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Article

To Which Degree Does Sector Specific Standardization Make Life Cycle Assessments Comparable?—The Case of Global Warming Potential of Smartphones

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Abstract: Here attributional life cycle assessments (LCAs) for the same smartphone model are presented by two different organizations (Orange, OGE and Huawei, HuW) and the effect of different modeling approach is analyzed. A difference of around 32% (29.6 kg and 39.2 kg) for CO_2e baseline scores is found using same study object and sector specific LCA standard, however, different metrics, emission intensities, and LCA software programs. The CO_2e difference is reduced to 12% (29.9 kg and 33.5 kg) when OGE use HuW metrics for use phase power consumption and total mass, and when HuW use OGE metrics for gold mass and silicon die area. Further, a probability test confirms that present baseline climate change results, for one specific study object modeled with two largely different and independent LCA modeling approaches, are comparable if both use the European Telecommunications Standard Institute (ETSI) LCA standard. The general conclusion is that the ETSI LCA standard strongly facilitates comparable CC results for technically comparable smartphone models. Moreover, thanks to the reporting requirements of ETSI LCA standard, a clear understanding of the differences between LCA modeling approaches is obtained. The research also discusses the magnitude of the CO_2e reduction potential in the life cycle of smartphones.

Keywords: climate change; life cycle assessment; modeling; smartphone; standardization

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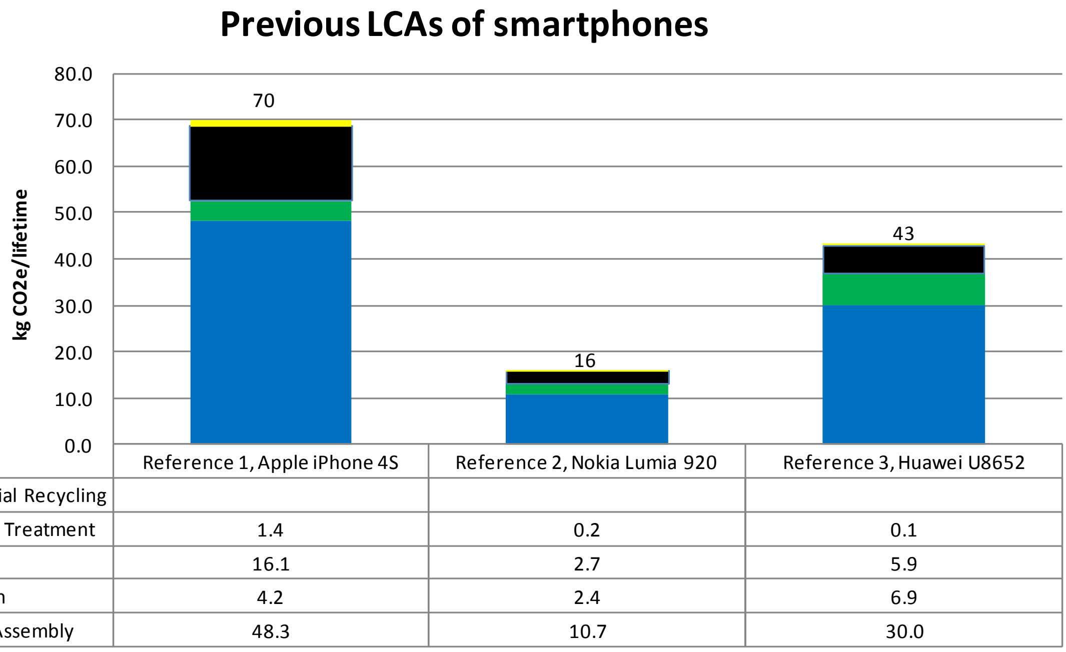
1. Introduction

Information and Communication Technology (ICT) and Entertainment and Media (E&M) are two of the fastest growing industries and a future is foreseen where almost all electronic devices are connected. The annual shipped number of mobile devices can be counted in billions. As such, smartphone sales are currently around one billion units. However, the share of the production of ICT and E&M Equipment, its use and end-of-life treatment of the global annual electricity usage and CO_2e emissions are currently relatively low at around 8% and 4%, respectively [1–4]. Moreover, certain ICT Services (such as, virtual meetings in enterprise offices) could help reduce the global CO_2 emissions and environmental impacts [5,6]. Still, the amount of ICT and E&M Equipment in use is increasing, especially end-user equipment such as mobile phones and tablets driven by a surge in cloud computing applications [7]. Mobile phones usually have a relatively short operating lifetime of one to three years, which negatively influences eco-environmental impacts beyond climate change (CC). Anyway, at least until 2020, the improving energy efficiencies within the ICT networks seem to counterbalance the mass production of consumer ICT devices [3]. Life Cycle Assessment (LCA) is a systematic analytical method and model by which eco-environmental effects for product systems can be estimated with a precision of around an order of magnitude. The impact assessment step in LCA makes use of mid-point categories and mid-point category indicators. Climate Change (CC) is a mid-point category and infrared forcing, e.g., expressed as Global Warming Potential during 100 years (GWP100), is a mid-point category indicator of CC. GWP100 is typically expressed as mass CO_2 equivalents (CO_2e). Examples of other mid-point categories are ozone depletion, acidification and land use [8]. CC is commonly reported, as the results can be obtained with relatively high convenience and confidence compared to other mid-point categories. A full LCA should nevertheless cover several mid-point categories beyond CC to arrive at a “complete” estimation of eco-environmental impacts. As shown in Figure 1, three previous non-comparable smartphone (LCAs) suggested that the total CO_2e per lifetime is around 16–70 kg CO_2e with the Raw Material Acquisition (RMA) + Part Production (PP) + Assembly + Distribution dominating the score [9–11]. The End-of-Life Treatment (EoLT) stage was of smaller importance in these studies.

Several CC and broader eco-environmental impact studies of mobile phones show similar relative ranking in between life cycle stages, however, still these and other electronics LCA studies often raise questions due to lack of transparency [12–14]. Recently three different mobile phone LCA studies came to these surprising conclusions for CC, challenging the common understanding of LCAs of smartphones; the charger was the main driver of the CC score [15], the use stage was the dominating life-cycle stage [16], and the smartphone had a better absolute eco-environmental performance than simpler entry phones with less functionality than smartphones [17]. These mobile phone LCAs are, unfortunately, not isolated occurrences as far as electronics LCAs studies are concerned. Hischier *et al*. identified, for LCA comparisons of media consumption via tablet or printed versions, that differences can be explained by different methodological approaches used for LCI modeling [18].

Figure 1. Results of three previous LCAs (CC) of different smartphones with a lifetime of three years.



