Life Cycle Assessment of the Fairphone 2

Final Report

Marina Proske

Christian Clemm

Nikolai Richter

Berlin, November 2016

Contact:

Fraunhofer IZM

Gustav-Meyer-Allee 25, 13355 Berlin, Germany

Phone: +49.30.46403-771

Fax: +49.30.46403-211

Email: marina.proske@izm.fraunhofer.de

Please note: The annex is excluded from this public version of the study as it contains confidential information. As the actual study text was not changed, several references to the annex are still included.

Content

List of Tables

List of Figures

Abbreviations

ADP	Abiotic resource depletion
AUO	AU Optronics Corporation, Taiwanese display manufacturer
BMS	Battery management system
BOD	Biological oxygen demand
BoM	Bill of materials
BtB connector	Board-to-board connector
CMOS	Complementary metal-oxide-semiconductor
Co	Cobalt
CO_2e	Carbon dioxide equivalents
COD	Chemical oxygen demand
CPU	Central processing unit
DCB-e	Dichlorobenzene equivalents
DIY	do-it-yourself
DRAM	Dynamic random access memory
ecoinvent	Life cycle inventory data base
EoL	End of life
FP1	Fairphone 1
FP2	Fairphone 2
GaBi	LCA software by thinkstep
GHG	Greenhouse gas
GWP	Global warming potential
HCl	Hydrochloric acid
Hi-P	Hi-P International Limited
IC	Integrated circuit
LCA	Life cycle assessment
LCD	Liquid crystal display
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCO	Lithium cobalt oxide
LED	Light emitting diode
LPG	Liquefied petroleum gas
MJ	Megajoule
NOx	Generic term for the mono-nitrogen oxides nitric oxide (NO) and nitrogen dioxide (NO_2)

ODS	Ozone-depleting substance
PC	Polycarbonate
PCB	Printed circuit board
PFC	Perfluorocarbons
SB-e	Antimony equivalents
SOx	Sulfur oxide
TPU	Thermoplastic polyurethane
TSS	Total suspended solids
VOCs	Volatile organic compounds

1 Executive Summary

The Fairphone 2 is a modular smartphone by Fairphone B.V. To assess the environmental impact caused by the production, use, and recycling of the smartphone a life cycle assessment (LCA) is conducted, covering the following impact categories:

- Climate change (GWP)
- Abiotic resource depletion (ADP)
- Human toxicity (Humantox)
- Ecotoxicity (Ecotox)

The data inventory is based on the bill-of-materials (BoM), a product tear-down, and material declarations for subparts from suppliers. Primary data for the final assembly process was obtained from Hi-P. Other materials and components are modelled with data from GaBi (plus electronics extension) and ecoinvent v3.2 plus individual data sources from public sources (e.g. on ICs, display, and battery). The functional unit is one Fairphone 2 for a three-year use.

Results

The results amount to 43.9 kg CO_2e with the production phase having the highest impact for all analyzed impact categories (Figure 1-1). Use phase and transport (to final assembly, to distribution hub, and to customer) have a low impact on the overall life cycle. Recycling has a positive effect for all impact categories (resulting in a negative impact[1]).

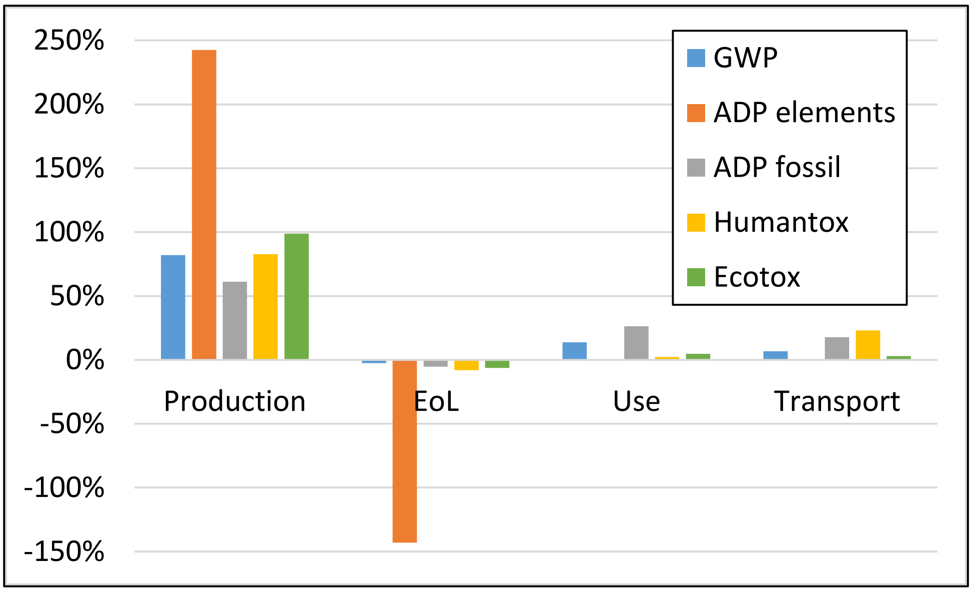

Figure 1-1: Relative impacts of the different life cycle phases per impact category

Within the production phase, the highest impact is caused by the ICs, followed by the printed circuit boards (PCBs) and the assembly process as such (see Figure 1-2). An exception is the impact category ADP elements where the board-to-board connectors cause the main production impact due to the amount of gold used for the contacts.

[1] The total impact of all life cycle phases adds up to 100 %. As the recycling processes are beneficial from environmental perspective, their calculated impact is negative leading to an impact of the other life cycle phases above 100 %.

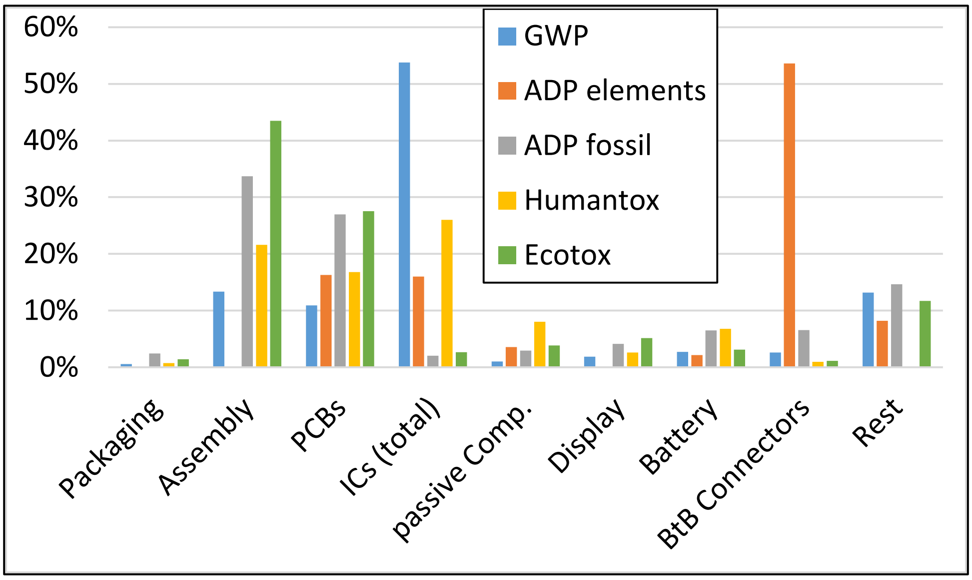

Figure 1-2: Relative impacts of the different component types per impact category

Modularity and Repair

The modular design itself causes an additional impact on manufacturing (compared to a fictional non-modular Fairphone 2) through sub-housing of the modules, board-to-board connectors, and additional PCB area for the connectors. However, the overall impact on the entire life cycle is minor (4 to 12 % depending on the impact category) and stems mostly from the additional PCB area and board-to-board connectors. The only exception is the impact category ADP elements, where the "modularity parts" are responsible for about half of the overall impact, which is mainly attributed to the gold used for the board-to-board connectors.[2]

To analyze the potential of the modular and therefore repairable design, a repair scenario is analyzed with an assumed use time of five years and an average number of repairs. This repair scenario has a positive effect seen across the whole life cycle and reduces the GWP by 28 % (see Figure 1-3).

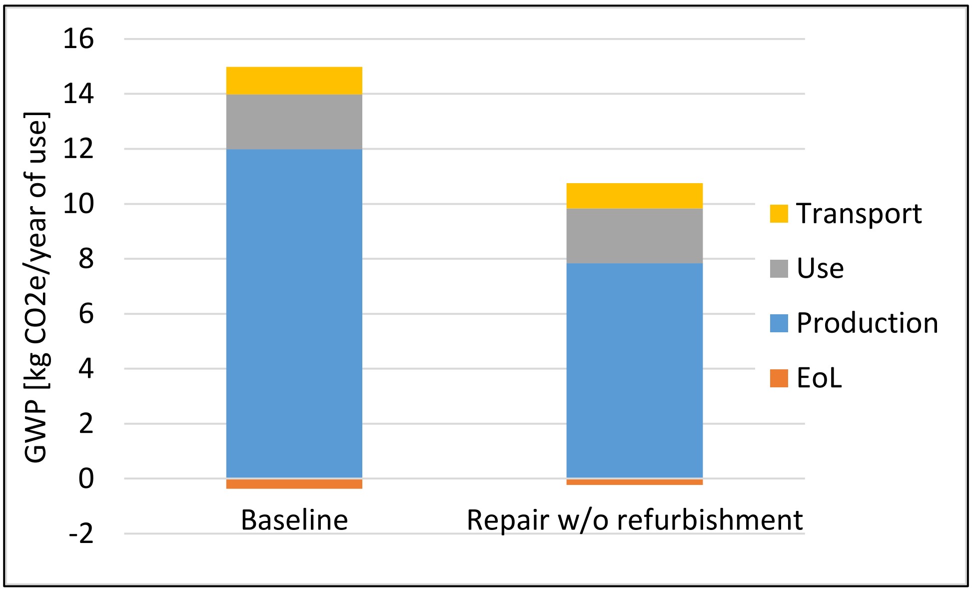

Figure 1-3: Results per year of use - baseline and repair scenario

[2] These impacts of the "modularity parts" are included in the total results described above.

Conclusions

The results show that the electronic components as such cause the main environmental impact. Industrial design decisions such as housing materials have a minor impact. Because the main impact is caused by the product manufacturing, prolonging the use time (number of years) has a high potential to reduce the overall environmental impact, as has also been shown by the analyzed repair scenario. Thereby, the modular design – although increasing the initial production impact slightly – has the potential to reduce the overall environmental impact through enabled repairs.

The analysis also shows the on-going problem with life cycle assessments for electronics: the availability of specific and up-to-date life cycle data on electronics is still not sufficient and variances between different data bases and sources is high. Nevertheless, the overall results are deemed reliable.

2 Goal and Scope Definition

2.1 Goal

The goals of this life cycle assessment (LCA) are to identify the hotspots in the life cycle of the Fairphone 2 and derive possible improvement measures. Therefore a baseline scenario is analyzed. In addition, the calculation of two scenarios is carried out as well (see section 5):

- Repair scenario: analyzing the effect of longer use time enabled through different repairs/module replacements
- Housing scenario: the effect of using different housings is analyzed
    - New plastic back cover (thinner than the existing plastic back cover)
    - Aluminum back cover

The intended applications of the study are:

- Use the results for improvement of the existing design of the Fairphone 2
- Use lessons-learned for possible future product designs
- Evaluate the importance and the effect of improvement measure during manufacturing processes and other life cycle stages (e.g. take-back and refurbishment activities for modules)
- Stakeholder communication

2.2 Scope

The scope of this study covers the entire life cycle of the Fairphone 2 from raw material acquisition, manufacturing, and use to end-of-life.

The functional unit for the baseline scenario is an intensive smartphone use over three years. The corresponding reference flow is the Fairphone 2 as delivered to the customer including sales packaging and manual (without charger, which is not part of the standard delivery).

The data inventory is based on the bill-of-materials (BoM), a product tear-down, and material declarations for subparts from suppliers. Suppliers were also asked for primary data regarding production processes (energy and material consumption in production, direct emissions), but no life cycle or process data could be obtained from Fairphone suppliers within the time of this study except several (full) material declarations. Only the final assembly process is modelled according to primary data from Hi-P (see section 3.1.8).

The following impact categories are covered (for definitions see section 4.1):

- Climate change (GWP)
- Abiotic resource depletion (ADP)
- Human toxicity (Humantox)
- Ecotoxicity (Ecotox)

However, not all processes used in the assessment cover all of the named impact categories. The effect will be described in the sensitivity analysis (section 4.3.5) and interpretation of the results (section 4.5).

Transport processes are covered for the product delivery to the customer, transport to the distribution hub and transport of parts of the final assembly. No further upstream transport processes were covered.

3 Life Cycle Inventory

The life cycle inventory is divided into the following sections:

- Raw material acquisition and manufacturing
- Use phase
- End-of-life (EoL)
- Transport

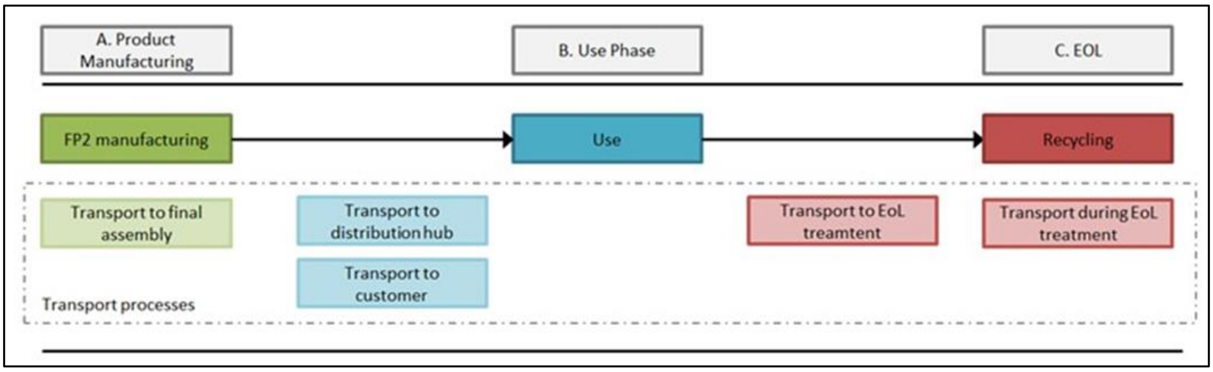

Figure 3-1: Life cycle phases and transport processes of the Fairphone 2

The raw material acquisition is indirectly covered using cradle-to-gate data sets for the manufacturing.

When not described otherwise for individual processes, data stems from the GaBi database incl. electronics extension and the ecoinvent v3.1 database. The modelling is carried out with the GaBi LCA software.

3.1 Raw material acquisition and manufacturing

Baseline for the modelling of the manufacturing phase was the BoM from the Fairphone 2 supplemented with a product teardown. Thereby all parts and corresponding masses were identified and life cycle data sets allocated. The modular design of the Fairphone 2 is reflected in the inventory model, so that the LCA model can be adjusted in future analyses with individual changes of the product design. The main product modules are shown in Table 3-1.

Table 3-1: Main parts per module

Module	**Main parts**	**Weight [g]**
Fairphone 2		168
Core module		40
	Mainboard with • Electronic components • Board-to-board connectors	18.9
	Antenna boards	0.373
	Volume button, power button, camera button assembly	0.141
Top module		6.5
	Top module board	1.25
	Front camera	0.338
	Receiver (speaker)	0.35

Module	Main parts	Weight [g]
Camera module		3.8
	Camera	0.791
	Camera board	0.445
Bottom module		9.2
	Bottom module board	1.32
	Vibration motor	0.923
	Microphone	
	Speaker	1.352
	USB connector	
Display module		52.5
	Display frame	10.8
	LCD display	
	Display board	0.955
Battery module		38
	Battery	
Back cover		20.1
	Outer case	19.6
	Battery pressure pad	
	Camera seal gasket	

The modelling of the different components is exemplarily shown in Figure 3-2.

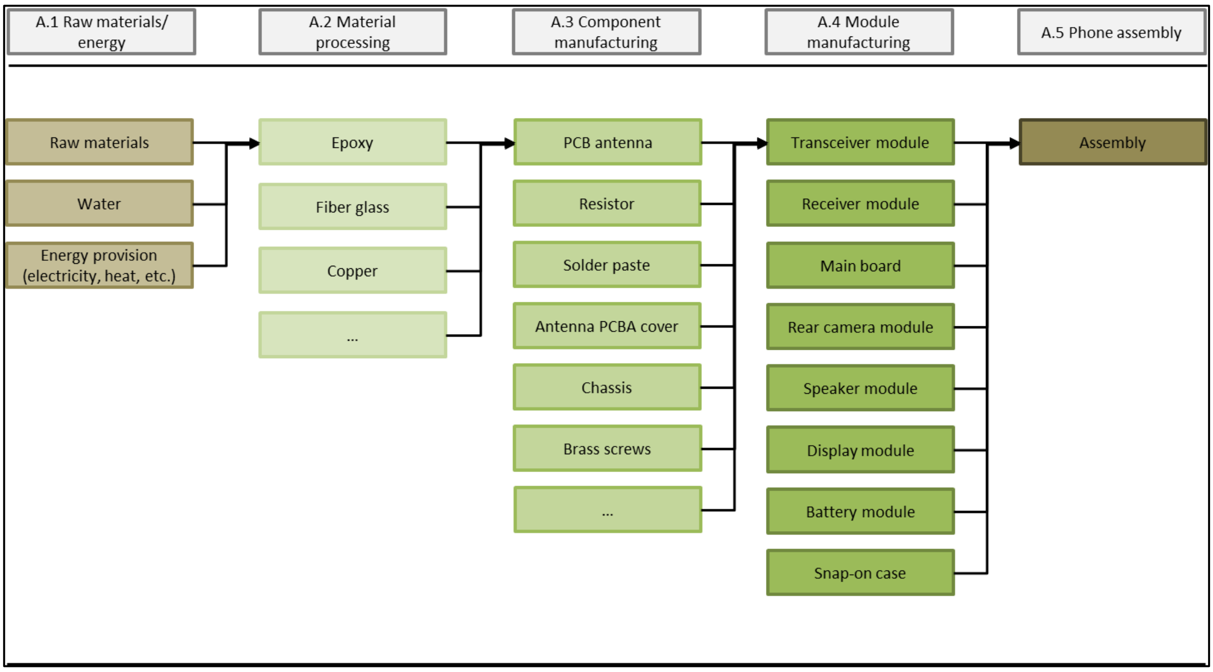

Figure 3-2: Exemplary modelling of the manufacturing phase

The following approach is used for the modelling of all modules:

- Mechanical parts were modelled based on the material composition and weights derived from the material declarations or the product tear-down.
- The boards consist of the printed circuit boards themselves, the electronic components and the board-to-board connectors. For the printed circuit board, a data set from the GaBi database was used. The detailed modeling is described in section 3.1.9.3.
- The passive electronic components are modelled with data sets from the GaBi electronics extension database. For some components (e.g. filters), no specific life cycle data sets were available in the data bases. These components were weighted and included as “electronic component, passive, unspecified” from ecoinvent and scaled per weight. Therefore the passive components were disassembled from the board and sorted (specific data set available or not). Thereby, a slight overestimation is possible as in case of doubt (whether a specific component is already covered with a specific data set). The weight of the component was included in the “unspecified” data set.
- For the ICs, a detailed model was developed with the die size as a scaling parameter (see section 3.1.9.4).
- The connectors were modelled according to the material composition (see section 3.1.9.1).

Module-specific parts and approaches are described in the following sections.

3.1.1 Core module

The main parts of the core module are:

- Mainboard with
  - Electronic components
  - Board-to-board connectors
- Antenna boards
- Volume button, power button, camera button assembly

The antenna and button boards consist of flexible printed circuit boards. As no life cycle data set for flexible boards is available in the data bases, they are modelled as 1-layer PCBs with a data set from the GaBi data base.

The detailed BoM with the assigned weight and life cycle data set for the core module can be found in the annex in Table 8-2 to Table 8-5.

3.1.2 Top module

The main parts of the top module are:

- Top module board
- Front camera
- Receiver (speaker)

For the modelling of the camera see section 3.1.9.1.

The detailed BoM with the assigned weight and life cycle data set for the top module can be found in the annex in Table 8-6.

3.1.3 Camera module

The main parts of the camera module are:

- Camera
- Camera board

For the modelling of the camera see section 3.1.9.1.

The detailed BoM with the assigned weight and life cycle data set for the camera module can be found in the annex in Table 8-7.

3.1.4 Bottom module

The main parts of the bottom module are:

- Bottom module board
- Speaker
- MicroUSB connector
- Vibration motor
- Microphone

For the modelling of the MicroUSB connector see section 3.1.9.2.

