]	Nickel, ion[water_lake]	9.22E-07	kg		7.20E-09 * 128
[E1318]	Zinc, ion[water_lake]	5.40E-07	kg		4.22E-09 * 128

Process = [P4099] SC2 - Silver Refining

Economic inflows

Label	Name	Value	Unit	Description	Calculation
[G571]	electricity, medium voltage, at grid[BE]	490	kWh	In order to refine 1 kg silver an energy input of 136 kwh or 485 MJ is needed (Navazo et al., 2014). A total of 1424 MJ or 490 kWh is needed.	3.63 kg silver * 136 kWh
[W4101]	Silver-Gold-PGM alloy	5.41	kg	Value was taken from Navazo et al. (2014)	-

Economic outflows

Label	Name	Value	Unit	Description	Calculation
[G3419]	silver, secondary, at precious metal refinery[SE]	3.63	kg	Production of secondary silver. Value taken from Navazo et al (2014)	-
[W4102]	Gold-PGM alloy	1.78	kg	The remainder alloy	5.41 - 3.63

Environmental emissions

Label	Name	Value	Unit	Description	Calculation
[E8]	Heat, waste[air_low population density]	4.32	MJ	All emission values are taken from EcoInvent process "silver, secondary, at precious metal refinery[SE, 2000-2005]". This process is the closest process that was found in the database. The output of this process is secondary silver. The original emission values were taken from this process and multiplied with 3.63 kg of secondary silver in order to match the silver production	1.19E+00 * 3.63
[E192]	Nitrogen oxides[air_low population density]	3.78E-04	kg		1.04E-04 * 3.63
[E221]	Sulfur dioxide[air_low population density]	2.94E-04	kg		8.11E-05 * 3.63
[E224]	Particulates, < 2.5 um[air_low population density]	2.91E-05	kg		8.02E-06 * 3.63
[E225]	Cadmium[air_low population density]	6.53E-08	kg		1.80E-08 * 3.63
[E227]	Copper[air_low population density]	9.80E-07	kg		2.70E-07 * 3.63
[E229]	Zinc[air_low population density]	3.63E-06	kg		1.00E-06 * 3.63

[E233]	Lead[air_low population density]	2.71E-05	kg		7.46E-06 * 3.63
[E314]	Particulates, > 10 um[air_low population density]	9.69E-06	kg		2.67E-06 * 3.63
[E340]	Particulates, > 2.5 um, and <10um [air_low population density]	1.94E-05	kg		5.34E-06 * 3.63
[E607]	Chlorine[air_low population density]	1.39E-04	kg		3.82E-05 * 3.63
[E634]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_low population density]	2.78E-09	kg		7.57E-10 * 3.63
[E661]	Fluorine[air_low population density]	1.11E-06	kg		3.06E-07 * 3.63
[E728]	Mercury[air_low population density]	1.31E-07	kg		3.60E-08 * 3.63
Process = [P4100] SC2 - Gold refining					
Economic inflows					
Label	Name	Value	Unit	Description	Calculation
[G571]	electricity, medium voltage, at grid[BE]	18.2	kWh	This electrolysis step requires an average energy consumption of 186 MJ or 51 kWh per kg of refined gold (Navazo et al., 2014)	51 kwh * 350 gram gold
[W4102]	Gold-PGM alloy	1.78	kg		
Economic outflows					
Label	Name	Value	Unit	Description	Calculation
[G3417]	gold, secondary, at precious metal refinery[SE]	0.35	kg	Production of secondary gold. Value taken from Navazo et al (2014).	
[W4103]	PGM alloy	1.43	kg	Value was taken from Navazo et al. (2014)	1.78 - 0.35

