Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.1. Results of environmental, economic and social preliminary analyses

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Executive summary

The C-SERVEES project aims to boost a resource-efficient circular economy in the electrical and electronic sector through the development, validation and transfer of new circular economy business models. These models are based on systemic eco-innovative services that include: (1) eco-leasing of EEE, (2) product customization, (3) improved WEEE management, and (4) ICT services to support other eco-services.

The new circular economic business models are being implemented and tested by means of demonstrations involving four target products: washing machines, laser printers and their toner cartridges, telecom equipment and TV sets. The demonstrations involve the whole life cycle of the four target products, their associated value and supply chains, and the proposed eco-innovative services.

The techno-economic, environmental and social feasibility of the target products and related eco-services will be determined by means of life cycle sustainability assessment tools, including environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA). Two different types of scenario will be assessed and compared for each target product:

- A conventional scenario, in which the products are produced and consumed under linear economy models.
- The C-SERVEES scenario, in which the products are produced and consumed under the new circular economy models relying on the systemic eco-innovative services demonstrated in the project.

This Deliverable 5.1 shows the life cycle sustainability assessment of each target product under the conventional scenario. It includes the environmental, economic and social impacts of each target product, which were calculated using LCA, LCC and S-LCA, respectively.

The environmental impacts were determined using the LCA methodology according to ISO standards (14040/14044). The assessment comprised the whole life cycle of the products, including: extraction and processing of raw materials, manufacturing, transport and distribution, use, maintenance (when required) and end of life. A complete life cycle inventory was first developed for each product, including energy and material uses and releases to the environment for each life cycle stage. The inventory was then converted into environmental impacts by using the life cycle impact assessment method ReCiPe, which allowed to assess 18 midpoint impact categories (including global warming) and 3 endpoint impact categories (damages to human health, ecosystem diversity and resource availability). Additionally, the Material Circularity Indicator (MCI) was determined to assess the circularity of the current products and business models.

In parallel to the environmental assessment, the economic evaluation of the four target products was carried out. The LCC methodology was used to assess all economic costs associated with the complete life cycle of the products, including internal cost (related to product manufacturing, use and end of life), as well as environmental externalities. The costs of environmental externalities were calculated by monetary valuation of the endpoint environmental impacts (obtained with the LCA).

Finally, the social impacts for the four target products were calculated using the S-LCA methodology. A cradle-to-gate assessment was applied, meaning that the scope of the social assessment covered from the extraction and processing of raw materials to the delivery of the finished product at the factory gate. In particular, the method and the indicators of the Social Hotspot Database were used. It allows to calculate social impacts for 26 social subcategories grouped into 5 categories. The SHDB offers a weighted aggregation model that converts the impact values of the social subcategories into aggregate impact values for each social category, which in turn can be aggregated into a single global social footprint for the products (the so-called Social Hotspot Index or SHI).

Below are shown the main environmental, economic and social indicators calculated for the four target products, including:

1) A **washing machine ARÇELIK 9123 WF**, which has 9 kg capacity and results in 24,750 kg of clothes washed during its 12.5-year lifetime (assuming 220 washing cycles/year)

Main sustainability indicators for the washing machine under conventional scenario (baseline)

Washing machine	Method & Indicators		Amount	Unit
	LCA	Global warming	2,344	kg CO_2 eq
		Human health	3.33E-02	DALY
		Ecosystems	1.76E-04	species.yr
		Resources	97.6	USD2013
		Recycling credits, Global warming	-32	kg CO_2 eq
		Recycling credits, Human health	-1.06E-04	DALY
		Recycling credits, Ecosystems	-2.07E-07	species.yr
		Recycling credits, Resources	-2.4	USD2013
		Material Circularity Indicator (MCI)	0.25	-
	LCC	Internal costs (€)	2,235	€
		External environmental costs (€)	5,794	€
		Total costs (€)	8,029	€
	S-LCA	Labour Rights & Decent Work (Pt)	663	Pt
		Health & Safety (Pt)	795	Pt
		Human Rights (Pt)	461	Pt
		Governance (Pt)	1,046	Pt
		Community (Pt)	388	Pt
		Total – Social Hotspot Index (Pt)	3,352	Pt

2) A **professional multifunctional laser printer LEXMARK CX860dte**, which results in 390,000 pages printed during its 5-year lifetime (assuming a standard business usage of 260 days/year and 300 pages per day)

Main sustainability indicators for the multifunctional laser printer under conventional scenario (baseline)

Multifunctional laser printer	Method & Indicators		Amount	Unit
	LCA	Global warming	2,535	kg CO_2 eq
		Human health	9.99E-03	DALY
		Ecosystems	4.11E-05	species.yr
		Resources	239.1	USD2013
		Recycling credits, Global warming	-129	kg CO_2 eq
		Recycling credits, Human health	-4.95E-04	DALY
		Recycling credits, Ecosystems	-9.29E-07	species.yr
		Recycling credits, Resources	-10.7	USD2013
		Material Circularity Indicator (MCI)	0.54	-
	LCC	Internal costs (€)	25,537	€
		External environmental costs (€)	1,741	€
		Total costs (€)	27,278	€
	S-LCA	Labour Rights & Decent Work (Pt)	16,652	Pt
		Health & Safety (Pt)	23,401	Pt
		Human Rights (Pt)	11,978	Pt
		Governance (Pt)	28,937	Pt
		Community (Pt)	9,725	Pt
		Total – Social Hotspot Index (Pt)	90,693	Pt

3) A **telecommunications equipment** composed by **an active ALM unit (ADVA 16ALM/#1650D/AC) and fourteen passive fibre-optic sensors**, which together offer continuous monitoring throughout its 8-year lifetime (i.e., 365 days/year and 24 h/day)

Main sustainability indicators for the ALM product under conventional scenario (baseline)

ALM product	Method & Indicators		Amount	Unit
	LCA	Global warming	406	kg CO_2 eq
		Human health	9.11E-03	DALY
		Ecosystems	4.92E-05	species.yr
		Resources	18.0	USD2013
		Recycling credits, Global warming	-7	kg CO_2 eq
		Recycling credits, Human health	-2.94E-05	DALY
		Recycling credits, Ecosystems	-7.41E-08	species.yr
		Recycling credits, Resources	-0.7	USD2013
		Material Circularity Indicator (MCI)	0.40	-
	LCC	Internal costs (€)	16,457	€
		External environmental costs (€)	680	€
		Total costs (€)	17,137	€
	S-LCA	Labour Rights & Decent Work (Pt)	5,369	Pt
		Health & Safety (Pt)	7,802	Pt
		Human Rights (Pt)	3,982	Pt
		Governance (Pt)	8,028	Pt
		Community (Pt)	2,959	Pt
		Total – Social Hotspot Index (Pt)	28,140	Pt

4) A **TV set GRUNDIG G43C 891 5A**, which is a 43" smart-TV that provides 10,784 hours of viewing during its 8-year lifetime (assuming an average use of 337 days/year and 4 h/day).

Main sustainability indicators for the TV set under conventional scenario (baseline)

TV set	Method & Indicators		Amount	Unit
	LCA	Global warming	472	kg CO_2 eq
		Human health	7.87E-03	DALY
		Ecosystems	3.87E-05	species.yr
		Resources	27.5	USD2013
		Recycling credits, Global warming	-17.9	kg CO_2 eq
		Recycling credits, Human health	-7.80E-05	DALY
		Recycling credits, Ecosystems	-1.94E-07	species.yr
		Recycling credits, Resources	-1.8	USD2013
		Material Circularity Indicator (MCI)	0.32	-
	LCC	Internal costs (€)	449	€
		External environmental costs (€)	1,324	€
		Total costs (€)	1,773	€
	S-LCA	Labour Rights & Decent Work (Pt)	1,277	Pt
		Health & Safety (Pt)	1,698	Pt
		Human Rights (Pt)	897	Pt
		Governance (Pt)	2,167	Pt
		Community (Pt)	727	Pt
		Total – Social Hotspot Index (Pt)	6,766	Pt

It should be noted that these results cannot be used to compare the products with each other, since each product has its own functions and functional unit, intensity of use, number of users per product unit and lifetime, resulting in products completely different in terms of composition, weight, life-cycle management and derived impacts; e.g., the washing machine is a consumer product used at home by a family, while the professional multifunctional laser printer is a large business product used by several office workers (over 30 users per product unit). These results will therefore constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of each product.

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List of acronyms and abbreviations

Acronym	Full form
CF_e	Endpoint characterization factors
CF_m	Midpoint characterization factors
CSS	Country-Specific Sector
CMOS	Complementary metal-oxide-semiconductor
DALY	Disability adjusted life years
DRAM	Dynamic random-access memory
EEE	Electric and electronic equipment
EI	Environmental impacts
EOL	End-of-life
EOL RR	End-of-life recycling rate
FS	Flat screens
FU	Functional Unit
GWP	Global Warming Potential
IC	Integrated circuit
IO	Input output
L	Lifetime
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFI	Linear flow index
LHA	Large household appliances
LPA	Large professional appliances
MCI	Materials circularity index
OSR	Old scrap ratio
PMU	Power management unit
PWB	Printed wiring board
RC	Recycled content
RIR	Recycling input rate
SHDB	Social Hotspot Database
SHI	Social Hotspot Index
S-LCA	Social life cycle assessment
SPA	Small professional appliances
TR	Percentage of time replaced
U	Functional unit
V	Virgin raw material
VAT	Value added tax
W	Waste
WCR	Waste collected for recycling or refurbishment
WEEE	Waste of electric and electronic equipment
WM	Washing machine
X	Product’s utility

1 Introduction

C-SERVEES is a European H2020 project that aims to boost a resource-efficient circular economy in the electrical and electronic sector through the development, testing, validation and transfer of new circular economic business models. The new circular business models, developed in WP2, are based on systemic eco-innovative services that include: (1) eco-leasing of EEE, (2) product customization, (3) improved WEEE management, and (4) ICT services to support the other eco-services. ICT tools are being developed in WP3 as a driver of the proposed eco-innovative services. Figure 1 shows a schematic overview of the C-SERVEES project and its main innovative solutions.

The new circular economic business models are being implemented and tested in WP4 by means of demonstrations involving four target products: washing machines, multifunctional laser printers and their toner cartridges, telecom equipment and TV sets. These products belong to different EEE categories that jointly account for 77% of the WEEE collected in the EU. The demonstrations involve the whole life cycle of the four target products, their associated value and supply chains, and the proposed eco-innovative services.

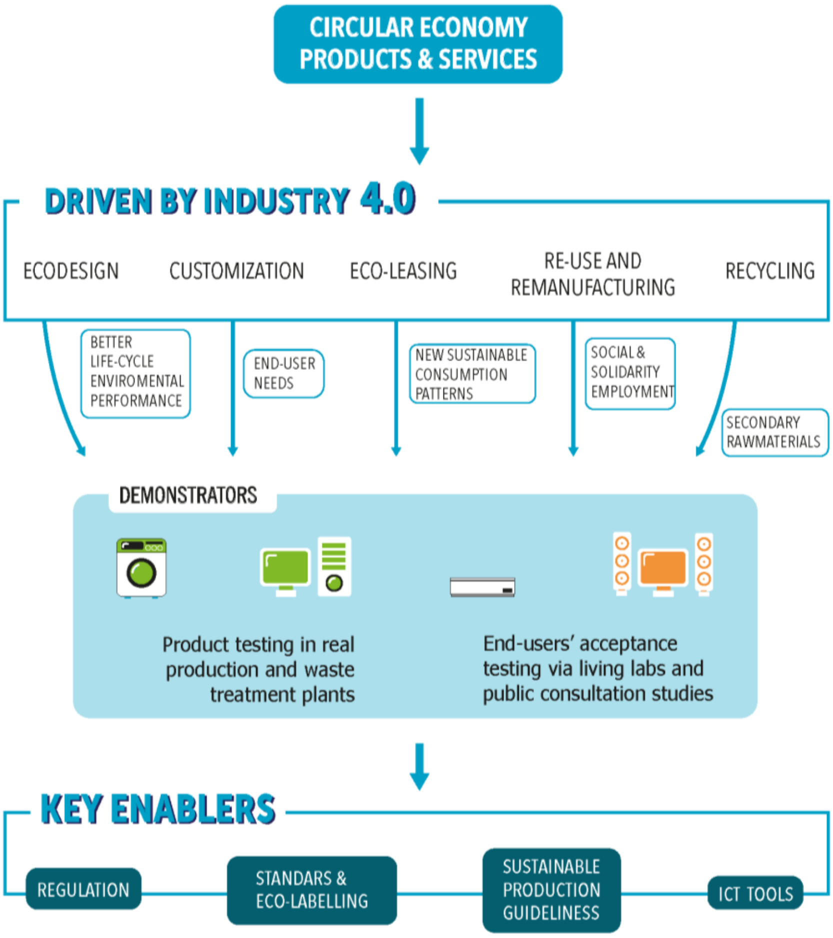

Figure 1. Schematic overview of the C-SERVEES project.

The environmental, economic and social viability of the target products and related eco-services will be determined in WP5 by means of life cycle sustainability assessment tools, including: environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA). Two different types of scenario will be assessed and compared for each target product:

- A conventional scenario, in which the products are produced and consumed under linear economy models.

- The C-SERVEES scenario, in which the products are produced and consumed under the new circular economy models relying on the systemic eco-innovative services demonstrated in the project.

This Deliverable 5.1 shows the life cycle sustainability assessment of each target product under the conventional scenario. It includes the environmental, economic and social impacts of each product, which were calculated using LCA, LCC and S-LCA, respectively.

1.1 Context and relationship with other WPs

C-SERVEES project is structured into 9 work packages (WPs). Figure 2 shows the overall structure of the project work plan as well as the interlinkages between the different WPs.