	Reference 1, Apple iPhone 4S	Reference 2, Nokia Lumia 920	Reference 3, Huawei U8652
🟦 Raw Material Recycling			
🟨 End-of-Life Treatment	1.4	0.2	0.1
⬛ Use	16.1	2.7	5.9
🟩 Distribution	4.2	2.4	6.9
🟦 RMA+PP+Assembly	48.3	10.7	30.0

Hence, without proper sector standardization, beyond the LCA standards of ISO, the robustness of LCA results in general, and ICT Equipment LCA results and ICT Sector footprint in particular, will be in doubt.

In 2009 and 2010 the European Commission (EC) addressed this problem [19,20] and as a result several standards/guides have emerged. The most detailed requirement specification for LCA of ICT Equipment was developed by European Telecommunications Standards Institute (ETSI) [8]. In 2012 Orange (OGE) and Huawei (HuW) were among the organizations that volunteered to participate in an EC pilot project, testing ICT LCA methodologies. A report about the outcome of the pilot test concluded that the tested LCA methodologies were in principle compatible and workable however, allowed considerable freedom regarding LCA modeling decisions that influenced the calculation outcomes for CC and primary energy usage [21].

This research will for the first time shed light on these conclusions by presenting two LCAs of one smartphone, one by HuW and the other by OGE. The additional goals are to understand the effect on CC impact category results in LCA of using different LCA tools, databases and methodological choices. We want to understand if the difference and uncertainty of electronics LCA scores are bearable for policy makers if the LCA studies are based on ETSI TS 103 199 (ETSI LCA) [8].

2. Materials and Methods—LCA Methodologies Used

Below is described how OGE and HuW, starting from the same goal and scope for the same studied product system, use different modeling approaches to perform the LCA. The baseline scenario is identical for OGE and HuW and two LCA calculations are done for one product.

2.1. Goal and Scope

The goal of the study is to estimate the CC mid-point impact category result of a Smartphone (U8350) during its lifetime, using attributional process-sum LCA. Process-sum LCA uses a bottom-up approach in which material contents and component inventories are used as the starting point for the analysis [22].

The study object (product system) is the U8350 (ICT Equipment) smartphone assembled in China and shipped to France for use on wireless networks, and then sent for end-of-life treatment in France.

HuW and OGE both strive for full compliance with ETSI LCA, *i.e.*, fulfilling all of its 83 mandatory requirements [23].

U8350 physically consists of these building blocks: smartphone, Li-ion battery, complete packaging (cardboard, plastic bags, manual, USB/µUSB cable, headset, charger).

These building blocks can be categorized according to parts defined in Table B.1 in ETSI LCA [8]. In this LCA the impact of eventual spare parts production is not included. Moreover, the CO_2e emissions associated with the operating system software program of U8350 are excluded from the studied product system.

Functional Unit

The mandatory basic functional unit (f.u) as required by ETSI LCA is total lifetime use. More specifically, the f.u. is defined as *two years of U8350 usage charging the battery from 0% to 100% once every 24 h*. The reference flow is one U8350 smartphone with its packaging and accessories.

2.2. System Boundaries

Table 1 of ETSI LCA (ETSI, 2011) specifies the mandatory, recommended, and optional life cycle stages/unit processes for ICT Equipment. A1, A2, B1.1, B1.2, C1, D2.1, D2.2, D3 (Figure 2) life cycle stages are included in this LCA.

Certain activities, B1.3, B2, B.3, C2-C4 and D1, are not part of the studied product system.

Furthermore support activities, such as marketing, development and sales, are not considered for unit processes because of lack of data and models.

OGE advocate a cradle-to-grave approach using the EIME 5.0 LCA tool database version 11.4. [24]. EIME 5.0 uses a database specifically designed for electrical and electronic products based on data compiled from the Federation of Electric and Electronic Industries and Communication (FIEEC). The current software database represents some 160 parts, 470 raw materials and 190 processes called “modules”.

HuW on the other hand use the SimaPro 7.3.2 LCA tool and an approach separating all life cycle stages such as RMA and PP.

In Figure 2 below the underlined processes are included in the studied product system whereas, the italic marked are excluded. G1, G2, G3, *etc*. denote reoccurring generic unit processes and A-D main life cycle stages for the Equipment for which the LCA is made.

Table 1. Summary of HuW CO_2e scores for raw materials used by U8350.

Raw Material	**Amount per Piece U8350**	**Unit**	**Mean g CO_2e per Unit and Uncertainty ±2σ**	**Mean g CO_2e per Piece U8350**
Iron/Steel alloys (primary)	13 × 1.25 = 16.3	g	6.13, 10%	100
Aluminum alloys (primary)	7.9 × 1.10 = 8.69	g	12.2, 15%	106
Copper alloys (primary)	28.8 × 1.25 = 36	g	3.34, 15%	120
Gold (primary)	0.123 × 1.01 = 0.124	g	18,800, 32%	2,336
Silver (primary)	0.179 × 1.01 = 0.181	g	145, 24%	26
Nickel	1.2 × 1.25 = 1.5	g	7.18, 25%	11
Tin	1.56 × 1.25 = 1.95	g	17.1, 46%	33
Palladium	0.0336 × 1.01 = 0.034	g	10,500, 22%	356
Zinc	0.972 × 1.25 = 1.215	g	4.29, 31%	5
Acrylonitrile butadiene styrene (ABS)	18.4 × 1.25 = 23	g	4.39, 7%	101
Polyester (e.g., PET)	2.29 × 1.25 = 2.86	g	2.7, 13%	8
PMMA	1.53 × 1.25 = 1.91	g	8.38, 6%	16
PA (Nylone)	1.3 × 1.25 = 1.62	g	8.5, 5%	14
PVC	14.5 × 1.25 = 18.1	g	2.01, 11%	36
Polyethylene (PE)—HD	6.9 × 1.25 = 8.62	g	2.02, 7%	17
Polycarbonate (PC)	2.15 × 1.25 = 2.69	g	7.78, 7%	21
Polypropylene	1.05 × 1.25 = 1.31	g	1.97, 10%	3
Polyurethane (PUR)	1.26 × 1.25 = 1.58	g	4.83, 22%	8
Epoxy	16 × 1.25 = 20	g	1.1, 11%	22
Glassfibre	34.6 × 1.25 = 43.3	g	2.79, 18%	121
SiO2	5.7 × 1.25 = 7.13	g	0.021, 10%	0.15
Glass	26.7 × 1.25 = 33.4	g	1.09, 32%	36
SUM of B1.1 and B1.2 including Ancillary Raw Material Acquisition				3,496, 2σ = 782

The geographical and temporal coordinates vary dynamically for the RMA and Production of the ICT Equipment. The presented results for RMA and Production will therefore represent a global average for the U8350.

OGE use a laboratory weighing machine (Milligram scale) to establish the mass of each part. HuW mass numbers for parts are originally provided by as material content declarations by part producers. U8350 is assembled in China and sent to France by plane.