For the speaker, an existing data set from GaBi (Micro Speaker (2g, dynamic, Nd magnet, SMD)) was used and scaled per mass.

The vibration motor is modelled according to the material composition given by the manufacturer (see Table 8-9 in the annex). The vibration motor contains Tungsten, rare earth metals (Neodymium) and precious metals (gold, platinum and palladium). As neither GaBi nor ecoinvent contain a data set on Tungsten, Tungsten was modelled according to the German life cycle data base ProBas[3].

The detailed BoM with the assigned weight and life cycle data set for the bottom module can be found in the annex in Table 8-8.

3.1.5 Display module

The display module consists of:

- Display frame
- LCD Display
- Display board

The detailed BoM with the assigned weight and life cycle data set for the display module can be found in the annex in Table 8-10.

3.1.5.1 LCD Display

The GaBi database does not include a dataset for an LCD display. Ecoinvent has an LCD display data set, which is however quite old (2001) and for a 17 inch display. Instead, data from the Taiwanese display manufacturer AUO is used which is derived from their CSR report (data for the year 2015).

The data is scaled by panel size. The Fairphone 2 display has a size of 73.7 cm^2.

Scope

AUO data covers scope 1 (direct emissions) and scope 2 (purchased energy). Scope 3 covers product use, business travel, and commuting but the impact of upstream suppliers and is therefore not taken into account. Production of input materials is not covered.

---

[3] Description of the Tungsten data set in German: ProBas: Wolfram, online: http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={A4A89322-AC81-4FA2-BB1C-5EE0B77E9180} (checked: 09/19/2016)

AUO data covers the panel manufacturing without backlight and electronics (display board).

Panel production AUO

The following data presented in Table 3-2 is given by the AUO CSR report. Data marked in orange is transferred to the LCA model.

The given values from AUO for scope 2 greenhouse gas (GHG) emissions (from purchased energy) are not directly transferred, but the energy consumption is included via the corresponding processes (electricity production, gas, diesel) to also address other impact categories. Purchased electricity for the production process is included as electricity from Taiwan.

Table 3-2: Panel production data by AUO

	Totals (2015)		**Per produced m²**		**Fairphone 2 display**	
Inputs						
Glass Substrate	106,911.70	tons	2.03	kg	0.015	kg
Liquid Crystal	76.90	tons	0.0015	kg	1.08E-05	kg
CF Thinner	1,040.00	tons	0.020	kg	1.45E-04	kg
Array Stripper Usage	5,221.00	tons	0.10	kg	7.30E-04	kg
Array Stripper Use of Renewable Materials	29.00	%				
GHG Chemicals						
PFCs	665.30	tons	0.013	kg	9.30E-05	kg
ODS						
Loading Volume	0.05	tons	9.49E-07	kg	6.99E-09	kg
Energy						
Total Energy	15,936,836.90	GJ	302,406.77	kJ	2,228.74	kJ
Total Energy for Production	4.133	Mio kWh	78.5	kWh	0.58	kWh
Purchased Electricity	15,276,372.10	GJ	289,874.23	kJ	2,136.37	kJ
Self-generated Solar Power	602,480.40	GJ	11,432.27	kJ	84.26	kJ
Wind Power	12,886.40	GJ	244.52	kJ	1.80	kJ
Natural Gas	44,479.10	GJ	844.01	kJ	6.22	kJ
LPG	606.90	GJ	11.52	kJ	0.085	kJ
Diesel	7.90	GJ	0.15	kJ	1.10E-03	kJ
Water						
Total Water Used	27,244.60	megaliters	0,52	m^3	3.81E-03	m^3
Total Water Used for Production	25,000	megaliters	0.47	m^3	3.46E-3	m^3
Ground Water	527.70	megaliters	0.010	m^3	7.38E-05	m^3
Fresh Water	26,701.30	megaliters	0.51	m^3	3.73E-03	m^3

	Totals (2015)		Per produced m^2		Fairphone 2 display	
Rain Water	15.60	megaliters	2.96E-04	m^3	2.18E-06	m^3
Output						
Scope 1 emissions (from PFCs)	310	kt CO_2e	5.86	kg	0.043	kg CO_2e
Scope 2 emissions (from purchased electricity)	247	kt CO_2e	46.93	kg	0.35	kg CO_2e
Gas Emissions						
SOx	43.3	tons	0.00082	kg	6.06E-06	kg
NOx	65	tons	0.0012	kg	9.09E-06	kg
HP	2.7	tons	5.12E-05	kg	3.78E-07	kg
HCl	2.3	tons	4.36E-05	kg	3.22E-07	kg
VOCs	126.1	tons	0.0024	kg	1.76E-05	kg
Waste Water Discharge						
Waste Water	20,909	megaliters	0.040	m3	2.92E-03	m^3
COD	751.7	tons	0.014	kg	1.05E-04	kg
BOD	154.3	tons	0.0029	kg	2.16E-05	kg
TSS	233.7	tons	0.0044	kg	3.27E-05	kg
Production Water Recycle						
Production Water Recycle Volume	120,886.2	megaliters	2.29	m^3	1.69E-02	m^3
Production Water Recycle Rate	88	%				
Waste Output						
Non-hazardous Waste	75,530.2	t	1.4332	kg	1.06E-02	kg
Hazardous waste	36,992.1	t	0.7019	kg	5.17E-03	kg

Electronics

Modelling is based on the specific smartphone display board similar to other printed circuit boards (see section 3.1.9.3).

Backlight assembly:

Die size of LEDs per screen area is based on [Deubzer 2012] for a comparable tablet display (see Table 3-3).

Table 3-3: Die area per display area [Deubzer 2012]

Backlight design (typical product)	Display diagonal	Brightness [cd/m²]	Total die area per display area [mm²/cm²]
edge lit (tablet)	7"	350	0.0094

For the Fairphone 2 display of 73.7 cm^2, this results in a die area of 0.0069 cm^2.

Life cycle modelling of the LEDs is based on data for CMOS logic from [Boyd 2012] as it is also described by [Zgola 2011]. For the details of the modeling, see section 3.1.9.4 for ICs.

Glass substrate

The production of the glass substrate is based on a data set by ecoinvent for LCD glass manufacturing.

Liquid crystal

For the production of liquid crystal, a data set from ecoinvent “polarizer, liquid crystals and color filters production, for liquid crystal display, GLO” is used. This data set does not cover liquid crystal directly, but a mix of polarizer, liquid crystal and color filters together and is already quite old (late 1990s). However, it is the only available data set providing related data on liquid crystal production.

Neglected

Not included is the production of input materials for the panel production (CF thinner, and array stripper) as corresponding life cycle data is missing. According to Zgola (2011), these materials have a low impact on the overall result of the display manufacturing.

3.1.6 Battery module

The Fairphone 2 includes a lithium cobalt oxide (LCO) battery. Therefore a specific LCO-battery data set was allocated which was developed by Fraunhofer IZM/TU Berlin for the German Federal Environment Agency in 2015 [Clemm 2016]. The data set was based on primary data from a manufacturer in China for an LCO battery of a laptop, but can be scaled to represent a smartphone battery as detailed below.

The Fairphone 2 battery consists of two main components being the cell and the battery management system (BMS). In terms of environmental impacts, the cell is the largest contributor to most impact categories, in particular the cathode, anode and electrolyte.

The material composition of the battery cell from the above mentioned study was found to be comparable with the battery cell of the Fairphone 2 as provided in the BoM (see Table 3-4). From the mass percentage ranges provided in the BoM, the midpoint value is considered.

Table 3-4: Mass percentage of the most important cell materials

	Mass percentage of the cell	
Material (function)	**Fairphone 2 BoM**	**Clemm et al. 2016**
LCO (cathode active material)	37 %	41 %
Graphite (anode active material)	24 %	20 %
LiPF6 (electrolyte)	14 %	14 %
Other materials	25 %	25 %

The total mass of the Fairphone battery is gravimetrically determined to be 39.8 g. According to the Fairphone 2 BoM, the mass of the cell, including its packaging, is 38 g. Hence, the assumed mass of the BMS is 1.8 g. The dataset for the LCO cell is scaled from the above mentioned study by weight: The mass of one laptop battery cell (59.51 g) was scaled down to 38 g by factor 0.6385. The BMS was not found to be scalable, as the laptop BMS is designed for more complex functionalities compared to the Fairphone 2 battery BMS, such as balancing of several cells, and smart battery technology. Hence, a new dataset was created to model the BMS according to the BoM and a visual inspection of the populated wiring board integrated into the battery housing (cp. section Table 8-11).

In the baseline scenario model, the battery is included twice as it is assumed that during the life cycle of three years the battery has to be replaced once (see section 3.2 for the detailed assumptions).

3.1.7 Back cover

The back cover consists of the following parts:

- Outer case
- Battery pressure pad
- Camera seal gasket

The casing consists mostly of polycarbonate (15.7 g) and thermoplastic polyurethane (4 g).

The detailed BoM with the assigned weight and life cycle data set for the back cover can be found in the annex in Table 8-12.

3.1.8 Assembly process

The Fairphone 2 is assembled by Hi-P in China. Primary data regarding the energy consumption was obtained with a questionnaire. According to Hi-P 4.698 kWh per product are used for the assembly process. The electricity is grid electricity, so the Chinese energy grid mix from the GaBi data base is used.

In comparison, according to Yamagouchi (2013) the energy consumption during the assembly process is roughly 16 Wh/g phone. This same value was used in the Fairphone 1 LCA. For the Fairphone 2 this would result in 2.688 kWh for the assembly, roughly half of the actual value.

Additionally, Hi-P states the use of 0.74 g alcohol, the use of cotton swaps (~ 1 per 100 products) and lint free wipers (~ 2 per 100 products). The alcohol is included as "benzyl alcohol production" (an alcohol with low toxicity), the wipes are neglected in the inventory.

3.1.9 Cross-module approaches

The following sections describe the approaches which are used in a similar way in different modules.

3.1.9.1 Cameras

The Fairphone 2 contains two cameras:

- Front camera: 2MP CMOS Sensor, Sensor Type Omnivision OV2685 integrated in the top module
- Rear camera: 8MP CMOS Sensor with flash, Sensor Type Omnivision OV8865 – Back Side Illuminated in the camera module

The total weight of the cameras is:

- Front camera: 338 mg
- Rear camera: 791 mg

For both cameras, a material declaration was available which was used for the modelling of the mechanical parts, but adjusted to the measured weight (which did not fit the weight in the material declaration) (see Table 8-6 and Table 8-7 in the annex). However, the main environmental impact is expected to stem form the CMOS sensor IC. The manufacturer Omnivision published the die size for the two ICs which were then modelled similar to the other ICs in the Fairphone 2 (see section 3.1.9.4) [OV2685, 2015; OV8865, 2014]:

- Front camera: die dimension (bigger size is used as worst case assumption)
    - CSP5: 4454 μm x 4014 μm = 17.878 mm^2
    - COB: 4420 μm x 3980 μm = 17.592 mm^2
- Rear camera: die dimensions: 5850 μm x 5700 μm = 33.345 mm^2

3.1.9.2 Connectors

Due to its modular design, the Fairphone 2 has more internal connectors than standard smartphones. There are different types of connectors in the Fairphone 2:

- Board-to-board connector (each module board)
- Battery connector (mainboard)
- MicroUSB connector (bottom module board)
- MicroSD card connector (mainboard)
- SIM card connector (two pieces on the mainboard)

Board-to-board connector

Each module board has a board-to-board connector linking the mainboard to the different modules. The connectors are gold-coated pogo pins produced by GSN in China:

- backside of mainboard: 5 pins, open connector for add-ons or upgrades of the phone
- top module: 32 pins
- camera module: 32 pins
- display module: 30 pins
- bottom module: 18 pins

The following Table 3-5 shows the summarized material composition of the board-to-board connectors according to the material declaration from GSN.

Table 3-5: Material composition of board-to-board connectors (totals) according to material declarations from GSN

Material	Weight [mg]
Liquid Crystal Polymer	1146.00
Cu	1426.47
Zn	27.92
Ni	44.34
Au	14.48
Silicon	29.31
Phosphorus	17.59
Manganese	322.41

The counterparts on the module boards are Ni/Au contacts directly on the printed circuit boards. For the inventory model, the amount of nickel and gold for the PCB material composition is used. As the material composition is derived from the whole PCB panel, the following assumptions (based on the PCB layout drawings) are applied:

- Ni/Au is only applied on the actual board area, not on the cut-offs
- 90 % of the Ni/Au on the module boards is associated to the board-to-board connectors, 10 % to conductive paths and other contacts

This results in the following amounts:

- Top module board: 2.19 mg nickel, 0.058 mg gold
- Display board: 2.19 mg nickel, 0.058 mg gold
- Camera board: 2.19 mg nickel, 0.058 mg gold
- Bottom module board: 5.325 mg nickel, 0.125 mg gold
- Mainboard (contacts below pins): 17.45 mg nickel 0.3375 mg gold

Other connectors

The other connectors are also manufactured by GSN except for the MicroUSB connector, which is manufactured by JAE. All connectors are modelled according to their material declarations (see Table 8-3 and Table 8-4 in the annex).

3.1.9.3 Printed Circuit Boards

Standard procedure in LCA to reflect printed circuit boards (PCBs) is to use the outer rectangular dimensions as produced panel area. However, this procedure can lead to under- or overestimation of the produced panel area:

- For PCBs with an even rectangular shape, this procedure can lead to underestimations as cut-offs are neglected.
- For PCBs with an unbalanced shape, this procedure can lead to overestimations as possible nesting of boards is neglected.

For the Fairphone 2 PCBs, the real size of the produced PCB panels was available and could be used to allocate the correct produced panel area. The Fairphone 2 PCBs are produced on three different panels (see Table 3-6).

Table 3-6: Allocation of PCB area

Panel	Board	Number of boards per panel	Width [mm]	Length [mm]	Number of layers	Size (outer dimensions) [cm^2]	Allocated size [cm^2]
1			121	208	12	251.68	
1	Mainboard	4	64.50	101.50		65.47	60.92
1	Antenna grounding	4	27.00	2.00		0.54	0.54
1	Antenna coaxial boards	4	11.00	13.30		1.46	1.46
2			143.00	87.25	4	124.77	
	Top module boards	4	54.20	13.40		7.26	12.58
	Display boards	4	9.00	47.50		4.28	9.59
	Camera boards	4	21.80	17.00		3.71	9.02
3			143.00	87.25	4	124.77	
	Bottom module boards	4	52.70	40.50		21.34	31.19

For panel 2 and 3, the standard procedure (using outer dimensions) would have let to underestimation of the total produced panel size. The resulting cut-offs were evenly allocated to all produced boards on the panel. For panel 1, the standard procedure would have let to an over-estimated panel size. The panel area was allocated as followed:

- Antenna grounding and antenna coaxial board: outer dimensions of the board
- Mainboard: Panel size minus the board area allocated to antenna grounding and antenna coaxial board.

For flexible printed circuit boards (FPCs) a data set of a 1-layer rigid PCB was applied as no data set for FPCs is available. The data set was scaled per weight.

3.1.9.4 ICs

The production of semiconductors (logic ICs and memory) is an energy and resource intensive process. However, not much environmental data is available. Data sets for semiconductors/ active components from GaBi and ecoinvent v3.1 are scaled per weight, which is not the main parameter of the environmental impact, but rather the die size and technology node, i.e. technology generations.

Main sources for the environmental impact of semiconductors are Boyd (2012) and Schmidt (2011).

Front-end processes

Boyd [2012] investigated in detail the carbon footprint for CMOS logic ICs (front-end processes) for different technology nodes. The newest technology node covered by Boyd's data is 32 nm in 2013. The wafer size is 300 mm with 347 good chips per wafer (chip size: 140 mm^2).

Table 3-7: Environmental impacts according to Boyd [2012] per cm^2 die for the technology 32 nm

	Energy [MJ]	GWP [kg CO_2e]	Photo-chemical smog [kg NOx]	Acidification [mol H+]	Eco-toxicity [kg 2,4-D]	Human Health Cancer [kg C6H6]	Human Health non cancer [kg C7H7]
Front-End							
Fab	33.6	0.9	0.006	0.356	0.030		2.444
Infrastructure (fab construction and equipment)	17.9	1.5	7.43E-03	3.86E-01	4.96E-05	7.36E-05	3.07E+00
Silicon	5.9	0.5	5.25E-03	3.03E-01	2.60E-02		2.08E+00
Chemicals	2.9	0.4					
Fab direct emissions and EoL			2.51E-04	2.00E-01	4.70E-04	1.89E-05	1.00E+00

Regarding the direct PFC emissions, the German semiconductor industry reports under the voluntary agreement to reduce non-carbon greenhouse gas emissions to a value of roughly 0.15 kg CO_2e per cm^2 produced wafer area [ZVEI 2011]. In comparison, Schmidt [2011] published for the reference year 2005 PFC emissions of 0.1 kg CO_2e per cm^2 logic die (memory dies have a lower value).

Back-end processes

According to the European Semiconductor Industry Association back-final energy consumption has a share of 25 – 37 % depending on the packaging type. Therefore it is assumed, that one third of the electricity consumption is for back-end and two third for front-end processes. For the materials, it is assumed that the impact of front-end and back-end processes is more or less the same. Similar assumption were made in the project "LCA to go" (2014).

Based on these assumptions, the figures presented in Table 3-8 result per cm^2 die for the technology node 32 nm.

Table 3-8: Front-end and back-end emissions per cm[2] die for the technology node 32 nm

	Energy [MJ]	GWP [kg CO_2eq]	Photochemical smog [kg NO_x]	Acidification [mol H+]	Ecotoxicity [kg 2,4-D]	Human Health Cancer [kg C6H6]	Human Health non cancer [kg C7H7]	Eutrophication to air [kg N]	Eutrophication to water [kg N]
Front-End									
Fab	33.6	0.9	0.006	0.356	0.030		2.444	2.22E-04	
infrastructure	17.9	1.5	7.43E-03	3.86E-01	4.96E-05	7.36E-05	3.07E+00	2.52E-04	
silicon	5.9	0.5	5.25E-03	3.03E-01	2.60E-02		2.08E+00	1.89E-04	
chemicals	2.9	0.4							
fab direct emissions and EoL (incl. PFC emissions)		0.15	2.51E-04	2.00E-01	4.70E-04	1.89E-05	1.00E+00	2.89E-06	9.86E-03
Totals Front end	**60.3**	**3.4**	**1.91E-02**	**1.2**	**0.1**	**0.0**	**8.6**	**0.0**	**0.0**
Back End									
Back End energy	25.7	1.2	6.80E-03	0.4	1.53E-02	3.68E-05	2.8	2.37E-04	
Back End materials	8.9	0.9	5.25E-03	0.3	2.60E-02	0.00E+00	2.1	1.89E-04	
Total Back-end	**34.6**	**2.0**	**1.20E-02**	**0.7**	**4.12E-02**	**3.68E-05**	**4.8**	**4.25E-04**	**0.0**
Totals	**94.9**	**5.4**	**3.11E-02**	**1.9**	**9.82E-02**	**1.29E-04**	**13.4**	**1.09E-03**	**9.86E-03**

The ICs on the different boards in the Fairphone 2 is modelled according to the data described before. Thereby it will be distinguished between the CPU, memory (DRAM), storage (flash) and other ICs.

CPU

The CPU of the Fairphone 2 is the Snapdragon 801 from Qualcomm with 4 cores, 28 nm technology node.

The die size of 111.28 mm^2 was identified through x-rays and grinding of the chip.

The front-end processes and back-end energy is modelled according to the data described before (Table 3-8) scaled according to the die size. The back-end materials are modelled based on the material composition derived from the data sheet.

Memory

The memory is a 2 GB FBGA, LPDDR3 chip from Samsung.

The die size of 68.63 mm^2 was identified through x-rays and grinding of the chip.

The front-end processes and back-end energy is modelled according to the data described before (Table 3-8) scaled according to the die size. The back-end materials are modelled based on the material composition derived from the data sheet.

Storage

The Fairphone 2 has a 32 GB NAND flash storage by Samsung.

The die size of 93.64 mm^2 was identified through x-rays and grinding of the chip.

The front-end processes and back-end energy will be modelled according to the data described before (Table 3-8) scaled according to the die size. The back-end materials are modelled based on the material composition derived from the data sheet.

Other ICs

For the other ICs in the Fairphone 2, the die size was identified either through x-rays or calculated based on the silicon weight from the data sheets, if this data was available. The front-end and back-end processes is modelled according to the data described before (Table 3-8) scaled according to the overall assumed die size.

When no information on the amount of silicon was available and x-rays were not revealing, a standard data set from ecoinvent for active components scaled per weight was used.