Environmental emissions					
Label	Name	Value	Unit	Description	Calculation
[E8]	Heat, waste[air_low population density]	24.4	MJ	All emission values are taken from EcoInvent process "gold, secondary, at precious metal refinery[SE, 2000-2005]". This process is the closest process that was found in the database. The output of this process is secondary gold. The original emission values were taken from this process and multiplied with 0.35 kg of secondary gold in order to match gold production	6.96E+01 * 0.35
[E192]	Nitrogen oxides[air_low population density]	2.14E-03	kg		6.10E-03 * 0.35
[E221]	Sulfur dioxide[air_low population density]	1.66E-03	kg		4.73E-03 * 0.35
[E224]	Particulates, < 2.5 um[air_low population density]	1.64E-04	kg		4.68E-04 * 0.35
[E225]	Cadmium[air_low population density]	3.68E-07	kg		1.05E-06 * 0.35
[E227]	Copper[air_low population density]	5.53E-06	kg		1.58E-05 * 0.35
[E229]	Zinc[air_low population density]	2.04E-05	kg		5.84E-05 * 0.35
[E233]	Lead[air_low population density]	1.52E-04	kg		4.35E-04 * 0.35
[E314]	Particulates, > 10 um[air_low population density]	5.46E-05	kg		1.56E-04 * 0.35
[E340]	Particulates, > 2.5 um, and < 10um[air_low population density]	1.09E-04	kg		3.12E-04 * 0.35
[E607]	Chlorine[air_low population density]	7.81E-04	kg		2.23E-03 * 0.35
[E634]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_low population density]	1.55E-08	kg		4.42E-08 * 0.35
[E661]	Fluorine[air_low population density]	6.27E-06	kg		1.79E-05 * 0.35
[E728]	Mercury[air_low population density]	7.35E-07	kg		2.10E-06 * 0.35

Process = [P4101] SC2 - PGM extraction

Economic inflows

Label	Name	Value	Unit	Description	Calculation
[G571]	electricity, medium voltage, at grid[BE]	41.7	kWh	Total energy consumption for recovering secondary PGM is 277 kwh or 1000 MJ per kg recovered Platinum group metals (PGM). 150 gram of PGM is recovered.	0.150 kg * 277
[W4103]	PGM alloy	1.43	kg	Value taken from Navazo et al (2014)	

Economic outflows

Label	Name	Value	Unit	Description	Calculation
[G3418]	palladium, secondary, at precious metal refinery[SE]	0.15	kg	Production of secondary palladium. Value taken from Navazo et al (2014)	
[W4104]	PGM Residue	1.28	kg		1.43 - 0.15

Environmental emissions

Label	Name	Value	Unit	Description	Calculation
[E8]	Heat, waste[air_low population density]	5.48	MJ	All emission values are taken from EcoInvent process "palladium, secondary, at precious metal refinery[SE, 2000-2005]". This process is the closest process that was found in the database. The output of this process is a secondary palladium. The original emission values were taken from this process and multiplied with 0.15 kg palladium in order to match the platinum group metals production	3.65E+01 * 0.15
[E192]	Nitrogen oxides[air_low population density]	4.79E-04	kg		3.19E-03 * 0.15
[E221]	Sulfur dioxide[air_low population density]	3.72E-04	kg		2.48E-03 * 0.15
[E224]	Particulates, < 2.5 um[air_low population density]	3.68E-05	kg		2.45E-04 * 0.15
[E225]	Cadmium[air_low population density]	8.27E-08	kg		5.51E-07 * 0.15
[E227]	Copper[air_low population density]	1.24E-06	kg		8.26E-06 * 0.15
[E229]	Zinc[air_low population density]	4.59E-06	kg		3.06E-05 * 0.15

[E233]	Lead[air_low population density]	3.42E-05	kg		2.28E-04 * 0.15
[E314]	Particulates, > 10 um[air_low population density]	1.23E-05	kg		8.17E-05 * 0.15
[E340]	Particulates, > 2.5 um, and < 10um[air_low population density]	2.45E-05	kg		1.63E-04 * 0.15
[E607]	Chlorine[air_low population density]	1.76E-04	kg		1.17E-03 * 0.15
[E634]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air_low population density]	3.47E-09	kg		2.31E-08 * 0.15
[E728]	Mercury[air_low population density]	1.65E-07	kg		9.36E-06 * 0.15
[E1661]	Ethene, trichloro-[air_low population density]	1.40E-06	kg		1.10E-06 * 0.15