2.3. Inventory

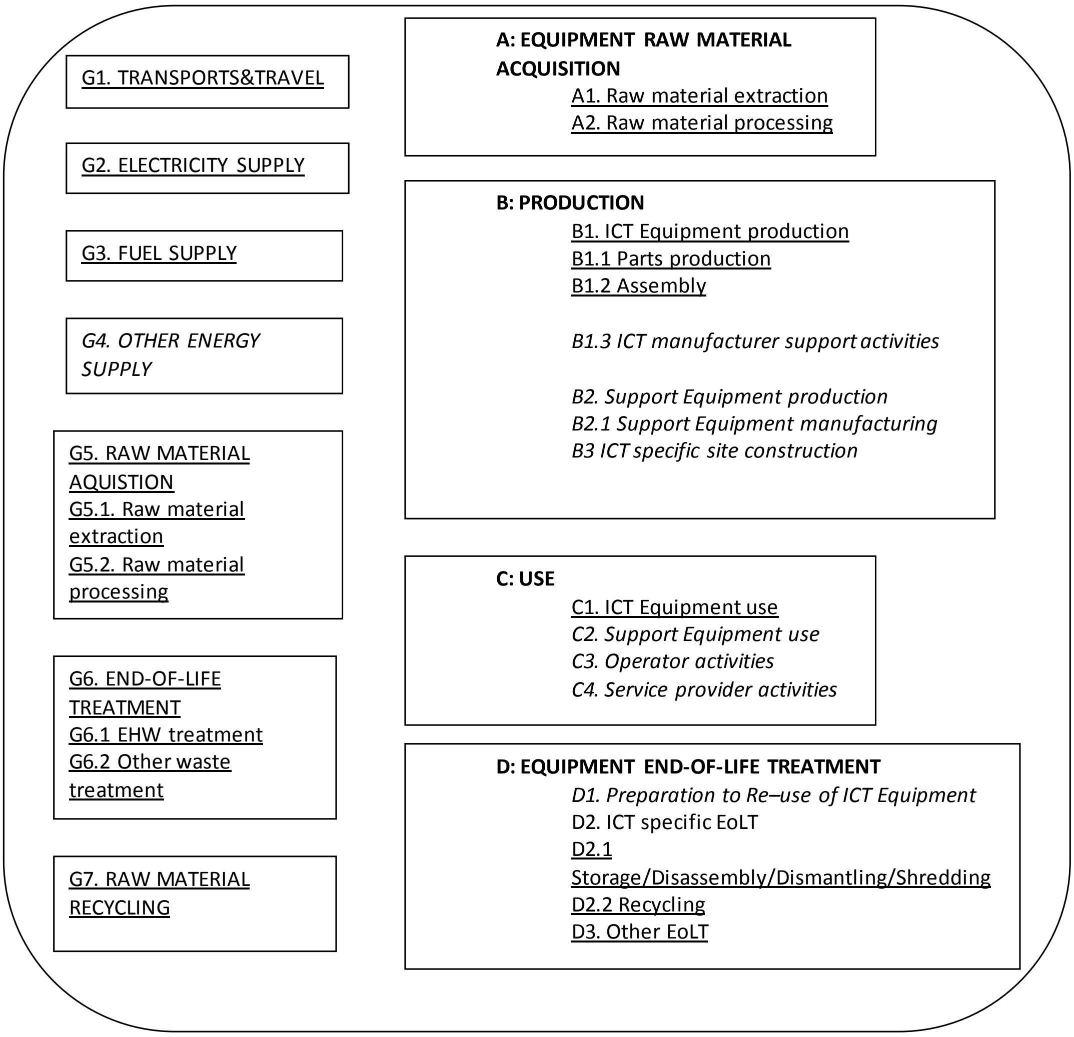
2.3.1. Data Collection

Raw Material Acquisition, Part Production, Assembly

OGE

Regarding data collection in the EIME 5.0 software RMA and PP are linked, *i.e.*, it is not possible to show separate results for RMA (A). For raw material extraction (A1) and raw material processing (A2) databases contained within the LCA tool/LCI databases are used representing a mix of primary and secondary content for world production. The transports occurring in RMA are modeled inside these LCI data.

Figure 2. The system boundary of the product system for OGE and HuW LCAs of the U8350.



The specific data, which constitutes measurements of material constituents and power consumption, are gathered at OGE Labs Grenoble laboratory as well as ICT specific [8], either primary or secondary, from manufacturers.

For the secondary specific data from EIME, the data quality requirements are established by Bureau Veritas. ETSI LCA clearly allows secondary specific data for electronic PP. Empirical measurement techniques, such as densitometry and flame tests are performed to identify plastic contents. Metal parts identification is carried out using tests, such as magnetization, color or presence of surface treatment. Feedback from plastic and metal part manufacturers is also used to identify these parts, as well as ISO 1,043 markings.

Passive parts (B1.1.8 Other PCBA components) are classified by function and dimension and divided into six categories; resistors, capacitors, inductors, filters, quartz. Small light emitting diodes (LED) for backlight are also considered in this category, even if they are actually active components. The material composition of passive parts appears relatively homogeneous among different part manufacturers.

Therefore, there is no motivation to request material composition and LCI data for the manufacturing of each part.

Active parts (B1.1.4 Integrated Circuits, IC) mainly include ICs, transistors and diodes. Previous LCAs of mobile phones tend to show that these parts have a relatively high eco-environmental impact. Therefore it is decided to analyze IC in greater detail than other parts. Importantly, there are many different types of IC package types whose architecture directly influences the eco-environmental impact of the IC parts [25]. For each IC with more than 12 connections the good silicon (Si) die area inside the IC chip is identified. Good Si area is the area of the bare die inside unpackaged ICs. Corcoran *et al*. [23] described further the OGE data collection for parts.

OGE measure values for parts and important examples of respective EIME models used for each part. Moreover OGE's approach with EIME makes use of other metrics than mass, for e.g., printed circuit boards and Displays, explaining why the total mass is not 326 g as given below in Table 2.

HuW

HuW's approach is based on supplier data from product data management (PDM) systems and the RMA and PP are modeled separately in SimaPro LCA tool and associated LCI databases (See Section 2.3.2). RMA includes the total use of Raw Materials, losses and connection to EoLT metal recycling.

HuW estimates the Si die area according to Equation (1):

$$Siarea = ChO \times \frac{CdW}{WO} + ChS \times \frac{CdW}{WS} + PO \times \frac{PdW}{WO} + PS \times \frac{PdW}{WS} = 7.26\ cm^2 \qquad (1)$$

where

ChO = share ordinary dies in Charger, 100%
ChS = share stacked dies in Charger, 0%
PO = share ordinary dies in Phone, 53.5%
PS = share stacked dies in Phone, 46.5%
CdW = mg Si dies in Charger, 47.25 mg
PdW = mg Si dies in Phone, 85.7 mg
WO = mg/cm^2 for ordinary Si dies, 150
WS = mg/cm^2 for stacked Si dies, 6

The measured value from OGE is 4.85 cm^2.

