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Sources of variation in life cycle assessments of smartphones and tablet computers

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ABSTRACT

Life Cycle Assessment (LCA) studies and reports on smartphones and tablet computers are analysed to detect the sources of variation across their results, considering the impact on global warming potential over 100 years (GWP100). The production and use phases are undoubtedly the life cycle phases contributing most strongly. Existing life cycle inventories (LCI) were analysed to determine the most important components, and a normalization of the use phases was performed. The results highlight the prevalence of the production phase. Integrated circuits (ICs) play a major role, and the estimation of their impact should be thoroughly scrutinized. Finally, the location of the production plants is crucial as electricity generation accounts for a significant part of the GWP. Assumed electricity mixes explain much of the variations in both production and use phases.

1. Introduction

The IPCC (Intergovernmental Panel on Climate Change) states that" Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." (Core Writing Team et al., 2014). The GHG (Greenhouse Gas) emissions are pointed as the cause of climate change.

The ICT(Information and Communication Technology) sector has a significant footprint, which request quite some effort to capture an accurate estimation. (Malmodin and Lundén, 2018) show that smartphone production makes up the largest part of the manufacturing footprint of ICT, which is more important than both desktop and laptop computers together. The market of mobile devices has seen sharp growth over the last decade, there are more mobile devices today than people in the world (Boren, 2014). Understanding the environmental impact of these devices is essential for assessing the global impact of the ICT sector as they play a major role in it (Malmodin and Lundén, 2018; Moberg et al., 2014). LCA methodology, defined by the ISO standards 14040 and 14044, allows researchers to fulfil this goal based on several mid-point and end-point indicators. The most studied indicator in this context is GWP100 which is provided as a quantity of GHG (greenhouse gas) emissions in $kgCO_2e$ (kilograms carbon dioxide equivalent). This partial LCA output is also known as the carbon footprint (ISO 14067).

In the context of global warming, when a coordinated effort must be done in order to achieve emission reduction goals from the Paris agreement and progress in the UN Sustainable Goals 13, reliable figures must be available for decision-makers.

Therefore, it is relevant to scrutinize the environmental role of mobile devices by analysing available LCA studies. Several authors have pointed out that the results for GHG emissions vary considerably across studies for devices that seem to be quite similar (Manhart et al., 2016; Andrae and Andersen, 2010; Arndt and Ewe, 2017; Suckling and Lee, 2015; Andrae and Vaija, 2014; Güvendik, 2014). These variations can in principle have two sources: (i) variations in the materials, energy sources and processes used (e.g. semiconductor device fabrication) and (ii) variations in the LCI data used to assess their environmental impact (primary or secondary data and their quality).

The scope of our study is the analysis of studies that reports the environmental impact of smartphones and tablet computers in terms of global warming potential over 100 years (GWP100). The target is to identify the main sources of variation in LCAs of smartphones and tablet computers to improve comparability across results.

Section 2 defines the materials and methods that have been used. Section 3 analyses scientific studies and reports from manufacturers, reporting the sources of variation. Section 4 details simplified LCAs that exclude some life cycle phases/processes. Section 5 concludes by discussing the results.

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2. Materials and methods

2.1. Literature review

A literature review was performed to collect LCA of smartphones and tablet computers (Moberg et al., 2014; Andrae and Vaija, 2014; Güvendik, 2014; Ahmadi Achachlouei et al., 2015; Ercan, 2013; Corcoran et al., 2014; Hischier et al., 2013; Ercan et al., 2016; Proske et al., 2016; Hischier et al., 2014; Teehan and Kandlikar, 2013). Additional reports from manufacturers were also considered in view of the scarcity of such studies (Apple Inc, 2017; Samsung, 2015; HP Development Company, 2017a; HP Development Company, 2017b; HP Development Company, 2017c; HP Development Company, 2017d; Stutz, 2011; Schafer, 2014; HTC Corporation, 2013; Huawei Investment and Holding Co, 2013; Huawei Technologies Co, 2017a; Huawei Technologies Co, 2017b; Huawei Technologies Co, 2016a; Lenovo, 2018; Huawei Technologies Co, 2016b; Huawei Technologies Co, 2016c; Nokia Corporation, 2011a; Nokia Corporation, 2012a; Nokia Corporation, 2012b; Nokia Corporation, 2012c; Nokia Corporation, 2012d; Nokia Corporation, 2012e; Santavaara and Paronen, 2014; Nokia Corporation, 2013; Nokia Corporation, 2011b; BlackBerry, 2011). Scientific studies were identified through literature searches on Google Scholar and through citations in other published studies and reports. The reports from the manufacturers were identified through searches on Google. The following keywords were combined:" life cycle assessment"," LCA"," life cycle analysis"," smartphone"," mobile phone"," tablet computer"," tablet"," carbon footprint"," environmental impact"," GHG emissions"," Greenhouse Gas Emissions". When necessary, values not concerning the devices were removed, i.e., the impact of accessories such as the charger or earplugs. For the Samsung devices (Samsung, 2015), we were not able to remove the impact of the product packaging. Apple (Apple Inc, 2017) includes the consumption impact of data centres due to the data transfer in the assessment of the use phase. In total, 76 LCA studies or reports were considered in this article.

2.2. Approach

Our approach is similar to the one of Teehan and Kandlikar (Teehan and Kandlikar, 2012) who performed a meta-analysis of LCAs for desktop computers based on decomposition. Firstly, they divided the LCA results into component life cycle phases. Secondly, they identified the largest sources of impacts for each significant life cycle phase (i.e., decomposing the production phase into key components such as mainboard, integrated circuits, etc.). Thirdly, they performed an inventory with the impact of material parts in $kgCO_2e$ and MJ (megajoules) for electricity. The assessment in MJ is interesting as it does not depend on the electricity mix and the geographic location as the $kgCO_2e$ unit does. Unfortunately, the data available for smartphones and tablet computers are scarcer. Therefore, we were not able to have enough data to evaluate the use phase impact in terms of MJ.

After collecting data from publicly available studies and relevant vendors, we normalized results from LCAs as follows:

1. Comparison of the relative share of life cycle phases in overall GHG emissions (GWP100 indicator)
2. Identification of the largest sources of GHG emissions and their variation for each life cycle phase, which includes in particular:
   a. A detailed analysis of the impact of the production of subcomponents
   b. A normalization of the use phase across studies (method described in section 2.3)
3. Conducting simplified LCAs of selected devices to avoid biases introduced by different ways of performing LCAs, thereby removing sources of variation.