10.3 - Midpoint categories and indicators

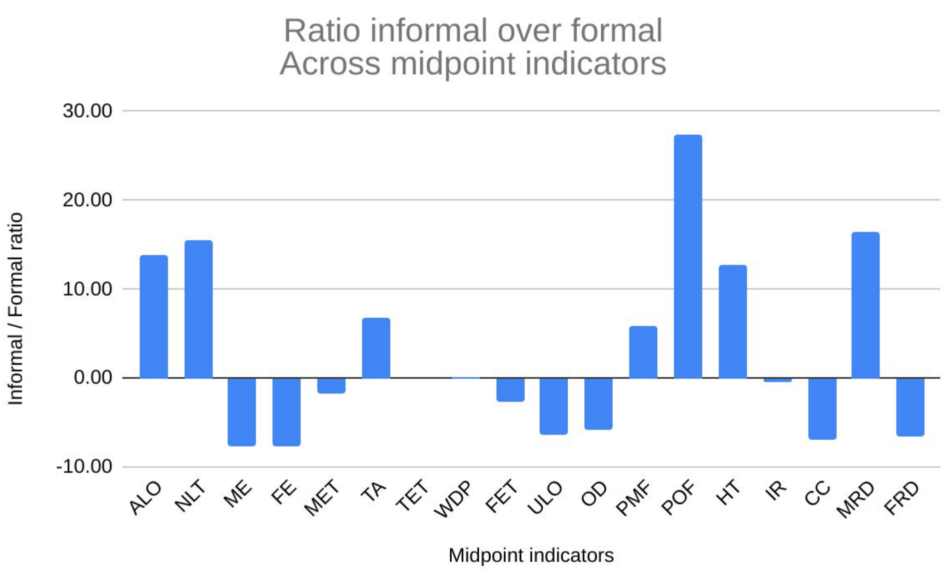
These midpoint categories were taken from Goedkoop et al. (2009).

Midpoint indicators	Abb.	Indicator name	Unit
Agricultural land occupation	ALO	Land use potential due to the effects of occupation of agricultural land.	m2 * year
Natural land transformation	NLT	Land use potential due to the effects of transformation of natural land.	m2
Marine eutrophication	ME	Eutrophication potential due to nitrogen concentration-eq emissions to freshwater	kg N-Eq
Freshwater eutrophication	FE	Eutrophication potential due to nitrogen phosphorus-eq emission to freshwater	kg P-Eq
Marine ecotoxicity	MET	Ecotoxicity potential due to 1,4-DCB-eq concentration to seawater	kg 1,4-DCB-Eq
Terrestrial acidification	TA	Terrestrial acidification potential due to SO2-eq in the air	kg SO2-Eq
Terrestrial ecotoxicity	TET	Ecotoxicity potential to industrial soil	kg 1,4-DCB-Eq
Water depletion	WDP	Water depletion potential due to fresh water use	m3
Freshwater ecotoxicity	FET	Ecotoxicity potential to freshwater	kg 1,4-DCB-Eq
Urban land occupation	ULO	Land use potential due to the effects of occupation of urban land	m2 * year
Ozone depletion	OD	Ozone depletion potential due to stratospheric ozone concentration	kg CFC-11-Eq
Particulate matter formation	PMF	Human health damage potential due to Pm10-eq intake	kg PM10-Eq
Photochemical oxidant formation	POF	Human health damage potential due to photochemical oxidant formation potential	kg NMVOC
Human toxicity	HT	Human toxicity potential for each emission to urban air	kg 1,4-DCB-Eq
Ionising radiation	IR	The potential ionising radiation due to absorbed dose	kg U235-Eq
Climate change (GWP100)	CC	Global warming potential for a 100-year time horizon for each greenhouse gas emission to the air	kg CO2-Eq
Metal depletion	MRD	Abiotic depletion potential for each extraction of minerals	kg Fe-Eq
Fossil depletion	FRD	Abiotic depletion potential for each extraction of fossil fuels	kg oil-Eq

10.4 - Full list of midpoint and endpoint indicators results

Endpoint	Midpoint indicators	Midpoint indicators	Informal (I)	Formal (F)	Unit	(I-F)/F
Ecosystem quality	Agricultural land occupation	ALO	38.80	2.60	m2a	13.92
	Natural land transformation	NLT	0.19	0.01	m2	15.58
	Marine eutrophication	ME	4,000.00	-598.00	kg N-Eq	-7.69
	Freshwater eutrophication	FE	4,000.00	-598.00	kg P-Eq	-7.69
	Marine ecotoxicity	MET	35.00	-41.80	kg 1,4-DCB-Eq	-1.84
	Terrestrial acidification	TA	10.30	1.31	kg SO2-Eq	6.86
	Terrestrial ecotoxicity	TET	381.00	0.04	kg 1,4-DCB-Eq	
	Water depletion	WDP	4.21	4.16	m3	0.01
	Freshwater ecotoxicity	FET	70.10	-43.50	kg 1,4-DCB-Eq	-2.61
	Urban land occupation	ULO	11.10	-2.07	m2a	-6.36
Human Health	Ozone depletion	OD	0.00039	-0.00008	kg CFC-11-Eq	-5.88
	Particulate matter formation	PMF	3.09	0.45	kg PM10-Eq	5.85
	Photochemical oxidant formation	POF	24.20	0.85	kg NMVOC	27.40
	Human toxicity	HT	1,320.00	96.40	kg 1,4-DCB-Eq	12.69
	Ionising radiation	IR	259.00	529.00	kg U235-Eq	-0.51
	Climate change (GWP100)	CC	3,160.00	-528.00	kg CO2-Eq	-6.98
Resources	Metal depletion	MRD	53.40	3.07	kg Fe-Eq	16.39
	Fossil depletion	FRD	811.00	-144.00	kg oil-Eq	-6.63