Transports

Transport of U8350 to use stage, Trp$_{U8350}$, is modeled by both companies on assumptions of share of air, truck and van transports (See Equation (2)).

HuW LCA used the following values

A = % of transports from B1.2 to France by Air. 1 (100% Air transport)
B = Average air distance from near B1.2 Airport to near France Airport (km). 9,600 km
C = Average emission factor for air-freight (kg CO$_2$e/tonkm, 1.07)
D = Average Distance B1.2 to near B1.2 Airport (km). 100 km
E = Average emission factor for lorry in B1.2 (kg CO$_2$e/tonkm, 0.279).
F = Average Distance France Airport to France warehouse (km). 230 km

G = Average emission factor for lorry in France (kg CO_2e/tonkm, 0.279).
H = Average Distance France warehouse (shop) to C1 use location site (km). 150 km
I = Average emission factor for van (kg CO_2e/tonkm, 1.51).
W= weight of U8350, 357 g

$$Trp_{U8350} = A \times W(B \times C + D \times E + F \times G + H \times I) = 3.78\ kgCO_2e \quad (2)$$

OGE do not consider the H transport due to high variability (mean of transport, distance…).

Use Stage Power

OGE

Use phase electricity energy usage is measured by OGE in its laboratory (uncertainty 2.6σ, 99% confidence interval around the mean value) using Software Labview and National Instruments for the capture card. A complete charge of the battery 0 to 100% is measured at the mains.

HuW

HuW use measurements of charger efficiency and battery capacity and assume one charge of the battery, 0 to 100%, per day.

Huawei estimate the electricity usage for the studied U8350, Use_{U8350}, according to Equation (3).

$$Use_{U8350} = \frac{BC}{1000} \times V \times Y \times \frac{DY}{CE} = 4\,754\ Wh \quad (3)$$

where

BC = (mAh) Battery capacity = 1,200
V = (Voltage, V) = 3.7
Y = (years) lifetime = 2
DY = (days per year), charging = 365
CE = (%), charger efficiency = 0.6817

A French average electricity mix for low voltage is applied ("Electricity, low voltage, at grid/FR U" from ecoinvent db, 0.108 kg CO_2e/kWh) as the U8350 is operating in France market and the purpose of the study is to estimate CC impact of the smartphone in French Networks.

End-of-Life

For end-of-life management, the U8350 follows the European WEEE directive requiring more than 85wt% recyclability [26].

OGE

For end-of-life, OGE use EIME database for specific EoLT for storage, disassembly, dismantling, shredding and recycling. The EoLT is assumed to be done in France and EoL transport distances are set accordingly [23].

HuW

HuW focuses the EoLT modeling on the metal recycling and use the 50/50 allocation method, however, no primary data are collected as EoLT for CC has shown to be of low importance in previous LCAs of mobile phones.

2.3.2. Data Calculation

OGE

As far as data calculation, OGE LCA value for CC is expressed as the total of A (all raw materials) + B (production) for all part types. For Assembly OGE use pre-made LCA modules. Further details of OGE modeling are reported in a separate report [23].

HuW

HuW on the other hand, separates these life cycle stages for all parts as shown in Tables 1 and 2. Assembly electricity is measured in the assembly factory.

Table 2. Summary of HuW CO_2e scores for part production including auxiliary raw materials.

Part Category	**Amount per Piece U8350**	**Unit**	**Mean g CO_2e per Unit and ± 2σ**	**Mean g CO_2e per Piece U8350**
B1.1 Batteries, Lithium	24.06	g	5.62, 18%	135
B1.1.2 Cables	*µUSB-cable included in B1.1.3*			
B1.1.3 Electro-Mechanics	42	g	5.64, 56%	237
B1.1.3 Chargers	56.3	g	35.6, 28%	2,004
B1.1.4 ICs, Si die area (front-end)	7.26	cm^2	2,170, 56%	15,754
B1.1.4 ICs, all types (back-end)	0.984	g	182, 14%	179
B1.1.4 Transistors	0.0737	g	141, 24%	10
B1.1.4 Diodes (Light Emitting, Transient Voltage Suppression, Metal-oxide-semiconductor field-effect transistor)	0.886	g	250, 20%	221
B1.1.5 Mechanics/Materials, Aluminum alloys	7.9	g	4.6, 14%	36
B1.1.5 Mechanics/Materials, Iron/Steel alloys	13	g	1.16, 11%	15
B1.1.5 Mechanics/Materials, Copper alloys	28.8	g	1.23, 15%	35
B1.1.5 Mechanics/Materials, Polymers	72.4	g	1.85, 16%	134
B1.1.6 Touch Screen+LCD module	20.16	cm^2	487, 68%	9,818
B1.1.7 Printed Circuit Board, Plastic multilayer boards (FR4)	35.6 (6 layers, 49 cm^2)	g	33.8, 12%	1,203
B1.1.8 Filters	0.057	g	537, 11%	31
B1.1.8 Inductors (chip type)	0.169	g	38.4, 30%	6
B1.1.8 Resistors (Thick film chip)	2.04	g	30.6, 35%	62
B1.1.8 Capacitors (Surface Mounted Device) ceramic)	0.675	g	40.7, 33%	27
B1.1.8 Quartz crystal oscillators (Crystal resonator, Temperature Compensated)	0.054	g	56.7, 11%	3

Table 2. *Cont.*

Part Category	**Amount per Piece U8350**	**Unit**	**Mean g CO_2e per Unit and ± 2σ**	**Mean g CO_2e per Piece U8350**
B1.1.9 Packaging materials, Cardboard box	132	g	0.445, 9%	59
B1.1.10 Electronic components, unspecified (Fuses, Speaker, Microphone)	1.34	g	282, 105%	378
B1.2 Assembly, PCBAs	1	p	680, 21%	680
G1. Transport, air scenario for Distribution	357	g	10.5, 11%	3,770
-Air	*357*	*g*	*10.2, 8%*	*3,641*
-Lorry	*357*	*g*	*0.092, 60%*	*32*
-Van	*357*	*g*	*0.23, 56%*	*81*
SUM of B1.1 and B1.2 including Ancillary Raw Material Acquisition				34,779, 2σ = 14,600

2.3.3. Allocation

OGE

Regarding allocation of data, due to limitations of the EIME 5.0 LCA tool, OGE is bound to use the 100/0 allocation method for Raw Material Acquisition with recycled content ratios for each Raw Material fixed by the EIME tool. No Raw Material Recycling discount is therefore included in the calculation model.

Moreover the EIME LCA tool is not able to handle metal, paper, cardboard or plastic recycling.