2.3. Normalization of the use phase

The use phase considers the amount of energy necessary to charge the battery of the device throughout its operating lifetime. Side effects, such as the energy consumed by data centres while processing and sending requested information (network consumption (Coroama and Hilty, 2014; Coroama et al., 2015)), are beyond the scope of this study. The impact of the use phase varies with the assumptions that are chosen: operating life time, electricity mix (depending on the geographic location), duration of one battery cycle, charger efficiency, no-load losses from the charger, average charger plugged-in time. In order to improve the comparability of the use phase impact across studies, a normalization was performed, using the characteristics of the different devices based on the following assumptions:

- Operating life time: 3 years (Thiébaud (-Müller) et al., 2017)
- Average charger plugged-in time: 7 h/day (Proske et al., 2016)
- Battery cycle: 24 h (tablet) and 30 h (smartphone) (Güvendik, 2014). This is likely to be a worst-case scenario.

If unknown, the efficiency and the no-load losses value for the charger were chosen according the minimum required by the EU code of conduct (European Commision, 2013). Nowadays non-load losses are negligible (1–2% of total consumption), but a decade ago they accounted for up to 30% of the total use phase. Average power losses dropped from 0.3 W to currently less than 0.03 W (Proske et al., 2016; Apple Inc, 2017; Nokia Corporation, 2011a; Nokia Corporation, 2012a; Nokia Corporation, 2012b; Nokia Corporation, 2012c; Nokia Corporation, 2012d; Nokia Corporation, 2012e; Santavaara and Paronen, 2014; Nokia Corporation, 2013; Nokia Corporation, 2011b).

Total electricity consumption is calculated as follows:

Electricity consumption [Wh] = (Capacity [mAh] * Voltage [V] * Lifetime [y] * Battery cycle number per year / Charger efficiency [%]) + (No-load losses [W] * Average charger plugged-in time [h/day] * Lifetime [y] * Battery cycle number per year).

This yields a comparable estimation of the devices' electricity consumption. The resulting impact depends on the electricity mix, which thus becomes a determinant factor of the use phase impact; the difference between market groups (consistent regions regrouping several countries) for electricity (low voltage) can vary by a factor of 5.25 according to Ecoinvent v3.4 (Wernet et al., 2016). Nonetheless, the ratio goes above 100 when comparing countries.

2.4. Simplified LCAs

We performed simplified LCAs, focussing on life cycle phases and processes causing the greatest contribution to GWP. The aim of these LCAs is to corroborate the importance of the most contributing processes identified previously, and to be able to compare the results of several devices by using the same calculation basis (methodology and LCI data).

2.4.1. Methodology

In order to be able to compare devices based on uniform LCI data, we performed simplified LCAs on several devices for which enough information were available (Moberg et al., 2014; Andrae and Vaija, 2014; Ercan, 2013; Corcoran et al., 2014; Ercan et al., 2016; Proske et al., 2016; Teehan and Kandlikar, 2013; Teehan, 2014). We used a process-based methodology for the LCI method, and the characterization model was the IPCC2007-100 years (characterization factor: GWP100). The scope of the analysis included the devices without any accessories. The functional unit was the use of the device for a period of 3 years. Our analyses do not pretend to be exhaustive, and the results may thus underestimate the impact. The focus again lies on the production (cradle-to-gate) and use phases for the GWP indicator, as we identified these phases as the ones causing the largest contributions.

2.4.2. *Inventory list of the components*

We identified the parts of the devices with the largest contributions. We extracted the relevant data to build a bill of material with the relevant specifications (see S4). For the Huawei U8350, measurements from Huawei were chosen as they allow extraction of the IC area of the device (whereas the baseline includes the charger as well) which is not possible with the data reported by Orange. The measurements of the PCBs are also easier to extract from the Huawei data. No information was available about the composition of the Sony W890 casing.

2.4.3. *LCI data*

We gathered LCI data from several transparent sources with the best accuracy possible. The IC impact considered is 5.4 $kgCO_2e/cm^2$, based on the work of Fraunhofer IZM (Proske et al., 2016). The PCB impact is based on the primary data from Ercan et al. (Ercan et al., 2016), which gives 875 $kgCO_2e/m^2$. The display impact is the value of 0.047 $kgCO_2e/cm^2$ used by Ercan et al. (Ercan et al., 2016) based on primary data. The battery impact is based on the work of Clemm et al. (Proske et al., 2016) with 25.8 $kgCO_2e/kg$. Finally, the casing impact is based on the Ecoinvent datasets about aluminium (6.73 $kgCO_2e/kg$), stainless steel (5.12 $kgCO_2e/kg$) and plastic (7.87 $kgCO_2e/kg$). The process” energy consumption, global electricity mix” of 0.81 $kgCO_2e/kWh$ from Ecoinvent v3.4 (Wernet et al., 2016) was used for the use phase. This figure could be an overestimation when compared with the figure from the International Energy Agency of 0.6 $kgCO_2/kWh$ (IEA, 2019). For 2007, Malmodin et al. (Malmodin et al., 2010) estimated world average electricity about 0.6 $kgCO_2e/kWh$ based on 0.52 $kgCO_2/kWh$ for production only. Nevertheless, it does not have a significant impact on the demonstration of the use phase importance.

3. Analysis and results

Many variations can be observed in smartphone and tablet computer LCAs. We will first give additional information on some studies and reports to explain major variations before investigating the different elements that impact the life cycle phases in detail.

3.1. *GHG emissions by life cycle phase*

Figs. 1 and 2 show the GHG emissions share of each life cycle phase of smartphones and tablet computers. The devices are listed chronologically. Samsung (Samsung, 2015) didn't provide the absolute GHG emissions in its study. From here onwards, we will focus on the production (cradle-to-gate) and use (energy consumption of the device only) phases as they represent more than 90% of the impact regarding the GWP100 indicator. This does not imply that transportation and end-of-life phases should be considered negligible for the environment; informal recycling processes have a major impact on human toxicity (Teehan and Kandlikar, 2012). Most studies and reports claim to follow the standards ISO 14040 and 14044. Blackberry and HP do not state which standard they apply, and Lenovo uses the Product Attribute to Impact Algorithm (PAIA) (Massachusetts Institute of Technology, n.d.). The Streak tablet is considered as a smartphone because of its specifications and features. Concerning the use phase, all studies and reports considered a lifetime usage of 3 years except HP (HP Development Company, 2017a; HP Development Company, 2017b; HP Development Company, 2017c; HP Development Company, 2017d), Dell (Stutz, 2011; Schafer, 2014) and the Huawei(HuW)-Orange(OGE) study (Andrae and Vaija, 2014), which chose 2 years.