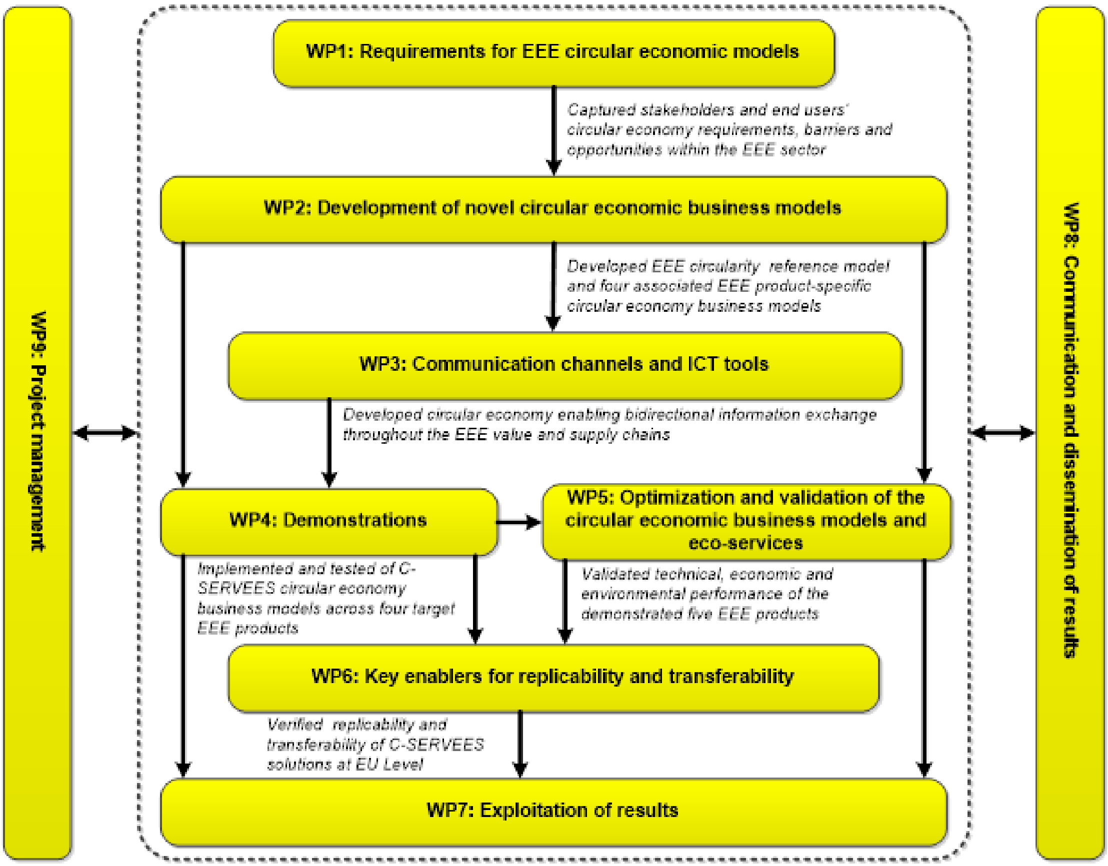

Figure 2. WP structure of the C-SERVEES project.

This Deliverable 5.1 is part of WP5, whose main objective is to validate the new circular business models by verifying their techno-economic, environmental and social feasibility. The relationship of WP5 (and Deliverable 5.1 in particular) with the other previous WPs is explained below.

WP1. Requirements for the new circular economic models

Stakeholder consultation was initially conducted to identify the awareness, opportunities, challenges and enablers to implement the circular economy business models in the electrical and electronic sector. These comprised technical, business & management, legislative, economic, social, supply chain and implementation aspects (discussed in Deliverable 1.2).

WP2. Definition of new circular economic business models

A circular business reference model for the electrical and electronic sector (REF-CIRCMODE) was developed based on a comprehensive literature review, the findings of the stakeholder consultation (conducted in WP1) and requirements from industry partners in the EEE value chains. The reference model comprises five interlinked layers (presented in Deliverable 2.1): (1) Business Strategy, (2) Circular Economic Business Model Canvas, (3) Challenges and Opportunities, (4) EU Policies relevant to the electrical & electronic sector, and (5) Circularity Indicators.

The REF-CIRCMODE was designed to be relevant to all EEE products and its layered structure provides a framework encompassing all possible circular economy options at a strategic level as well as each stage of a product's life cycle (design, production, use and EoL). This ensures that all options are initially available when implementing the REF-CIRCMODE to meet the requirements of any specific EEE product, providing the most appropriate actions that will lead to the optimum product-specific circular economic business model.

The REF-CIRCMODE was further customised and tailored to the four specific products targeted in the project, resulting in four oriented product-specific circularity models:

- WASH-CIRCMODE for washing machines produced by ARÇELIK (presented in Deliverable 2.2).
- PRINT-CIRCMODE for printer products produced by LEXMARK, including laser printers and toner cartridges (presented in Deliverable 2.3).
- ALM-CIRCMODE for telecom equipment produced by ADVA (presented in Deliverable 2.4).
- TV-CIRCMODE for TV sets and displays produced by ARÇELIK (presented in Deliverable 2.5).

The four product-specific circular economic business models are therefore equally based on the characteristics of the REF-CIRCMODE. Each business model, however, relates to the specificities of the specific product, since each one was developed using the information provided by the corresponding producer and other actors in its associated value chain.

WP3. Communication channels and ICT tools

C-SERVEES is also dealing with the development of ICT tools for bi-directional communication and secure information exchange throughout the EEE value chains to support the new circular economic business models. These tools are based on blockchain and zero-knowledge technology, enabling the communication about individual products without the need for full disclosure of information, but with trust and accountability.

New ICT services will thus be provided and supported by information transfer through the EEE value chains, including EEE producers and their supply chains, end users and WEEE managers. These services will rely on QR codes (requiring product labelling), providing access to end users via their smartphones, while WEEE managers can use QR code scanners. Functionalities will include product life-cycle tracking and feedback to producers, as well as interactive user manuals, repair manuals, warranty tracking or consumables management.

The ICT tools are currently being developed in sprints with industry partners that are testing them to validate and optimise their features and functionalities. They are being structured in such a way that any type of EEE can be added to the ICT platform.

WP4. Demonstrations of the circular economic business models and eco-services

The practical utility of the product-specific circular economic business models (developed in WP2) lies in the possibility of posing and reviewing a series of circular economy options and evaluating them according to their viability and timeframes for implementation (short, medium or long term). This exercise was already carried out by each EEE producer in C-SERVEES (ARÇELIK, LEXMARK and ADVA), leading to the selection of a set of circular economy actions that can be reasonably applied to their demo products within the timescale of the project (i.e., in the short term).

The actions selected for each target product are now being implemented through the demonstrations (presented in Deliverable 4.1). These actions are summarized in Table 1, including some actions supported by the ICT tools developed in the project (in WP3). In addition, other circular economy actions considered feasible over a longer timescale (i.e., medium and long term) will be explored by EEE producers for possible progression outside the confines of the project.

Table 1. Demonstrations conducted in the C-SERVEES project.

Demo product (producer)	Life-cycle stage	Circular economy action	Action description
Washing machines (ARÇELIK) 	Design & production	Eco-design of the washing machine	• Increase recycled plastic content in selected parts • ICT to provide certification
		Increase circularity in production process	• Perform LCA to detect improvement areas in production
	Use	Develop a renting model for B2B market	• Demonstration with focus on corporate customers
	End of life	Expand and improve repair & refurbishment operations	• Explore the use of 3D printing for spare parts and/or customisation • Study potential for refurbishment centres in Europe • Provide repair/refurbishment/disassembly procedures • ICT to provide secure supply chain communication
		Improve recycling process of the washing machine	• ICT to improve reverse logistics for EoL products • ICT to provide information for recyclers
Printer products, incl. laser printers and toner cartridges (LEXMARK) 	Design & production	Eco-design of the printer	• Determine potential for eco-design of printers • Reduce amount of packaging • Increase recyclable materials in printers
		Increase circularity in the printer's life cycle	• Increase the number of printers/cartridges recovered
	Use	Improve data collection and management	• Improve repair operations • Explore the competitiveness of 3D printing for spare plastic parts
	End of life	Improve the LCCP	• Increase the number of collected cartridges and optimise classification • Implement ICT tools for improvement in logistics
		Improve repair & refurbishment operations	• Increase the number of refurbished printers and spare parts recovered
		Improve the recycling of printers and cartridges	• Ensure data security • Provide data to recyclers
Telecom equipment (ADVA) 	Design & production	Eco-design of ALM system	• Design for longevity • Design for recycling
		Improve circularity in ALM production	• Perform LCA to detect improvement areas in production
	Use	Improvements in logistics	• Reusable packaging • Enhancing own ADVA ICT tool for logistics
		Explore feasibility of renting/shared use/PSS	• Demonstration of leasing/renting with selected stakeholder
	End of life	Improve repair and refurbishment operations	• Provide recyclers with information about materials • Support from ICT tools
		Improve recycling of the ALM system	• Improve the proportion of components, parts and/or materials recovered • Cost analysis
TV sets (ARÇELIK) 	Design & production	Eco-design of the TV set	• 30% recycled plastic content in TV back cover • Reusable packaging for corporate customers
		Increase circularity in production process	• Perform LCA to detect improvement areas in production
	Use	Develop a renting model for B2B market	• Demonstration with focus on corporate customers
	End of life	Expand and improve repair and refurbishment operations	• Explore the use of 3D printing for spare parts and/or customisation • Study potential for refurbishment centres in Europe • Provide repair/refurbishment/disassembly procedures • ICT to provide secure supply chain communication
		Improve recycling process of the TV set	• ICT to improve reverse logistics for EoL products • ICT to provide information for recyclers

WP5. Optimization and validation of the circular economic business models and eco-services

The main objective of this WP is to validate the new circular economic business models by verifying their sustainability in the demonstrations of the four EEE products. The evaluation of the proposed solutions is being conducted by applying life cycle sustainability assessment tools over the demonstrations to measure their performance in relation to the three pillars of sustainability (Figure 3):

- Environmental viability, measured with life cycle assessment (LCA, performed in Task 5.1).
- Economic viability, measured with life cycle costing (LCC, performed in Task 5.2).
- Social viability, measured with social life cycle assessment (S-LCA, performed in Task 5.3).

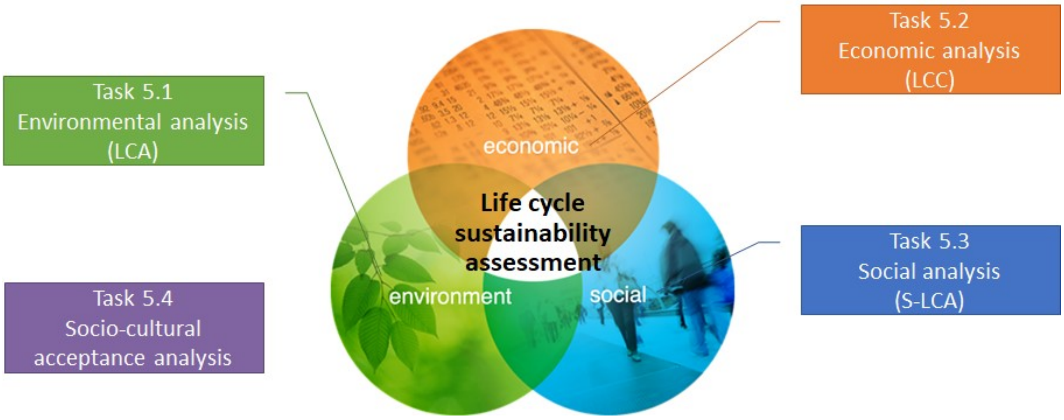

Figure 3. Life cycle sustainability assessment approach applied in the C-SERVEES project.

Two different types of scenario will be assessed and compared for each target product:

- A conventional scenario, in which the products are produced and consumed under linear economy models.
- The C-SERVEES scenario, in which the products are produced and consumed under the new circular economy models relying on the eco-innovative services demonstrated in the project (in WP4).

This Deliverable 5.1 shows the life cycle sustainability assessment of each target product under the conventional scenario. It includes the environmental, economic and social impacts of each product, which were calculated using LCA, LCC and S-LCA, respectively. In a later phase of the project, the impacts of the C-SERVEES scenario will be assessed and compared to those for the conventional scenario (compiled herein) in order to calculate the sustainability benefits that can be achieved with the solutions developed in the project.

1.2 Structure of the Deliverable

Deliverable 5.1 contains the following sections:

- Introduction to C-SERVEES project with the overview of WP5 and its relationship with previous WPs.
- Definition of the Goal and Scope of the Deliverable.
- General overview of the Methodology followed for the whole life cycle sustainability assessment (with a common approach for the four products assessed), encompassing life cycle inventory, LCA (including MCI), LCC and S-LCA.
- Summary of the Main Results obtained for each target product.
- Four Annexes (one for each target product) containing the full sustainability assessment studies (LCA, LCC and S-LCA) and their detailed results.

2 Goal and scope

The present study aimed to calculate the environmental, economic and social impacts of four different EEE products used for demonstrations in the C-SERVEES project. The target products investigated include:

- Washing machine
- Multifunctional laser printer (including its toner cartridges)
- Telecom equipment
- TV set

These products and their main characteristics are described below.

2.1 Washing machine

The washing machine selected for demonstration is ARÇELIK 9123 WF, which has 9 kg capacity, energy efficiency class A^{+++} and connectivity features. It is manufactured in Çayırova (Turkey) and currently sold worldwide. ARÇELIK selected this model for its smart home technology, which allows the users to access the HomeWhiz app from their smartphones or tablets and control the smart features of the product (switch on/off, program selection, user instructions, etc.). By using connected products, ARÇELIK will have a chance to collect data and learn customer usage habits in order to improve customers' experience and offer maintenance and repair services to extend product life. The selected washing machine has 8% recycled materials and ARÇELIK aims to increase it further in the project, improving the product circularity. More details on the current washing machine selected for demonstration are shown in Table 2.

The functional unit considered in the present study is one washing machine ARÇELIK 9123 WF, which results in 24,750 kg of clothes washed during its 12.5-year lifetime (assuming 220 washing cycles/year).

Table 2. Technical specifications of the demo washing machine.

MODEL	ARÇELIK 9123 WF
Image	
Product number	7150370100
Colour	White
Size	840 mm × 600 mm × 610 mm
Weight	75 (±4) kg
Capacity	9.0 kg
Max. spin speed	1,200 rpm
Fascia	Grundig
Dynamic group	Large
Number of programs	16

Features	HomeWhiz, ProSmart (Brushless Motor with 10-year guarantee), Wi-Fi and BLE, Steam Function, Anticrease+
Energy class	A^{+++} (-30%)
Electricity consumption per year	148 kWh
Water consumption per year	10,318 L
Country of origin	Turkey

2.2 Multifunctional laser printer

LEXMARK identified and selected a number of laser printer models to include in the demonstration, such as the following models: CX860dte, X950de, MS812 and CX510. All of them are multifunctional laser printers that were selected due to their suitability for refurbishment operations.