HuW

HuW's modeling approach within SimaPro is flexible regarding allocation and recycled content. ETSI LCA prescribes cartian principles allocation rules for recycling (8, Section 6.3.3). 100/0 allocation and no recycled content is used for RMA and 50/50 allocation and 50wt% material recovery for steel, aluminum, copper, gold, silver, and palladium for RM recycling of the metals within the Phone Device.

All raw materials used are assumed to be 100% primary, *i.e.*, no recycled content (Equation (4)). At G7 (raw material recycling), according to the 50/50 allocation method, 50% of the secondary raw material acquisition is allocated to the present life cycle. Moreover, 50% metal recovery efficiency is assumed not to overestimate the recycling benefit.

As a result, the impact of metal production, I_{metals}, per mass according to 100/0 + 50/50 and 50/50 allocation methods, is given by Equations (4) and (5), respectively.

$$I_{metals} = 1.0 \times P \times I_P + 0.0 \times S \times I_S + 0.5 \times (S + R_P) \times I_S - 0.5 \times (S + R_P) \times I_P \tag{4}$$

$$I_{metals} = 0.5 \times P \times I_P + 0.5 \times S \times I_S + 0.5 \times R_P \times S + 0.5 \times L_P \times P \tag{5}$$

P = share primary, %, 100
S = share secondary, %, 0
I_P = Impact primary production
I_S = Impact secondary production
R_P = Recovered material, %, 50
L_P = Lost material, %, 50

The share of the U8350 (smartphone + charger + Li-ion battery + packaging materials) that goes to metal recycling is 33.3 g of 357 g, *i.e.*, 9.3%. The remaining 324.7 g is cardboard box (smartphone packaging materials), charger packaging materials, Li-ion battery, charger, mechanical polymers in smartphone, and residuals.

Example of 100/0 + 50/50 Allocation Method for Gold

For gold the 100/0+50/50 allocation method according to Equation (4) results in 14,311 g CO_2e/g gold (1.0 × 1.0 × 18,800 (burden upstream) + 0.0 × 0.0 × 846 (burden upstream) + 0.5 × (0 + 0.5) (burden downstream) × 846 − 0.5 × (0 + 0.5) (credit downstream) × 18,800).

The 50/50 allocation method according to Equation (5) gives the same result as 100/0 + 50/50 method, (0.5 × 1.0 × 18,800 + 0.5 × 0.0 × 846 + 0.5 × 0.5 × 846 + 0.5 × 0.5 × 18,800).

For Gold per piece U8350, (−)556 g CO_2e (0.5 × 0.5 × 0.124 g × 846 g/g − 0.124 g × 0.5 (allocation) × 0.5 (recovery efficiency) × 18,800 g/g) is avoided.

Hence, the CC impact for Gold per U8350 life cycle is 1,774 g CO_2e (0.124 × 14,311), where 2,331 (0.124 × 18,800) is from Raw Material Acquisition, and (−)556 from metal recycling.

These effects are shown below in Figures 3 and 4 and more details in Corcoran *et al.* [23].

2.4. Data Quality

2.4.1. OGE

OGE seek high quality of LCI data for the most impacting flows (e.g., area of good Si dies, area of Display LCD screen, and the CO_2e intensities for these parts).

Both companies do a qualitative evaluation of the data quality based on criteria listed in ETSI LCA Section 5.2.4 and find the quality "good" according to the Product Environmental Footprint guide [27].

OGE make a data quality rating (DQR) according to Equation (6).

$$\begin{aligned} DQR = {} & (\mathit{Completeness\ score}, C + \mathit{Acquisition\ method\ score}, AM \\ & + \mathit{Data\ Representativeness\ score}, DR + \mathit{Data\ Age\ score}, T \\ & + \mathit{Geographical\ correlation\ score}, GC \\ & + \mathit{Technological\ correlation\ score}, TC \\ & + (\mathit{weakest\ quality\ obtained}) \times 4/(6+4) \end{aligned} \tag{6}$$

Due to lack of time only IC data quality is estimated as (1.4 + 1 + 1 + 2 + 3 + 2 + 4×3)/(10) = 2.24.

2.4.2. HuW

HuW estimate the overall data quality by Equation (7).

$$\begin{aligned} DQR = {} & (\mathit{Methodological\ consistency}, MC + C + \mathit{Uncertainty}, U + AM \\ & + \mathit{Supplier\ Independece}, SI + DR + T + GC + TC + \mathit{Cut} \\ & - \mathit{off\ rules}, RIE + (\mathit{weakest\ quality\ obtained}) \times 4/(10+4) \end{aligned} \tag{7}$$

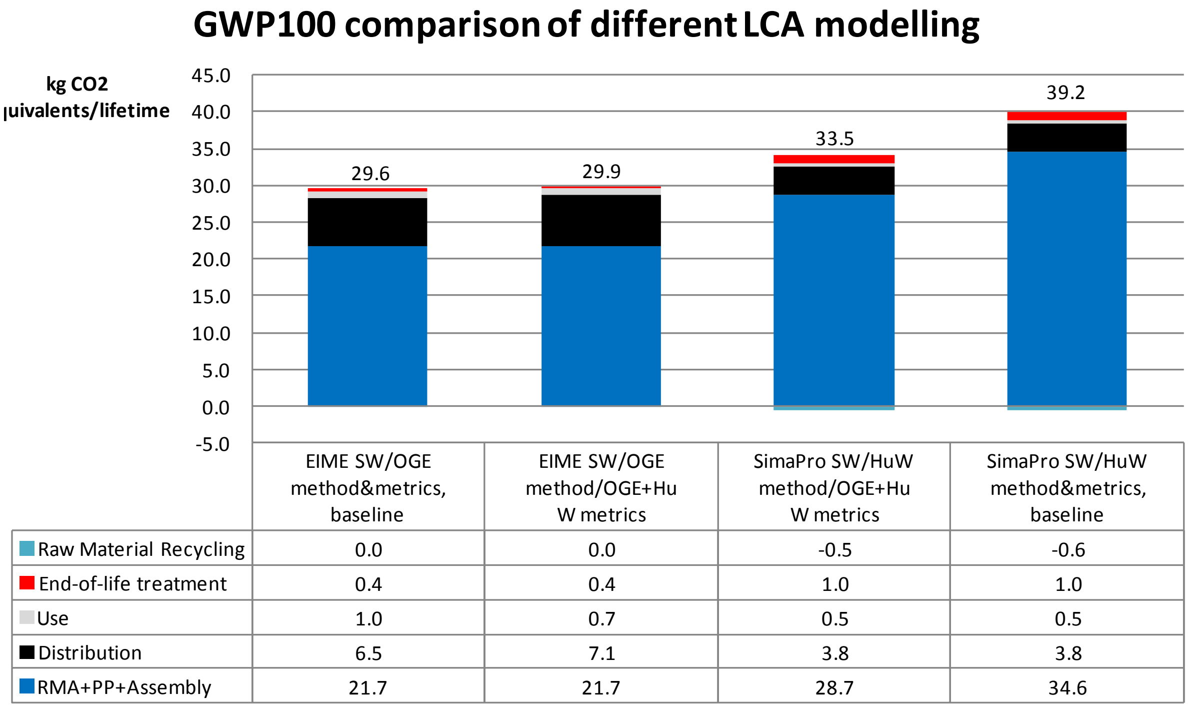
= 1.75 + 1.5 + 2.75 + 2.25 + 2.25 + 2 + 2 + 2 + 2.25 + 1.25 + 2.75 (weakest quality obtained) × 4)/(10 + 4) = 2.21.