3.1.1. *Smartphones*

Fig. 1 shows a high relative share for the production phase, 70 ± 12%. Some outliers are present: early Apple phones and Fairphone 1. Several clusters can be distinguished among the absolute values. Firstly, Nokia's phones have very small footprints which are similar. The only phones which have comparable values are the Sony Mobile W890 and Fairphone 1. According to Fraunhofer IZM (Proske et al., 2016), Merve underestimated by far the environmental impact of IC production for the Fairphone 1, which explains its low result. Secondly, Apple iPhone 6 and 6Plus have the biggest footprints, which is linked to the fact Apple chose a 128Gb storage for their LCI (From iPhone 6S onwards, the GHG emissions difference can reach up to 19$kgCO_2e$ based on the storage capacity). Thirdly, early Apple phones and the Dell Streak have a use phase value that are more than twice the mean value (8.6 ± 6.6$kgCO_2e$). Apple defined a use phase” that reflects intensive daily use” until the iPhone 6. Since the iPhone 6s, they use historical customer data. Finally, the other phones, which are mainly the most recent ones, have an average footprint of 55 ± 12 $kgCO_2e$.

3.1.2. *Tablet computers*

The lack of transparent LCA studies for tablets is even more critical than it is for smartphones. The only studies available are from Teehan and Kandlikar (Teehan and Kandlikar, 2013) and Hischier et al. (Hischier et al., 2014). Fig. 2 shows a relative share for the production phase similar to the one observed for smartphones, 68.4 ± 21.3%, although the standard deviation indicates a greater dispersion of values. In the interest of readability, the Lenovo Tab3 8 Plus is not included in Fig. 2: its footprint is 660 $kgCO_2e$, which makes it an outlier. The Lenovo's devices emit less GHG emissions than most other tablets. Otherwise, the most noticeable difference is between the results of the two LCA studies and the producer reports: the LCA studies report very low footprints compared to the footprints from the reports. Both studies and Huawei used the Ecoinvent database (Frischknecht et al., 2005), while Lenovo, Dell and HP used PAIA and Apple does not mention the databases used.

3.2. *Production - impact of subcomponents*

Fig. 3 shows clearly that the ICs, the display and the PCBs are the top contributors, followed by the casing and the battery.

3.2.1. *Integrated circuits*

As the major contributor, the ICs production is very sensitive. Its impact is evaluated based on the *package mass* (Ecoinvent) or the *area of the die* (GaBi, EIME) which lies in the chip package.

The unit processes contributing most to the IC unit process are the wafer and the energy necessary for the cleanroom (Manhart et al., 2016) and the manufacturing line. Ecoinvent v3.4 (Wernet et al., 2016) estimates that electricity contributes to 38% of the total impact. Ercan (Ercan et al., 2016) reports electricity consumption of 2–3 kWh/cm^2 for die production, which corresponds to 1.2–1.8 $kgCO_2e/cm^2$ (Ercan uses 0.6 kgCO2e/kWh as the global electricity mix emission factor). Considering the total impact of IC chips from Ercan, 3–4 $kgCO_2e/cm^2$, the contribution of electricity accounts for 40–45%. Therefore, changes in the electricity mix can lead to substantial variations. In Ecoinvent v2 (Frischknecht et al., 2005), the wafer size necessary to produce 1 kg of ICs is calculated on the basis of the size of the package and the share of the processed wafer of the total package of the chip (see S1). Based on the values of 0.4% (Philips SOT514) and 2.7% (ST microelectronics PBGA256), Ecoinvent chose the value of 2%. This results into a high uncertainty (namely more than 25%) if we consider that the share of the wafer is 0.02 ± 0.005. Teehan mentions values from 0.9% to 5%. He made an analysis of 22 IC chips and assumed a wafer area of 7.8% of the packaged chip area (Teehan, 2014), which is 3.9 times higher than the assumption of Ecoinvent. Huawei measured 85.7 mg of Si dies for 0.984 g of packaging, which yields a ratio of 8.7% for the Huawei U8350 (Andrae and Vaija, 2014; Corcoran et al., 2014).

In Ecoinvent v3.0 to v3.3 (Wernet et al., 2016), the wafer share of 2% is still used, resulting in the same degree of uncertainty. Moreover, the dataset contains several errors that were acknowledged by the Ecoinvent team upon our inquiry (see S1); the wafer thickness and the