The laser printer selected as the reference for the life cycle sustainability assessment was the LEXMARK CX860dte. It is a network-ready, professional multi-function device with standard 2-sided printing and scanning, a 1.6 GHz quad-core processor and 2GB of standard memory that prints at up to 60 ppm black and colour. The printer fuses different colours to a medium (such as paper) to create hard copy images from electronic or hard copy originals. The printer product delivered to the customer consists of the printer, a power cord, printed setup instructions, a CD/DVD that includes the User Guide and Printer Drivers and an initial set of product supplies. The printer is delivered in packaging that can be recycled locally and is not needed for product operation. Product supplies include toner cartridges, imaging kits and the fusing mechanism. The power supply is internal to the product and the imaging kit and fusing mechanism are installed at the factory. Only the toner cartridges must be installed by the customer. More details on the current multifunctional laser printer selected for the sustainability assessment are shown in Table 3.

The functional unit considered in the present study is one multifunctional laser printer LEXMARK CX860dte, which results in 390,000 pages printed during its 5-year lifetime (assuming a standard business usage of 260 days/year and 300 pages per day). It should be noted that this product is a shared printing and copying device that is used by a pool of business users.

Table 3. Technical specifications of the demo 25multifunctional laser printer.

MODEL	LEXMARK CX860dte
Image	
Product number	42K0071
Print technology	Colour Laser
Functions	Colour copying, colour faxing, colour printing, colour scanning, colour network scanning
Display	Lexmark e-Task 10-inch (25 cm) class colour touch screen

Size / Packaged size	1162 x 559 x 588 mm / 1380 x 762 x 830 mm
Weight / Packaged weight	131.3 kg / 157.4 kg
Print speed (up to)	Black: 60 ppm / Colour: 60 ppm (pages per minute)
Recommended monthly page volume	5,000 - 50,000 pages
Laser cartridges yield (up to)	55,000-page Black and Colour (CMYK) Ultra High Yield Cartridges 22,000-page Colour (CMY) Extra High Yield Cartridges 33,000-page Black Extra High Yield Cartridge 17,000-page Colour (CMY) High Yield Cartridges 8,000-page Black and Colour (CMYK) Cartridges
Photoconductor estimated yield (up to)	175,000 pages, based on 3 average letter/A4-size pages per print job and ~ 5% coverage
Developer unit(s) estimated yield (up to)	300,000 pages, based on 3 average letter/A4-size pages per print job and ~ 5% coverage
Cartridge(s) Shipping with Product	8,000-page Black Return Program Toner Cartridge 17,000-page Colour (CMY) High Yield Return Program Toner Cartridges
Electricity consumption	0.391 kWh/1,000 pages (ENERGY STAR Certified)
Average power	0.3 W (Hibernate Mode), 3.3 W (Sleep Mode), 125 W (Ready Mode), 870 W (Printing), 650 W (Copying), 115 W (Scanning)
Country of origin	China

2.3 Telecom equipment

The telecommunications equipment selected by ADVA for demonstration belongs to their ALM line (Advanced Link Monitoring) for optical networks, which is a relatively new and still upraising product line. It splits into an (electrically) active unit and passive fibre-optic sensors for fibre monitoring tasks like real-time information on fibre integrity, fast and easy localization of user traffic and remote passive fire detection in sites accessed with a fibre. The novelty in the ALM product line makes it suitable for the demonstration purposes since it makes it simpler to introduce changes on the product line. Two variants of the active ALM units were considered for the demonstration, namely 16ALM and 64ALM. In addition, two different configurations were considered for the passive sensors. The ALM product selected as the reference for the life cycle sustainability assessment was the ADVA 16ALM/#1650D/AC, while the two sensor configurations were included in the assessment. More details on the current ALM product selected for the sustainability assessment are shown in Table 4.

The functional unit considered in the present study is one ALM product, including the active unit (ADVA 16ALM/#1650D/AC) and fourteen passive fibre-optic sensors, which offers continuous monitoring throughout its 8-year lifetime (i.e., 365 days/year and 24 h/day).

Table 4. Technical specifications of the demo telecom product.

MODEL	**ADVA 16ALM/#1650D/AC**
Image	
Product number	1043709841-02
Description	Advanced Link Monitor (ALM), 16 ports with LC/APC connectors, AC powered
Colour	Grey
Size	44 × 215 × 213 mm
Weight / Packaged weight	< 2 kg / 11.6 kg
Power typical / maximum	10 W / 13 W
Country of origin	Germany

2.4 TV set

The TV set selected for demonstration is GRUNDIG G43C 891 5A, which is a 43” smart-TV model with energy efficiency class A^+ and connectivity features. This product is manufactured in Tekirdağ (Turkey) and currently on sale in Turkey and the EU. ARÇELIK selected this model because it has convenient size (43”) for hospitality customers targeted in the demonstration. The selected TV has enclosure and stand made of halogen-free plastics, while the back cover is made of plastics with around 30% recycled content. More details on the current TV set selected for demonstration are shown in Table 5.

The functional unit considered in the present study is one 43” TV set GRUNDIG G43C 891 5A, which provides 10,784 hours of viewing during its 8-year lifetime (assuming an average use of 337 days/year and 4 h/day).

Table 5. Technical specifications of the demo TV set.

MODEL	**GRUNDIG G43C 891 5A**
Image	
Product (EAN) number	8690842398605
Description	43" / 108 cm, UHD (3.840 x 2.160), 50 Hz, HEVC/H.265, Smart
Colour	Black
Size	625 × 231 × 976 mm
Weight / Packaged weight	9.2 kg / 12.0 kg
Features	Picture features: Picture Noise Reduction, DLTI , DCTI, DNR, Digital Comb Filter (3D) Colour system: Multisystem USB supported files: .mp3, .m4a, .aac, .jpg, .jpe, .bmp, .png, .mov, .mpg, .mpe, .vob, .dat, .trp, .ts, .avi, .mp4, .mkv, .div
Energy class	A^+
Electricity consumption per year	53.3 kWh
Average power	0.15 W (Stand-by), 38.8 W (Nominal)
Country of origin	Turkey

3 Life cycle assessment

The environmental impacts of the four products targeted in the project were calculated using LCA methodology according to ISO standards (14040/14044). LCA is a methodology to evaluate the environmental burdens associated with a product or process by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the whole life cycle of the product or process, which encompasses: extraction and processing of raw materials; manufacturing, transport and distribution; use, re-use and maintenance; and end of life.

According to ISO standards, LCA consists of four phases (Figure 4): (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. LCA software (SimaPro) was used to tackle the development of these phases more effectively.

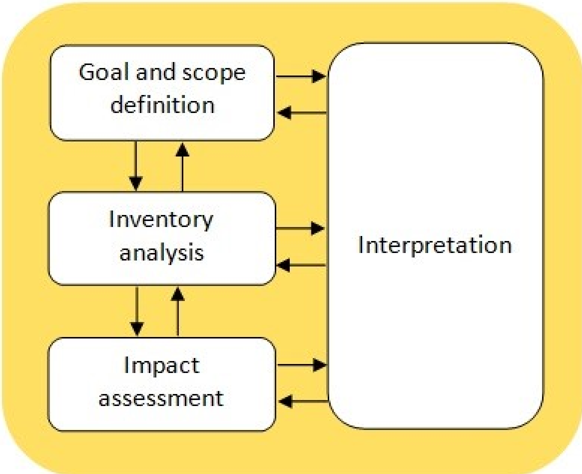

Figure 4. Framework of the LCA methodology.

The goal and scope definition determines the guidelines to be followed during the rest of the study by specifying the reason for conducting the study, intended use of the results, intended audience, system boundaries, functional unit, data requirements, and study limitations. The inventory analysis involves collecting data to create a life cycle inventory (LCI) of the inputs (energy and materials) and outputs (environmental releases and waste) associated with each stage of the life cycle. The impact assessment translates the LCI data into potential environmental impacts. To this end, the impact categories under study must be defined (categorization), the inventory data must be assigned to specific impact categories (classification), and the level of impact must be evaluated according to predefined assessment methods (characterization). Impact assessment may also include other additional steps (normalization, grouping and weighting) to facilitate the interpretation phase, but these are not mandatory according to ISO standards. Finally, the interpretation phase combines and summarizes the results from inventory analysis and impact assessment (consistent with the defined goal and scope) in order to reach conclusions and recommendations.

A complete life cycle inventory was then conducted for each target product by collecting primary data from the industry partners producing them (ARÇELIK, LEXMARK and ADVA). The environmental studies focused on greenhouse gases emissions, resources consumption, waste generation associated with the life cycle of each product, etc. Additionally, the studies included the determination of a Material Circularity Indicator[1] (MCI) that assesses the circularity of the current products and business models. Below are described the main methodological aspects considered for the development of the LCA studies in the project.

3.1 Life cycle inventory

The LCI for the EEE products is divided herein into manufacturing (cradle-to-gate), use and end of life. It was based on primary data supplied by the EEE producers (ARÇELIK, LEXMARK and ADVA). LCI datasets taken from the Ecoinvent database[2] (available for SimaPro software) and literature data were used to model the inventories of the materials, processes, energy and transport operations included in the LCI of the products. WEEE management and treatment were modelled based on the methodology and datasets provided by the WEEE LCI project[3] (which are also available for SimaPro software). The specific datasets used for each input/output included in the LCI of each EEE product are listed in the Annexes.

3.1.1 Manufacturing

Manufacturing includes raw material extraction and processing, manufacturing of components and their assembly to produce the finished EEE product, as well as transport of raw materials and components. LCI for the manufacturing of the target products were based on data provided by industry partners, while Ecoinvent database was used to model the related materials, processes, energy and transport (used as inputs/outputs in the LCI). Some electronic components were, however, modelled using literature data. The detailed LCI for each product and the linked inputs/outputs are shown in the Annexes. Below are explained the assumptions made for the inventory modelling of specific electronic components, namely printed wiring boards, integrated circuits and electronic components containing precious metals.

Printed wiring boards

Printed wiring boards (PWB) are among the EEE components with the highest environmental impact and greatest uncertainty. Recent studies[4] have shown that existing LCIs for PWB (either from Ecoinvent or GaBi databases), which are defined just by the number of layers and surface finish, are likely to either under or overestimate the environmental impact (depending on the specific PWB being assessed). For example, on a per-area basis for conventional PWB, the impact for a 6-layer board is around 20% less. Note that the data used for the LCI of PWB in Ecoinvent[2] and Gabi[5] databases were collected in the early years of the 21st century and later extrapolated to the present day. The iNEMI Phase 3 Eco-Impact Estimator Project[6] will update these inventories.

The GHG emissions of PWB increase with the number of layers, but the increase level depends on the type of layers added. The environmental impacts for PWB were obtained in this study using the inventory available in Ecoinvent database for a 6-layer PWB for surface mounting and Pb free, which was used as a reference. For PWB containing a different number of layers, the ratio shown in Figure 5 was applied.

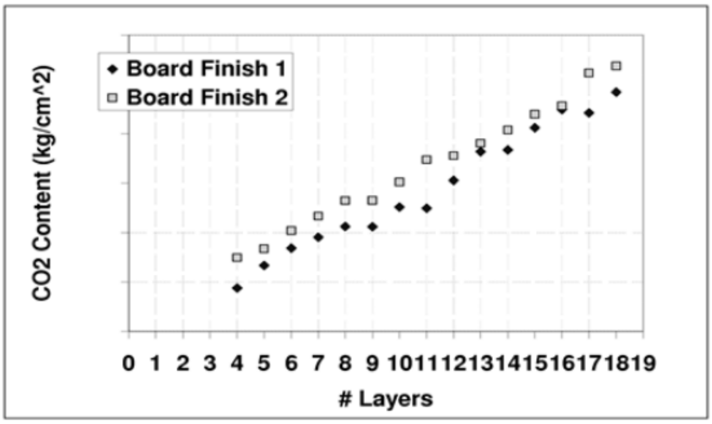

Figure 5. Global Warming Potential (GWP) for manufacturing of PWB depending on the number of layers.[6]

Integrated circuits

Silicon die process is an very energy-intensive process that affects significantly the environmental impacts of integrated circuits (IC), accounting for around 70-90% of the total impacts[7] (Figure 6). The amount of energy required by this process is defined by the die section processed and the node technology[8] (Figure 7). Environmental impacts per-area were improved from CMOS 350 nm to CMOS 130 nm. From this node technology, the environmental impacts per-area started to increase, although the impacts per IC were still improving due to the density benefits. There is now evidence that the final benefit of scaling was lost in the 28 nm feature size. This is mirrored in the spike in environmental impacts after 45 nm.

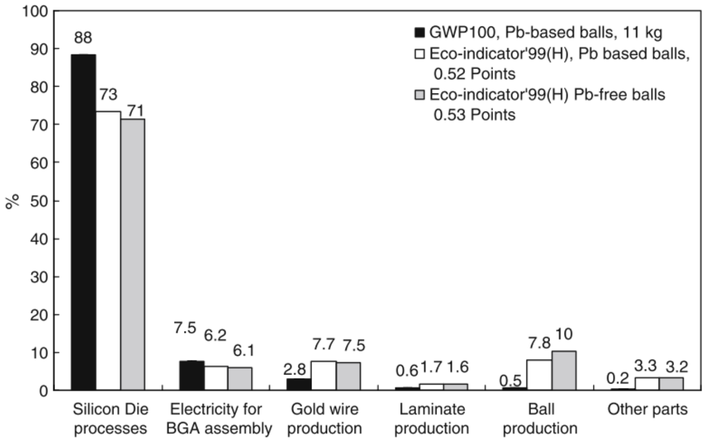

Figure 6. Environmental importance of sub-parts of a IC (Metal BGA-560 microchip).[7]

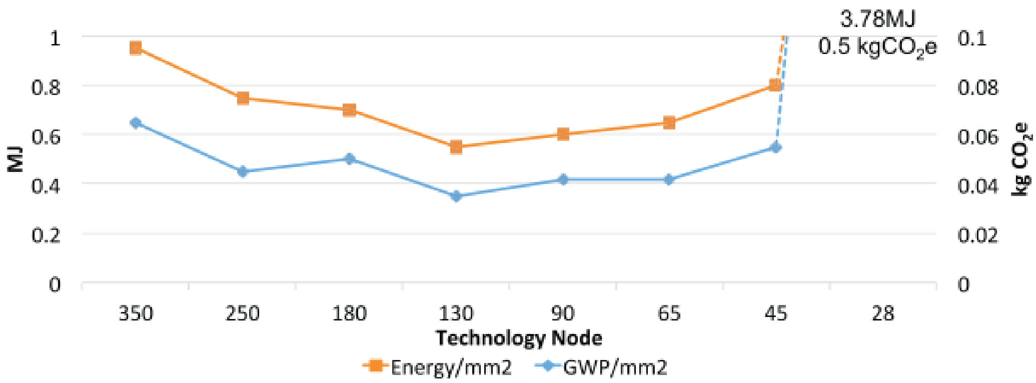

Figure 7. Energy demand and Global Warming Potential (GWP) for manufacturing of IC (CMOS).[8]

Silicon die processing distinguishes between wafer fabrication for memory and for logic devices. The equipment and processes used for both are in principle the same, but the logic wafer must go through these processes more frequently. Dynamic random-access memory (DRAM) wafer fabrication needs approximately 250 process steps, while logic wafer fabrication needs 360 process steps. The basic unit processes are photolithographic patterning, etching, doping, deposition of various materials, metallization, wafer cleaning, polishing and furnace operations. The equation below is used to model the environmental impacts of the IC, considering the electricity consumed in the silicon die process, the silicon die area and the rest of the IC.

$$EI_{IC} = EI_{Si\ die\ process} + EI_{Si} + EI_{rest\ package} \tag{1}$$

Table 6 shows electricity consumption for silicon die process for each technology node, which was obtained from Boyd[9] for logic IC and Schmidt et al.[10] for memory IC. It was assumed that IC are manufactured in China and the convention of 10.7 MJ of primary energy per kWh electricity was used. The same electricity consumption was assumed for a given die area regardless of the number of layers contained in the IC.[8]

Table 6. Electricity consumption for silicon die processing per area unit.