The following resulting die sizes were used:

- Top module board: 0.019 cm^2
- Display board: 0.262 cm^2
- Mainboard:
  - 0.933 cm^2
  - 0.162 g unspecified ICs

3.1.10 Packaging

Packaging covers the final sales packaging and the bulk packaging for transport to the distribution hub. Further upstream packaging is not included in the analysis.

3.1.10.1 Bulk packaging (to distribution hub)

The bulk packaging consists of the following parts:

Table 3-9: Bulk packaging of the Fairphone 2 to the distribution hub

Product part	Item packing method	Weight shipping box (per component[4]) [g]
Fairphone 2	Unit in bubble plastic bag (not closed) inserted in Brown Cardboard box with separator	30.75
Back cover	Unit In plastic bag with Zip closure inserted in Brown Cardboard box with separator	30.65
Battery	Unit In plastic bag sealed, transparent inserted in inner box of card board in bulk of 8. Inner box inserted in Brown Cardboard box	15.85

For the inventory it is assumed that the packaging weight consists of 20 % plastic and 80 % card board, resulting in the following weights:

- 61.8 g card board
- 15.4 g plastic

For consistency reasons with the Fairphone 1 LCA, the same data sets from the ecoinvent database were applied for card board and plastic:

- "Packaging film, LDPE, at plant [RER]"
- "packaging, corrugated board, mixed fiber, single wall, at plant [RER]"

Packaging of the individual components to the final assembly processes is not taken into account in the inventory.

3.1.10.2 Sales packaging

The individual sales packaging consists of the following parts:

Table 3-10: Individual sales packaging

	Quantity in box	Weight [g]	Supplier	Supplier country	Material type
FP2 User Guide Combo Package v2	1	33	Ecodrukkers	NL	Paper
FP2 White Box Bottom	1	15	Paxpring	NL	Paperfoam®
FP2 White Box Lid	1	14	Paxpring	NL	Paperfoam®
FP2 White Box Tray	1	13	Paxpring	NL	Paperfoam®
FP2 White Box External Wrap (Blue ribbon)	1	1	Paxpring	NL	Plastic and glue strip
FP2 Phone IMEI Label	1	0.5	Rhenus	NL	Paper label
FP2 Shipping Box Outer	1	78	Paxpring	NL	Brown Cardboard
FP2 Shipping Box Tray	1	13	Paxpring	NL	Brown Cardboard
FP2 Shipping Box Closing Tape	1	0.5	Paxpring	NL	Brown Cardboard
Logistics Delivery Note A4	1	2	Rhenus	NL	Paper
Courier Shipping label over Shipping Box	1	1	Rhenus	NL	Paper label
Totals		**42**			**Paperfoam®**
		36.5			**Paper**
		91.5			**Cardboard**
		1			**Plastic and glue strip**

[4] The total weight of the shipping box is divided by the number of items per shipping box.

The packaging was modelled with the following data sets from GaBi and ecoinvent:

- Paper: recycled paper
- Cardboard: corrugated board
- Plastic and glue strip: neglected

The Paperfoam® consists of 70 % potato starch and 20 % cellulose fibers. A GWP value was available from a separate packaging LCA (cradle to gate)[5], giving a result of 5.9 g CO_2e for the 42 g Paperfoam® used. Within this study, the GWP value of the existing LCA is used. The other impact categories are modelled according to the material composition.

3.2 Use phase

The following use pattern is applied for the Fairphone 2:

Table 3-11: Summary of use-phase assumptions (baseline scenario)

Assumptions	
Time in use	3 years

Use pattern	• Daily charging
	• 7 h/d no-load losses though plugged in charger
	  ○ 20 % of users: 20 h/d
	  ○ 30 % of users:10 h/d

Charger specifications	Charger currently sold by Fairphone B.V.: • Efficiency: 69 % • No-load losses: 30 mW
Battery specifications	• 2420 mAh • 3,8 V
Electricity consumption	• 4.9 kWh/a • 14.8 kWh in 3 years

As a baseline scenario, a use time of three years is assumed for the Fairphone 2. For the battery a lifetime of two years is assumed resulting in a use of two batteries over the lifetime of three years.

Three years use time is assumed in LCA/Carbon Footprints of several smartphone manufacturers (e.g. Apple 2016, Nokia, Sony 2008, HTC 2013, Blackberry 2014) and therefore allows a basic comparability in that aspect.

Daily charging reflects an intensive use of the Fairphone 2 and might be closer to a worst-case assumption than to the average user. However, this use pattern is applied (if stated at all) also by other smartphone manufacturers (e.g. [Apple 2016] and [Blackberry 2014]) and therefore allows a basic comparability in that aspect.

Besides the electricity consumption caused by the charging itself, it is assumed that some users leave the charger plugged after charging and thereby cause no-load losses. According to a user survey conducted for the Fairphone 1 in 2014, 19.4 % of the users leave the charger

[5] The results, but not the whole study, of the packaging LCA were provided by Fairphone B.V. within the context of this Fairphone 2 LCA.

"always" plugged after charging, 28.9 % "sometimes", and 51.7 % "never". Although this survey was for the Fairphone 1, it is assumed for this study that the user behavior is more or less the same. Therefore the following rounded figures are applied:

- 20 % of the users leave the charger "always" plugged: 20 h/d
- 30 % of the users leave the charger "sometimes" plugged. 10 h/d
- ➔ The average charger is plugged in without charging for 7 h/d.

The Fairphone 2 is not delivered with a charger as many users already have universal chargers at home and therefore automatically delivering the charger with the phone would only generate more waste. So a charger has to be purchased additionally or users can use one they already possess. Therefore the production of the charger is not included in the LCA. Nevertheless, for the use phase, specifications of a charger have to be assumed.

Users will use chargers already existing in their homes from other devices, buy the Fairphone charger or purchase a new charger somewhere else. New chargers are mostly more efficient than older ones, partly fulfilling the up-to-date requirements of the External Power Supply Code of Conduct v5 requiring no-load losses < 0.075 W and efficiency > 75 % for products sold in 2016 [CoC EPS 2013]. However, older chargers have lower efficiencies and higher no-load losses. Some older devices might not even fulfill the current legal requirements according to Ecodesign Implementing Measure for External Power Supplies (< 0.3 W no-load losses and efficiency > 69 % at 6 W) [EC 278/2009]. Therefore, the charger currently sold by Fairphone[6] seems like a good proxy.

An energy mix reflecting the distribution of sales within Europe is applied (see Table 3-12). Thereby, countries with less than 1 % of the sales are neglected.

Table 3-12: Regional distribution of sales used for the energy mix in the use phase

Country	Part of Sales
Austria	5.61%
Belgium	5.53%
Switzerland	15.91%
Germany	36.74%
Denmark	1.28%
Spain	2.13%
France	6.55%
Great Britain	11.05%
Italy	1.44%
Netherlands	6.56%
Sweden	7.19%

3.3 End-of-Life

For the baseline scenario it is assumed that the Fairphone 2 is properly recycled at its end-of-life (EoL). In other words, 100 % of the device in the modelled product system enters the re-

[6] U_{out}: 1200 mA, I_{out}: 5 V, No load power: < 30 mW / < 150 mW, Efficiency: > 69 % (CoC v 4), online: http://www.salcomp.com/SalcompDocuments/Cosmos6W.pdf

cycling process chain. To date, the EoL procedures for smartphones have not been fully established due to a lack of relevant numbers of devices reaching the recycling facilities. Hence, a number of assumptions was made to model the EoL.

It was assumed that the entire phone is disposed of by the user at an unspecified point of collection. The unit is then transported from the collection point to a pre-processing facility, where the phone is depolluted (i.e. removal of the battery from the unit). For the depollution process, the separation rate was assumed to be 100 %, i.e. no losses are generated in the separation process. After depollution, the phone unit (without battery) is transported to a recycling facility for metals recovery without further dismantling steps.

As an approximation for the EoL transportation distances, the assumptions from the Fairphone 1 LCA (Güvendik 2014), based on (Hischier 2007), were adopted:

- Total transportation distance from user to recycling plant: 1500 km
- Mode of transportation is by lorry (75 % by distance) and by train (25 % by distance)

The modelling of the metals recovery processes was based on the process flow of recycling of metals from electronics scraps reported by Umicore (Hagelüken 2006). The relevant processes were identified to be the

- Copper smelter process
- Electrowinning process
- Precious metal refinery

Other processes were not considered relevant for metals recovery from the Fairphone 2 (i.e. sulfuric acid plant, lead blast furnace, lead refinery, special metals refinery for In, Se, Te recovery).

The electrowinning process yields secondary copper and nickel. The precious metal refining yields gold, silver, and palladium. The amount of recovered metals from the Fairphone 2 were approximated via data provided in the BoM (screws, solder paste, display frame, shields) and material data sheets on several components (display, mainboard, speaker, SIM card, micro USB, micro SD, vibration motor). The assumed recycling rates per element are 95 % for gold, silver, palladium and copper, and 90 % for nickel, based on Chancerel et al. (2016).

The batteries are treated at a dedicated battery recycling plant. At the plant, the batteries are firstly sorted according to their chemistry. For the sorting, it is assumed that 95 % of the batteries are sorted correctly [Sommer 2013]. During the recycling of the lithium-ion battery, it is assumed that 95 % of the contained cobalt and copper are recovered. All other materials are assumed to be lost.

As two batteries are consumed in the base case, the treatment of two EoL batteries is taken into account, both in terms of environmental burdens and recovered materials.

All burdens and all credit associated with the EoL was allocated to the modelled life cycle of the Fairphone 2.

3.4 Transport

Transport processes take place in all life cycle phases (see Figure 3-3), but the general modelling happens according to the same rules. Therefore, it is summarized in this individual subsection.

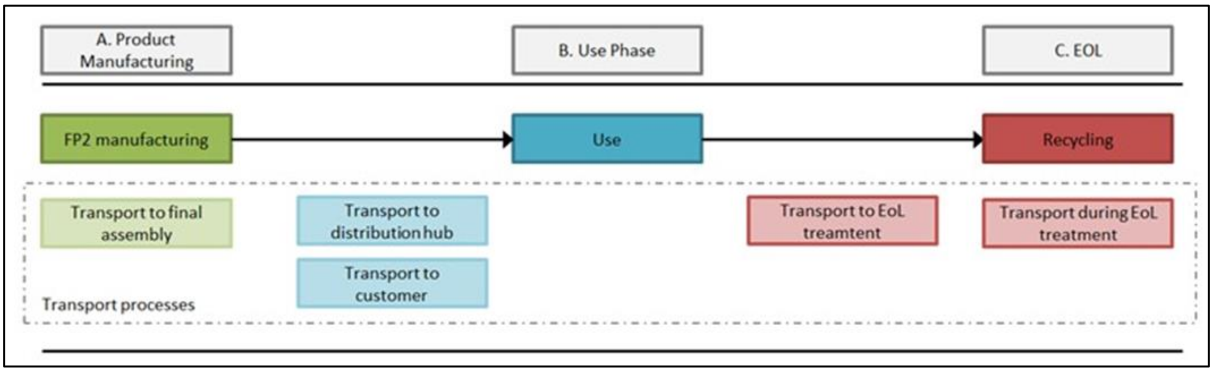

Figure 3-3: Life cycle phases and transport processes of the Fairphone 2

Transport will be separated into the following parts:

- Transport of components to final assembly
- Transport from final assembly to distribution hub in the Netherlands
- Transportation to customers

Thereby the weight of the components or final product incl. packaging, the transported distance, and mode of transportation (air, land, sea) are allocated to calculate the "t*km per mode of transportation" which than will be connected with the corresponding data set.

The transport processes occurring within the EOL processes are included in the dedicated EOL model.

3.4.1 Transport to final assembly

Primary data regarding the packaging of the components to final assembly could not be retrieved. Therefore a factor will be applied on the component weight to estimate the additional weight for the packaging. Within the Fairphone 1 LCA, packaging factors were estimated based on exemplary weighing of a capacitor [Güvendik 2014]. The established factors seem reasonable also for the Fairphone 2:

- Components with weight > 0.5 g: factor 0.1
- Components with weight < 0.5 g: factor 1.94

For the mode of transportation the following assumption are made:

- Transportation within China: land (truck)
- International transportation: air, if applicable additional transportation from and to the airport per truck

For some manufacturers, the specific production facility could not be identified. For the related parts a default value for the transported distance of 500 km per truck was assigned.

The corresponding transport distances result in:

- Truck transport: 24.157 kg*km
- Air transport: 0.811 kg*km

3.4.2 Transport to distribution hub

The Fairphone 2 is transported in three parts to the distribution hub in Netherlands:

- Phone
- Back cover
- Battery

The phone and back cover is transported from the place of final assembly and the battery from the battery supplier 3Sun (see Table 3-13). The packaging weight is based on information from

Fairphone B.V. including the package of parts and overall pallets. Transport of the battery is calculated twice as it is assumed that two batteries are used over the life cycle of three years.

Table 3-13: Transportation to distribution hub

Component	from	to	Mode of transporta-tion	Distance [km]	Compo-nent weight [g]	Packag-ing weight [g]	Total weight [g]	kg*km
Phone	Suzhou	Shanghai	Land (truck)	55	114.5	30.75	145.3	8.0
	Shanghai	Amsterdam	Air	8860	114.5	30.75	145.3	1286.9
	Amsterdam	Ekkersrijt	Land (truck)	120	114.5	30.75	145.3	17.4
Back cover	Suzhou	Shanghai	Land (truck)	55	20.1	30.65	50.8	2.8
	Shanghai	Amsterdam	Air	8860	20.1	30.65	50.8	449.6
	Amsterdam	Ekkersrijt	Land (truck)	120	20.1	30.65	50.8	6.1
Battery	Shenzhen	Shanghai	Land (truck)	300	38	15.85	53.8	16.2
	Shanghai	Amsterdam	Air	8860	38	15.85	53.8	477.1
	Amsterdam	Ekkersrijt	Land (truck)	120	38	15.85	53.8	6.5
Total			**Air**					**2213.6**
Total			**Land (truck)**					**56.9**

3.4.3 Transport to customer

The Fairphone 2 is shipped within Europe. The transportation distance is estimated based on the split of sales. The transported weight includes the weight of the phone, packaging and manual. It is assumed that transport within Europe takes place via truck. Fast delivery, which normally means air transport, is not included.

Table 3-14: Transportation to customer

Country	Share of Sales [%]	Distance [km]	Total weight [g]	kg*km	kg*km (weighted)
Austria	5.61%	1000	344	34.4	19.3
Belgium	5.53%	200	344	68.8	3.8
Switzerland	15.91%	750	344	258	41.1
Germany	36.74%	450	344	154.8	56.9
Denmark	1.28%	800	344	275.2	3.5
Spain	2.13%	1800	344	619.2	13.2
France	6.55%	800	344	275.2	18.0
Great Britain	11.05%	800	344	275.2	30.4
Italy	1.44%	1500	344	516	7.4
Netherlands	6.56%	100	344	34.4	2.3
Sweden	7.19%	1600	344	550.4	39.6
Total					**235.5**

Additionally, a separate transport of a second battery is assumed over the life cycle. Thereby the same distances and share of sales is assumed with a product weight of 38 g (plus the same weight as packaging) resulting in 52.0 kg*km truck transport.

4 Impact Assessment

Based on material flows defined in the LCI, the life cycle impact assessment (LCIA) will be carried out according to the recognized CML methodology [CML 2001] using LCA software GaBi. For the following impact categories the results will be displayed and discussed in detail:

- Climate change:
  - Global Warming Potential (GWP) 100 years
- Resource depletion:
  - Abiotic resource depletion (ADP) elements
  - ADP fossil
- Human toxicity:
  - Human Toxicity Potential
- Ecotoxicity:
  - Terrestrial Ecotoxicity Potential

Table 4-1: Impact categories and category indicators according to [CML 2001]

Impact category	Category indicators
GWP 100 years	kg CO_2 equivalents
ADP elements	kg Sb equivalents
ADP fossil	MJ
Human Toxicity Potential	kg DCB equivalents
Terrestrial Ecotoxicity Potential	kg DCB equivalents

Normalization, grouping, and weighting of the results (optional steps in the impact assessment of an LCA) will not be applied.

4.1 Definition of impact categories

For the impact categories covered in this LCA study, the following definitions from CML are used:

- Global Warming Potential (GWP) 100 years: "Global warming is considered as a global effect. Global warming - or the "greenhouse effect" - is the effect of increasing temperature in the lower atmosphere. The lower atmosphere is normally heated by incoming radiation from the outer atmosphere (from the sun). A part of the radiation is normally reflected from the surface of the earth (land or oceans). The content of carbon dioxide (CO2) and other "greenhouse" gasses (e.g. methane (CH4), nitrogen dioxide (NO2), chlorofluorocarbons etc.) in the atmosphere reflect the infrared (IR)-radiation, resulting in the greenhouse effect i.e. an increase of temperature in the lower atmosphere to a level above normal. […]The GWP for greenhouse gases is expressed as CO2-equivalents, i.e. the effects are expressed relatively to the effect of CO2." [Stranddorf 2005]
- Resource depletion: "The model of abiotic resource depletion […] is a function of the annual extraction rate and geological reserve of a resource. In the model as presently defined, the ultimate reserve is considered the best estimate of the ultimately extractable reserve and also the most stable parameter for the reserve parameter. However, data for this parameter will by definition never be available. As a proxy, we suggest the ultimate reserve (crustal content)." [Oers 2016]

- Abiotic resource depletion (ADP) elements: "The impact category for elements is a heterogeneous group, consisting of elements and compounds with a variety of functions (all functions being considered of equal importance)." [Oers 2016]
- ADP fossil: "The resources in the impact category of fossil fuels are fuels like oil, natural gas, and coal, which are all energy carriers and assumed to be mutually substitutable. As a consequence, the stock of the fossil fuels is formed by the total amount of fossil fuels, expressed in Megajoules (MJ)." [Oers 2016]

- Human Toxicity Potential: "The normalisation references for human toxicity via the environment should reflect the total human toxic load in the reference area caused by human activity, i.e. the potential risk connected to exposure from the environment (via air, soil, provisions and drinking water) as a result of emissions to the environment from industrial production, traffic, power plants etc. Ideally, all emissions of substances potentially affecting human health should be quantified and assessed. However, the multitude of known substances (>100.000) and an even larger number of emission sources logically makes that approach unfeasible. The inventory used for calculating the normalisation references is therefore based on available emission registrations for substances, which are believed to contribute significantly to the overall load." [Stranddorf 2005]
- Terrestrial Ecotoxicity Potential: "The impact category ecotoxicity covers the possible effects of toxic substances released during the life cycle of a product to the environment. The sources of toxicants are quite different depending on the type of environment as well as the methods used in the assessment of the impact. Consequently, the impact on aquatic and terrestrial systems are usually considered separately. In principle, the normalisation reference for ecotoxicology includes all toxic substances emitted to the environment due to human activities, and it requires extensive data on all types of emissions. In general, however, only few data on environmental releases of toxic substances are available, and the normalisation therefore relies on extrapolations from a relatively limited set of data.
  The normalisation reference includes the following emission types: […] Terrestrial environment: Pesticide use, Agricultural use of sewage sludge, Atmospheric deposition of metals and dioxins" [Stranddorf 2005]

4.2 Results

The results for the different impact categories can be found in Table 4-2. The main driver for all impact categories is the production phase causing mostly more than ¾th of the impact. Transport, EoL, and use phase have a comparably small influence (except for the impact category ADP fossil). The EoL results are even negative meaning a positive effect on the overall life cycle, which can be seen especially for the impact category ADP elements.[7]

[7] The negative impact of the recycling processes leads to an impact above 100 % for the other life cycle phases.