Further details can be found in Corcoran *et al*. [23].

3. Results

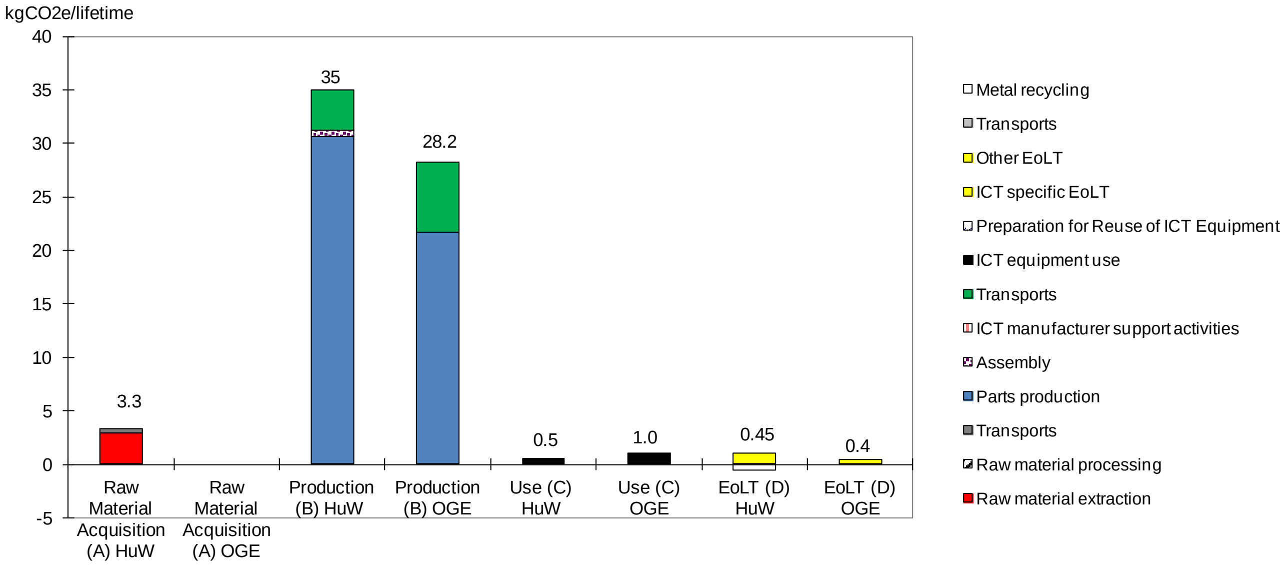
Below in Figures 3 and 4 are shown the key results of the present paper.

Figure 3. The effect of different LCA modeling approach and metrics choice on CC impact category.



	EIME SW/OGE method&metrics, baseline	EIME SW/OGE method/OGE+HuW metrics	SimaPro SW/HuW method/OGE+HuW metrics	SimaPro SW/HuW method&metrics, baseline
Raw Material Recycling	0.0	0.0	-0.5	-0.6
End-of-life treatment	0.4	0.4	1.0	1.0
Use	1.0	0.7	0.5	0.5
Distribution	6.5	7.1	3.8	3.8
RMA+PP+Assembly	21.7	21.7	28.7	34.6

Figure 4. Partition of HuW and OGE baseline scenario CC scores for U8350.



OGE's LCA method has a higher precision (mainly due to measurement of part masses) than HuW's, however, both lead to the same conclusions for CC impact category. Different inventory databases could lead to diverse results because of vague system boundary definitions and incomplete data quality [12]. However, as shown in Figure 4, thanks to the reporting requirements of the ETSI LCA [8], a clear understanding of the differences between LCA modeling approaches is obtained. For smartphone LCAs, the differences between two different practitioners modeling choice are apparently not crucial for understanding the main drivers of CC. The ETSI LCA [8] allows the LCA practitioner to rather freely choose a methodological approach. However, the large number of requirements of ETSI LCA [8] suggests that methodological choices concerning allocation, cut-off, and system boundary setting are in reality somewhat limited.

4. Discussion

Different LCA approaches are allowed by the current LCA ICT standards, which will lead to different absolute scores but hopefully not different conclusions for eco-design. In Table 3 are shown the most important metrics used by OGE and HuW, which partly explain the CC score differences. The two middle columns shall be interpreted as follows: "EIME SW/OGE method/OGE&HuW metrics" means that OGE use EIME LCA tool and OGE modeling approach, however, used HuW metrics for use stage electricity and total mass. "SimaPro SW/HuW method/OGE & HuW metrics" means that HuW use SimaPro LCA tool and HuW modeling approach, however, use OGE metrics for gold mass and Si die area.

Table 3. Effect of the four most important metrics used by OGE and HuW for LCA of U8350.

Metric	**EIME SW/OGE Method & Metrics, OGE Baseline**	**EIME SW/OGE Method/OGE & HuW Metrics**	**SimaPro SW/HuW Method/OGE & HuW Metrics**	**SimaPro SW/HuW Method & Metrics, HuW Baseline**
Si die area (cm^2)	4.85	4.85	*4.85*	7.26
Au mass (mg)	119	119	*119*	123
Use electricity (kWh)	6.57	*4.75*	4.75	4.75
Total mass (g)	326	*357*	357	357
kg CO$_2$e	**29.6**	**29.9**	**33.5**	**39.2**

Table 3 shows that if OGE and HuW would have been able to obtain the same metrics values the differences induced by the LCA tools (allocation, databases, algorithms) would be significantly reduced. Rules for measurement and calculation defined in product category rules (PCR) can solve this problem. Then two different smartphone models from different companies could then theoretically be compared, should they be technically comparable. Anyway, a clearly achievable improvement compared to the present situation is that the relative change within product groups such as smartphones can be measured more consistently and credibly. With a high likelihood the strictness of ETSI LCA [8] indicates that PCR might be unnecessary for comparing smartphone LCAs.

4.1. Uncertainty Analyses

The uncertainly analysis by OGE is made by an estimation as the EIME LCA tool is incapable of uncertainty analysis. However, EIME claim that their modules have less than 20% uncertainty range.