IC device	Technology node	Electricity (MJ/Si mm^2)
Logic[9]	350	0.160
	130	0.084
	90	0.087
	65	0.091
	45	0.106
DRAM[10]	-	0.035

The die area is obtained from the IC area using empirical relation for each housing type as used in GaBi database.[5] This approach is sufficient for small chips. However, for larger chips it is convenient to obtain the die area from technical data sheets. If these are not available, 18 mm^2 die per gram of packaged chip can be assumed.[11] This relation is significantly larger than those used in Ecoinvent database (5.5 mm^2 die per gram for logic chips and 10.1 mm^2 die per gram for memory chips). The lower estimates in Ecoinvent database are apparently due to erroneous assumptions.[2]

The technology node for each package type was obtained from GaBi database.[5] The inventories of the electricity (for silicon die processing), silicon for electronics and rest of materials for the IC package were taken from the Ecoinvent database.

Other electronic components

Energy consumption for transistors, capacitors and other electronic components is lower than for IC. However, the presence of some precious metals, especially gold, highly increases the environmental burden in most impact categories; e.g., the overall impacts of the transistors SMD SOT23 vary from 0.48 times up to 167 times to that of a reference transistor, primarily depending on the gold content.[12] Thus, the inventories available from Ecoinvent database[2] were used for these electronic components except for those containing precious metals, which were modelled using data from technical data sheets.

3.1.2 Use

Use includes product distribution (to retailers or final customers), product operation including electricity consumption and other consumables (e.g., water and detergents for washing machines, toner cartridges and paper for printers), transport of consumables and product maintenance (if required). LCI for the use of the target products were based on data provided by industry partners and completed with data from Ecoinvent database and literature.[13–15] The detailed LCI for each product and the linked inputs/outputs are shown in the Annexes. Below are explained the assumptions made for the inventory modelling of product distribution, electricity consumption and maintenance.

Distribution

Product distribution was modelled using data provided by industry partners, which included the share of sales by country for each target products and the transport modes used to deliver them to each destination country.

Electricity consumption

Environmental impacts caused by electricity consumption during the use of the products were calculated using the European electricity mix as reference. Two different electricity mix scenarios were assessed:

- A first scenario where the share of electricity sources is constant along the product lifetime.
- A second scenario where the share of electricity sources varies along the product lifetime. The evolution of the European electricity mix was taken from the IRENA database,[16] which provides figures for the years 2016 and 2050 (Figure 8), while the electricity mix for intermediate years was modelled by linear interpolation.

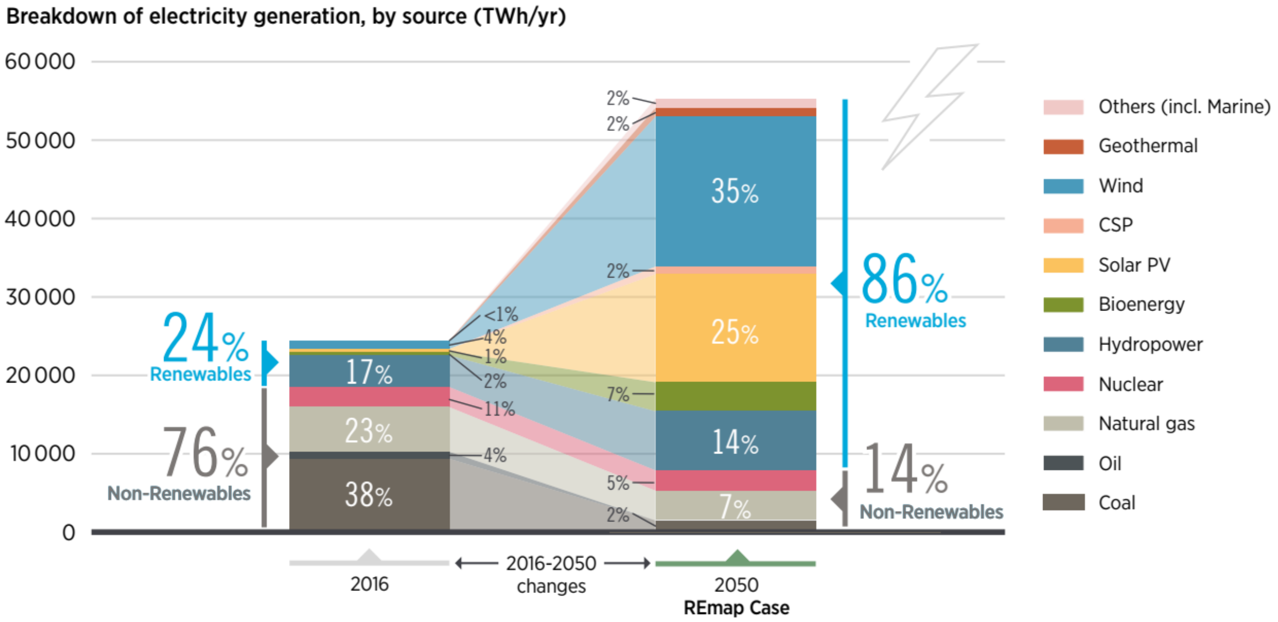

Figure 8. Evolution of the European electricity mix.[16]

The energy transition process assessed in the second scenario constantly increases the share of renewable sources in the European electricity mix. This scenario will therefore result in a considerably decrease of the environmental impacts caused by the use of the product during its lifetime (compared to the impacts of the scenario where the current electricity mix is assumed for the entire product lifetime). As an example, Figure 9 shows the decrease in the estimated Global Warming Potential of the modelled European electricity mix over 20 years.

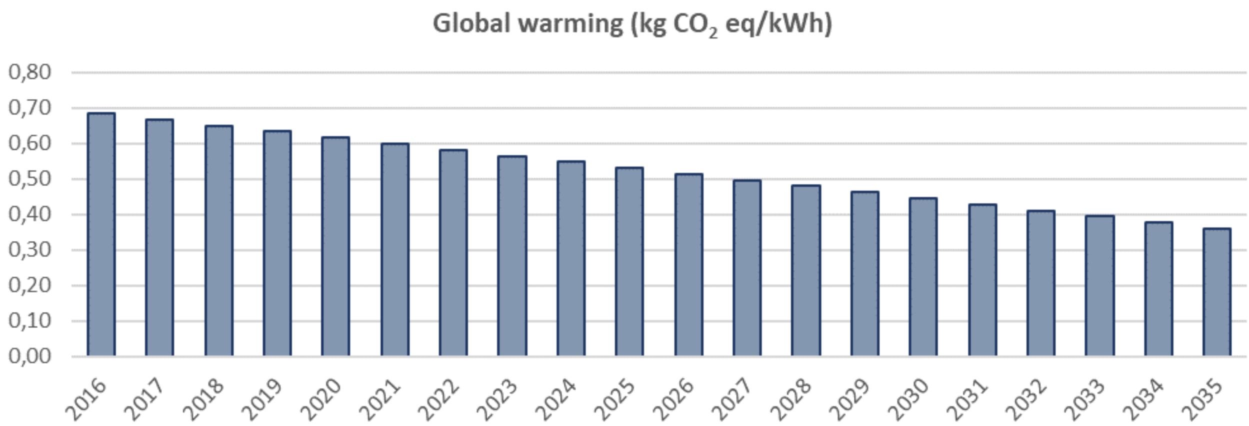

Figure 9. Global Warming Potential for low-voltage electricity production for the period 2016-2035 according to the European electricity mix evolution.

Maintenance

Maintenance was included in the LCA scope only for the multifunctional laser printer since it was the only product for which data were available from the corresponding industry partner. Nevertheless, maintenance for the other products is less frequent and the derived impacts were considered as insignificant compared to the impacts of the other life cycle phases.

3.1.3 End of life

End of life includes the waste management operations applied to the target EEE products once they reach the end of their useful life. These operations comprise waste collection and transport, WEEE treatment, recycling and landfill disposal of materials and components. LCI for the end of life of the target products was modelled based on the methodology and datasets provided by WEEE LCI project.[3] The detailed LCI for each product and the linked inputs/outputs are shown in the Annexes. Below are explained the methodology followed and assumptions made for the inventory modelling of end-of-life operations.

Waste collection

Waste collection data provided by the industry partners were used when available. Otherwise, statistical data for the EU-27 were used. Specifically, waste collection rates for the EU-27 were obtained from data published by Eurostat[17] for the year 2017 (Table 7).

Table 7. EEE products and their wastes in the EU-27 for the year 2017. Source: Eurostat.[17]

Product category according to Directive 2012/19/EU	Products put on the market	WEEE collected	Collection rate
Total	8,037,753	3,700,320	46.0%
Large household appliances	4,214,649	1,950,118	46.3%
Small household appliances	785,442	375,561	47.8%
IT and telecommunications equipment	884,347	523,425	59.2%
Consumer equipment and photovoltaic panels	641,395	539,970	84.2%
Lighting equipment	515,662	64,318	12.5%
Electrical and electronic tools	478,984	124,536	26.0%
Toys, leisure and sports equipment	189,829	22,452	11.8%
Medical devices	82,434	14,944	18.1%
Monitoring and control instruments	126,944	35,320	27.8%
Automatic dispensers	63,294	15,915	25.1%

Table 8 shows the waste collection rates assumed for the EEE products targeted in the project. EU average collection rates (from Table 7) were considered for those products for which specific collection rates were not available.

Table 8. WEEE collection rates for target products in the C-SERVEES project.

Product	Product category	WEEE category according to Directive 2012/19/EU	Collection rate	WEEE LCI category
ARÇELIK 9123 WF	Washing machine	Large household appliances	46.3%	Large household elec. equip. non cold (LHA)
LEXMARK CX860dte	Multifunctional laser printer	IT and telecommunications equipment	66.7%	Large professional elec. equip. (LPA)
ADVA 16ALM/#1650D/AC	ALM	IT and telecommunications equipment	59.2%	Small professional elec. Equip. (SPA)
GRUNDIG G43C 891 5A	TV set	Consumer equipment and photovoltaic panels	84.2%	Flat screens (FS)

Waste treatment

LCI of WEEE management was obtained from the WEEE LCI project,[3] whose inventory datasets are available for SimaPro software. It provides inventory data for the management of WEEE collected, with specific datasets for different WEEE categories (WEEE LCI categories in Table 8) according to their take-back scheme frameworks. The end-of-life management system for a material/WEEE stream pair covers all transport and treatment operations between the collection of the WEEE stream and the range of final destinations reached by the material (Figure 10).

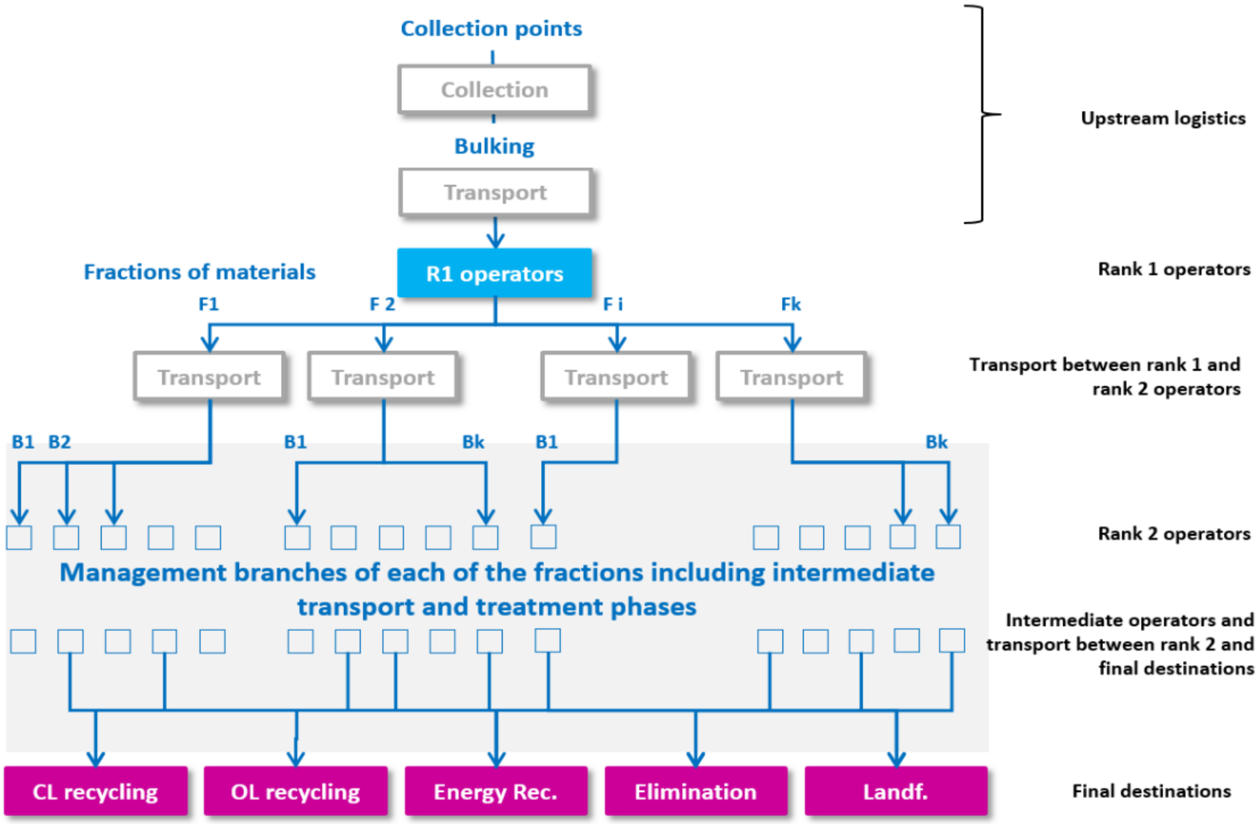

Figure 10. System boundaries for the LCI of WEEE management.[3]

WEEE management is thus divided into the following phases:

- Upstream logistics. This phase includes WEEE transport from collection points to waste transfer stations where the WEEE undergoes accumulation and it is later transferred to rank 1 treatment operators; a small portion of the WEEE collected may also be transported directly from the collection points to rank 1 treatment operators.
- Rank 1 treatment operators. These operators are responsible for the first WEEE treatment phase, including decontamination. This phase results in various fractions of materials with different levels of complexity. Indeed, these fractions rarely consist of a single material (e.g., PP) or a single material category (e.g., plastics), but they correspond to:
    - A set of materials in which one category is dominant (e.g., ferrous metals), but other materials/components (PWB, inductors, etc.) separated from the main category are still present as impurities.
    - A genuine mixture of various material categories (mixture of metals/plastics, fluff, shredding residue, etc.).
- Transport between rank 1 and rank 2 operators. The various fractions of materials produced by rank 1 treatment operators are transported to rank 2 treatment operators. For a given fraction from a given rank 1 operator, several rank 2 operators may be involved.
- Rank 2 operators. Depending on the case, rank 2 operators may consist of:
    - Treatment operators related to final destinations reached by the materials (incineration with energy recovery, thermal destruction, storage and recycling for some fractions with low levels of impurities).