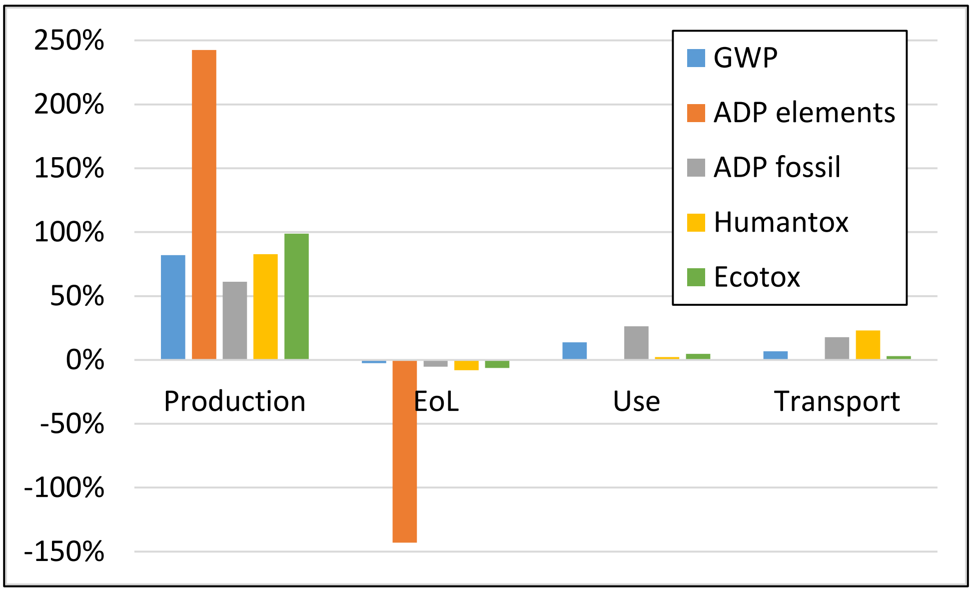

Figure 4-1: Relative impacts of the different life cycle phases per impact category

Table 4-2: Results per life cycle phase

Impact category	Unit	Total	Production	EoL	Use	Transport
GWP	kg CO_2e	43.85	35.98	-1.11	5.98	3.00
		100.0%	82.1%	-2.5%	13.6%	6.8%
ADP elements	kg Sb-e	6.09E-04	1.48E-03	-8.71E-04	2.66E-06	6.05E-07
		100.0%	242.5%	-143.0%	0.4%	0.1%
ADP fossil	MJ	241.65	148.03	-12.85	63.46	43.01
		100.0%	61.3%	-5.3%	26.3%	17.8%
Humantox	kg DCB-e	10.11	8.35	-0.81	0.24	2.32
		100.0%	82.7%	-8.0%	2.3%	23.0%
Ecotox	kg DCB-e	1.08E-01	1.07E-01	-6.87E-03	5.00E-03	3.18E-03
		100.0%	98.8%	-6.4%	4.6%	2.9%

4.3 Contribution Analysis

4.3.1 Production

In Figure 4-2, the results of the production phase are displayed per module (plus final assembly and packaging which are also assigned to the production phase). It can be seen that the main driver is the core module with the mainboard for most impact categories (see Table 4-3). The core module including the display contains the biggest PCB, the major share of electronic components (incl. CPU, storage, and memory), and the main part of the board-to-board connectors (nickel-gold coated pins).

For ADP fossil and Ecotoxicity, the assembly process itself is also a main driver. This is due to the fact that the impact category ADP fossil is driven mainly by energy consumption (see also the definition of the impact categories in section 4.1). Also Ecotoxicity is driven by the energy consumption (assembly process) and PCB manufacturing.

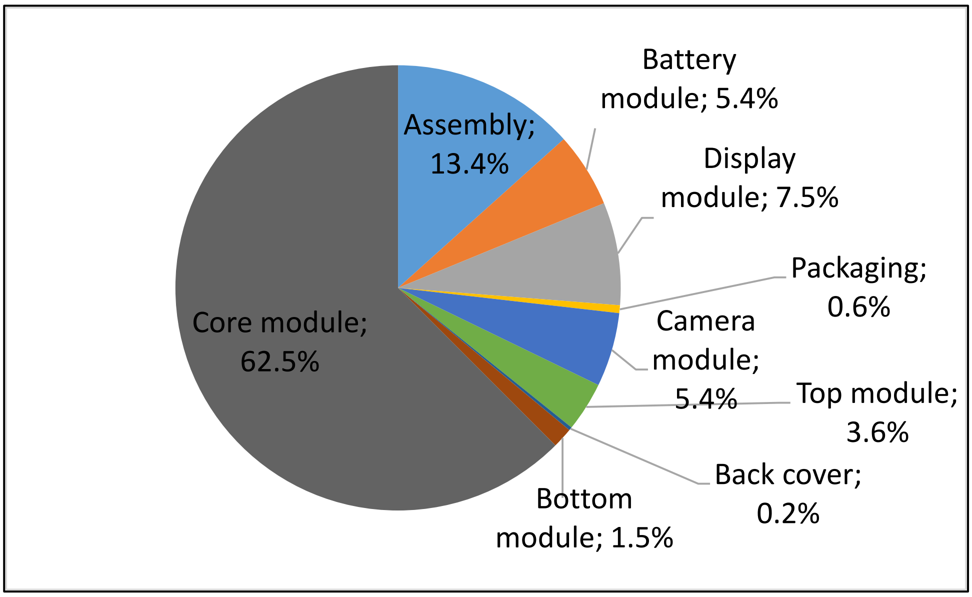

Figure 4-2: Relative impacts of the different modules of the production phase, impact category GWP

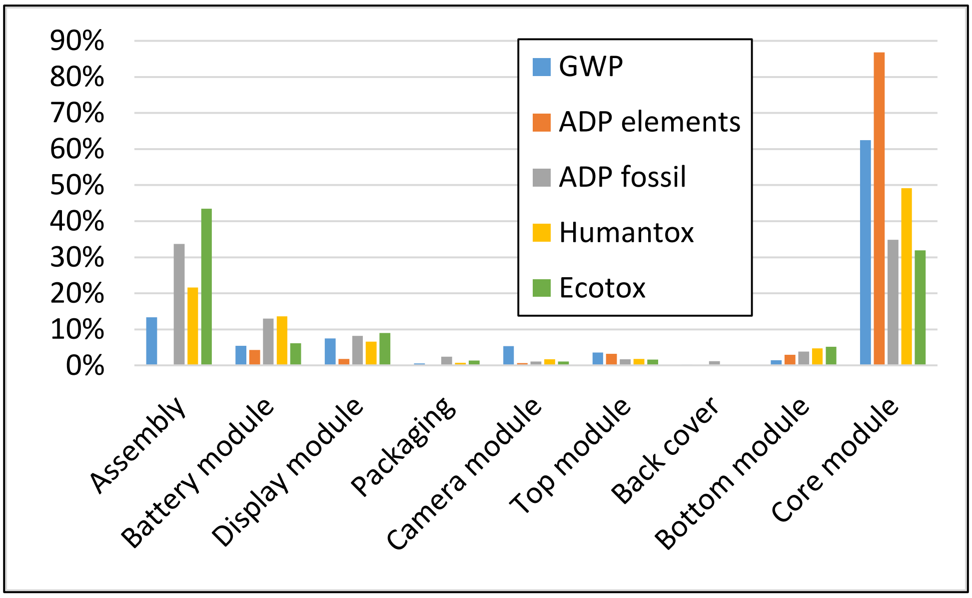

Figure 4-3: Relative impacts of the production phase per module and impact category

The main impact of the mainboard is caused by the ICs and the PCB, the passive components and connectors have a minor impact (except for the impact category ADP elements, see Figure 4-4 and Figure 4-5).

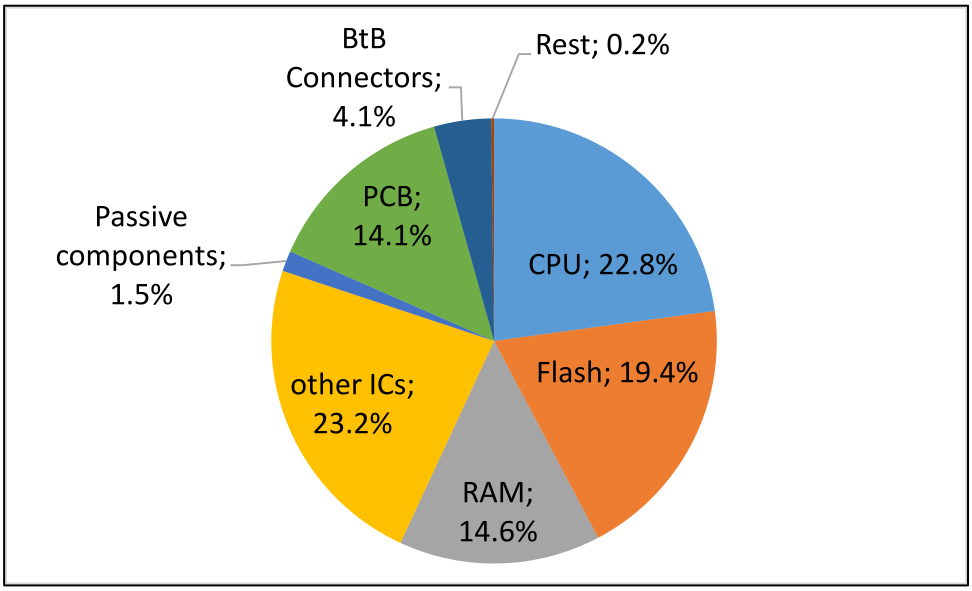

Figure 4-4: Relative impacts for the mainboard, impact category: GWP

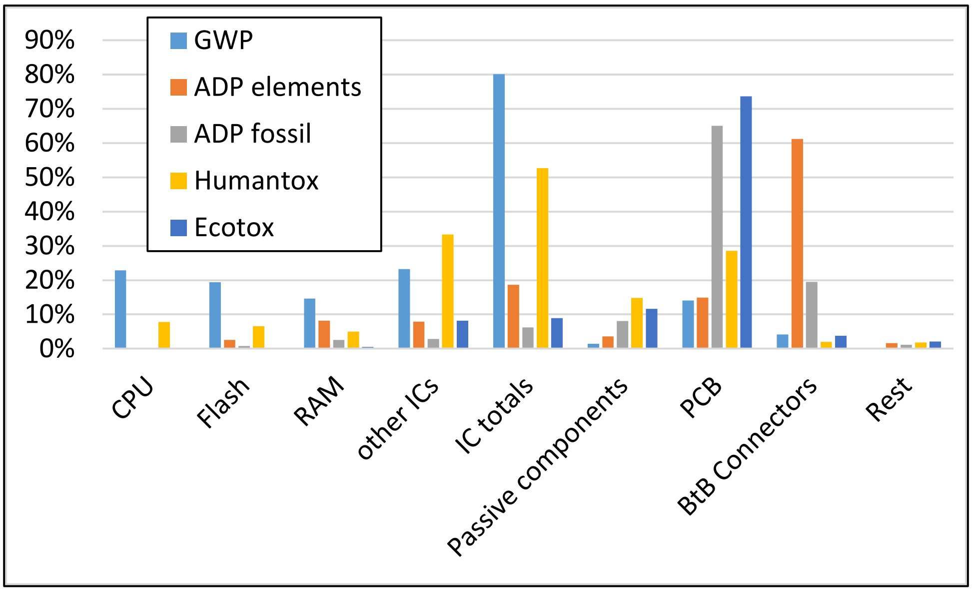

Figure 4-5: Relative impacts of the mainboard per impact category

Also across the modules, the PCBs and ICs have a major impact on the result. The passive electronic components have a small overall impact (see Table 4-5, Figure 4-6 and Figure 4-7). An exception is only the impact category ADP elements, where the board-to-board connectors cause the main part of the overall impact. This is caused by the high amount of gold used for the contacts in the connectors.

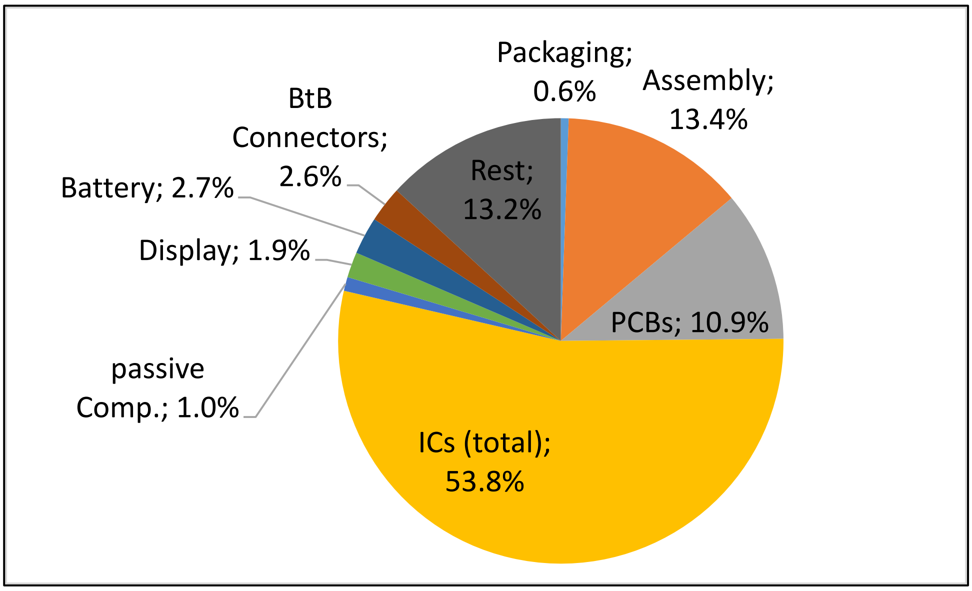

Figure 4-6: Relative impacts of the different component types, impact category GWP

IC manufacturing is a highly energy intensive process (see also Table 3-7 in section 3.1.9.4) as e.g. production takes place in clean rooms, high-purity materials and process gases are used, etc. This is reflected in the fact that the ICs cause the major share of the production impact for the impact category GWP.

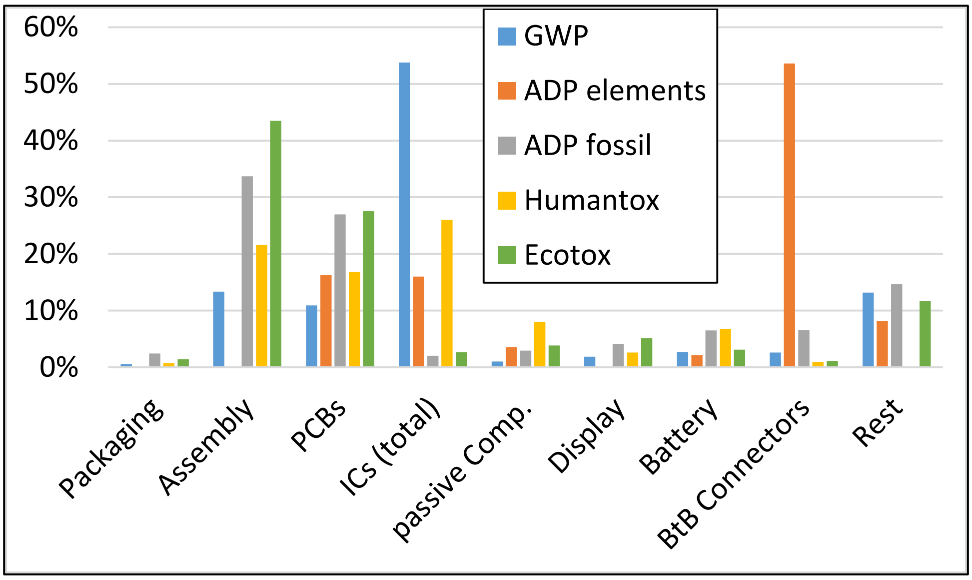

Figure 4-7: Relative impacts of the different component type per impact category

The data set used for the ICs does not cover the impact categories ADP elements and ADP fossil (only the material for the back-end processes for CPU, memory and storage, see section 3.1.9.4). Therefore, the impact of the ICs is underrepresented for the ICs and the relative impact of the other components (e.g. PCB in Figure 4-5 and Figure 4-7) is too high. ADP elements is driven by the materials of the different components (e.g. gold and copper in the PCBs and connectors). Many of these materials can be recovered in the recycling process (see section 4.3.3), but the impact for the processing of these components is only marginally visible in this impact category.

Table 4-3: Results of the production phase per module

Impact category	Unit	Production	Assembly	Battery module	Display module	Packaging	Camera module	Top module	Back cover	Bottom module	Core module
GWP	kg CO2e	35.98	4.81	1.96	2.68	0.20	1.93	1.29	0.09	0.53	22.48
			13.4%	5.4%	7.5%	0.6%	5.4%	3.6%	0.2%	1.5%	62.5%
ADP elements	kg Sb-e	1.48E-03	1.94E-07	6.39E-05	2.73E-05	1.61E-06	1.03E-05	4.81E-05	3.69E-07	4.33E-05	1.28E-03
			0.0%	4.3%	1.9%	0.1%	0.7%	3.3%	0.0%	2.9%	86.8%
ADP fossil	MJ	148.03	49.89	19.31	12.11	3.60	1.61	2.52	1.81	5.65	51.54
			33.7%	13.0%	8.2%	2.4%	1.1%	1.7%	1.2%	3.8%	34.8%
Humantox	kg DCB-e	8.35	1.80	1.14	0.55	0.06	0.14	0.15	2.57E-03	0.39	4.11
			21.6%	13.6%	6.6%	0.7%	1.7%	1.8%	0.0%	4.7%	49.2%
Ecotox	kg DCB-e	1.07E-01	4.63E-02	6.60E-03	9.63E-03	1.49E-03	1.17E-03	1.71E-03	8.58E-05	5.55E-03	3.40E-02
			43.5%	6.2%	9.0%	1.4%	1.1%	1.6%	0.1%	5.2%	31.9%

Table 4-4: Results of the production of the mainboard

Impact category	Unit	Mainboard	CPU	Flash	RAM	other ICs	IC totals	Passive components	PCB	BtB Connectors	Rest
GWP	kg CO_2e	22.26	5.09	4.32	3.26	5.16	17.83	0.33	3.13	0.92	0.05
		100.0%	22.8%	19.4%	14.6%	23.2%	80.1%	1.5%	14.1%	4.1%	0.2%
ADP elements	kg Sb-e	1.27E-03	4.47E-07	3.27E-05	1.03E-04	1.00E-04	2.37E-04	4.60E-05	1.89E-04	7.76E-04	2.00E-05
		100.0%	0.0%	2.6%	8.1%	7.9%	18.7%	3.6%	14.9%	61.2%	1.6%
ADP fossil	MJ	48.85	0.02	0.40	1.25	1.37	3.05	3.94	31.79	9.52	0.54
		100.0%	0.0%	0.8%	2.6%	2.8%	6.2%	8.1%	65.1%	19.5%	1.1%
Humantox	kg DCB-e	3.97	0.31	0.26	0.20	1.32	2.10	0.59	1.14	0.08	0.07
		100.0%	7.8%	6.6%	5.0%	33.3%	52.7%	14.8%	28.6%	2.0%	1.9%
Ecotox	kg DCB-e	3.18E-02	1.90E-05	5.08E-05	1.58E-04	2.59E-03	2.82E-03	3.68E-03	2.34E-02	1.21E-03	6.52E-04
		100.0%	0.1%	0.2%	0.5%	8.2%	8.9%	11.6%	73.7%	3.8%	2.1%

Table 4-5. Results per component type – production phase

Impact Category	Unit	Total	Packaging	Assembly	PCBs	ICs (total)	passive Comp.	Display	Battery	BtB Connectors	Rest
GWP	kg CO2-e	35.98	0.20	4.81	3.93	19.34	0.36	0.67	0.98	0.94	4.75
			0.6%	13.4%	10.9%	53.8%	1.0%	1.9%	2.7%	2.6%	13.2%
ADP elements	kg Sb-e	1.48E-03	1.61E-06	1.94E-07	2.41E-04	2.37E-04	5.27E-05	2.28E-07	3.19E-05	7.92E-04	1.22E-04
			0.1%	0.0%	16.3%	16.0%	3.6%	0.0%	2.2%	53.6%	8.2%
ADP fossil	MJ	148.03	3.60	49.89	39.94	3.05	4.34	6.11	9.65	9.72	21.72
			2.4%	33.7%	27.0%	2.1%	2.9%	4.1%	6.5%	6.6%	14.7%
Humantox	kg DCB-e	8.35	0.06	1.80	1.40	2.18	0.67	0.22	0.57	0.08	1.38
			0.7%	21.6%	16.8%	26.0%	8.0%	2.6%	6.8%	1.0%	16.5%
Ecotox	kg DCB-e	1.07E-01	1.49E-03	4.63E-02	2.93E-02	2.82E-03	4.10E-03	5.50E-03	3.30E-03	1.23E-03	1.25E-02
			1.4%	43.5%	27.5%	2.6%	3.9%	5.2%	3.1%	1.2%	11.7%

4.3.2 Use phase

The use phase emissions cause a smaller share of the life cycle emissions of the Fairphone 2. Within the use phase, emissions caused by Germany have a share of about 50 % while making up about 37 % of the sales (compare Figure 4-8 and Figure 4-9).

The effect that the relative environmental impact differs from the share of sales is caused by the different energy grid mixes which exist in the countries across Europe. For instance, the German energy mix causes more emissions than the European average. Therefore, the relative environmental impact is higher than the share of sales. In contrast, the Swedish energy grid mix has very low GHG emissions leading to a significantly lower share in the environmental impact than the share of sales.