Moreover, as OGE make numerous measurements for masses and areas of Si die and screens, the largest uncertainty is found in the intensity measures from the EIME LCI database, e.g., kg CO_2e/cm^2 Si die area. Furthermore, EIME's LCI database is updated systematically and on this basis OGE estimates, with a 95% confidence interval, 23.7–35.5 kg CO_2e.

HuW use SimaPro's uncertainty calculation, which is based on Monte Carlo simulation resulting in a 95% confidence interval of 24.5–53.9 kg CO_2e.

Based on the above data HuW make a *t-test* [28] in which here a high probability, of mistakenly favoring one score before other, is desired.

The *t*-test shows (Table 4) that it is a 49% probability that OGE baseline score 29.6 kg could be higher than HuW baseline score 39.2 kg and *vice versa*.

Table 4. HuW *t*-test of baseline scenario LCA scores.

Various Inputs and Outputs for t-Test	**Value**	**Coeffcient of Variation%**	**Details**
OGE U8350 basic CO_2e (kg)	29.6	0.1	20% 2σ
HuW U8350 basic CO_2e (kg)	39.2	0.178	35.6% 2σ
σ	0.0997	0.177	SQRT(LN(0.1^2 + 1)) = 0.0997, SQRT(LN(0.178^2 + 1)) = 0.177
e(σ)	1.105	1.193	e0.099751 = 1.105, e0.177 = 1.193
$(e(\sigma))^2$	1.220	1.423	1.105^2 = 1.2208, 1.193^2 = 1.423
log10	0.086	0.153	log10 (1.2208) = 0.0866, log10 (1.423) = 0.153
			LOG(29.6/39.2)/(SQRT(0.0866^2 + 0.153^2)) = −0.69243
	t-test	0.49	0.692011 = TINV(0.49, 150)

This means that the CC results for one study object, at least smartphones, modeled with two largely different and independent LCA modeling approaches, are likely robust if both use ETSI LCA. Nevertheless, comparisons between ICT LCAs performed by different organizations were agreed to be beyond the scope of ETSI LCA [8], as such comparisons would require that the assumptions and context of each study are exactly equivalent. Here the context is exactly equivalent, whereas several assumptions are different.

4.2. The Effect of Skills and Competence of LCA Practitioners on the Outcome

Less skilled LCA practitioners might not be able to choose intensity data carefully enough, which will lead to unnecessary uncertainty of the end result.

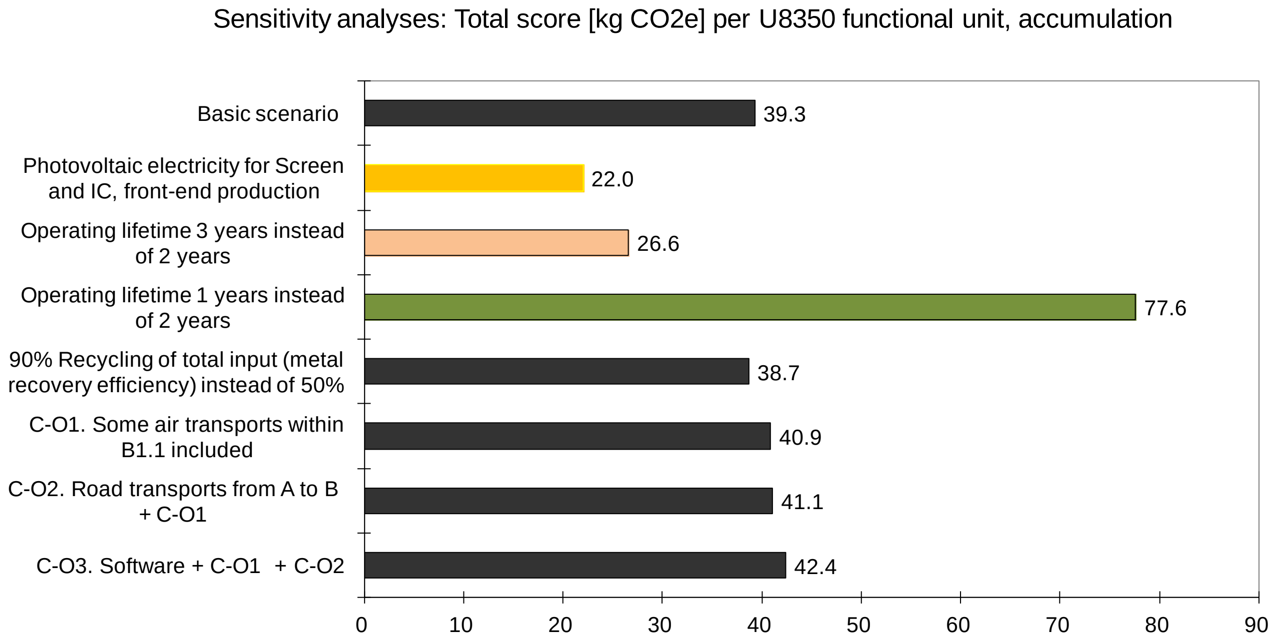
For example, consider the need to use an LCI data model for production of 1 m^2 of Si die. In EIME one LCA practitioner could choose "Wafer, from silicon; before dies slicing; France, FR" or "Wafer, from silicon; before dies slicing; China, CN". In Simapro another could pick ecoinvent's "Wafer, fabricated, for integrated circuit, at plant/GLO". The ratio between these EIME and SimaPro LCI data is 1:2.4 and 1:5, respectively, and could therefore be significant for the whole smartphone LCA or other electronics LCAs. It is evident that the LCA practitioner needs to possess the necessary skills to assess the data quality and representativeness and test it carefully against the requirements of ETSI LCA.

4.3. Sensitivity Analyses

OGE evaluate the robustness of the results based on sensitivity analysis including four parameters (*electricity consumption* in the use stage, *area* of display LCD touch screen, *distance* of Air transportation and *area* of good Si dies).

A change of ±1% in the input values for these four drivers gives a change of ±0.84 % for the outcomes. HuW sensitivity analysis is founded in cut-off analyses and changing of flows for lifetime, electricity mix and metal recovery (Figure 5).

Figure 5. Results of HuW sensitivity analyses.



4.4. Relation to Eco-Rating of Mobile Phones

Moreover, this research is associated with the Eco-Rating (ER) schemes proposed by telecom operators for mobile phones [29]. The reason is that these schemes include a section for simplified LCA in which several metrics based criteria are defined. Here two sensitivity checks are also made with OGE ER Basic LCA [30], and a linear model for RMA+PP+Assembly+Distribution using display screen mass, battery mass, and printed circuit board assembly (PCBA) mass as inputs [31].