- o Intermediate treatment operators (sorting of plastics, sorting of fine metals/plastics, shredding/sorting of compressors, etc.).
- o Accumulation/trading operators (that may play an important role in ensuring a steady supply to subsequent handlers).

- Transport and intermediate operators between rank 2 treatment operators and final destinations. According to the nature of the operations carried out by rank 2 operators, further transport and treatment phases may be required before reaching the final destinations.
- Final destinations. The final destinations consist of operators for material recovery (steelworks, aluminium refinery, copper/precious metals refinery, plastic recycling, inert material recovery in construction sector, etc.), energy recovery, incineration and landfill disposal.

Recycling

WEEE LCI[3] provides inventory data for waste treatment in the final destinations according to two different accounting methods:

- With benefits. The impacts associated with the treatment operations applied to the material/component in the final destination are considered, as well as the benefits associated with the material and/or energy recovered (which are counted as environmental credits because they avoid the production of primary raw materials or energy).
- Without benefits. Only the impacts associated with the treatment operations in the final destinations are considered, whereas the benefits provided by the material and/or energy recovery are excluded. This is the recycled content method, also referred as cut-off method (Figure 11).

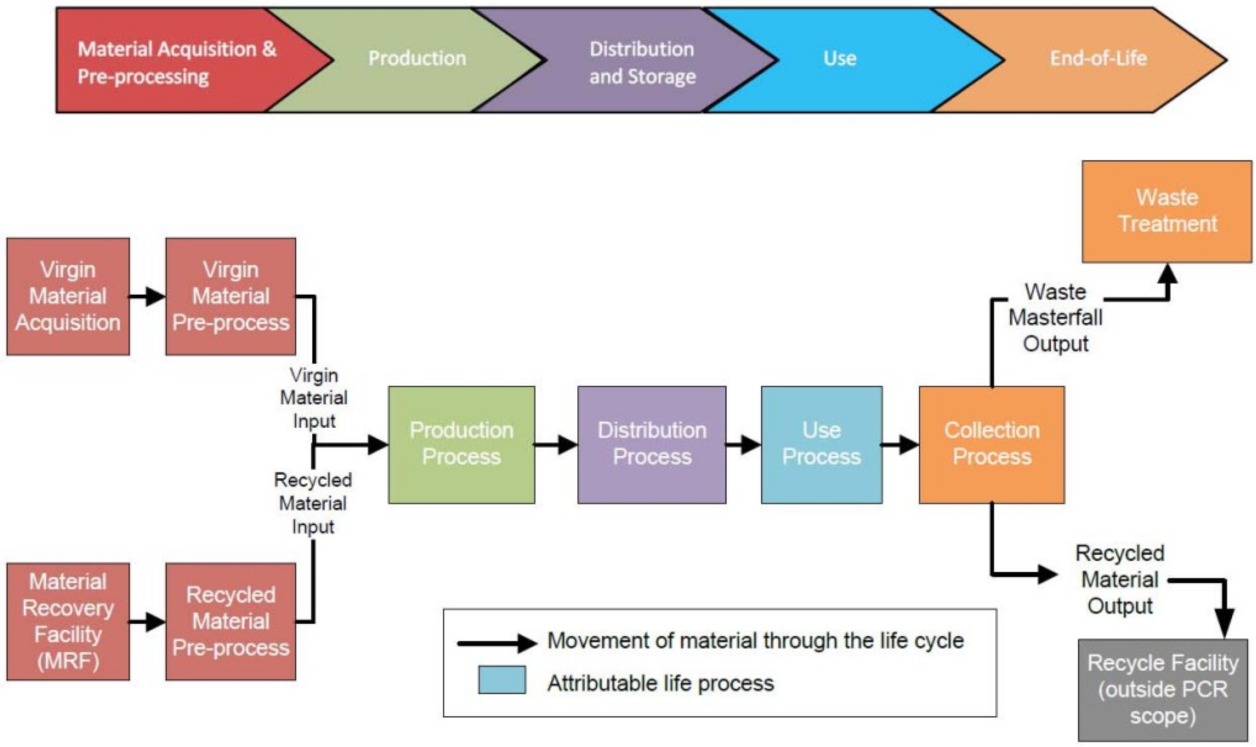

Figure 11. Example of the cut-off method.

According to ISO 14044, the cut-off method must be applied for recycling operations at the EoL. Waste by-products are materials with no economic value under EoL conditions and, consequently, there is no interest in collecting them without economic compensation. Hence, producers usually have to pay for waste management of their EoL products. This is the case for WEEE. The environmental burdens due to waste management and treatment are in this case allocated completely to the waste-producing activity (life cycle of EEE product). Any product (or non-waste by-product) obtained from the waste treatment are outside the LCA scope when applying the cut-off method and does not give an environmental credit to the waste-producing activity. The point of cut-off is therefore the end of the waste treatment, with the materials and/or energy recovered being excluded from the system boundaries.[18]

However, in the present study, impacts due to waste collection, transport, intermediate and final treatment operations were considered as indicated in Figure 10. Environmental benefits due to recycling were not added to the total life-cycle environmental impact of the EEE products but they were provided as recycling credits. Recycling credits were obtained as the difference in environmental impacts between the two accounting methods for recycling in WEEE LCI[3] (i.e., with and without benefits):

$$Credits = Impacts_{cut-off} - Impacts_{with\ benefits} \tag{2}$$

On the other hand, recyclable by-products are materials with no or little economic value that can serve as the input or resource for a recycling activity. There is therefore an interest in their collection.[18] This is the case of the paper consumed in the laser printers once it becomes waste. In this case, the point of cut-off is at the end of the activity producing the recyclable material, while transport to the recycling facility is the beginning of the supply chain for the secondary use (i.e., waste treatment of paper or other recyclable by-products is outside the LCA scope of the EEE products).

Landfill disposal

WEEE not collected for treatment was assumed to be landfilled. Waste landfilled was characterized as plastics, aluminium and inert materials. Inventory datasets for landfill disposal of these materials were taken from Ecoinvent database.[2]

3.2 Life cycle impact assessment

The impact assessment was conducted in this study by applying the impact assessment method ReCiPe v1.03, which is incorporated within the LCA software SimaPro. The updated ReCiPe2016[19] provides a state-of-the-art impact assessment method to convert LCI to a number of harmonised impact scores on midpoint and endpoint level (Figure 12).

Eighteen impact categories can be assessed at the midpoint level, including: global warming, ozone depletion, ionizing radiation, photochemical oxidant formation (human health and terrestrial ecosystems), particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity (carcinogenic and non-carcinogenic), land use, mineral resource scarcity, fossil resource scarcity, and water consumption. Inputs and output collected in the LCI (i.e., resources and environmental releases) are translated into environmental impact scores for these midpoint categories by means of the so-called characterization factors (Table 9).

These midpoint impact categories are further converted and aggregated into three endpoint categories: damage to human health, damage to ecosystem diversity and damage to resource availability (Table 10). Endpoint impacts are directly derived from the midpoint impacts by means of endpoint characterization factors (CF_e) that varies depending on the cultural perspective used for the assessment (egalitarian, hierarchist or individualist). Environmental impacts were assessed in this study according to hierarchist perspective, which is based on scientific consensus with regards to time horizon and other issues (adaptation capacity, technology development, and so forth).

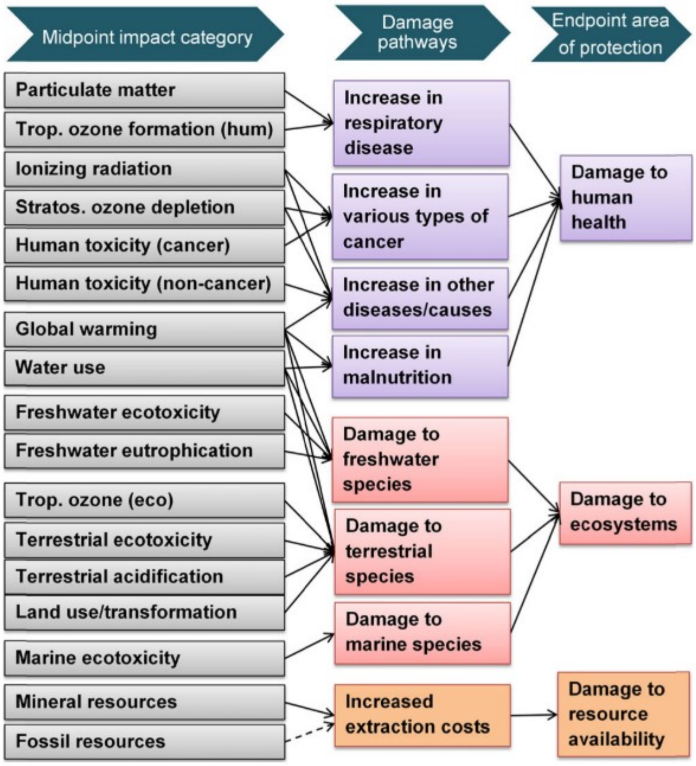

Figure 12. Impact categories covered in the ReCiPe2016 method.

Table 9. Midpoint impact categories and related characterization factors and units in the ReCiPe2016 method.

Impact category	Characterization factor (CF_m)	Unit
Global warming	Global warming potential (GWP)	kg CO2 to air
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 to air
Ionizing radiation	Ionizing radiation potential (IRP)	kBq Co-60 to air
Fine particulate matter formation	Particulate matter formation potential (PMFP)	kg PM2.5 to air
Photochemical oxidant formation: ecosystem quality	Photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx to air
Photochemical oxidant formation: human health	Photo-chemical oxidant formation potential: humans (HOFP)	kg NOx to air
Terrestrial acidification	Terrestrial acidification potential (TAP)	kg SO2 to air
Freshwater eutrophication	Freshwater eutrophication potential (FEP)	kg P to fresh water
Human toxicity: cancer	Human toxicity potential (HTP_c)	kg 1,4-DCB to urban air
Human toxicity: non-cancer	Human toxicity potential (HTP_{nc})	kg 1,4-DCB to urban air
Terrestrial ecotoxicity	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB to industrial soil
Freshwater ecotoxicity	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB to fresh waters
Marine ecotoxicity	Marine ecotoxicity potential (METP)	kg 1,4-DCB to marine water
Land use	Land occupation potential (LOP)	m2×yr annual crop land
Water use	Water consumption potential (WCP)	m3 water consumed
Mineral resource scarcity	Surplus ore potential (SOP)	kg Cu
Fossil resource scarcity	Fossil fuel potential (FFP)	kg oil

Table 10. Endpoint impact categories and related characterization factors and units in the ReCiPe2016 method.

Impact category	Area of protection	Impact indicator / Unit
Damage to human health (HH)	Human health	Disability-adjusted loss of life years / DALY
Damage to ecosystem quality (ED)	Natural environment	Time-integrated species loss / species.yr
Damage to resource availability (RA)	Resource scarcity	Surplus cost / Dollar (USD2013)

3.3 Material Circularity Indicator

The Material Circularity Indicator[1] (MCI) methodology was used in C-SERVEES to assess the circularity of the target products and business models under the conventional scenario. The MCI is thus provided herein as an additional environmental impact category of the LCA studies.

The MCI for a product measures the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product. The MCI gives a value between 0 and 1 where higher values indicate a higher circularity. Any product that is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase can be considered a fully 'linear' product (MCI = 0). On the other hand, any product that contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% can be considered a fully 'circular' product (MCI = 1). In practice, products will sit somewhere between these two extremes and the MCI measures the level of circularity in the range 0 to 1.

The MCI is essentially constructed from a combination of three product characteristics: the mass V of virgin raw material used in manufacture, the mass W of unrecoverable waste that is attributed to the product, and a utility factor X that accounts for the length and intensity of the product's use. The associated material flows are summarised in Figure 13. The dashed lines indicate that the methodology does not require a closed loop (i.e., recycled feedstock and reused components do not have to be sourced from the same product but can be sourced on the open market).