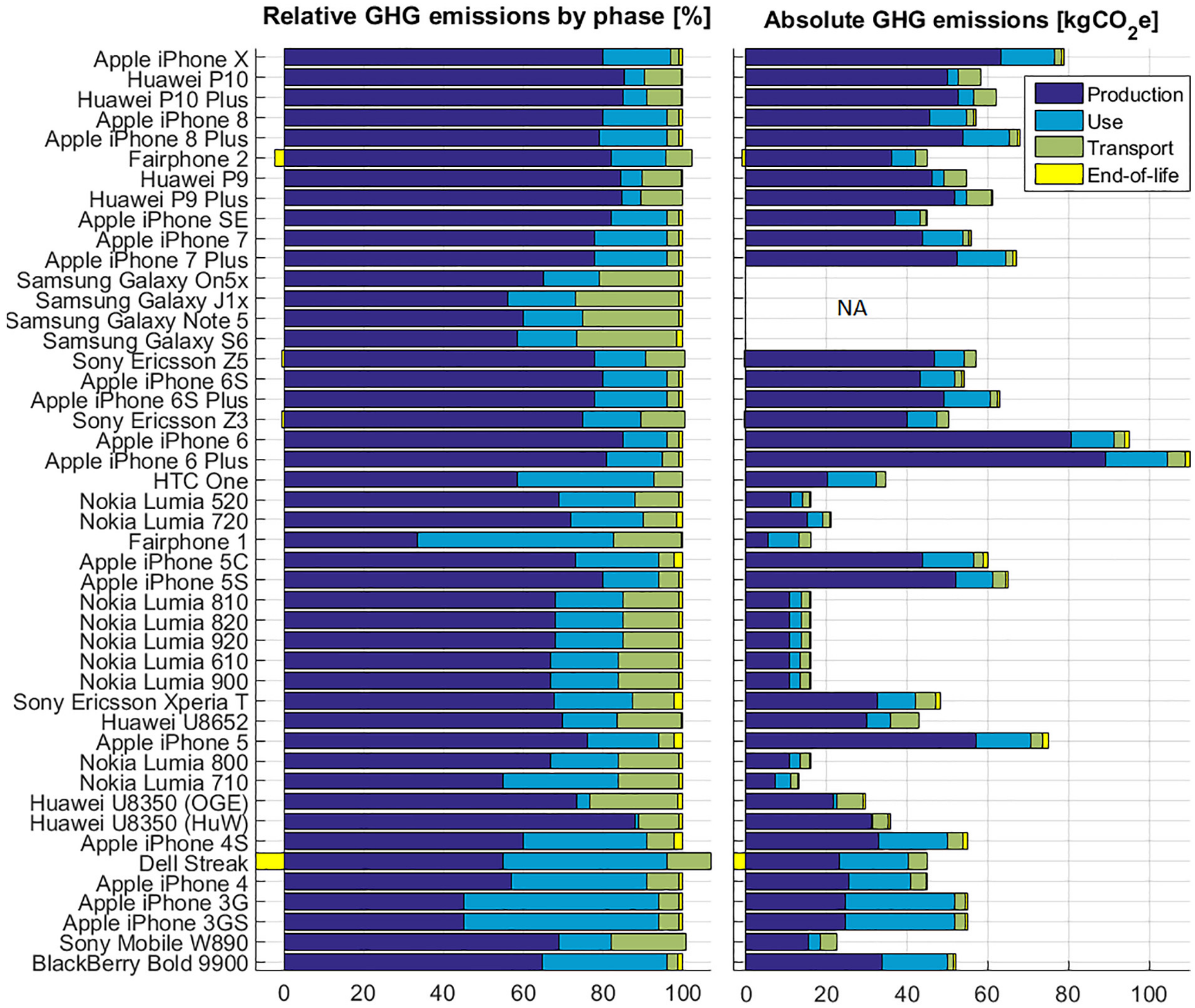

Fig. 1. GHG emissions per smartphone by life cycle phase (Moberg et al., 2014; Andrae and Vaija, 2014; Güvendik, 2014; Ahmadi Achachlouei et al., 2015; Ercan, 2013; Corcoran et al., 2014; Ercan et al., 2016; Proske et al., 2016; Teehan and Kandlikar, 2013; Apple Inc, 2017; Samsung, 2015; Stutz, 2011; HTC Corporation, 2013; Huawei Investment and Holding Co, 2013; Huawei Technologies Co, 2017a; Huawei Technologies Co, 2017b; Huawei Technologies Co, 2016a; Huawei Technologies Co, 2016b; Nokia Corporation, 2011a; Nokia Corporation, 2012a; Nokia Corporation, 2012b; Nokia Corporation, 2012c; Nokia Corporation, 2012d; Nokia Corporation, 2012e; Santavaara and Paronen, 2014; Nokia Corporation, 2013; Nokia Corporation, 2011b; BlackBerry, 2011).

weight of the wafer for one chip are incorrect, which affects most of the unit processes, and the transformation of medium voltage electricity to low voltage electricity was not taken into consideration. The most critical error is the fact that the amount of wafer is calculated for one chip instead of one kilogram of chips (the reference product). According to our own calculation, these errors together lead to an underestimation by a factor of 78 (logic chip) and 120 (memory chip) concerning the size of the" wafer, fabricated, for integrated circuit". As the value of the size of the wafer is used in 11 processes afterwards, it introduces a major bias. Ultimately, the" IC production, logic chip" and" IC production, memory chip" datasets were underestimated by a factor of 1.6 and 1.4, respectively (see S1). In the GaBi database, the amount of silicon (necessary for the die) is even lower than the one estimated by Ecoinvent (see S2). The LCI for an identical BGA 256 chip (2.62 g) is quite different in terms of processes, although the comparable processes show values of the same magnitude.

Many different types of packaging are currently in use in electronic parts, which makes them hard to assess. Some studies agree that using the package mass is no longer relevant (Proske et al., 2016) or less accurate (Teehan, 2014) due to the diversity of packaging techniques. For example, the die area for the iPad 1st Gen processor (Apple A4) calculated by Teehan is 130 mm^2 for a packaged area of 196 mm^2 (ratio: 66%), which does not follow the assumptions discussed previously concerning the ratio. Moreover, the diversity of packaging, the precision of the processor engraving and wafer specifications makes it hard to perform reliable comparisons.

In Ecoinvent, the" integrated circuit production" datasets use 2D-chips (one die in the package chip) as the reference product. During the last decade, most of the chips dedicated for mobile devices were 3D-chips (stacked ICs: multiple dies stacked in one package) (Teehan, 2014). Therefore, it seems that the datasets provided by Ecoinvent cannot accurately represent these 3D-chips.

In the Huawei U8350 study (Andrae and Vaija, 2014), Andrae and Vaija state that the share of stacked dies in the phone represents 46.5% of the total Si die area and that their Si density is 6 mg/cm^2 while the Si density for ordinary dies is 150 mg/cm^2. Considering that the U8350 phone is quite old (2011), we can assume that the chips currently embedded in mobile devices mainly use the stacked technology. The value of 150 mg/cm^2 corresponds to 2.069 mg/mm^3 for a chip produced from a 300 mm-wafer (0.725 mm thick). It is a bit lower than the density of pure silicon, 2.33 g/cm^3, which is used by Ecoinvent and Teehan (Teehan, 2014).

Continuing on from older studies by Teehan (Teehan, 2014), Table 1 compares the range of values available. Most of the studies use the die