For OGE ER 27.44 kg CO_2e is obtained using 7.26 cm^2 as Si die area [23], and with Teehan/Kandlikar linear model 0.18 × 100 g (mass PCBA) + 0.3 × 24 g (mass battery) + 0.065 × 28.3 g (mass display screen) = 27.0 kg. The result for OGE ER is not surprising as the carbon footprint indicator algorithms are based on the information of hundreds of mobile phone models. Teehan and Kandlikar simplified method for RMA + PP + Assembly + Distribution with 27.0 kg shows a good precision compared to OGE full LCA value for RMA + PP + Assembly + Distribution, 28.2 kg.

4.5. Marginal Electricity

Partly smartphones are charged at night and partly at daytime. Marginal electricity mixes can be used instead of average ones to reflect the difference in time and season when the present smartphone is charged. As shown in Tables 5 and 6, the marginal electricity in France is a mix of thermal power (≈56%) and renewable (≈44%) calculated on the basis of electricity statistics [32], in this case between 2008 and 2009. Due to data unavailability we cannot confirm further the hour-by-hour French marginal mixes.

Table 5. Sources of French electricity production (TWh) 2008–2010 and 2020.

Source of Electricity	**Gross Generation (g.g.) in 2008 [33]**	**G.g. in 2009 [34]**	**G.g. in 2010 [35]**	**Expected in 2020 [35]**
Thermal, all			59.4	90
Thermal, Coal	27	28.7		
Thermal, Oil	6	6.17		
Thermal, Gas	22	21.0		
Nuclear	439	409.7	407.9	385
Hydro	68	61.9	68	79
Other renewables	12.9	14.5	15	96
TOTAL	575	542	550	650

Table 6. HuW estimation of French marginal electricity mixes 2009 and 2020.

Source of Electricity	**Change 2008-2009 (TWh)**	**Applied Mix, 2009**	**Expected Change 2010-2020 (TWh)**	**Applied Mix, 2020**
Thermal, all	-		30.6	25%
Thermal, Coal	1.7	46.3%	-	-
Thermal, Oil	0.2	10.1%	-	-
Thermal, Gas	0	0%	-	-
Nuclear	0	0%	0%	0%
Hydro	0	0%	11	9%
Other renewables	1.6	43.6%	81	66%
TOTAL	3.7	100%	122.6	100%

The 2008–2009 French marginal mix, being some 0.6 kg CO_2e/kWh, is assumed to be used at night when demand is lower than at day.

The 2010–2020 French marginal mix is expected to be thermal (≈25%), hydro (≈9%), and other renewables (≈66%), which would render around 0.3 kg CO_2e/kWh.

Therefore nighttime charging of smartphones, with French marginal mix, suggests higher use stage emissions than the average French electricity mix around 0.1 kg CO_2e/kWh dominated by nuclear. The marginal mix at day is assumed to be close to the average French mix.

All in all however, also in France, the use stage electricity usage for smartphones will still be relatively small.

The Big Picture

Moreover, the smart mobile devices are used in a larger context of wireless networks which in 2012 used around 10% of the annual ICT Sector electricity globally (appr. 1100 TWh) whereas the smartphone RMA + PP + Assembly + Distribution (appr. 23 TWh) and charging (appr. 5 TWh) only used 2.5% [23].

In this context the relation between the receiver sensitivity of the mobile phones and the radio base station power usage has been highlighted [36]. Possibly this relation could be an extension of the mobile phone LCA or ER schemes.

4.6. Potential for Reduction of CO_2e Emissions

The following reduction potentials generally do not include any system expansion and we are aware of the limitations of the attributional LCA model for analyzing the net *consequences* of decisions [37].

Nevertheless, the upstream and the display LCD screen is the most important part and it has to be determined if it is the direct CO_2e emissions, or indirectly the grid electric power mixes, which is the main source of the problem. In 2012 research showed that NF_3 is a marginal contributor in LCD flat-screen manufacturing [38]. This suggests that gases contributing to global warming, released from the production upstream, are not the main issue for screen production.

Then, if the main reason for CO_2e emissions in Display LCD screen production is instead average grid electric power production mixes [23], and if it could somehow be replaced by renewable electricity, the reduction potential for U8350 life cycle is 22%. As shown in Figure 5, another 21% is possible if also the average grid electric power production mixes used in IC wafer fabs could also be replaced.

Valkering compared five different OLED lighting technologies to LED and fluorescent lighting and showed that at the moment, OLED lighting has higher environmental impacts than the other technologies [39]. This was explained by the dominance of the use phase in the life cycle impacts of all lighting technologies. In order to compete with current LED and fluorescent lighting, the luminous efficacy of the OLEDs should be comparable to those of the other lighting technologies. However, it is not straightforward to translate Valkering's results to smartphone application. Anyway, the CO_2e emissions for the manufacturing and end-of-life of OLED foils were estimated to 0.6–1.2 g CO_2e/cm^2 (0.099–0.2 kg/Mega Lumen-hour) [39]. However, Valkering's scope was basically only the light emitting foil itself without electronics such as ICs with gallium arsenide/Si dies inside. According to OGE ER, mobile phone LCD manufacturing cradle-to-gate, including these dies, emits around 480 g CO_2e/cm^2. Seen from a CC manufacturing point of view, OLED screen technologies will likely be preferable to LCD, should the OLED screen design require fewer semiconductors than LCD or LED. OGE is currently investigating the issue of next screen technology eco-environmental impacts.

Distribution of U8350 by ship ought to be more CO_2e efficient than air transport. OGE estimate from EIME that ship transports emit around 100 times less CO_2e per kg × km than air transports, opening an opportunity to reduce the total CC score by 22% (HuW 9%). The difference between OGE and HuW is due to LCI data used, generating different CO_2e for air transports.

5. Conclusions

In conclusion the LCAs show that the most significant activity for the CC category is the *production stage* driven by the area of screen and the amount of Si die area (good Si die area) used by the U8350. As far as transports are concerned, the CO_2e emissions are also significant from a life cycle perspective.

Differences in smartphone LCA results arise mostly due to modeling choices and less to secondary emission intensity data from upstream processes and LCA tools.

This research shows that the results of two different LCAs of smartphones are comparable if both LCAs use ETSI LCA and the study objects have comparable technical function and physical characteristics, such as battery capacity, display screen size and type, memory capacity, and chipset.

6. Looking Ahead

By this research the basic CC footprint of smartphones is meticulously confirmed by two organizations. HuW fulfill all requirements of ETSI LCA [8] except two, whereas OGE cannot fulfill the requirements to this degree depending on LCA tool limitations [23].

The subjective choices made by an individual LCA analyst are likely unavoidable, however it will be challenging to establish calculation rules for all situations.

Nevertheless, this underlines the need for more public data sets for upstream processes such as those listed in Annex B of ETSI LCA [8].

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Author Contributions

Anders S. G. Andrae wrote the paper and Mikko Samuli Vaija contributed with Orange input data and wrote Clause 4.2.

Conflicts of Interest

The authors declare no conflict of interest.

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