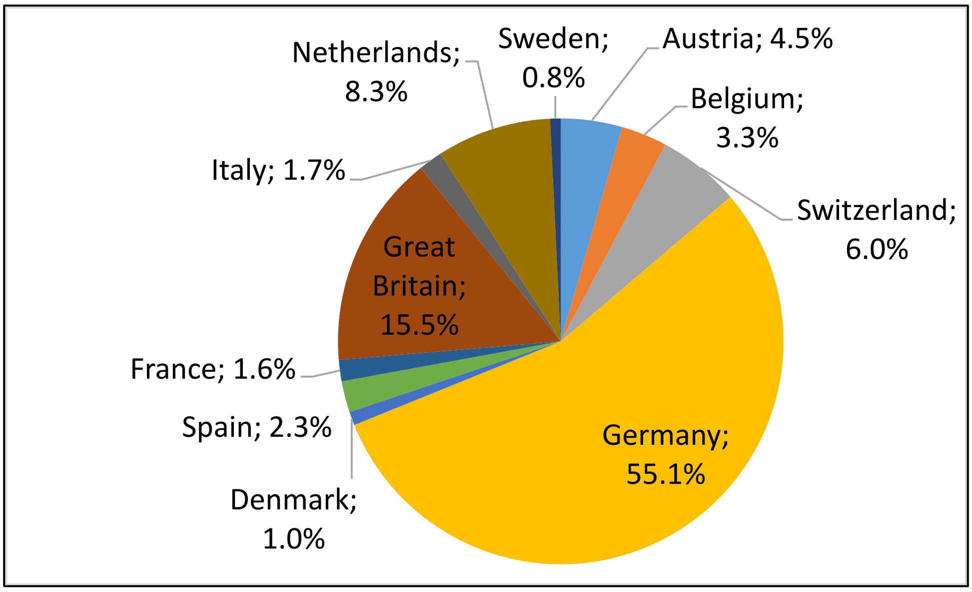

Figure 4-8: GHG emissions of the use phase per country

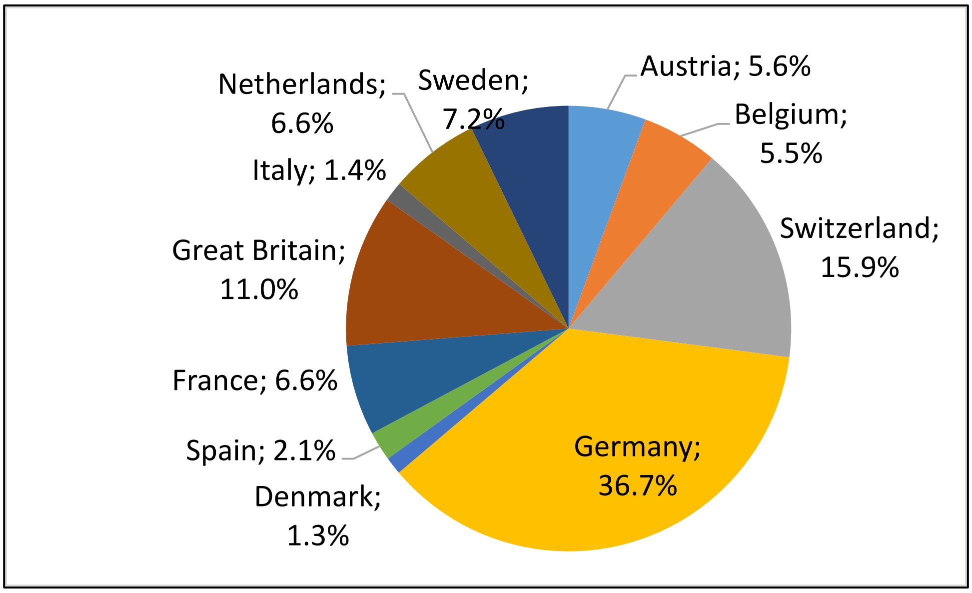

Figure 4-9: Share of sales per country

There are no major differences regarding the impact per country between the different impact categories (see Table 4-6).

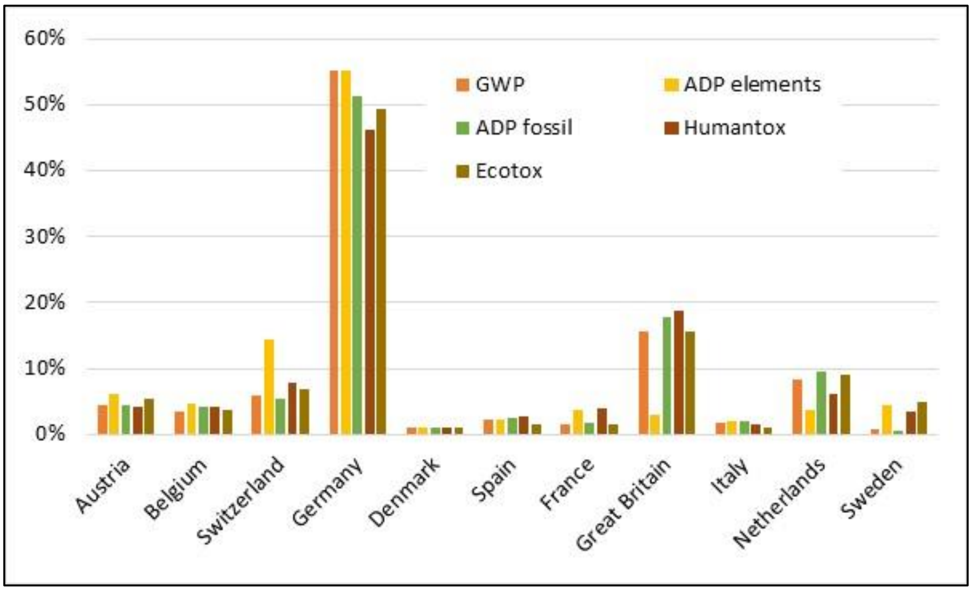

Figure 4-10: Relative impacts of the use phase per country and impact category

4.3.3 EoL

The EoL has for most impact categories a low impact on the overall life cycle. The results are negative for all impact categories, meaning the recycling leads to an environmental benefit (see Table 4-8). Within the EoL model, the energy consuming processes (transportation, smelter processes) have a negative environmental impact, while recovery of secondary metals (Co from battery recycling, gold recovery from precious metals refining) result in a positive impact (credit for avoided metals production). The negative and positive impacts are roughly balanced, resulting in considerably low overall results across all impact categories (see Figure 4-11) except ADP elements where the recycling is strongly positive (see Figure 4-12).

The strongly positive effect (meaning negative result) is connected to the gold. The main impact of ADP elements is predominantly caused by the use of gold. However, the assumed recycling rate of gold is high (95 % according to Chancerel et al. (2014)). Besides, within this study it is assumed that the 100 % of the Fairphone 2 – or in other words all phones – are recycled. The impact of ADP elements is mainly influenced by material consumption of non-fuel resources (e.g. coal, oil, etc.). So the energy input needed for the recycling process as such is almost not reflected in this impact category. These effects together lead to the strongly positive effect of recycling for the impact category ADP elements.

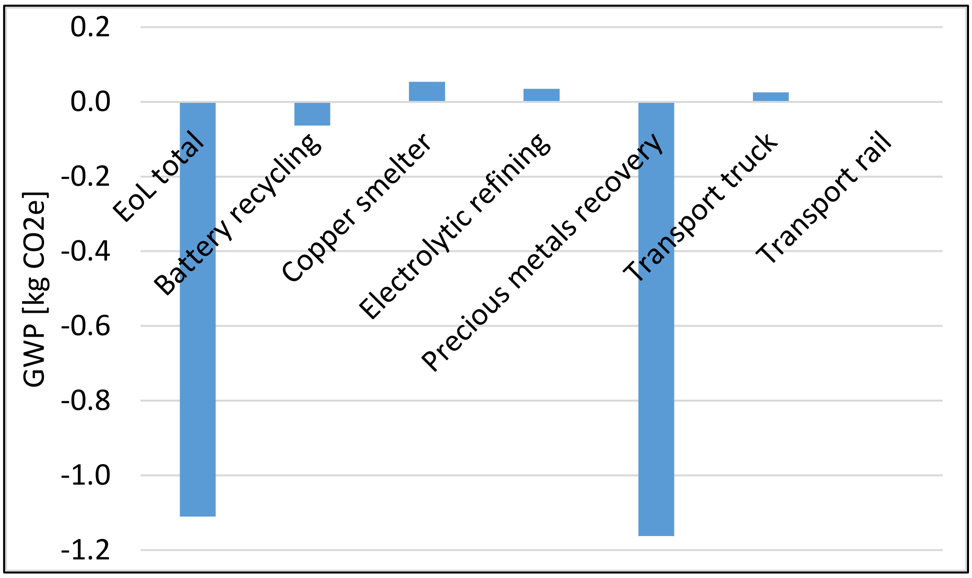

Figure 4-11: Impacts of the EoL phase per process for the impact category GWP

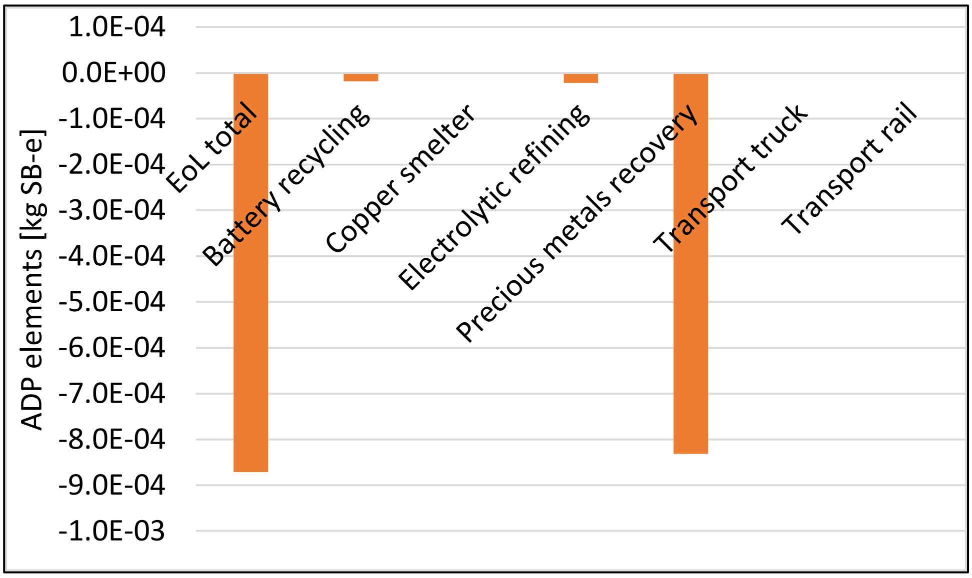

Figure 4-12: Impacts of the EoL phase per process for the impact category ADP elements

4.3.4 Transport

The transportation phase emissions cause a smaller share of the overall life cycle emissions of the Fairphone 2. The highest influence of the transportation phase can be seen for the impact category human toxicity.

Figure 4-13 shows the influence of the transport processes to assembly, to the distribution hub, and to the customer.

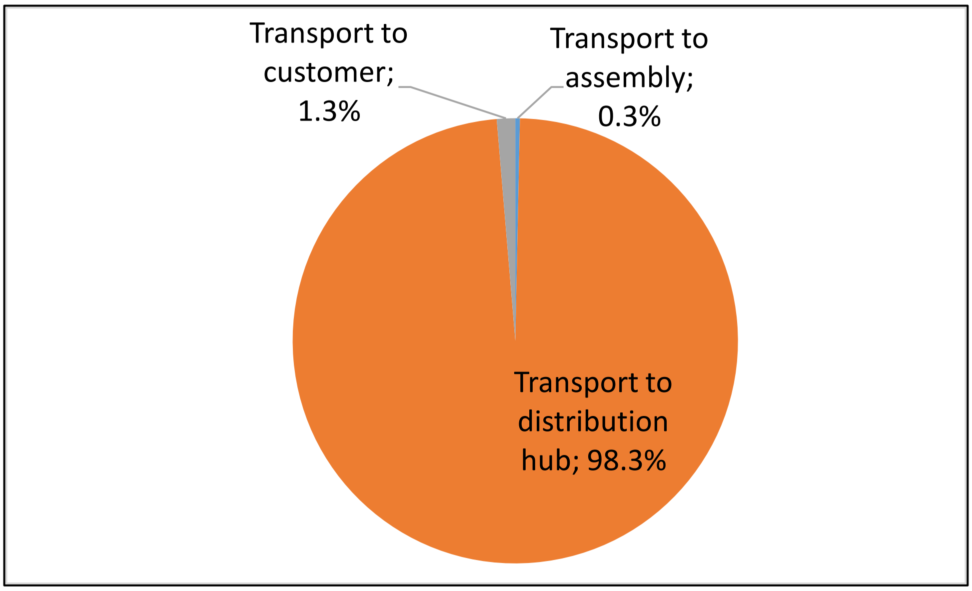

Figure 4-13: Relative impact of transportation phases "to assembly", "to distribution", and "to customer", impact category: GWP

The main influence from the transport processes is caused by the air transport. Truck transport has a smaller influence, which results in the fact, that the transport to customers has a small relative impact (only truck transport assumed) and transport to the distribution hub a high impact (oversea air transport) (see Figure 4-14).

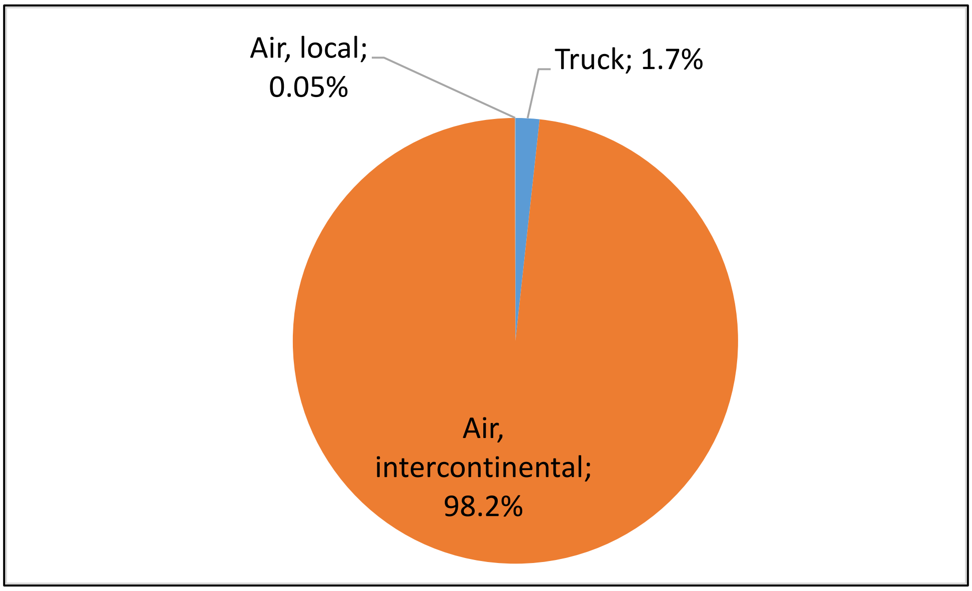

Figure 4-14: Relative impact of the mode of transportation, impact category GWP

There are no major differences between the impact categories (see Table 4-7).

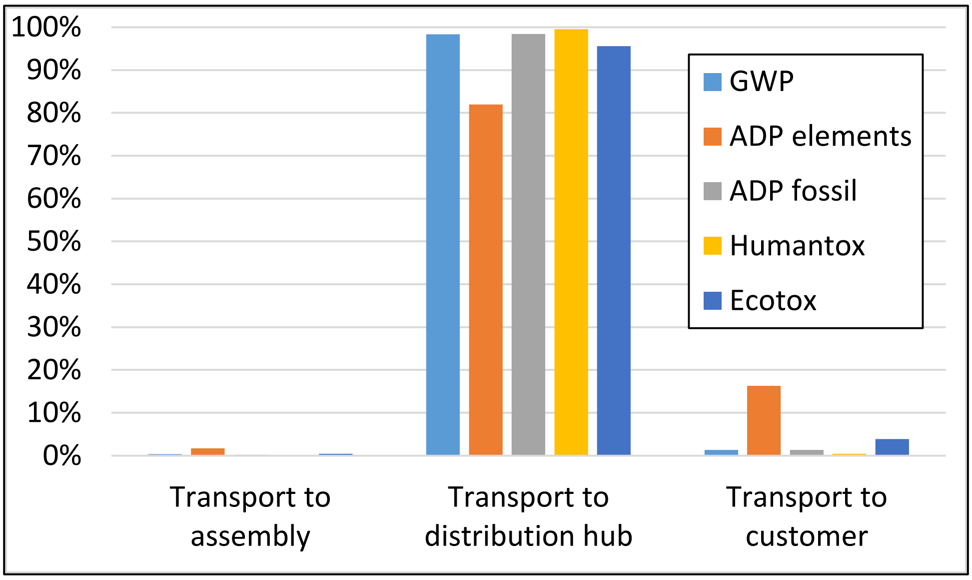

Figure 4-15: Relative impact of the transportation phases “to assembly”, “to distribution”, and “to customer” per impact category

Table 4-6: Results of the use phase

Impact category	Unit	Use	Austria	Belgium	Switzer-land	Germany	Denmark	Spain	France	Great Britain	Italy	Nether-lands	Sweden
GWP	kg CO2e	5.98	0.27	0.20	0.36	3.29	0.06	0.14	0.09	0.93	0.10	0.50	0.05
			4.45%	3.34%	5.99%	55.09%	0.99%	2.26%	1.55%	15.51%	1.74%	8.31%	0.77%
ADP ele-ments	kg Sb-e	2.68E-06	1.65E-07	1.22E-07	3.83E-07	1.48E-06	2.70E-08	5.67E-08	9.83E-08	8.19E-08	5.49E-08	9.57E-08	1.15E-07
			6.17%	4.57%	14.29%	55.18%	1.01%	2.12%	3.67%	3.06%	2.05%	3.57%	4.31%
ADP fos-sil	MJ	63.46	2.85	2.60	3.38	32.52	0.60	1.57	1.09	11.21	1.31	6.03	0.31
			4.49%	4.10%	5.32%	51.24%	0.94%	2.48%	1.72%	17.67%	2.06%	9.49%	0.48%
Humantox	kg DCB-e	2.36E-01	9.83E-03	9.83E-03	1.84E-02	1.09E-01	2.58E-03	6.67E-03	9.44E-03	4.40E-02	3.61E-03	1.44E-02	7.95E-03
			4.17%	4.17%	7.79%	46.29%	1.09%	2.83%	4.00%	18.65%	1.53%	6.12%	3.37%
Ecotox	kg DCB-e	5.00E-03	2.74E-04	1.89E-04	3.47E-04	2.46E-03	4.98E-05	7.49E-05	7.47E-05	7.77E-04	4.60E-05	4.56E-04	2.51E-04
			5.47%	3.78%	6.94%	49.24%	1.00%	1.50%	1.49%	15.54%	0.92%	9.11%	5.02%

Table 4-7: Results of the transportation phase

Impact category	Unit	Transport	Truck	Air, interconti-nental	Air, local	Transport to as-sembly	Transport to distribution hub	Transport to customer
GWP	kg CO2e	3.00	0.05	2.94	0.00	0.01	2.95	0.04
			1.74%	98.22%	0.05%	0.18%	98.53%	1.29%
ADP elements	kg Sb-e	6.05E-07	1.32E-07	4.72E-07	1.65E-10	1.03E-08	4.96E-07	9.84E-08
			21.87%	78.10%	0.03%	1.70%	82.03%	16.27%
ADP fossil	MJ	43.01	0.78	42.21	0.02	0.08	42.35	0.58
			1.80%	98.15%	0.05%	0.18%	98.47%	1.34%
Humantox	kg DCB-e	2.32	0.01	2.31	0.00	0.00	2.31	0.01
			0.54%	99.42%	0.05%	0.09%	99.51%	0.40%
Ecotox	kg DCB-e	3.18E-03	1.65E-04	3.01E-03	1.34E-06	1.39E-05	3.04E-03	1.23E-04
			5.20%	94.76%	0.04%	0.44%	95.69%	3.87%

Table 4-8: Results for the EoL

Impact category	Unit	EoL total	Battery recycling	Copper smelter	Electrolytic refin-ing	Precious metals recovery	Transport truck	Transport rail
GWP	kg CO2e	-1.11	-0.06	0.05	0.03	-1.16	0.03	9.45E-04
ADP elements	kg Sb-e	-8.71E-04	-1.82E-05	7.38E-09	-2.20E-05	-8.31E-04	6.25E-08	3.04E-10
ADP fossil	MJ	-12.85	-0.60	0.33	0.15	-13.14	0.39	1.02E-02
Humantox	kg DCB-e	-8.08E-01	-3.29E-02	4.18E-02	-4.57E-03	-8.19E-01	6.19E-03	4.22E-05
Ecotox	kg DCB-e	-6.87E-03	-3.79E-04	1.88E-04	-8.72E-05	-6.67E-03	8.29E-05	7.80E-07

4.3.5 Modularity

The modularity has a positive effect on reparability and recyclability and can thereby reduce the overall life cycle emissions (see repair scenario in section 5.1). However, the material footprint for the initial production of the Fairphone 2 is higher (compared to a fictional non-modular Fairphone 2) due to the following aspects:

- Board-to-board connectors are needed to connect the different modules
- Additional PCB area are needed for the connectors
- Sub-housing of the modules

In this part of the contribution analysis, the impact of these three aspects is calculated and set into relation to the overall result. The impact of these parts is included in the before discussed total results

For the sub-housing the resulting materials are displayed in Table 4-9.