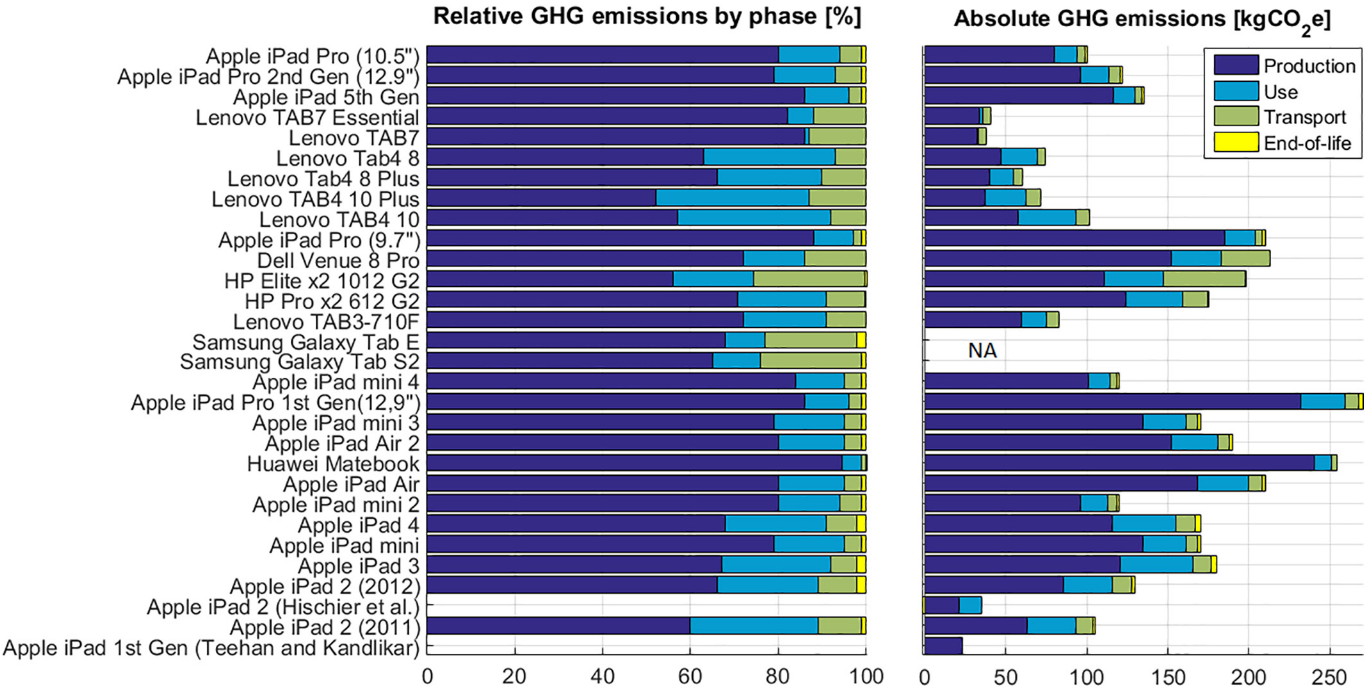

Fig. 2. GHG emission per tablet computer by life cycle phase (Ahmadi Achachlouei et al., 2015; Hischier et al., 2013; Hischier et al., 2014; Teehan and Kandlikar, 2013; Apple Inc, 2017; Samsung, 2015; HP Development Company, 2017a; HP Development Company, 2017b; HP Development Company, 2017c; HP Development Company, 2017d; Schafer, 2014; Lenovo, 2018; Huawei Technologies Co, 2016c).

area to assess the production impact of the chip. Proske et al. (Proske et al., 2016) based their data on the work of Boyd (Boyd, 2012).

To conclude, there is a consistent lack of transparent LCI data on IC chips. Many parameters are only known by the manufacturer, which are difficult to obtain, leading to uncertainties and a wide range of results. It would be a big step forward to have a complete analysis of the different technologies and their impacts.

3.2.2. Printed circuit boards

Joyce and al. demonstrated that the number of layers has a significant impact on the PCB carbon footprint (Joyce et al., 2010). Ecoinvent provides datasets based on an FR4-double-sided PWB with 2

Table 1
Impact of integrated circuits.

	Impact/die area	Impact/package mass
	[kgCO$_2$e/cm^2]	[kgCO$_2$e/g]
Hischier et al. (2007)	/	1
Boyd (2012)	5.5	/
Andrae et al. (2014)	2.2	/
Ercan (2016)	2.7–4.3	/
Proske et al. (2016)	5.4	/

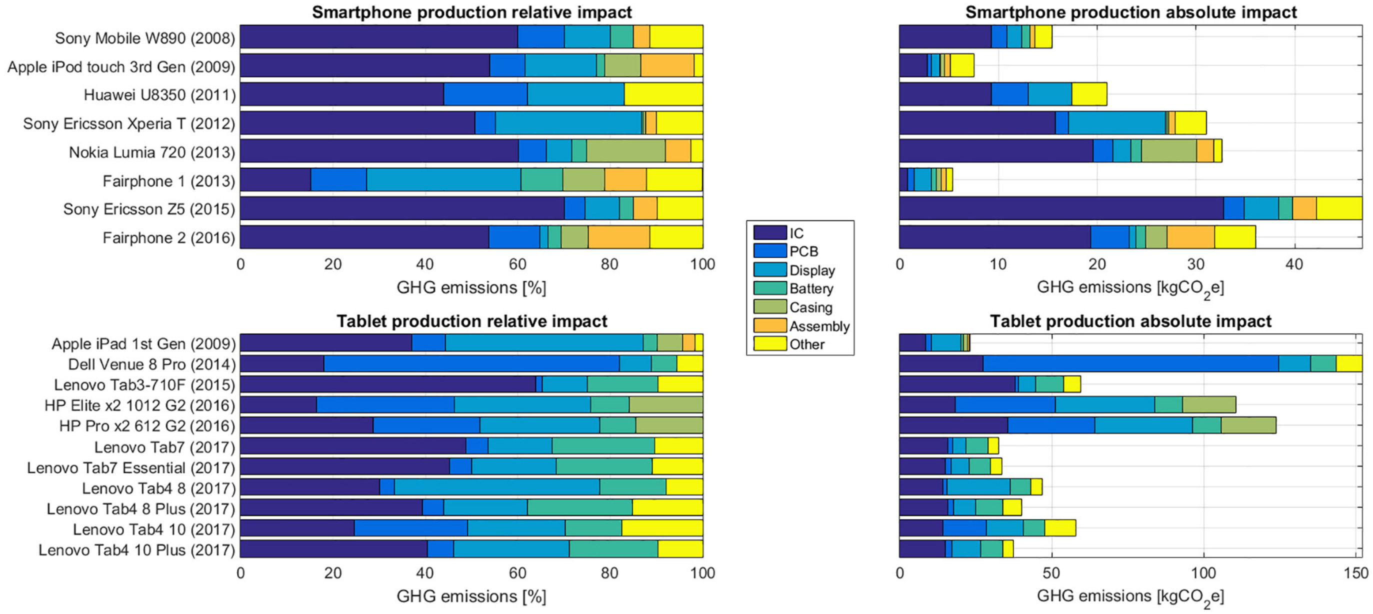

Fig. 3. Subcomponents production impact.