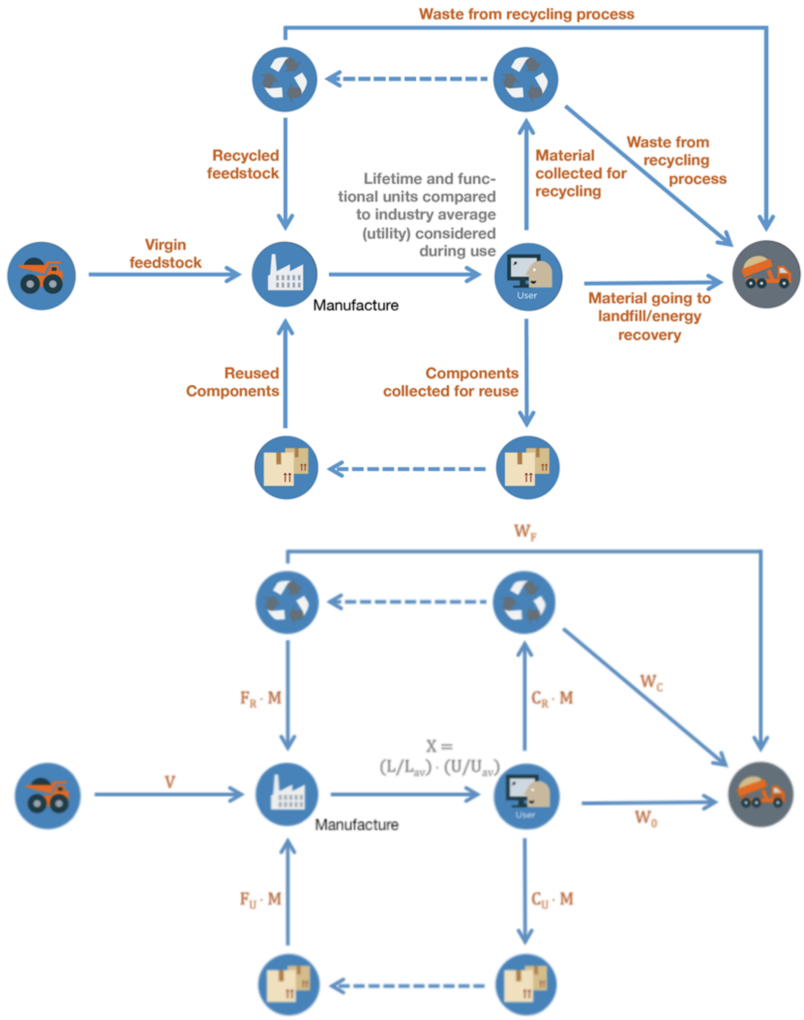

Figure 13. Diagrammatic representation of material flows used in MCI methodology.

Virgin feedstock

The mass V of virgin raw material is calculated as follows:

$$V = M \cdot (1 - F_R - F_U) \tag{3}$$

where M is the mass of the finished product, F_R is the fraction of feedstock derived from recycled sources and F_U is the fraction from reused sources.

Unrecoverable waste

The mass W of unrecoverable waste that is attributed to the product is calculated as follows:

$$W = W_0 + \frac{W_F + W_C}{2} \tag{4}$$

where W_0 is the amount of waste going to landfill or energy recovery, W_C is the amount of waste generated in the recycling process and W_F is the amount of waste generated to produce any recycled content used as feedstock (as represented in Figure 13).

These amounts of unrecoverable waste are calculated as follows:

$$W_0 = M \cdot (1 - C_R - C_U) \tag{5}$$

$$W_C = M \cdot (1 - E_C) \cdot C_R \tag{6}$$

$$W_F = M \cdot \frac{(1 - E_F) \cdot F_R}{E_F} \tag{7}$$

where C_R is the fraction of the mass of the product being collected for recycling at the end of its use phase, C_U is the fraction of the mass of the product going into component reuse, E_C is the efficiency of the recycling process for the product at the end of its use phase and E_F is the efficiency of the recycling process used to produce the recycled feedstock.

Linear flow index

The linear flow index (LFI) measures the proportion of material flowing in a linear fashion; i.e., sourced from virgin materials and ending up as unrecoverable waste. The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow. The index is derived as follows:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{8}$$

Utility

The utility X has two components: one accounting for the length of the product's use phase (lifetime L) and another for the intensity of use (functional units U). These two components are combined to form the utility X as follows:

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right) \tag{9}$$

Increasing the lifetime L when the industry average L_{av} remains fixed leads to an increase in X and, correspondingly, to an increase (and thus an improvement) in the product's MCI. Conversely, if the industry average increases (e.g., because most producers start producing more durable or repairable products) while the assessed product's lifetime remains constant, its MCI will decrease. The same argument applies to functional units (U/U_{av}).

In most cases, either lifetimes or functional units, but not both, are used to calculate X. If lifetimes are used exclusively, this means assuming that $U/U_{av} = 1$. If functional units are used exclusively, this means assuming that $L/L_{av} = 1$. In some cases, both lifetimes and functional units can be used, but it is important to make sure that any given effect is only considered once, either as an impact on lifetimes or on intensity of use, but not both.

Material Circularity Indicator

The MCI of a product is defined by considering the Linear Flow Index of the product (LFI) and a factor F(X), built as a function of the utility X that determines the influence of the product's utility on its MCI. It is defined as this positive value:

$$MCI = \max(0, MCI^*) \tag{10}$$

where MCI^* is obtained as follows:

$$MCI^* = 1 - LFI \cdot F(X) \tag{11}$$

where F(X) takes the form:

$$F(X) = \frac{0.9}{X} \tag{12}$$

3.3.1 Input data for MCI

Data input into the MCI model for each target product was based on primary data supplied by the EEE producers (ARÇELIK, LEXMARK and ADVA). Where the information was not known, generic industry data or best approximations were used instead, as described below.

Recycled feedstock

The recycled feedstock (F_R) in the target products was first determined in order to subsequently estimate the mass of virgin raw material (V). The recycled feedstock for the different materials composing the products was determined using market data from industry databases and literature. Two different indicators were used to quantify the recycled feedstock, namely recycling input rate (RIR) and recycled content (RC). The distinction between RIR and RC is subject to different interpretations about which flows should be used as a basis for calculation, although the selection is often driven by the availability of data rather than by the principle.[24] Both terms are sometimes used interchangeably and sometimes not (e.g., for metals RC is used at the finished product level and RIR is used at the metal production level including metal produced by semi-manufacturers).

The RIR can be calculated as follows:

$$RIR = \frac{i + k}{a + i + k} \tag{13}$$

where a is the flow of primary metal into the anthropogenic metal cycle, i is the flow of collected and separated old scrap and k is the flow of collected and separated new scrap (see Figure 14).

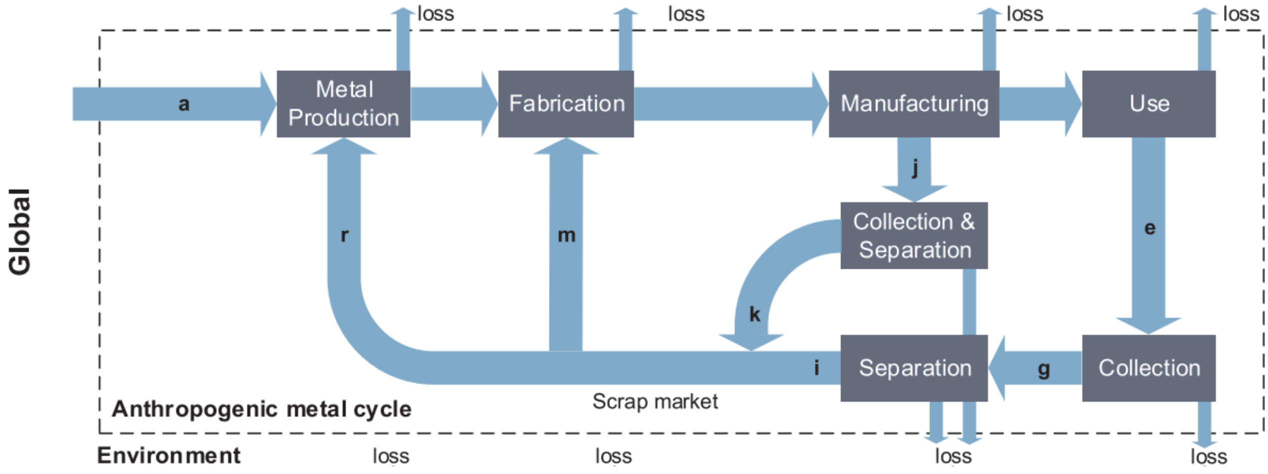

Figure 14. Material flows used in the definition of metal recycling rates.[25]

Table 11 shows the values used in the present study to determine the recycled feedstock in the target products. It distinguishes recycled content (either RIR or RC) for the different materials and, whether available, specific values are provided according to the country or region where the material is sourced.

Table 11. Input data used for recycled feedstock fraction (FR) for target products in the C-SERVEES project.

Material	Indicator	Global	China	Other Asia	EU	USA	Other America	Japan	Turkey
Steel[26] (electric arc furnace)	RIR	27.9	10.4	63.7	40.9	67.8	32.6	24.5	67.8
Aluminum[27] (secondary)	RIR	21.4	16.5	19.5	26.9	67.1	18.4	100	
Copper	RIR	35[28]	44[29]		52[30]				
Flat glass	RC				6[31]-11[32]				
Paper[33]	RIR	50.3	72.6		54.0	38			
Tin	RIR	13[34]							
Tin in alloys	RIR	31[34]							
Gold	RC	25.0[35]							
Silver	RC	13.9[36]							
Palladium	RC	25.3[37]							
Platinum	RC	25.8[37]							
Plastics	RC	11.8[38]							
Lead	RIR	54.0[39]							

Unrecoverable waste

The amount of waste collected for recycling or reuse was assumed to be the same as the waste collection rate defined for each target product in Table 8, while the amount W_0 of waste going to landfill or energy recovery was deducted directly from the waste collection rate.

The amount W_C of waste generated in the recycling process was taken from the inventory data in WEEE LCI project.[20] Datasets provided in the inventories were analysed to determine the efficiency of the recycling process (E_C) for each material/WEEE stream pair.

The amount W_F of waste generated to produce the recycled content used as feedstock was obtained from the average efficiency of the recycling process (E_F) for each material, which was assumed to be 75% for plastics and 90% for all other materials (metals, glass and others).

Utility

The industry average lifetime and intensity of use used to determine the utility X of the target products were based on literature and average market data. Table 12 shows the values used in the present study for industry average lifetime and functional units for the target products.

Table 12. Industry average lifetime and intensity of use for target products in the C-SERVEES project.

Product category	Average industry lifetime (L_{av}, in years)	Average industry intensity of use (U_{av}, functional units)
Washing machine	12.5[15]	280 cycles/year[15]
Multifunctional laser printer	5[21]	50 ppm[23]
ALM	8	365 days/year, 24 h/day
TV set	8[13]- 6[22]	4h/day; turned off 4 weeks/year[13]

4 Life cycle costing

In parallel to the LCA, an economic evaluation of the four target products was carried out. The LCC methodology also follows a life cycle approach, but it assesses the economic costs of the products instead of the environmental impacts as in LCA. Thus, LCC was used to assess all economic costs associated with the whole life cycle of the products, including both internal and external costs (Figure 15).

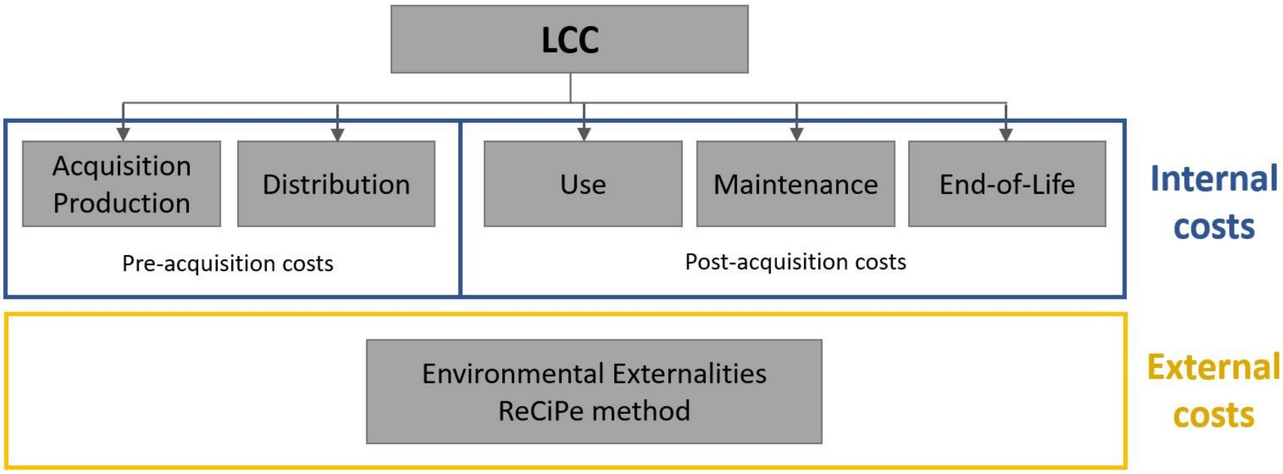

Figure 15. Scope of the LCC in the C-SERVEES project.

Calculation of internal costs was mainly based on operational and economic data collected from the industry partners producing the EEE products (ARÇELIK, LEXMARK and ADVA). Additionally, the external costs related to environmental externalities were calculated by applying monetisation factors to the environmental impacts obtained from the LCA studies. Below are described the main methodological aspects considered for the development of the LCC studies in the project.

4.1 Internal costs

The economic assessment of the target products includes the internal costs for: (i) acquisition of raw materials and components, including their transport to the product manufacturing plant; (ii) manufacturing of the product; (iii) product distribution to retailers or final customers; (iv) use, (v) maintenance (if required) and (vi) end of life. Most of the data required for the calculation of these internal costs were provided by industry partners. However, some data were gathered from literature, such as the market prices for the electricity, water and other consumables consumed by the products during their use.

According to the cost structure proposed, the internal costs were grouped into three categories:

- Manufacturing, which includes (i) costs for acquisition and transport of raw materials and components, (ii) costs for all manufacturing processes required to produce the finished product and (iii) costs for product distribution.
- Use, which includes (iv) costs for product operation (incl. electricity, water and other consumables) and (v) maintenance costs.
- End of life, which includes (vi) costs related to WEEE management.

4.1.1 Manufacturing

The sales price for each target product was assumed herein to include all the internal costs for manufacturing (including all investment and operating costs related to raw materials/components, product manufacturing and distribution, as well as additional costs related to product development like R&D costs). Sales price also includes the net revenues for the EEE producers and it represents the acquisition or purchase cost for the final customer. The sales price used in the LCC studies for each target product was taken from the website of the product manufacturers or retailers.

4.1.2 Use

This cost category includes the costs for operating the products and the costs for their maintenance. All the target products demand electricity for operation during their lifetime. In addition, some products need other additional consumables and spare parts for their operation and maintenance. The washing machine consumes water and detergent, while the printer needs paper, laser cartridges, photoconductors, colour developer units and fuser kits. Detailed information on the amounts of electricity and other consumables demanded by the target products and their linked costs are available in the Annexes, together with the complete cost breakdown for each product.