Table 4-9: Material for sub-housings

Module	Part	Material	Weight [mg]
Top module	Decorated Top Cover Top Module (plastic)		
		Polycarbonate Granulate (PC)	1602.3
		Glass fibers	686.7
	Top Cover Top Module Plate (SUS)	Stainless steel cold rolled coil (304)	1100
	Bottom Cover Top Module	Polyamide 6.6 Granulate (PA 6.6) Mix	773
		Glass fibers	773
Camera module	Top Cover assembly 8M Camera, Print, FP2		
		Stainless steel cold rolled coil (304)	688
	Rear camera module housing		1422
		Polyamide 6.6 Granulate (PA 6.6) Mix	506.5
		Glass fibers	506.5
Bottom module	Top Chassis Bottom Module Assembly		
		Polyamide 6.6 Granulate (PA 6.6) Mix	1355.5
		Glass fibers	1355.5
		Brass (CuZn20)	84
	Base Chassis Bottom Module Assembly		
		Polycarbonate Granulate (PC)	767.2
		Glass fibers	328.8
		Stainless steel cold rolled coil (304)	1199
Totals		Polycarbonate Granulate (PC)	2369.5
		Glass fibers	3650.5
		Stainless steel cold rolled coil (304)	2987
		Polyamide 6.6 Granulate (PA 6.6) Mix	1279.5
		Brass (CuZn20)	84

The additional PCB to enable the board-to-board connectors adds up to the following:

- Mainboard (12 layers): 9.86 cm^2
- Display board (4 layers): 2.70 cm^2
- Top module board (4 layers): 2.88 cm^2
- Bottom module board (4 layers): 0.72 cm^2
- Camera module board (4 layers): 1.47 cm^2

No additional factor for cut-offs was assumed within the sensitivity analysis.

The “modularity parts” make up 4 to 12 % of the production phase depending on the impact category (except ADP elements) and are for most impact categories mainly connected to the additional PCB area and board-to-board connectors (see Table 4-10).

For the impact category ADP elements the situation is different. The “modularity parts” cause about half of the total impacts of the Fairphone 2, which is connected to the amount of gold used in the board-to-board connectors. On the one hand, the use of gold has always a high impact in the impact category ADP elements. On the other hand, the used data set for ICs underestimates the ADP value (see also section 4.4 and 4.5) which leads to a higher share of all other parts.

Table 4-10: Results modularity

Impact category	Unit	Production total	Modularity total	BtB con-nector	Sub-housing	PCB
GWP	kg CO_2e	35.98	1.64	0.94	4.21E-02	0.66
			4.6%	57.4%	2.6%	40.0%
ADP ele-ments	kg Sb-e	1.48E-03	8.33E-04	7.92E-04	9.72E-07	4.02E-05
			56.4%	95.1%	0.1%	4.8%
ADP fossil	MJ	148.03	17.03	9.72	6.52E-01	6.66
			11.5%	57.1%	3.8%	39.1%
Humantox	kg DCB-e	8.35	3.58E-01	8.07E-02	4.38E-02	2.33E-01
			4.3%	22.6%	12.3%	65.2%
Ecotox	kg DCB-e	1.07E-01	6.93E-03	1.23E-03	8.19E-04	4.88E-03
			6.5%	17.8%	11.8%	70.4%

4.4 Sensitivity Analysis

The sensitivity analysis has the goal to analyze how sensitive the results react to changes in the modelling. Therefore, key parameters and parts are analyzed in the following, possible other data sets and modelling approaches are used and the influence on the results shown. This will be done for the following aspects:

- ICs
- Display
- Battery

4.4.1 ICs

The results showed the high impact of ICs on the overall life cycle of the Fairphone 2 for all impact categories except ADP as the used data set does not cover this impact category. Regarding the sensitivity of the results, the result for the mainboard will be described in the following in comparison with two different modelling approaches:

- Use of ecoinvent data sets (all impact categories)
- Use of data from Ercan (2016) (only GWP)

The results are only compared for the mainboard ICs. However, the effect would be the same for ICs on the other module boards and the camera ICs.

Ecoinvent IC data

The relative and absolute impact of the ICs is significantly higher than in the Fairphone 1 LCA (see also section 4.5.1). To show the effect of the different data bases the different data sets used in the modelling, the mainboard of the Fairphone 2 is modelled again with the same ecoinvent data set as used in the Fairphone 1 LCA:

- integrated circuit production, logic type
- integrated circuit production, memory type

The comparison shows that the results drop heavily for the impact category GWP and increases significantly for the other impact categories (see Figure 4-16, for detailed figures see Table 4-11). ADP (elements and fossil) is not covered by the used baseline data model (as described in section 3.1.9.4). Therefore, it was obvious that the impact would increase for these impact categories. However, human- and ecotoxicity were covered by the data set, but the results differ significantly. This sensitivity analysis shows the high variability of the results, but gives no indication which of the toxicity is more closely to "reality".

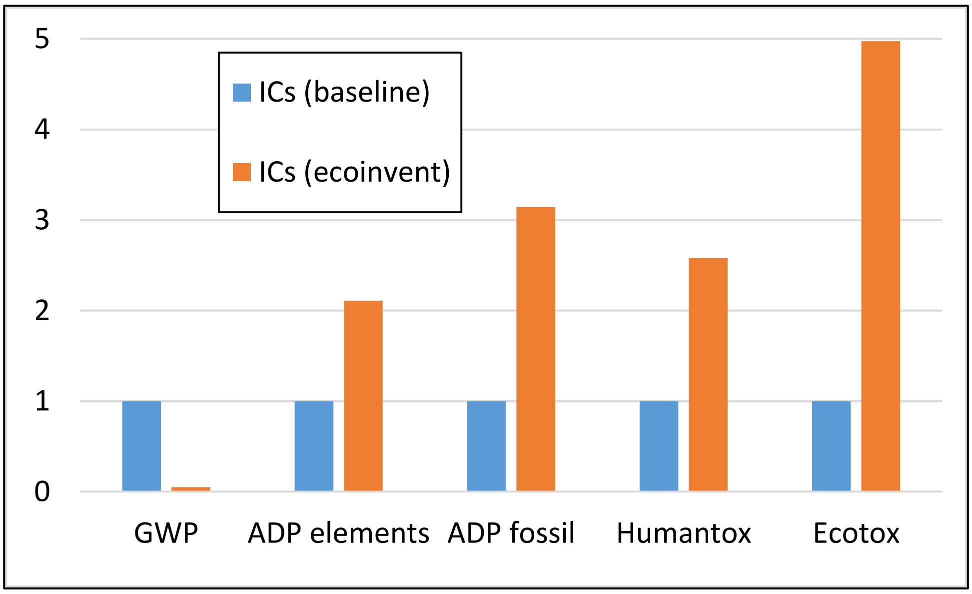

Figure 4-16: Sensitivity ecoinvent IC data – comparison with baseline results (baseline results set to 1)

When comparing the results, it has to be taken into account that the differences of the results do not stem from the differences in the data set alone but also from the different reference flow used. Ecoinvent IC data is scaled by mass, baseline IC data per die size. The assumed die-to-package ratio for the ecoinvent data is not known. So the differences can stem from completely different assumptions regarding the process emissions or from different assumptions regarding the share of front-end and back-end processes. However, the authors of this study consider the die size as the more relevant scaling factor for ICs and the "ecoinvent results" as not reliable.

With the changes in the absolute results, the relative impact of the mainboard changes as well (see Figure 4-17). The PCB becomes the most important impact part of the mainboard for the impact categories GWP, ADP fossil and Ecotox. The ICs are most important for the categories ADP elements and Humantox.

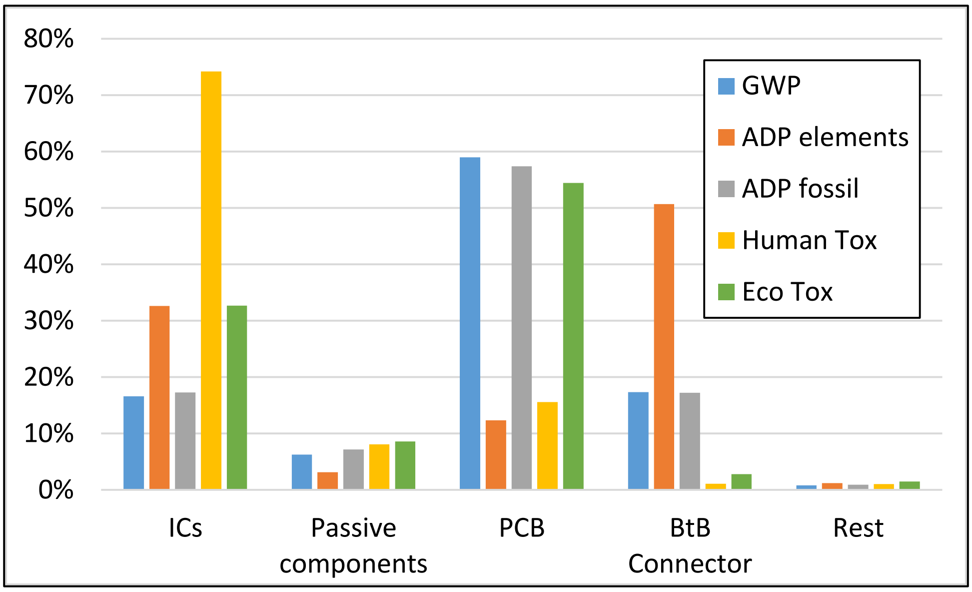

Figure 4-17: Sensitivity ecoinvent IC data - relative impacts of the mainboard per impact category

IC data from Ercan (2016)

Ercan (2016) published an LCA of a smartphone. They used a specific IC data set based on (unpublished) industry data for GWP:

- Logic IC: 3.5 kg CO_2e/m^2 die (front-end), 1 kg CO_2e/m^2 die (back-end)
- Memory IC: 3 kg CO_2e/m^2 die (front-end), 1 kg CO_2e/m^2 die (back-end)

These values are lower than the values used for the baseline calculations, but in the same range and with the same reference flow (die size). The overall results for the mainboard show a slightly lower impact of the ICs (see Figure 4-18, for detailed figures see Table 4-12). The total mainboard results drop by about 9.4 %.

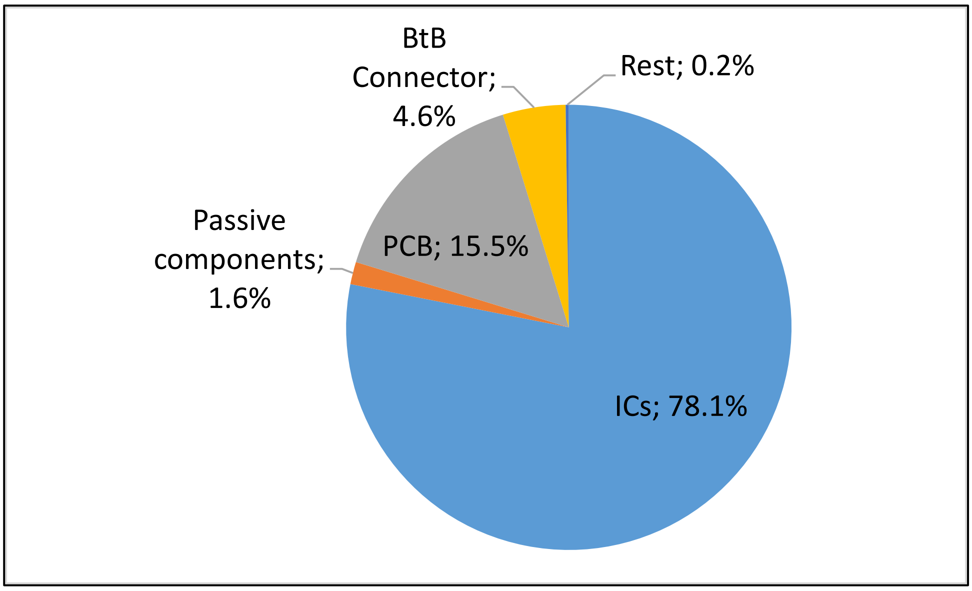

Figure 4-18: Sensitivity Ercan (2016) IC data – relative impact of the mainboard, impact category GWP

Table 4-11: Results mainboard, sensitivity analysis for ICs – ecoinvent data

Impact category	Unit	Mainboard	ICs	Passive components	PCB	BtB Connector	Rest
GWP	kg CO2e	5.31	0.88	0.33	3.13	0.92	0.04
		100.0%	16.6%	6.2%	59.0%	17.3%	0.8%
ADP elements	kg Sb-e	1.53E-03	5.00E-04	4.80E-05	1.89E-04	7.76E-04	1.81E-05
		100.0%	32.6%	3.1%	12.3%	50.7%	1.2%
ADP fossil	MJ	55.37	9.58	3.97	31.79	9.52	0.52
		100.0%	17.3%	7.2%	57.4%	17.2%	0.9%
Human Tox	kg DCB-e	7.29	5.41	0.59	1.14	0.08	0.07
		100.0%	74.2%	8.1%	15.6%	1.1%	1.0%
Eco Tox	kg DCB-e	4.30E-02	1.40E-02	3.69E-03	2.34E-02	1.21E-03	6.50E-04
		100.0%	32.7%	8.6%	54.4%	2.8%	1.5%

Table 4-12: Results mainboard, sensitivity analysis for ICs – data according to Ercan (2016)

Impact category	Unit	Mainboard	ICs	Passive components	PCB	BtB Connector	Rest
GWP	kg CO2e	20.24	15.81	0.33	3.13	0.92	0.05
		100.0%	78.1%	1.6%	15.5%	4.6%	0.2%

4.4.2 Display

For the display sensitivity, the baseline results were compared with a result using an ecoinvent data set for a 17 inch LCD computer display. The data set is scaled per weight (36.7 g). The result is by factor 3.5 higher than for the baseline scenario (impact category GWP).

In comparison, the display result by Ercan (2013) amounts to 3.5 kg CO_2e which most likely includes not only the LCD panel itself but the whole 5.2 inch display unit. This would be in the same range as the result within this study of 2.7 kg CO_2e for the 5 inch display

According to Ercan (2013), the electricity consumption of display manufacturing is about 0.1 kWh/cm^2, which would be a factor 10 compared to the figures by AUO: However, the electricity value from AUO does not include the production of upstream materials.

4.4.3 Battery

The result of the impact assessment for the battery module are relatively low compared to the other components (e.g. 5.6 % contribution to GWP for two battery modules). To evaluate the impact of a different scaling approach from the original data set (notebook battery cell) to the Fairphone 2 battery, the gravimetric energy density of both batteries was compared (Table 4-13).

Table 4-13: Comparison of cell properties

	Comparison of cell properties	
Cell properties	**Fairphone 2 BoM**	**Clemm et al. 2016**
Mass per cell [g]	38	59.51
Capacity per cell [mAh]	2420	3650
Energy per cell [Wh]	9.2	13.9
Gravimetric energy density [Wh/kg]	242	234

In terms of gravimetric energy density, also known as specific energy, both cells were found to be in a similar range, with the Fairphone 2 battery cell having a slightly higher energy density than the laptop cell of the data source (Clemm et al. 2016). This supports the assumption that the cell data set can be scaled by weight (cp. section 3.1.6)

When the original laptop cell is scaled down to the Fairphone 2 cell via energy rather than mass, the scaling factor is 0.6619 (9.2 Wh over 13.9 Wh) as opposed to 0.6385. This means that roughly 3.7 % more material and consumables are required to produce a battery with 9.2 Wh. Consequently, the results of the impact assessment associated with the production of a battery cell are increased by 3.7 % as well. The BMS is not affected by the scaling approach. The results of the battery module using the alternative scaling approach are summarized in Table 4-14.

Table 4-14: Results of the battery module sensitivity analysis

Impact category	**Unit**	**Battery Module scaled via mass**	**Battery Module scaled via energy**
GWP	kg CO_2e	1.96	2.02
		5.6%	5.7%
ADP elements	kg Sb-e	6.39E-05	6.60E-05
		8.16%	8.42%

Impact category	Unit	Battery Module scaled via mass	Battery Module scaled via energy
ADP fossil	MJ	19.31	19.95
		13.88%	14.34%
Humantox	kg DCB-e	1.14	1.17
		13.78%	14.16
Ecotox	kg DCB-e	6.60E-03	6.82E-03
		6.31%	6.50%

4.5 Interpretation

The results shown before are interpreted and set into context regarding data quality, data availability and other existing studies.

Data Quality

The data in this LCA study is based mostly on the data bases ecoinvent and GaBi. From GaBi, especially the electronics extension is used. The overall quality of the GaBi data is estimated to be high. However, there is often not enough documentation in detail.

The basic ecoinvent data is also expected to be good, however electronics data sets (which are used within this data just for components where no specific GaBi data set was available) are quite old (partly ten years and older).

For three main components, individual data not from the data bases was used.

- Battery
- ICs
- Display

Data Availability

As described in the inventory, most parts were modelled according to their material composition if available. Primary data was only available for the assembly process at Hi-P. However, for some parts no specific material compositions were available.

For other components, especially electronic components, modelling according the material composition is not suitable as the use of energy and process chemicals in the production process causes the main environmental impact. Not for all electronic components used in smartphones reliable and up-to-data data sets exist, e.g. no sufficient data sets were included in the data bases GaBi and ecoinvent for:

- ICs
- Displays

Battery

The battery data set stems from Clemm (2016) and is based on primary data from one of the largest manufacturer of battery cells, with the production site located in China. Although the data set is originally for a laptop battery, the technology and material composition fits the Fairphone 2 battery. The primary data set contains data from cell manufacturing in the year 2013, however, more recent data sets are not publicly available.

For the electronic components on the BMS, no perfectly fitting data set could be identified for both the battery protection IC and MOSFET, hence the closest approximation was selected by package size.

Overall, the contribution of the two battery modules assumed during the life cycle of the Fairphone 2 is comparatively low in terms of GWP, but is considerably larger in terms of ADP fossil and Humantox with 13.88 % and 13.78 %, respectively.

ICs

The data for ICs is described in section 3.1.9.4 and is based mainly on data from Boyd (2012) plus additional assumptions. The data set is estimated to be representative for logic ICs, but was used for memory ICs as well as no specific memory data was available and is the closest fit.

There are existing data sets on specific ICs in the GaBi electronics extension data base, however these are scaled per weight or number of pieces. The relevant parameter is the die size though (which is not documented in the GaBi data sets). Therefore it is quite difficult to allocate the correct data set there.

The established IC data set is estimated to be of good quality for logic ICs (especially the CPU) and an acceptable good fit for memory ICs regarding the impact categories GWP and toxicity. This was also shown in the sensitivity analysis with the comparison with data from Ercan (2016). Compared with Ercan (2016), IC front-end data used within this study is comparable, back-end data is higher and leads to differences in the result of the mainboard of about 10 %.

However, data for ADP are missing for the ICs, see also Table 4-4 and Table 4-5 where entries for ICs are "0" for ADP (or very low caused by the material entries for the package). This results in the effect, that the results for ADP are not only too low overall, but also the relative impact of the modules and component types is different from other impact categories.

Display

The display (panel) data set is based on the CSR report from AUO with detailed information regarding PFC and other emissions, energy consumption and waste. The data is estimated reliable for the direct panel production process, but, as the report focusses on scope 1 and 2 emissions, it might be that needed chemicals and processes gases are not named in full detail and are therefore neglected. The named chemicals CF thinner and array stripper are not described further and therefore had to be neglected.

Comparison with data from ecoinvent and Ercan (2013) (see section 4.4.2) showed that the result for the Fairphone 2 calculated here is rather on the low end, but in the right overall dimension. However, up-to-date data is very rare and not detailed enough to assess different display types (e.g. differences in resolution or technology such as OLED).

Board-to-board connectors

The board-to-board connectors are a specific difference between the Fairphone 2 and other smartphones as they are the enablers of the modularity and were modelled according to the material declaration. This study shows that they have a small but considerable impact on the overall life cycle for most impact categories (between 2 and 7 %, see Table 4-5). An exemption is the impact category ADP elements, where the board to board-connectors cause about half of the overall impact (of which a considerable amount can be recycled). This is caused by the gold used for the nickel-gold coated pins in the connectors.