or 6 layers and no datasets for flexible PCB, which forced some studies to make approximations (Moberg et al., 2014; Güvendik, 2014; Teehan and Kandlikar, 2013). The different datasets available in Ecoinvent, for the PCBs that are already populated, use data from the IC datasets and propagate their errors (see S1). For unpopulated PCBs, Liu et al. (Liu et al., 2014) report $3.92 * 10^{-3}$ $kgCO_2e/cm^2$ while Ecoinvent v3.4 (Wernet et al., 2016) states $4.24 * 10^{-2}$ $kgCO_2e/cm^2$. GaBi does not provide any dataset for flexible PCB, either, leading to some approximations for the Fairphone 2 (Proske et al., 2016). Ercan et al. (Ercan et al., 2016) report $8.75 * 10^{-2}$ $kgCO_2e/cm^2$ for a PCB of 24 cm^2 from primary data. The studies on the Huawei U8350 (Andrae and Vaija, 2014; Corcoran et al., 2014) use the EIME database, which provides a great panel of datasets. However, the research teams from Orange (OGE) and Huawei (HuW) use different inventories. They do not assume the same PCB areas, PCB weights, or even the same number of layers. The inventory by Orange is far more detailed, although it assumes the smallest PCB area by a factor of 1.5 compared to the area assumed by Huawei. As it is the case for ICs, the electricity mix has an important impact according Ecoinvent data; 58% for an unpopulated PCB. Liu et al. (Liu et al., 2014) state that the electricity share is 47.51% for an epoxy-based PCB.

3.2.3. Display

Smartphone screens are made of three parts; the front glass, the touch screen panel and the display. The European and American markets are quite homogeneous regarding the front glass and the display. Little information was found about the touch screen panel. Gorilla glass is used worldwide (Chan, 2016). Display technology is currently experiencing a shift from LCD to AMOLED. This change is slightly beneficial (by about 14%) for the environment from the perspective of GHG emissions regarding a cradle-to-gate analysis (Ercan, 2013). Andrae et Vaija (Andrae and Vaija, 2014) state that the main source of GHG emissions in LCD screen production comes from global average electricity production. Ercan (Ercan et al., 2016) reports that electricity consumption is around 0.1 kWh/cm^2, which supports that statement. The Taiwanese display manufacturer AUO (AU Optronics Corporation) indicates 0.0079 kWh/cm^2. According to Fraunhofer IZM (Proske et al., 2016), the AUO value does not include the production of upstream materials. As the data used by Fraunhofer IZM from AUO does not make a distinction between the type of displays, the GHG emissions could give a lower average per cm^2 by including large displays (e.g. TV, PC monitor). Ercan obtains an impact of 3.5 $kgCO_2e$ (for 74 cm^2) with primary data, while Fraunhofer IZM finds 2.68 $kgCO_2e$ for screens of similar size (73.7 cm^2). The information provided by Andrae et al. and Ercan shows a significant impact from electricity consumption.

3.2.4. Battery

The market for mobile device batteries is homogeneous. All devices use prismatic lithium-ion batteries ($LiCoO_2$). The literature provides environmental impact values that differ by a factor of 5. The studies from Clemm et al. (Proske et al., 2016) and Ercan (Ercan, 2013; Ercan et al., 2016) (both using primary data) report 25.8–29 $kgCO_2e/kg$ while Andrae et al. (Andrae and Vaija, 2014) and Ecoinvent v3.3 (Wernet et al., 2016) report only 5.6–8.3 $kgCO_2e/kg$ with secondary data.

3.2.5. Casing

The casing can have a significant impact depending on the materials used. While aluminium and stainless steel have similar GHG emissions, those of polystyrene are 1.6 to 3 times lower than aluminium per unit of mass, according to Ecoinvent (Wernet et al., 2016) and GaBi (Ercan, 2013), respectively. Nevertheless, in order to make a correct comparison, one must consider the density of the materials used for the casing. The dimensions of an iPhone 8 back face were taken as a reference (see S3), the mass for each material was then calculated and the associated GHG emissions from the Ecoinvent and GaBi databases were applied. Polycarbonate was considered as a reference for the order of magnitude between the different materials. Finally, the impact of using Gorilla glass (Chan, 2016) was also compared to both database results. Table 2 shows that aluminium alloys and especially stainless steel have greater GHG emissions than plastic and glass. However, the net GHG emissions of metals and glass are far lower if they are recycled, as reported by Apple, which has launched a specific programme to recover materials from its smartphones since the iPhone 6 (Apple Inc, 2017). On the other hand, plastics such as polycarbonate are not easily recyclable.

Table 2
Impact comparison of different materials for the casing.

Material	Ecoinvent v3.4 (2017)	GaBi (2012)
Polycarbonate [Reference]	1	1
Glass	1.2	NA
Aluminium	1.9	7
Stainless Steel	4	18
	For comparison: data for Gorilla Glass by Corning (2016)	
Gorilla Glass	0.7	1.5

These comparisons held uncertainties due to the predominant role played by the different national and regional grid mixes. A publication from the International Aluminium Institute (International Aluminium Institute (IAI), 2017) states that the electrical energy consumption used in the electrolysis process (main source of GHG emissions) in China is on average around 13 $kgCO_2e/kg$ of aluminium. Depending of the province, the GHG emissions can vary by a factor of 4.6. These figures are above Ecoinvent v3.4 (6.7 $kgCO_2e/kg$) and GaBi 2012 (11 $kgCO_2e/kg$).

3.3. Normalization of the use phase

Fig. 4 shows the values from the studies with and without normalization. To give two examples, the normalized values were calculated for the world average (0.813 $kgCO_2e/kWh$) and for the Swiss electricity mix (0.097 $kgCO_2e/kWh$) with the values from Ecoinvent v3.4 (Wernet et al., 2016). The normalized values are lower for the smartphones and higher for the tablets compared with the original values. This can be explained either by different definitions of the use phase (e.g. including network consumption) or different assumptions regarding user habits. The values from Apple are not consistent before the iPhone 5S (late 2013). This is probably due to the fact that Apple considers the energy consumption of its own data centres in the use phase of the phone. Since 2014, their data centres have mainly used green energy, which lowers the impact by a factor of 100 compared to the global energy mix. Apple states that from 2008 to 2014, it reduced the GHG emissions of its products by 61% (Apple Inc, 2017). As shown by the power consumption data (Apple Inc, 2017), this was partly achieved by improving the efficiency of the charger and drastically reducing the no-load losses. From 2015, real use pattern data were used that most likely contribute to improving the analysis. Huawei products display coherent values in comparison with the normalization; a ratio from a different choice of electricity mix or battery cycles per day would explain the differences. Dell Streak, which is considered as a smartphone because of its specifications, has a higher value due to the poor performance of its charger and the fact that a 10 h charger plugged-in time is considered. Nevertheless, the value without the no-load losses is similar assuming the EU electricity mix (4–4.5 $kgCO_2e$). Fairphone 2 has a consistent value considering the use of a custom electricity mix depending on the sales distribution. Nokia defines neither the geographic scope of its use phase nor its definition. There is insufficient information to explain the difference of values for the Blueberry Bold 9900. The values obtained for tablet computers vary widely because of the diversity in battery specifications. Nevertheless, the values from the studies are consistent with the ones from the normalization. The latest Apple tablets consume less than expected. This is most likely due to a change in the assumptions