Results from the midpoint categories and midpoint units



Ratio of informal and formal across midpoint indicators. The full names of the acronyms for the midpoint indicators can be found in the section above.

Endpoints	Midpoints	Points		%	
Human health	Particulate matter formation	1.30E+01	2.07E+00	12.7%	-17.3%
	Photochemical oxidant formation	1.68E-02	6.49E-04	0.0%	0.0%
	climate change, human health	7.32E+01	-1.46E+01	71.8%	121.7%
	ionising radiation	5.15E-02	1.72E-01	0.1%	-1.4%
	human toxicity	1.55E+01	3.74E-01	15.2%	-3.1%
	ozone depletion	1.43E-02	-4.33E-03	0.0%	0.0%
	total	102	-12	100.0%	100.0%
Resources	metal depletion	1.56E-02	1.43E-03	0.0%	0.0%
	fossil depletion	6.10E+01	-1.51E+01	100.0%	100.0%
	total	61	-15.1	100.0%	100.0%
Ecosystem quality	agricultural land occupation	8.33E-01	6.52E-02	0.5%	-0.7%
	natural land transformation	5.12E-01	1.43E-02	0.3%	-0.2%
	freshwater eutrophication	1.78E-01	9.55E-03	0.1%	-0.1%
	marine ecotoxicity	5.76E-05	2.12E-04	0.0%	0.0%
	terrestrial acidification	1.11E-01	1.63E-02	0.1%	-0.2%
	terrestrial ecotoxicity	1.11E+02	4.19E-03	68.9%	0.0%
	climate change, ecosystems	4.79E+01	-9.58E+00	29.8%	100.9%
	freshwater ecotoxicity	3.48E-02	7.07E-02	0.0%	-0.7%
	urban land occupation	4.33E-01	-9.11E-02	0.3%	1.0%
	total	161	-9.49	100.0%	100.0%
Total	Human health	102	-12	31.5%	32.8%
	Resources	61	-15.1	18.8%	41.3%
	Ecosystem quality	161	-9.49	49.7%	25.9%
	Total	324	-36.6	100.00%	100.00%

Endpoint categories in points and percentage

10.5 - Midpoint categories and characterization factors

Midpoint categories and their related characterization factors. If the values from the midpoint categories in midpoint units are multiplied with these factors, then these values are converted into endpoint units. The midpoint categories can therefore be converted into the following endpoint categories with their units: Human health (DALY), Ecosystems (Species per year) and Resources ($).

Midpoint impact category	Unit	Abbrevation	Human health	Ecosystems	Resources
Climate change	kg CO2 eq	CC	1.40E-06	7.93E-09	
Ozone depletion	kg CFC-11 eq	OD			
Terrestrial acidification	kg SO2 eq	TA		5.80E-09	
Freshwater eutrophication	kg P eq	FE		4.44E-08	
Human toxicity	kg 1,4-DB eq	HT	7.00E-07		
Photochemical oxidant formation	kg NMVOC	POF	3.90E-08		
Particulate matter formation	kg PM10 eq	PMF	2.60E-04		
Terrestrial ecotoxicity	kg 1,4-DB eq	TET		1.51E-07	
Freshwater ecotoxicity	kg 1,4-DB eq	FET		8.61E-10	
Marine ecotoxicity	kg 1,4-DB eq	MET		1.76E-10	
Ionising radiation	kg U235 eq	IR	1.64E-08		
Agricultural land occupation	m2a	ALO			
Urban land occupation	m2a	ULO			
Natural land transformation	m2	NLT			
Fossil depletion	kg oil eq	FRD			1.65E-01
Metal depletion	kg Fe eq	MRD			7.15E-02