To compare board-to-board connectors with other connection options in the future, the material declaration is suitable.

Cameras

There was little information on the material composition of the cameras and the disassembly process was quite difficult. Therefore, modelling of the mechanical parts was based on estimations. However, there was direct manufacturer information available on the die size of the CMOS sensor chips, which have a high environmental impact compared to the mechanical parts in the camera. So the high-impact parts are covered well.

4.5.1 Comparison with Fairphone 1 LCA

The Fairphone 1 LCA shows a significantly lower result for the Fairphone 1. The difference is mainly related to the production phase, which is for the Fairphone 1 only 15% of the Fairphone 2. Use phase, transport and EoL are similar in both studies with a little higher result for the use phase in the Fairphone 1 LCA.

The hardware of the two phones is different. The following differences of the Fairphone 1 compared to the Fairphone 2 have a direct influence on the LCA modelling:

- 16 instead of 32 GB storage
- 4.3 instead of 5 inch display and thereby overall smaller form factor
- Not modular

However, these differences are not the major reason for the great variance in the results. This is caused by different modelling approaches and data sets used. The main difference in the result is the modelling of the ICs. The ICs are modelled in the Fairphone 1 LCA with ecoinvent "Integrated circuit, logic/memory type", scaled per weight. As shown in the sensitivity analysis (see section 4.4.1), the ecoinvent data leads to significantly lower results and seems (at least for the impact category GWP) not realistic for current IC technologies (see also comparison with Ercan [2016]). Therefore, the IC results between Fairphone 1 and 2 differ by more than factor 20.

For a more in-depth comparison see section 8.1 in the annex.

4.5.2 Comparison with other smartphone LCAs

The overall GHG emission results of the Fairphone 2 LCA are 43.9 kg CO2e (results for the other impact categories can be found in Table 4-2). Compared to other smartphone carbon footprints provided by the different manufacturers, this is a result in the midrange[8]. However, as the comparison with the Fairphone 1 LCA showed, the absolute results depend more on the used data sets than on the actual smartphone properties and functionalities. For most public company LCAs/Carbon Footprints no specific details on modelling approaches and used data are available. However, modelling of the use phase seems (if information is available) quite consistent with three years use and daily charging.

A recent study on the Sony Z3 and Z5 with similar assumption regarding the modelling of ICs by Ercan (2016) (see also section 4.4.1) shows results in the same range for the GWP of 50 kg CO_2e (Z3)/57 kg CO_2e (Z5). Also the distribution of the impacts is similar. The main environmental impact is connected to the electronics (specifically the ICs). This allows no conclusions on differences between the specific smartphones models, but shows that the overall range of results for the Fairphone 2 is realistic.

---

[8] See e.g. Apple 2015; Nokia 2012; Huawei 2012; HTC 2013; Sony 2008; Fairphone 2015; Blackberry 2014, 2015

5 Scenarios

5.1 Repair Scenario

In addition to the baseline scenario, a repair scenario is analyzed assuming an extended use time of five years plus necessary repairs within that time. The following assumptions are applied:

- All phones have to be repaired once within 5 years use
  - 60 % display
  - 20 % camera module
  - 10 % top module
  - 10 % bottom module
  - A replacement of the core module is not assumed for the repair scenario.
- Battery has to be replaced after 2 years, resulting in 3 batteries in 5 years (2 exchange batteries)
- 75% of broken modules are returned to Fairphone B.V. (except display and battery)
- 50% of the broken and returned modules can be repaired or used for refurbishment of other modules/devices
- The environmental impact of the refurbishment process itself (e.g. due to energy use, process gases) is neglected as no data is available.

Batteries cannot be refurbished and a recycling is assumed. For displays, a refurbishment of a broken display module itself is possible (e.g. by replacing broken glass and keeping the LCD panel). However, the process is difficult and requires specialized equipment. Therefore, a refurbishment of the display module was not deemed likely in the near future, in accordance with discussions with Fairphone B.V.

For the repair scenario, a do-it-yourself-approach (DIY) by the user is assumed. “Professional repair” in the Netherlands would cause additional transportation as the entire phone would need to be transported instead of only the broken modules, but no (significant) additional energy consumption is likely as no specialized electric tools or extensive testing is used at the repair side in the Netherlands.

Table 5-1: Assumed repairs and part changes within five years use

	Need for Replacement within 5 years	**% returned to Fairphone B.V.**	**% being repaired/refurbished**	**Total number of modules repaired per 100 broken modules**
Top module	0.1	75	50	3.75
Camera module	0.2	75	50	7.5
Bottom module	0.1	75	50	3.75
Display module	0.6	0		0
Battery	2	0		0

These repair assumptions are established in reference to existing failure rates of smartphones, showing that broken displays are the main failures, followed by water damage, camera and speaker problems. Water damage can lead to different unspecific failures and often fatal damage of the device and is therefore not addressed in the repair scenario. Besides, the existing failure statistics often only cover devices in their first one or two years of use. It is therefore assumed that technical failures will increase compared to accident-induced failures (such as broken displays and water damage).

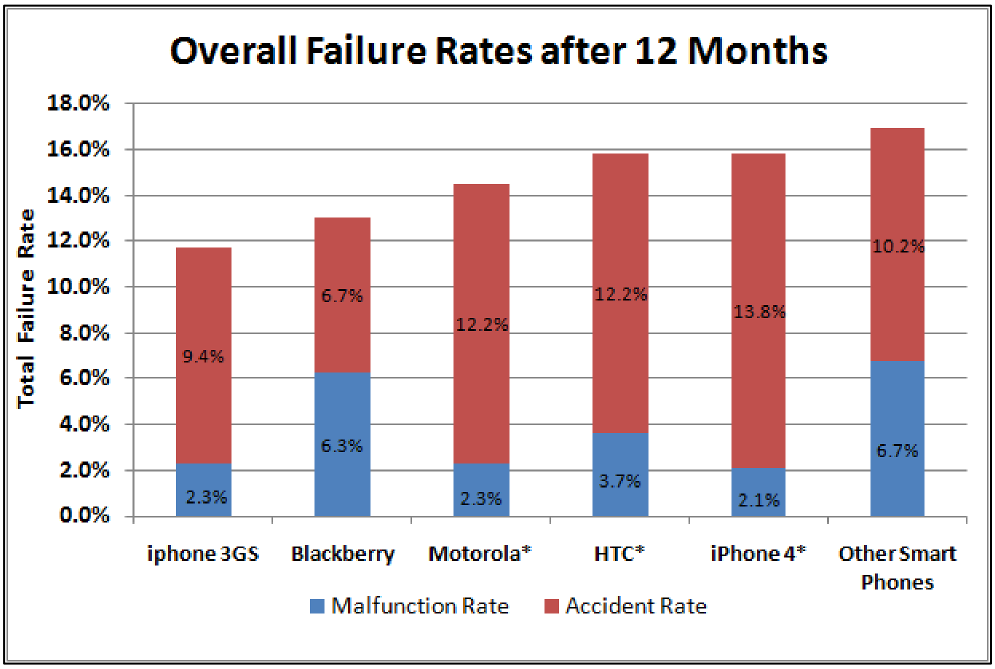

Figure 5-1: Overall failure rate (malfunctioning and accidents) in the first twelve months [Squaretrade 2010]

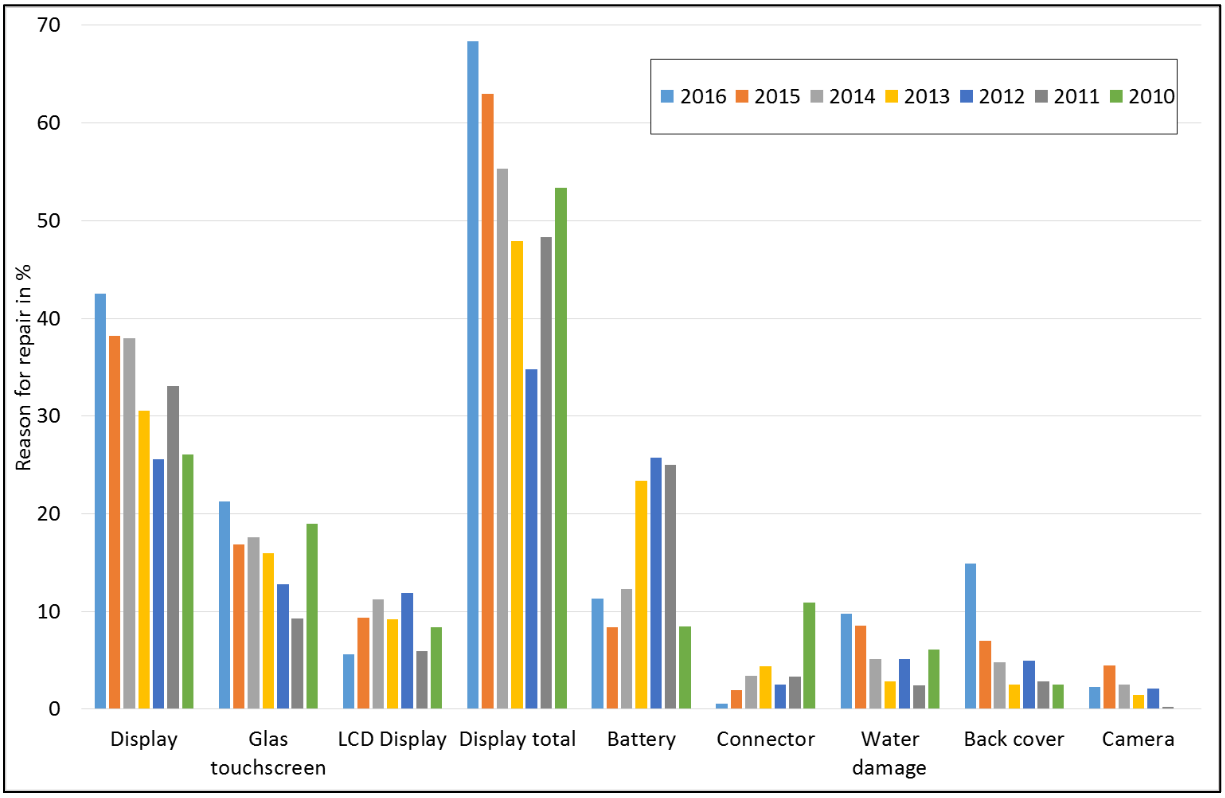

Figure 5-2: Repair reasons according to handyreparaturvergleich.de (calculated as averages per publication year of the devices)

5.1.1 Production

For the repair scenario, an additional production of the replaced modules is assumed. Thereby the number of produced modules is reduced by the number of modules which will be repaired.

The following Table 5-2 shows the number of modules and parts which have to be produced additionally.

Table 5-2: Additional production of parts

	Need for Replacement within 5 years	% returned to Fairphone B.V.	% being repaired/refurbished	Total number of modules repaired per 100 broken modules	Additional parts compared to baseline scenario
Top module	0.1	75	50	3.75	**0.0625**
Camera module	0.2	75	50	7.5	**0.125**
Bottom module	0.1	75	50	3.75	**0.0625**
Display module	0.60	75	50	22.5	**0.6**
Battery	2	0		0	**1**

5.1.1.1 Packaging

Due to repair and replacement additional packaging is calculated. Thereby, only packaging during transport to the distribution hub and to the customer is calculated:

- 3rd battery
- Top module: 0.1 modules per phone
- Camera module: 0.2 modules per phone
- Bottom module: 0.1 modules per phone
- Display module: 0.6 modules per phone

A factor 1 is assumed for the weight of the sales packaging (cardboard) and a factor 0.5 for the bulk packaging (20 %, 80 % cardboard). This results in the following additional packaging:

- Sales packaging: 72 g cardboard
- Bulk packaging:
    - 29 g cardboard
    - 7 g plastic

The same assumptions as for the baseline scenario apply (see section 3.1.10).

5.1.2 Use

The use time in the repair scenario is extended to five years (compared to three years in the baseline scenario). This results in an energy consumption of 24.5 kWh. All other assumptions for the use phase stay the same (see section 3.2).

5.1.3 End-of-Life

The assumptions regarding recycling are not adjusted.

5.1.4 Transport

Due to repair and replacement additional transport is calculated. Thereby, only transport to the distribution hub and to the customer is calculated:

- 3rd battery
- Top module: 0.1 modules per phone
- Camera module: 0.2 modules per phone
- Bottom module: 0.1 modules per phone

- Display module: 0.6 modules per phone

As transported weight, a factor 1 is assumed for the sales packaging and a factor 0.5 for the bulk packaging. The transportation to customer (for modules except display and battery) is calculated twice as it is assumed that broken modules are returned to Fairphone B.V.

This results in the following additional transportations:

- Transportation to customer: 98.33 kg*km truck
- Transportation to distribution hub:
    - Truck: 18.9 kg*km
    - Oversea air: 956.88 kg*km

The same assumptions as for the baseline scenario apply (see section 3.4).

5.1.5 Results and Interpretation

The results for the repair scenario can be found in Table 5-3.

Table 5-3: Results repair scenario (with module refurbishment)

Impact category	Unit	Total	Production	EoL	Use	Transport
GWP	kg CO2e	52.39	38.97	-1.14	9.97	4.59
		100.0%	74.4%	-2.2%	19.0%	8.8%
ADP elements	kg Sb-e	6.56E-04	1.53E-03	-8.81E-04	4.44E-06	9.21E-07
		100.0%	233.3%	-134.2%	0.7%	0.1%
ADP fossil	MJ	324.71	166.11	-13.07	105.79	65.89
		100.0%	51.2%	-4.0%	32.6%	20.3%
Humantox	kg DCB-e	12.42	9.29	-0.82	0.39	3.56
		100.0%	74.8%	-6.6%	3.2%	28.7%
Ecotox	kg DCB-e	1.22E-01	1.16E-01	-7.04E-03	8.34E-03	4.86E-03
		100.0%	94.9%	-5.8%	6.8%	4.0%

The results are higher than for the baseline scenario, but thereby it has to be taken into account that they are calculated for a five year (instead of three year) use. To set that into context, the following Figure 5-3 shows the results per year of use for the baseline and repair scenario.

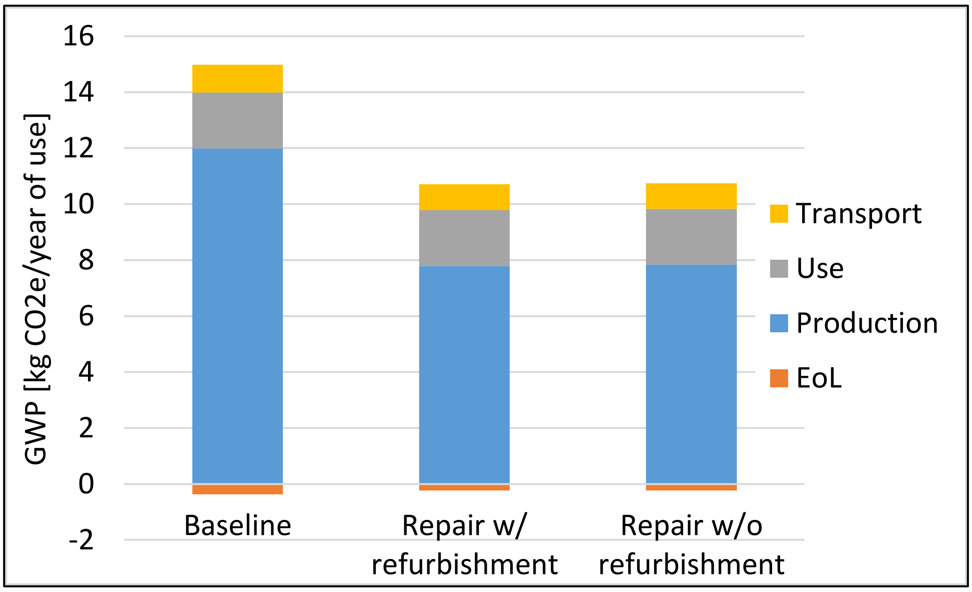

Figure 5-3: Results per year of use - baseline and repair scenario (with and without refurbishment of modules)

This shows that a longer use time of the Fairphone 2 is beneficial even when additional modules have to be produced in case of repairs. This is due to the fact that the main environmental impact is caused by the core module (see section 4.3.1) which is kept over the whole life cycle in the repair scenario.

The benefits through repair and longer use compared to the baseline scenario are between 20 and 35 % depending on the impact category and thereby outweigh the additional impact through the modular design in all impact categories (see section 4.3.5).

The impact of the refurbishment process itself was neglected for the repair scenario, but as the number of refurbished modules is assumed to be small in the analyzed repair scenario, the repair scenario is beneficial even without refurbishment of broken modules (see Figure 5-3 and Table 5-4).

Table 5-4: Results repair scenario (without module refurbishment)

Impact category	Unit	Total	Production	EoL	Use	Transport
GWP	kg CO2e	52.61	39.18	-1.14	9.97	4.59
		100.0%	74.5%	-2.2%	18.9%	8.7%
ADP elements	kg Sb-e	6.61E-04	1.54E-03	-8.81E-04	4.44E-06	9.21E-07
		100.0%	232.5%	-133.3%	0.7%	0.1%
ADP fossil	MJ	325.13	166.53	-13.07	105.79	65.89
		100.0%	51.2%	-4.0%	32.5%	20.3%
Humantox	kg DCB-e	12.45	9.32	-0.82	0.39	3.56
		100.0%	74.8%	-6.6%	3.2%	28.6%
Ecotox	kg DCB-e	1.22E-01	1.16E-01	-7.04E-03	8.34E-03	4.86E-03
		100.0%	95.0%	-5.8%	6.8%	4.0%

5.2 Scenario Housing

The Fairphone 2 has a plastic housing. Two different design housing designs are analyzed as options:

- “New” plastic housing

- Metal housing

The changes in the model only effect the back cover (see section 3.1.7). All other modules, life cycles phases and assumptions are not changed. Also the EoL-model was not adjusted.

“New” plastic Housing

For future versions of the FP2, the current back cover will eventually be replaced by a new plastic housing, which consists of 17.47 g polycarbonate (PC) and 1.21 g thermoplastic polyurethane (TPU), resulting in a total weight of 18.68 g. This case will be slightly lighter than the previous one, with a higher share of PC, giving it a minor environmental advantage since less material is used. The material composition does not have a significant influence as the environmental impacts of both materials (PC and TPU) are roughly the same, leaving aside that 50 % of the PC used is stated to be post-consumer recycled. This would lower the impact greatly, but could also be applied to other case designs. The additional effect of post-consumer plastic could not be assessed as no corresponding life cycle data was available.

Metal housing

As a different design option, the effect of a metal housing instead of plastic housing is analyzed. The specifications of the metal housing do not exist yet. Therefore, the aluminum back cover of the iPhone 6, which has roughly the same form factor as the Fairphone 2, is used as a proxy. The weight of the aluminum back cover is ~ 32 g compared to ~ 20 g of the plastic back cover.

5.2.1 Results and Interpretation

The replacement of the casing has no significant impact on the absolute results or the relative share of the life cycle phases (see Table 5-5). The only exemption is the impact category human toxicity which increases in case of an aluminum housing.

The scenario neglects changes in the recycling process. For the aluminum back cover – assuming a positive effect of the recycling (as it can be easily separated and recycled) –, the overall impact on the whole life cycle would be even lower.

Table 5-5: Results for the housing scenario

Impact category	Unit	Production	Back cover	New Plastic Housing	Metal Housing
GWP	kg CO_2e	35.98	0.09	0.08	0.32
			0.2%	0.2%	0.9%
ADP elements	kg Sb-e	1.48E-03	3.69E-07	3.58E-07	2.26E-07
			0.02%	0.02%	0.02%
ADP fossil	MJ	148.03	1.81	1.71	3.46
			1.2%	1.2%	2.3%
Humantox	kg DCB-e	8.35	2.57E-03	2.46E-03	1.05
			0.03%	0.03%	12.6%
Ecotox	kg DCB-e	1.07E-01	8.58E-05	8.08E-05	5.11E-04
			0.08%	0.08%	0.5%

6 Conclusions and Recommendations

The results show that the electronic components as such cause the main environmental impact. Industrial design decisions such as housing materials have a minor impact. Because the main impact is caused by the product manufacturing, prolonging the use time (number of years) has a high potential to reduce the overall environmental impact as it was also shown by the analyzed repair scenario. Thereby, the modular design – although increasing the initial production impact slightly – has the ability to reduce the overall environmental impact through enabled repairs.

The analysis again also shows the on-going problem with life cycle assessments for electronics: the availability of specific and up-to-date life cycle data on electronics is still not sufficient and variances between different data bases and sources is high. Nevertheless, the overall results are deemed reliable.