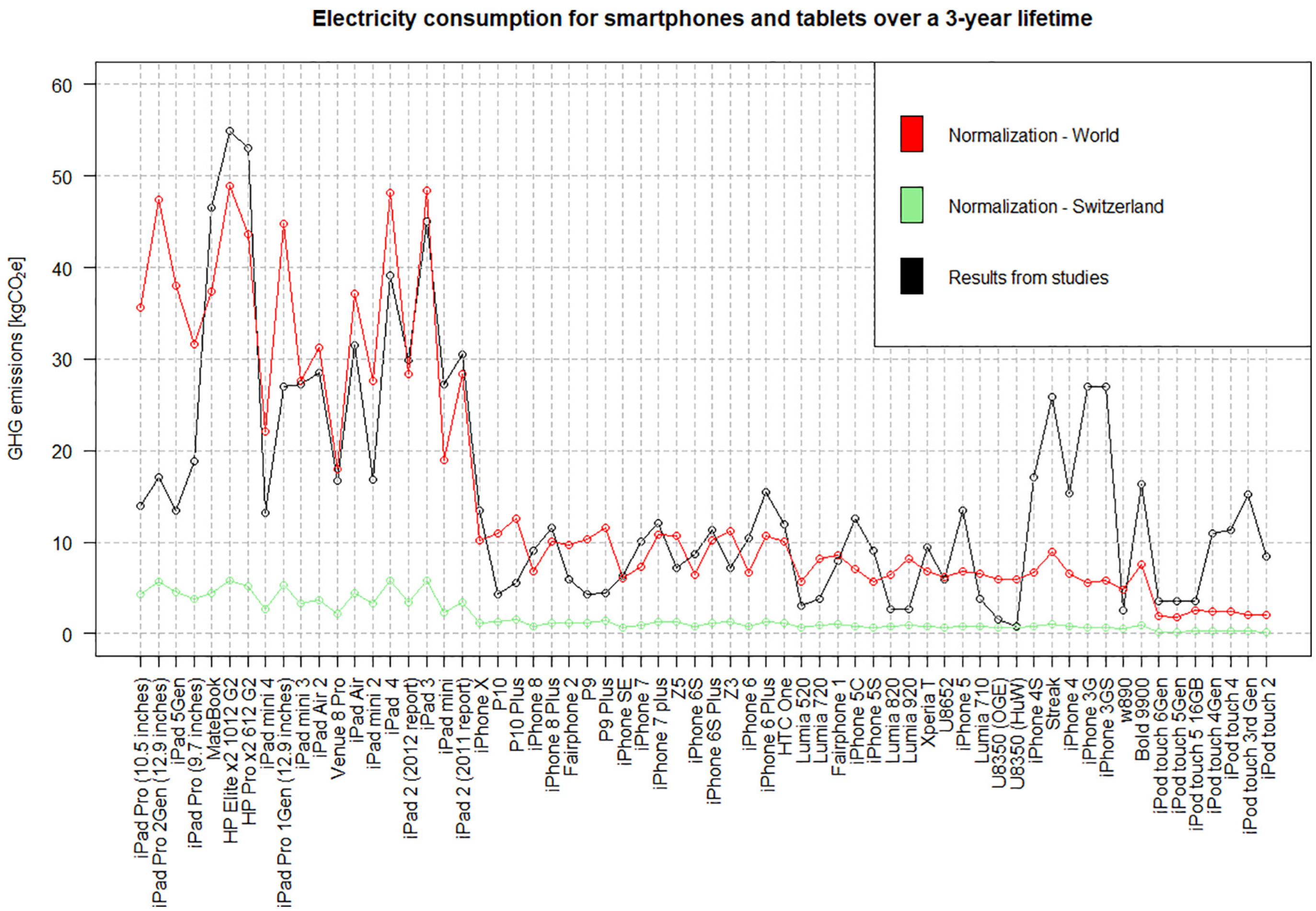

Fig. 4. Normalization of energy consumption (Moberg et al., 2014; Andrae and Vaija, 2014; Güvendik, 2014; Ahmadi Achachlouei et al., 2015; Ercan, 2013; Corcoran et al., 2014; Hischier et al., 2013; Ercan et al., 2016; Proske et al., 2016; Hischier et al., 2014; Teehan and Kandlikar, 2013; Apple Inc, 2017; Samsung, 2015; HP Development Company, 2017a; HP Development Company, 2017b; HP Development Company, 2017c; HP Development Company, 2017d; Stutz, 2011; Schafer, 2014; HTC Corporation, 2013; Huawei Investment and Holding Co, 2013; Huawei Technologies Co, 2017a; Huawei Technologies Co, 2017b; Huawei Technologies Co, 2016a; Lenovo, 2018; Huawei Technologies Co, 2016b; Huawei Technologies Co, 2016c; Nokia Corporation, 2011a; Nokia Corporation, 2012a; Nokia Corporation, 2012b; Nokia Corporation, 2012c; Nokia Corporation, 2012d; Nokia Corporation, 2012e; Santavaara and Paronen, 2014; Nokia Corporation, 2013; Nokia Corporation, 2011b; BlackBerry, 2011).