Electricity

According to other LCC studies,[41,42] the cost of the electricity consumed was calculated as the electricity price paid by the customers to operate the EEE products during their entire lifetime. Industry partners provided primary data on the product lifetime, power and/or electricity consumption (per unit of time or operation). The European average price for electricity for the year 2019 was used herein to estimate the cost of electricity consumption during product use. The European average electricity price was taken from Eurostat, distinguishing between price for household customers (0.216 €/kWh, including taxes and VAT, applied for washing machine and TV set) and prices for non-household customers (0.117 €/kWh, excluding VAT, applied for professional multifunctional laser printer and ALM product). The costs for electricity consumption for the following years (after 2019) were estimated assuming a 30% increase in the electricity price for the period 2018-2030, according to estimates by the European Commission.[43]

Water

Similarly, the water price paid by the customers to operate the washing machines during their lifetime was calculated herein. According to Eurostat, the average European price for water for the year 2018 was 0.0016 €/litre, considering an expense of 290 €/inhabitant/year and a water consumption ratio of 180,000 litres/inhabitant/year. The same cost for water consumption was assumed for the following years, given that price variations in the last 5 years have been negligible. ARÇELIK provided primary data on the lifetime and water consumption of the washing machine used for demonstration in the project.

Other consumables

The costs of the specific consumables for the multifunctional laser printer (cartridges, photoconductors, etc.) were directly obtained from the LEXMARK website, while the costs of other consumables like paper (used by laser printer) or detergent (consumed by washing machine) were based on their current average market prices.

4.1.3 End of life

The costs for WEEE management was assumed herein to correspond to the EEE fees paid by producers for EoL management of the products they put on the market. Table 13 shows the EEE fees used as reference costs for the EoL of the target EEE products. These were taken from the database of the SEWA, member of the European Recycling Platform.

Table 13. Costs for WEEE management for target products in the C-SERVEES project.

Product	WEEE category	RECYCLING FEE (€/piece)
ARÇELIK 9123 WF	4.4.2 "Washing machines except portable mini washing machines, dryers, dishwashers, cookers, owns for baking" from the Household appliances section	3.86
LEXMARK CX860dte	4.11.1 "Large multifunctional printers" from the Large IT and telecommunications equipment section	15.00
ADVA 16ALM/#1650D/AC	6.3.2 "Unclassified IT&C equipment up to max. 3 Kg" from the IT and telecommunications equipment section	0.19
GRUNDIG G43C 891 5A	2.5.1 "Television sets from 37" to 49" diagonal" from the Consumer electronics section	1.20

4.2 External costs

Monetary valuation of environmental impacts was applied to assess the costs of environmental externalities. Different approaches for monetizing environmental damages exist, however, their application to LCA still shows some limitations.[44] For example, the observed-preferences approach, which is based on the willingness to pay in an existing market, is not extensively applied in LCA. Although partial applications of the market-price method in LCA are found in ReCiPe, the availability of appropriate market-price data that can be linked directly to the environmental impacts in LCA is a major limitation of this method. In general, hedonic-pricing and travel-cost approaches, both based on the willingness to pay in surrogate markets, appear to be excessively geographically- and temporarily-specific for most LCA applications, and their results are difficult to generalize consistently. Additionally, the application of the contingent-valuation approach, based on the willingness to pay in hypothetical markets or trade-off situations, has been scattered and no work exists that applies contingent valuation consistently to all areas of protection in LCA. Finally, the experiment method and the budget constraint method are proposed as the best options for monetary valuation in LCA.[44] The experiment method is very appropriate for use in LCA because it focuses the monetary valuation on the trade-off between different impacts and matches the objective of impacts' weighting. The budget constraint method is based on the willingness to pay for an additional Quality-Adjusted Life Year (QALY) in a hypothetical situation without externalities. It represents a relatively new contribution that finds its application in LCA to reduce the uncertainty in determining the budget constraint, which is a key parameter and source of uncertainty in other monetary valuation approaches.

Based on the critical review of existing approaches and methods, the monetary valuation was carried out taking as a reference the budget constraint method used by Weidema[45] in combination with the impact assessment method ReCiPe to obtain monetary values for environmental impacts as made in other previous study.[46] Table 14 shows the monetisation factors used herein to convert the environmental impacts calculated by means of LCA (both endpoint impacts and global warming) into external costs. It should be highlighted that monetisation factor for global warming can show a considerable uncertainty regardless of the estimation method and application contexts. The factor used herein for global warming is 130 €/tonne CO_2 eq, which is similar to that estimated in other studies, such as 97.12 €/tonne CO_2,[47] 94.79 €/tonne CO_2,[48] 101.06 €/tonne CO_2[49] or 134.74 €/tonne CO_2.[50] Other studies consider, however, very different magnitudes, such as 24.28 €/tonne CO_2[51–53] or 303.96 €/tonne CO_2.[54]

Table 14. Monetisation factors considered in the C-SERVEES project.[46] Values in €2017.

Impact category	Monetization factor
Human health (HH)	101,311 €/DALY
Ecosystem quality (ED)	1.23E+07 €/species.yr
Resource availability (RA)	0.9295 €/USD2013
Global warming	130 €/tonne CO_2 eq

As the results provided by ReCiPe method are expressed in $\$_{2013}$, they had to be adapted to $€_{2017}$ values, considering that 1 $\$_{2013}$ is worth 1.05 $\$_{2017}$ and 1 $\$_{2017}$ is worth 0.885 $€_{2017}$ (ECB and IMF official data).

The costs of environmental externalities were therefore obtained for each life cycle phase applying the monetisation factors to the LCA results for the global warming impact and the three endpoint impacts (human health, ecosystems and resources). The costs for externalities used in the LCC studies, which are added to internal costs, are those obtained through monetary valuation of endpoint impacts. However, the external costs obtained considering global warming impact are also included herein as additional results.

5 Social life cycle assessment

Finally, an evaluation of the social impacts of the four target products was performed by using the S-LCA methodology. In particular, the method and indicators of the Social Hotspot Database (SHDB) were used (Figure 16). The SHDB (which is available for software SimaPro) assesses 26 social sub-categories that can be grouped into 5 social categories. The SHDB offers a weighted aggregation model that converts the values of impacts for each social subcategory into aggregated impact values for each social category, which in turn can be aggregated until arriving at a single global social impact indicator (the so-called Social Hotspot Index).

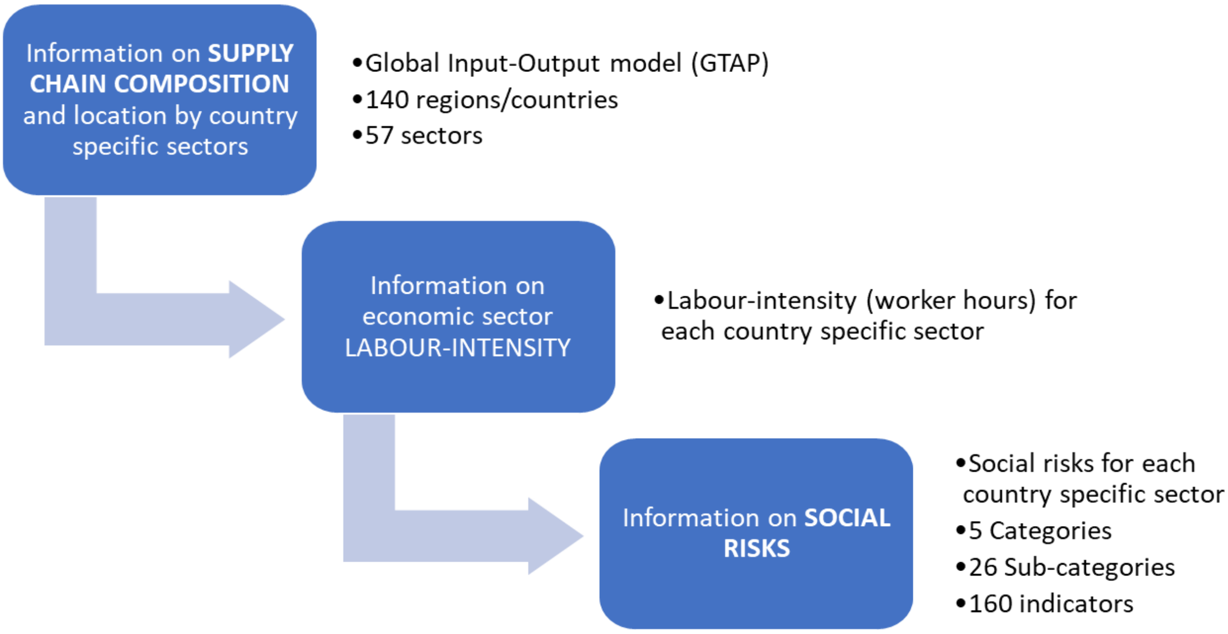

Figure 16. S-LCA methodology applied in the C-SERVEES project.

Figure 16 outlines the S-LCA methodology followed herein to develop the social studies of the target products. It includes the following steps and components:

Information on supply chain composition and location

Knowledge on where the production activities are taking place is a major consideration for S-LCA because of the influence of societal, political and cultural differences on the potential social impacts.[55,57,59] The first step in S-LCA is therefore to define the supply chain composition by describing how the production costs are distributed among the supply chain by country-specific sectors (CSS); i.e., how costs are allocated to each sector/country pair (e.g., Euros spent in electrical equipment sector in China).

A breakdown of the total manufacturing cost by CSS was provided by industry partners (ARÇELIK, LEXMARK and ADVA) for each target product, considering their Tier 1 level suppliers. The manufacturing costs were grouped into the following sectors in several countries (that were different depending on each product): plastic and rubber materials, ferrous metals, non-ferrous metals, paper products, mineral products, electronic equipment and wood (only in some cases for packaging).

The SHDB incorporates a Global Input-Output model that provides information on the trade flows between the economic sectors of each country or region of the world (including 57 sectors in 140 regions/countries). The so-called GTAP (Global Trade Analysis Project) model was used to complete the definition of the supply chain composition for the target products by modelling how the economic amounts purchased from the CSS related to Tier 1 suppliers are contributed by other CSS (related to lower-Tier suppliers).

Information on the economic sector labour-intensity

Labour-intensity, expressed in terms of worker-hours, plays the role of what environmental LCA refers to as an 'elementary flow'; i.e., the basic or first-order 'intervention' by a production process that ultimately is linked to outcomes or impacts of interest. More generally, worker hours are relevant because they represent evidence of the intensity of work required by each CSS directly related to production.[55,57]

The SHDB provides a worker-hours model that is based on average wage payments for each sector in each of the GTAP country/region. Thus, the SHDB was used to identify how many worker-hours are involved for each CSS involved in the supply chain of the target products, according to the economic demands from each CSS quantified in the previous step.

Information on social risks

The SHDB also provides information on social risks and opportunities by country and economic sector, including over 160 social impact indicators for the CSS covered by the GTAP model. 26 impact subcategories (Figure 17) can thus be assessed by a number of indicators depending on the data context; sometimes only one indicator is available and relevant and sometimes several indicators are used for a specific social subcategory. The interpretation of data and the determination of risk levels (from low to very high) are most often performed through consideration of the range and distribution of values exhibited for the indicators across the full population of sectors and countries.[55,57]

The labour-intensity information for each CSS can be used together with the social risk levels there to determine how many worker-hours are linked to the social risk level for a given social subcategory in each CSS.

Figure 17. Social categories and subcategories included in the S-LCA (using SHDB).

Social Hotspot Index (SHI)

The SHDB database includes information on 160 indicators covering 26 impact subcategories, 5 impact categories and 4 stakeholder groups: workers, local communities, value chain actors and society (Figure 17).[55,57]

Due to the large number of indicators and impact subcategories used and taking into account the specific evaluation for each country and economic sector, the S-LCA generates a large amount of data on social impacts that makes difficult to base decisions on. Therefore, to facilitate the understanding of the results and make sense of the social impact information available for each CSS, the Social Hotspot Index (SHI) was created and it has been used in several studies.[55,58,59]

The SHI is an impact assessment method that combines the labour-intensity information with the social risk levels to express social risks (and opportunities) in terms of medium risk hours equivalent (Mrheq), by sector and country for the 5 social impact categories and the 26 social impact subcategories. The SHI is determined by first weighing the level of risk identified for each social impact subcategory, using weighting factors shown in Table 15. This weighting augments or lower the number of workers-hours depending on the risk level, converting them into Mrheq. Thus, the same unit is used to calculate the impact on each social subcategory, so the impacts for different subcategories can be aggregated into single impact values for the corresponding social categories, which in turn can be aggregated into a single global social impact indicator, namely the so-called Social Hotspot Index or SHI. In the method, social subcategories and categories are all weighted equally when adding them together (i.e., they are all given the same relevance).

Table 15. SHDB Impact Assessment method. Weighting factors used by default.[55,57]

Risk level	Weighting factor
Very high risk	10
High risk	5
Medium risk	1
Low risk	0.1

The expression of social impacts in Mrheq was also applied herein to aggregate the social impacts into a social footprint given by the SHI, which was calculated using the SHDB in combination with SimaPro software. Furthermore, it was helpful to identify target areas in the supply chains to improve social conditions; i.e., social hotspots or individual production activities/countries (identified by CSS) that contribute most to the risk (overall and/or by impact category or subcategory).

6 Main results

This section summarises the results from the life cycle sustainability assessment of each target product. It includes various environmental, economic and social indicators obtained by means of the LCA, LCC and S-LCA studies, respectively. The main indicators for each target product are collected below, while additional indicators and more detailed results are included in the respective Annexes.

Table 16 shows the results for a **washing machine ARÇELIK 9123 WF**, which has 9 kg capacity and results in 24,750 kg of clothes washed during its 12.5-year lifetime (assuming 220 washing cycles/year).

Table 16. Main sustainability indicators for the washing machine under conventional scenario (baseline).

Washing machine	Method & Indicators		Amount	Unit
	LCA	Global warming	2,344	kg CO_2 eq
		Human health	3.33E-02	DALY
		Ecosystems	1.76E-04	species.yr
		Resources	97.6	USD2013
		Recycling credits, Global warming	-32	kg CO_2 eq
		Recycling credits, Human health	-1.06E-04	DALY
		Recycling credits, Ecosystems	-2.07E-07	species.yr
		Recycling credits, Resources	-2.4	USD2013
		Material Circularity Indicator (MCI)	0.25	-
	LCC	Internal costs (€)	2,235	€
		External environmental costs (€)	5,794	€
		Total costs (€)	8,029	€
	S-LCA	Labour Rights & Decent Work (Pt)	663	Pt
		Health & Safety (Pt)	795	Pt
		Human Rights (Pt)	461	Pt
		Governance (Pt)	1,046	Pt
		Community (Pt)	388	Pt
		Total – Social Hotspot Index (Pt)	3,352	Pt

Table 17 shows the results for a **multifunctional laser printer LEXMARK CX860dte**, which results in 390,000 pages printed during its 5-year lifetime (for standard business usage of 260 days/year and 300 pages per day).