6.1 Recommendations

One of the goals of this LCA study was to identify hotspots and derive recommendations. In the following recommendations regarding product design but also limitations are described.

ICs

ICs have the highest environmental impact when modelled according to this study or Ercan (2016). This is also in accordance with other studies (e.g. LCA to go (2014)). Reducing the number of ICs and thereby the die size would result in significant reduction of the environmental impact. But as the ICs are directly enabling the functionality of the device, they cannot be easily reduced. However, this is a clear indicator that overdimensioning of the hardware performance has a significant environmental impact. A balance between designing an up-to-date product which can keep up with on-going trends and avoiding overdimensioning is needed at the same time.

PCBs

The results also show a significant impact of the PCBs. The environmental impact of the PCBs is allocated to area and number of layers, and thus, reducing the overall PCB area in a device has a positive effect. However, environmental trade-offs are expected if the area reduction is achieved through an increased number of layers. At the same time, reducing the number of layers is only beneficial when it is not achieved through an increase in area.

When designing the PCB in miniaturized products such as smartphones and tablets, the PCB area is often designed around other components (e.g. battery) leading to unusual shapes (L- and U-shapes) which can have a high production impact due to large cut-offs even when the actual board area is quite small. So the design process should try to achieve the following:

- Small overall board area
- Simple shapes to reduce cut-offs
- Reduce produced area by nesting boards on the produced PCB panel (as it is already done for the Fairphone 2 PCBs, see Figure 6-1)

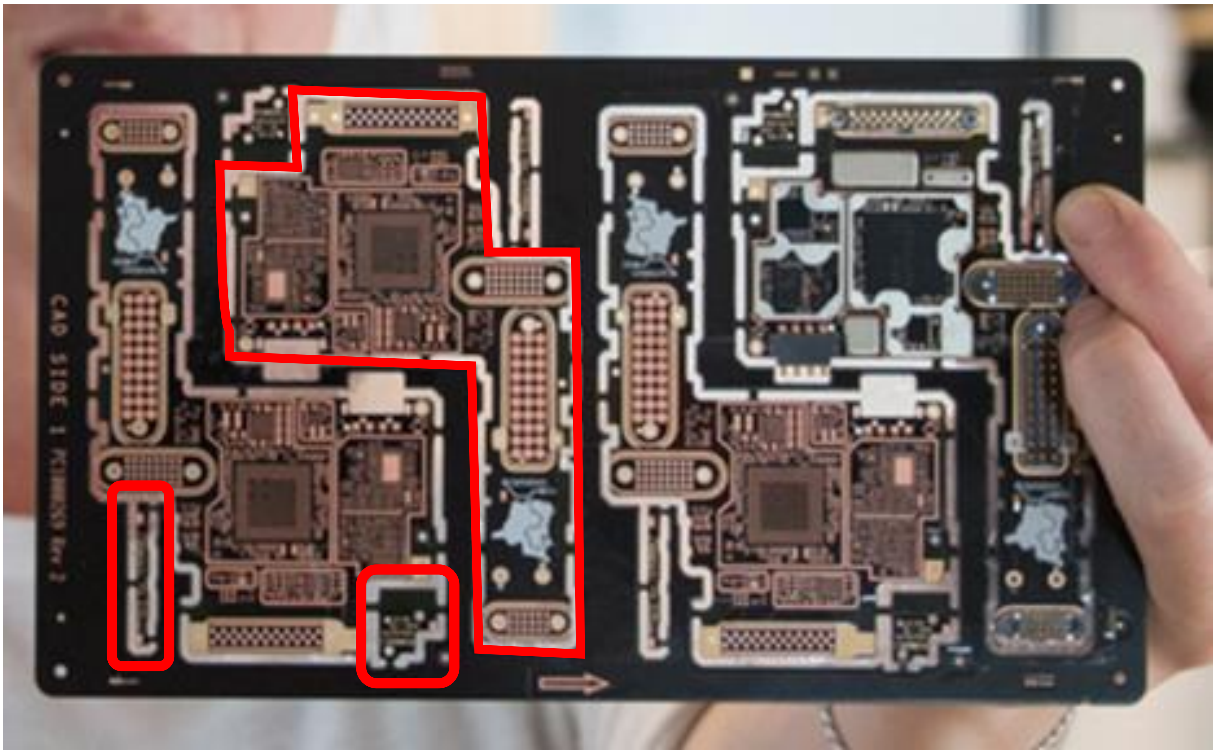

Figure 6-1: Arrangement of mainboard and two antenna boards of the Fairphone 2 on one production panel, 4 boards each per panel [Source: Fairphone B.V.]

Connectors

The board-to-board connectors are a component designed specifically for the modular approach of the Fairphone 2. The contribution analysis in section 4.3 shows that the connectors have a minor share in most impact categories. An exception is the impact category ADP elements where the connectors cause a significant share of the impact (see section 4.3.5) which is mainly attributed to the gold which is used for the connector pins and contacts on the PCB.

Reducing the coating thickness of pins and contacts would reduce the amount of gold used and thereby the environmental impact. The thickness of the gold coating is connected to the long-term reliability as a thinner coating will abrade faster. However, the existing pins of the board-to-board connectors consist of 1 mass percent gold. As the boards are not constantly un- and replugged (as e.g. the MicroUSB connector), a thinner gold coating would be worthwhile to consider (and test).

Another option to reduce the impact of the connectors indirectly would be to reduce their size. Section 4.3.5 shows that for the other impact categories, the main impact of the modularity is caused by the PCB area needed for the board-to-board connectors (see also Figure 6-2). Hence, by reducing the size of the connectors, the corresponding PCB area could also be reduced.

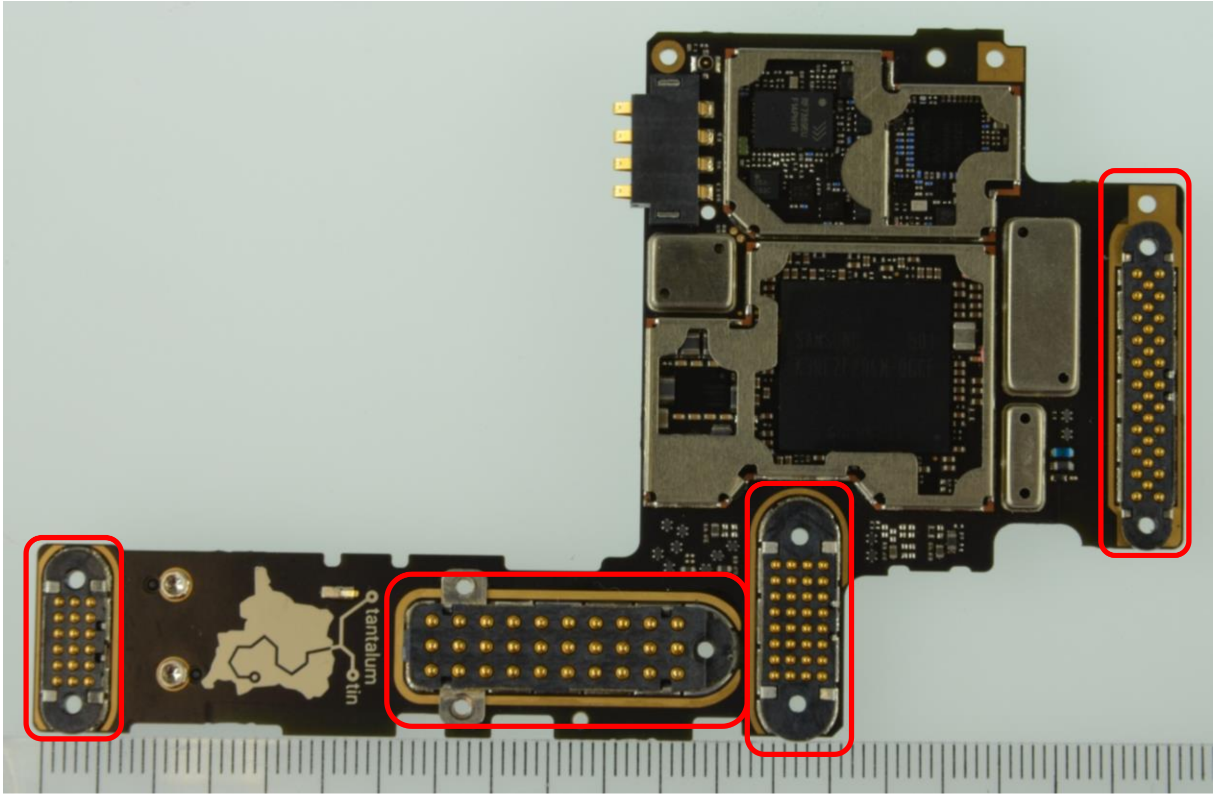

Figure 6-2: Mainboard, board-to-board connectors marked in red [Source: Fraunhofer IZM]

Display

The size of the display is directly correlated to the environmental impact. Thus, reducing the display size would be an obvious option to reduce the overall impact.

Displays are one of the weak points of a smartphone's robustness and a broken display glass is a common defect (see e.g. handyreparaturvergleich.de). Therefore, protecting the display through design measures should be a priority. This is already done for the Fairphone 2 with the plastic rim extending form the back cover along the display. It should be monitored whether the plastic rim fulfills its planned function and effectively reduces the actual number of broken displays.

As a following point, repair should be enabled (as it is done with the modular design of the Fairphone 2). The repair scenario showed that replacement of the display as a repair measure has a positive overall result. However, this positive effect could even be increased if the display itself would be repairable. The display causes a share of about 2 to 5 % of the overall impact. The main share is caused by the production of the LCD panel. Most defects are only broken cover glasses while the actual display panel is still intact.

Therefore, display glass and LCD panel which are not fused together can allow a repair in case of broken glass. This of course would require qualified repair personnel and equipment. On the other hand, robustness has to be taken into account to ensure that a display without fused LCD/glass is sufficiently reliable and offers enough ingress protection against humidity and dust.

Regarding the technology type, existing data is not sufficient to give specific advice. OLED is a technology option instead of LED. However, as described in the LCI, there is not even a reliable data set for an LED touch display yet, which had to be derived from a company CSR report. No data sets exist for OLED displays. Hence, a comparison from an LCA perspective is currently not possible.

OLED displays are expected to improve energy efficiency slightly compared to similar LCD displays while (at the moment) a lower lifetime compromises the benefits. At the same time, manufacturing of OLEDs is more complex which however cannot yet be described in environmental terms, as life cycle data is missing. Due to the lack of suitable data sets, a quantification of the trade-off is currently not possible, but it is assumed that – because the energy consumption in the use phase causes a smaller share of the life cycle impact of a smartphone – at the current state of technology an OLED display does not pay-off from environmental perspective.

Dimensioning of the hardware

In case of the overall design and hardware configuration, it has to be kept in mind that all parts have to be produced and no functionality comes "for free". Therefore, over-dimensioning should be avoided. Besides, the production efficiency increases for many parts (especially memory and storage). So upgradeable hardware can be beneficial from an environmental perspective, instead of a maximum configuration right from the start.

Battery

The battery has a relevant environmental impact. The battery lifetime determines how many batteries have to be produced over the whole life cycle, so using high-quality, durable batteries is important. In a similar fashion to the discussion on overdimensioning of ICs above, there may be trade-offs in terms of battery durability and environmental impact of the production process. While a battery with a high capacity relative to the power consumption of the device may reduce the number of charging cycles required per time, this may also mean an increase in the amount of materials and consumables required for the production process of such a cell.

Although it is expected that the energy density of battery cells will continue to increase, a higher capacity battery cell may also mean increased dimensions of the battery. While many smartphone manufacturers are able to maximize the battery dimensions within the device while keeping devices lean in design, this often comes at the cost of integrating batteries, rendering them non-accessible to the user. For the sake of the longevity of the Fairphone, it is not recommended to integrate the battery in a future version of the Fairphone, thus keeping the battery accessible and replaceable by the user.

Mode of transportation

Smartphones tend to be shipped from their place of manufacturing, most commonly China, to the distribution hubs in Europe and the USA via air freight. If the option of shipping via rail or oceanic vessel is feasible as an alternative, it has the potential to reduce the impacts associated with the transportation of the final product. However, considerable delays compared to air freight are to be expected.

Data availability/acquisition

The LCA showed that – not only for the Fairphone 2 but for electronics in general – up-to-date and specific life cycle data for electronics is missing. Collecting primary data from component manufacturers is time consuming and difficult, as e.g. confidentially problems might occur. Therefore, it was not possible to derive primary data from component suppliers within this study. Nevertheless, Fairphone B.V. should pursue this work. Focus on the primary data collection should be on parts and components with a high production impact:

- ICs, especially CPU and memory
- Display
- PCBs
- Battery

Such primary data has the potential to improve the quality of the LCA and enhance the accurate fitting to the specific Fairphone characteristics. It also builds the foundation for an individual hotspot analysis in the Fairphone manufacturing process.

The effect of an increased share of primary data on the numeric LCA result is difficult to predict. It is often the case that more detailed analyses result in higher estimated environmental impacts (as more processes and materials are covered). This however should not be seen as a drawback, as it still helps to improve the overall quality of the assessment and increase the knowledge about the product’s manufacturing processes.

7 Literature

Apple 2015 — Environmental Product Reports, overview, online: http://www.apple.com/environment/reports/ (8/31/2016)

Apple 2016 — Apple: Environmental Responsibility FAQ, online http://www.apple.com/environment/answers/

Blackberry 2014 — Blackberry: Fiscal 2014 Corporate Responsibility Report., 2014, online: http://us.blackberry.com/content/dam/bbCompany/Desktop/Global/PDF/corporate-responsibility/Corporate_Social_Responsibility_Report_2014.pdf (08/31/2016)

Blackberry 2015 — Blackberry: Lifecycle Sustainability, 2015, online: http://us.blackberry.com/company/about-us/corporate-responsibility/product-sustainability.html#longer-life (08/31/2016)

Boyd 2012 — Sarah B. Boyd: Life-Cycle Assessment of Semiconductors, 2012

Chancerel 2016 — Perrine Chancerel, Max Marwede: Feasibility study for setting - up reference values to support the calculation of recyclability/recoverability rates of electr(on)ic products – DRAFT REPORT, JRC Technical Reports, 2016, online: http://eplca.jrc.ec.europa.eu/uploads/TUB-JRC_Feasibility-study_Final-report_Draft-for-stakeholder-consultation.pdf

Clemm 2016 — Christian Clemm, Paul Mählitz, Alexander Schlösser, Vera Susanne Rotter, Klaus-Dieter Lang: Umweltwirkungen von wiederaufladbaren Lithium-Batterien für den Einsatz in mobilen Endgeräten der Informations- und Kommunikationstechnik (IKT), TU Berlin, Herausgeber: Umweltbundesamt, Dessau-Roßlau, 2016

CML 2001 — Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

CoC EPS 2013 — Code of Conduct on Energy Efficiency of External Power Supplies – Version 5, Ispra, 29 October 2013, online: http://iet.jrc.ec.europa.eu/energyefficiency/sites/energyefficiency/files/files/documents/ICT_CoC/code_of_conduct_for_eps_version_5_-_final.pdf

Deubzer 2012 — Deubzer, O.; Jordan, R.; Marwede, M.; Chancerel, P.: Categorization of LED products, Project cycLED - Cycling resources embedded in systems containing Light Emitting Diodes, Deliverable 2.1, Berlin, May 2012

EC 78/2009 — Commission Regulation (EC) No 278/2009 of 6 April 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for no-load condition electric power consumption and average active efficiency of external power supplies, online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:093:0003:0010:EN:PDF

Ercan 2016 Mine Ercan, Jens Malmodin, Pernilla Bergmark, Emma Kimfalk, Ellinor Nilsson: Life Cycle Assessment of a Smartphone, ICT4S, Netherlands, September 2016

Fairphone 2015 Fairphone: Examining the Fairphone's environmental impact, 2015, online: https://www.fairphone.com/2015/01/22/first-fairphones-environmental-impact/ (08/31/2016)

Güvendik 2014 Merve Güvendik: From Smartphone to Futurephone – Assessing the Environmental Impacts of Different Circular Economy Scenarios of a Smartphone Using LCA, Delft University of Technology, Leiden University, August 2014

Hagelüken 2006 Christian Hagelüken: Recycling of Electronic Scrap at Umicore. Precious Metals Refining. Conference: Acta Metall. Slovaca, At Strbske Pleso, Slovakia, Volume: Waste - Secondaery Raw Materials III

Hischier 2007 Roland Hischier: Life Cycle inventories of Packagings and Graphical Papers. Ecoinvent report nr. 11. Dübendorf.

HTC 2013 HTC One Carbon Footprint Report, 2013, online: https://www.htc.com/assets-desktop/images/csr/tw/download/HTC-One-CFP-report.pdf

Huawei 2012 Huawei Investment & Holding Co., Ltd.: 2012 Sustainability Report, online: www.huawei.com/ilink/en/download/HW_263589 (08/31/2016)

LCA to go EU FP7-Project: Boosting Life Cycle Assessment Use in European Small and Medium-sized Enterprises – Serving Needs of Innovative Key Sectors with Smart Methods and Tools, 2011-2014, online: http://www.lca2go.eu

Nokia 2012 Nokia Lumia 920 Eco profile, 2012, online (only available in cache anymore): http://webcache.googleusercontent.com/search?q=cache:1DbgUodRf8kJ:nds1.nokia.com/eco_declaration/files/eco_declaration_phones/Lumia_920_Eco_profile.pdf+&cd=1&hl=de&ct=clnk&gl=de

Oers 2016 Lauran van Oers, Jeroen Guinée: The Abiotic Depletion Potential: Background, Updates, and Future, Resources, 2016, online: http://www.mdpi.com/2079-9276/5/1/16 (checked: 10/24/2016)

OV2685 2015 OmniVision: OV2685 2MP product brief, October 2015, online: http://www.ovt.com/download_document.php?type=sensor&sensorid=141 (checked: 08/29/2016)

OV8865 2014 OmniVision: OV8865 8MP product brief, October 2014, online: http://www.ovt.com/download_document.php?type=sensor&sensorid=134 (checked: 08/29/2016)

Prakash 2013 Siddharth Prakash, Ran Liu, Karsten Schischke, Dr. Lutz Stobbe: Schaffung einer Datenbasis zur Ermittlung ökologischer Wirkungen der Produkte der Informations- und Kommunikationstechnik (IKT) Teilvorhaben C des Gesamtvorhabens Ressourcenschonung im Aktionsfeld Informations- und Kommunikationstechnik (IKT), Dessau-Roßlau, 2013

Schmidt 2011 Mario Schmidt, Heidi Hottenroth, Martin Schottler, Gabriele Fetzer, Birgit Schlüter: Life cycle assessment of silicon wafer processing for microelectronic chips and solar cells, International Journal of Life Cycle Assessment, 2011

Sommer 2013 Philipp Sommer: Recycling Potential of Rare Earth Elements and Cobalt in WEEE-Batteries. Diploma Thesis. Technische Universität Berlin, Fachgebiet Abfallwirtschaft. Berlin, 2013.

Sony 2008 Sony: Carbon Footprint, 2008, online: http://blogs.sonymobile.com/about-us/sustainability/carbon-footprint/approach/ (31/08/2016)

Squaretrade 2010 Squaretrade: Smart Phone reliability: Apple iPhones with fewest failures, and major Android manufacturers not far behind, November 2010, online: http://www.squaretrade.com/cell-phone-comparison-study-nov-10

Stranddorf 2005 Heidi K. Stranddorf, Leif Hoffmann, Anders Schmidt: Update on Impact Categories, Normalisation and Weighting in LCA – Selected EDIP97-data, Environmental Project Nr. 995, 2005, online: http://www2.mst.dk/udgiv/publications/2005/87-7614-570-0/pdf/87-7614-571-9.pdf (checked: 10/24/2016)

Yamagouchi 2013 Yamaguchi, H., Taharn, K., Itsobo, N., & Inaba, A.: A Life Cycle Inventory Analysis of Cellular Phones, EcoDesign2003/P-I 0, p. 445–451, 2003

Zgola 2011 Melissa Lee Zgola: A Triage Approach to Streamline Environmental Footprinting: A Case Study for Liquid Crystal Displays, MIT, 2011

ZVEI 2011 Russ, R.; Bipp, H.-P.; Jantschak, A.; Stiewe, M.; Cedzich, A.; Dietrich, M.: Abschlussbericht zur Selbstverpflichtung der Halbleiterhersteller mit Produktionsstätten in der Bundesrepublik Deutschland zur Reduzierung der Emissionen bestimmter fluorierter Gase, ZVEI - Zentralverband Elektrotechnik und Elektronikindustrie e.V., Fachverband Electronic Components and Systems, Frankfurt, November 2011

8 Annex

Excluded from this public version of the report.