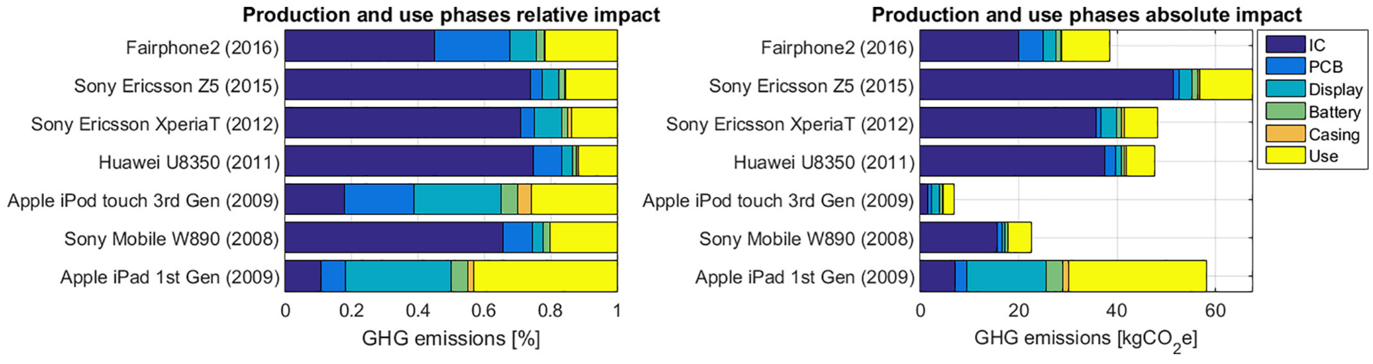

Fig. 5. GHG emissions for production and use phases.

such as the number of cycles per day.

3.3.1. GHG emissions of individual parts

A study on the Openmoko Neo Freerunner (Carroll and Heiser, 2010) and validated for phones released in 2010 shows that, during regular workload, the GSM module consumes the most power (44%). CPU and GPU follow with 14% each, while the display (LCD) with the backlight accounts for 11%. Nevertheless, the backlight impact shows high variability depending on its intensity. Nowadays, tasks performed are not much using the GSM module but the CPU and GPU. Over time, processor chips consume less energy for the same performance thanks to new hardware designs such as stacked chips. Nevertheless, more powerful chips are used, and identifying and removing energy leaks is still a crucial matter. These leaks can come from two sources: programming errors and application design (Zhang, 2013). The increase in GPU computation power needs to be optimized for displaying information. Today, smartphones usually embed an AMOLED display which is on average even less power-consuming than the LCD (Pargman et al., 2016) because a backlight is no longer needed. However, we can assume an increase in consumption due to bigger screens. The 3G and 4G networks are energy-consuming due to the overhead of the network connection session and should be taken into account, while the earlier consumption issues of Wi-Fi seem to have been resolved (Chen et al., 2016).

4. Simplified LCAs

Fig. 5 shows the results for the production and the use phase. The two major contributors are the IC production and the use phase. The iPad is the only tablet computer in the data, consequently some of its emissions are higher than the ones of the smartphones due to its specifications: a tablet has a larger screen, which results in the high emissions observed, and a tablet consumes more energy, which explains that the use phase emissions are more important. The four most recent smartphones have Snapdragon chips from Qualcomm with chip areas that are larger than the ones in the W890 and the iPod touch, which explains the higher footprint. These results strengthen the importance of the ICs and the electricity mixes that were highlighted in” Production - Impact of subcomponents”. Nevertheless, the choices that we made in building our LCI database can still be sources of error. It would be necessary to perform the same process with several different LCI databases to verify the consistency of these results.

5. Discussion

The purpose of this work is to determine the most important sources of variation in LCAs. Since LCAs are covered by ISO standards and several of them follow the ETSI standards, the methodology alone cannot explain the variations we observe.

Firstly, the materials used are important: the analysis of the impact of subcomponents on the production phase shows that several of them have a major impact on the footprint of devices.For example, Fig. 1 shows that the footprints of iPhones 6 and 6 Plus are the largest: Apple started to use aluminium with the iPhone 5 and determined that it has a major impact which partially explains the peak. By” prioritizing aluminium that was smelted using hydroelectricity rather than fossil fuels” and” reengineering their manufacture process to reincorporate the scrap aluminium”, they were able to cut in half the carbon footprint associated with the aluminium enclosure for the next iPhones (Apple Inc, 2016). Nonetheless, it is mainly due to the increase of storage that we see a significant higher impact compared to previous iPhones. The GHG emissions concerning tablet computers (Fig. 2) are more dispersed than those for smartphones: the specifications of tablets (size, weight, components) are also more eclectic, and bigger devices imply relatively larger amounts of materials. The simplified LCA of the iPad in Fig. 5 shows the important impact of a big display compared to the comparatively small displays of the smartphones.

Secondly, the sources of energy are a major source of variation for both the production and use phases. Electricity is required at every step of the production, and its share in the IC and PCB processes is around 50%. The largest IC die manufacturers are in Taiwan and South-Korea, which have electricity mixes with high GHG emissions. The normalization of the use phase shows that the electricity footprint can vary by a factor of 5.25 for market groups (and even 100 when comparing countries) depending on the electricity mix and thus on geographic location. This highlights that not only the manufacturing location is important, but also the location of the end-user.

Thirdly, the different processes used during production influence the footprint of the components: the complexity of the process, the amount of chemical products needed, the amount of electricity required, and the type of plant. Even with a homogeneous market for batteries, the values provided by the literature vary by a factor of 5. When it comes to ICs, there is a huge diversity of products in the market, which means numerous possible influences and variation in the production process.

Finally, the LCI is a crucial part of the LCA. The lack of appropriate data can force some studies to use unsuitable datasets and make false assumptions: the study of the Fairphone 1 (Güvendik, 2014) used the Ecoinvent v2.2 database (Frischknecht et al., 2005), which includes electronic datasets that are a decade old. Fraunhofer IZM (Proske et al., 2016) does not consider the Ecoinvent IC's datasets to be reliable, and Teehan (Teehan, 2014) reports some underestimations. We point out several errors in the calculation and a considerable margin of uncertainty in the results for both versions 2.2 and 3.3 (see S1). The IC datasets from Ecoinvent may suit some models of chips but we have shown that for ICs in particular, the diversity of the market makes it difficult to have accurate data, which is unfortunate considering the importance of these components.

LCA is a powerful tool which is as good as the quality of its data. There are only a few LCI databases that are used widely. Therefore, a mistake in one database can have effects on multiple studies. Because of the comparisons made among them to validate their results, the studies are even more susceptible to propagation of potential errors. When available, primary data are very helpful in order to detect these mistakes. Reliable data need to be available in order to make informed decisions on how to leverage ICT in order to reduce GHG emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

The Supporting Information includes a description of several errors found in the Ecoinvent database about ICs; a comparison between the data from Ecoinvent and GaBi about the IC chip BGA 256 2.62 g; the footprint impact of a casing for different materials; and the data used for the simplified LCAs. Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2020.106416.

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