Table 17. Main sustainability indicators for the multifunctional laser printer under conventional scenario (baseline).

Multifunctional laser printer	Method & Indicators		Amount	Unit
	LCA	Global warming	2,535	kg CO_2 eq
		Human health	9.99E-03	DALY
		Ecosystems	4.11E-05	species.yr
		Resources	239.1	USD2013
		Recycling credits, Global warming	-129	kg CO_2 eq
		Recycling credits, Human health	-4.95E-04	DALY
		Recycling credits, Ecosystems	-9.29E-07	species.yr
		Recycling credits, Resources	-10.7	USD2013
		Material Circularity Indicator (MCI)	0.54	-
	LCC	Internal costs (€)	25,537	€
		External environmental costs (€)	1,741	€
		Total costs (€)	27,278	€
	S-LCA	Labour Rights & Decent Work (Pt)	16,652	Pt
		Health & Safety (Pt)	23,401	Pt
		Human Rights (Pt)	11,978	Pt
		Governance (Pt)	28,937	Pt
		Community (Pt)	9,725	Pt
		Total – Social Hotspot Index (Pt)	90,693	Pt

Table 18 shows the results for a **telecommunications equipment** composed by **an active ALM unit (ADVA 16ALM/#1650D/AC) and fourteen passive fibre-optic sensors**, which together offer continuous monitoring throughout its 8-year lifetime (i.e., 365 days/year and 24 h/day).

Table 18. Main sustainability indicators for the ALM product under conventional scenario (baseline).

ALM product	Method & Indicators		Amount	Unit
	LCA	Global warming	406	kg CO_2 eq
		Human health	9.11E-03	DALY
		Ecosystems	4.92E-05	species.yr
		Resources	18.0	USD2013
		Recycling credits, Global warming	-7	kg CO_2 eq
		Recycling credits, Human health	-2.94E-05	DALY
		Recycling credits, Ecosystems	-7.41E-08	species.yr
		Recycling credits, Resources	-0.7	USD2013
		Material Circularity Indicator (MCI)	0.40	-
	LCC	Internal costs (€)	16,457	€
		External environmental costs (€)	680	€
		Total costs (€)	17,137	€
	S-LCA	Labour Rights & Decent Work (Pt)	5,369	Pt
		Health & Safety (Pt)	7,802	Pt
		Human Rights (Pt)	3,982	Pt
		Governance (Pt)	8,028	Pt
		Community (Pt)	2,959	Pt
		Total – Social Hotspot Index (Pt)	28,140	Pt

Table 19 shows the results for a **TV set GRUNDIG G43C 891 5A**, which is a 43" smart-TV that provides 10,784 hours of viewing during its 8-year lifetime (assuming an average use of 337 days/year and 4 h/day).

Table 19. Main sustainability indicators for the TV set under conventional scenario (baseline).

TV set	Method & Indicators		Amount	Unit
	LCA	Global warming	472	kg CO_2 eq
		Human health	7.87E-03	DALY
		Ecosystems	3.87E-05	species.yr
		Resources	27.5	USD2013
		Recycling credits, Global warming	-17.9	kg CO_2 eq
		Recycling credits, Human health	-7.80E-05	DALY
		Recycling credits, Ecosystems	-1.94E-07	species.yr
		Recycling credits, Resources	-1.8	USD2013
		Material Circularity Indicator (MCI)	0.32	-
	LCC	Internal costs (€)	449	€
		External environmental costs (€)	1,324	€
		Total costs (€)	1,773	€
	S-LCA	Labour Rights & Decent Work (Pt)	1,277	Pt
		Health & Safety (Pt)	1,698	Pt
		Human Rights (Pt)	897	Pt
		Governance (Pt)	2,167	Pt
		Community (Pt)	727	Pt
		Total – Social Hotspot Index (Pt)	6,766	Pt

All these indicators will constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of the different products. It should be noted that these results cannot be used to compare the products with each other, since each product has its own functions and functional unit, intensity of use, number of users per product unit and lifetime, resulting in products completely different in terms of composition, weight, life-cycle management and derived impacts;

e.g., the washing machine is a consumer product used at home by a family, while the professional multifunctional laser printer is a large business product used by several office workers (over 30 users per product unit).

References

1. Ellen MacArthur Foundation. *Circularity indicators. An approach to measuring circularity. Methodology*. (2015). doi:10.4324/9780429061028-7

2. Hischier, R., Classen, M., Lehhmann, M. & Scharnhorst, W. *Life cycle inventories of Electric and Electronic Equipment: Production, Use and Disposal. Ecoinvent report No. 18*. **0**, (2007).

3. Bleu Safran. *End-of-life management LCI of constituent materials of Electrical and Electronic Equipment (EEE) within the framework of the French WEEE take-back scheme Methodological summary*. (2018).

4. Alcaraz Ochoa, M. L. *et al.* Design parameters and environmental impact of printed wiring board manufacture. *J. Clean. Prod.* **238**, 117807 (2019).

5. Gabi. XI Electronics. Available at: http://www.gabi-software.com/international/support/gabi/gabi-5-lci-documentation/data-sets-by-database-modules/extension-databases/xi-electronics/. (Accessed: 13th August 2020)

6. Okrasinski, T. A. & Benowitz, M. S. Quantifying Environmental Life Cycle Impacts for ICT Products-A Simpler Approach. in *2020 Pan Pacific Microelectronics Symposium, Pan Pacific 2020* 1–4 (IEEE, 2020). doi:10.23919/PanPacific48324.2020.9059483

7. Andrae, A. S. G. & Andersen, O. Life cycle assessment of integrated circuit packaging technologies. *Int. J. Life Cycle Assess.* **16**, 258–267 (2011).

8. Kline, D. *et al.* Sustainable IC design and fabrication. in *2017 8th International Green and Sustainable Computing Conference, IGSC 2017* **2017**-**Octob**, 1–8 (Institute of Electrical and Electronics Engineers Inc., 2018).

9. Boyd, S. B. Life-cycle Assessment of Semiconductors. (University of California, Berkeley, 2009).

10. Schmidt, M., Hottenroth, H., Schottler, M., Fetzer, G. & Schlüter, B. Life cycle assessment of silicon wafer processingfor microelectronic chips and solar cells. *Int. J. Life Cycle Assess.* **17**, 126–144 (2012).

11. Teehan, P. & Kandlikar, M. Comparing embodied greenhouse gas emissions of modern computing and electronics products. *Environ. Sci. Technol.* **47**, 3997–4003 (2013).

12. Gómez, P., Elduque, D., Sarasa, J., Pina, C. & Javierre, C. Influence of the material composition on the environmental impact of surface-mount device (SMD) transistors. *J. Clean. Prod.* **107**, 722–730 (2015).

13. Hischier, R. Life cycle assessment study of a field emission display television device. *Int. J. Life Cycle Assess.* **20**, 61–73 (2015).

14. Talens Peiró, L., Ardente, F. & Mathieux, F. *Analysis of material efficiency aspects of Energy related Product for the development of EU Ecolabel criteria - Analysis of product groups: personal computers and electronic displays*. (2016). doi:10.2788/642541

15. Tecchio, P., Ardente, F. & Mathieux, F. *Analysis of durability, reusability and reparability - Application to washing machines and dishwashers*. (2016). doi:10.2788/51992

16. IRENA. *Global Energy Transformation: The REmap transition pathway (Background report to 2019 Edition)*. (2019).

17. Eurostat. Waste statistics - electrical and electronic equipment - Statistics Explained. *Eurostat Statistics Explained* (2020). Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment#EEE_put_on_the_market_and_WEEE_collected_in_the_EU. (Accessed: 5th August 2020)

18. Ecoinvent Centre. Cut-Off System Model. *Ecoinvent Online* (2018). Available at: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html. (Accessed: 7th August 2020)

19. Huijbregts, M. A. J. *et al.* ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **22**, 138–147 (2017).

20. Bleu Safran. *LCI for end-of-life management of constituent materials of electrical and electronic equipment within the framework of the French accredited WEEE take-back scheme FAQ*. (2018).

21. innov8 Printers & MFP. How Long Should My Multifunction Printer/Copier Last? *innov8 Digital Solutions^{TM}* (2019).

22. Hischier, R., Reale, F., Castellani, V. & Sala, S. Environmental impacts of household appliances in Europe and scenarios for their impact reduction. *J. Clean. Prod.* **267**, 121952 (2020).

23. Harrison, K. How to Choose a Digital Copier for Your Business - Business News Daily. *Busines News Daily* (2019).

24. UNEP. *Recycling rates of metals. A status report. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E.; Allwood, J.; Birat, J.-P.; Reck, B.K.; Sibley, S.F.; Sonnemann, G.; Buchert, M.; Hagelüken, C.* (2011).

25. Tercero Espinoza, L. A. & Soulier, M. Defining regional recycling indicators for metals. *Resour. Conserv. Recycl.* **129**, 120–128 (2018).

26. World Steel Association. *2020 World steel in figures*. (2020).

27. BIR. Bir Global Facts & Figures. Non-Ferrous Metals Global Non-Ferrous Scrap Flows 2000-2015. (2016).

28. Glöser, S., Soulier, M. & Tercero Espinoza, L. A. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environ. Sci. Technol.* **47**, 6564–6572 (2013).

29. Soulier, M. *et al.* The Chinese copper cycle: Tracing copper through the economy with dynamic substance flow and input-output analysis. *J. Clean. Prod.* **195**, 435–447 (2018).

30. Soulier, M., Glöser-Chahoud, S., Goldmann, D. & Tercero Espinoza, L. A. Dynamic analysis of European copper flows. *Resour. Conserv. Recycl.* **129**, 143–152 (2018).

31. AGC Glass Europe. *AGC. Recycled content declaration*. (2016).

32. Saint-Gobain Glass Europe. *Recycled content declaration*. (2018).

33. BIR. BIR Global Facts & Figures. Recovered paper and board recycling in 2018. (2020).

34. International Tin Association. Recycling - International Tin Association. (2020). Available at:

https://www.internationaltin.org/recycling/. (Accessed: 31st July 2020)

35. Philip Newman *et al. Metals Focus. Gold Focus 2019*. (2019).

36. O'Connell, R. *et al. World Silver Survey 2018*. (2018).

37. Alexander, C. *et al. Platinum and Palladium Survey 2019*. (2019).

38. Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **3**, e1700782 (2017).

39. International Lead Organisation. Lead Recycling. (2015).

40. World Steel Association. Fact Sheet: Steel and Raw materials. *Wsa* **15**, 710–739 (2019).

41. Kara, S., Li, W. & Sadjiva, N. Life Cycle Cost Analysis of Electrical Vehicles in Australia. *Procedia CIRP* **61**, 767–772 (2017).

42. Patil, R. B., Kothavale, B. S., Waghmode, L. Y. & Pecht, M. Life cycle cost analysis of a computerized numerical control machine tool: a case study from Indian manufacturing industry. *J. Qual. Maint. Eng.* (2020). doi:10.1108/JQME-07-2019-0069

43. European Commission. Energy prices and costs in Europe. 13 (2019).

44. Pizzol, M., Weidema, B., Brandão, M. & Osset, P. Monetary valuation in Life Cycle Assessment: A review. *Journal of Cleaner Production* **86**, 170–179 (2015).

45. Weidema, B. P. Using the budget constraint to monetarise impact assessment results. *Ecol. Econ.* **68**, 1591–1598 (2009).

46. Dong, Y., Hauschild, M., Sørup, H., Rousselet, R. & Fantke, P. Evaluating the monetary values of greenhouse gases emissions in life cycle impact assessment. *J. Clean. Prod.* **209**, 538–549 (2019).

47. Hope, C. The Social Cost of Co2 from the Page09 Model. *Econ. Discuss. Pap. E-Journal* **2011**–**39**, 0–31 (2011).

48. Stern, N. *Stern review: the economics of climate change*. (2006).

49. van den Bergh, J. C. J. M. & Botzen, W. J. W. A lower bound to the social cost of CO2 emissions. *Nat. Clim. Chang.* **4**, 253–258 (2014).

50. Institute Victoria transport Policy. 5.10 Air pollution. in *Transportation Cost and Benefit Analysis Techniques, Estimates and Implications* (2017).

51. Eshet, T., Ayalon, O. & Shechter, M. Valuation of externalities of selected waste management alternatives: A comparative review and analysis. *Resour. Conserv. Recycl.* **46**, 335–364 (2006).

52. Tol, R. S. J. On the Uncertainty About the Total Economic Impact of Climate Change. *Environ. Resour. Econ.* **53**, 97–116 (2012).

53. Tol, R. S. J. A cost-benefit analysis of the EU 20/20/2020 package. *Energy Policy* **49**, 288–295 (2012).

54. Dietz, S. High impact, low probability? An empirical analysis of risk in the economics of climate change. *Clim. Change* **108**, 519–541 (2011).

55. Benoit-Norris, C., Cavan, D. A. & Norris, G. A. Working with the Social Hotspots Database - Methodology and Findings from 7 Social Scoping Assessments. in *19th CIRP International Conference on Life Cycle Engineering* (2012). doi:10.1007/978-3-642-29069-5

56. Benoit-Norris, C., Norris, G. A., Azuero, L. & Pflueger, J. Creating social handprints: Method and case study in the electronic computer manufacturing industry. *Resources* **8**, 1–15 (2019).

57. Benoit-Norris, C. & Norris, G. A. Chapter 8 : The Social Hotspots Database. in *The Sustainability Practitioner's Guide to Social Analysis and Assessment* 52–73 (2015).

58. Benoit-Norris, C., Cavan, D. A. & Norris, G. A. Identifying social impacts in product supply chains: Overview and application of the social hotspot database. *Sustainability* **4**, 1946–1965 (2012).

59. Benoit-Norris, C., Norris, G. A. & Cavan, D. A. Efficient assessment of social hotspots in the supply chains of 100 product categories using the social hotspots database. *Sustain.* **6**, 6973–6984 (2014).

60. Google. Google Maps. Available at: https://www.google.com/maps.

61. Sea-distances.org. Sea-distances.org. Available at: https://sea-distances.org.

Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.1. Results of environmental, economic and social preliminary analyses.
Annex 1 – Washing machine

Acronym: **C-SERVEES**

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1 Introduction

This Annex includes the comprehensive documentation related to the life cycle sustainability assessment of the current washing machine used for demonstration in the C-SERVEES project. It includes more details on the methodological aspects and assumptions done, life cycle inventory developed and detailed results for the following studies:

- Life cycle assessment, including midpoint and endpoint environmental impact categories and material circularity indicator.
- Life cycle costing, including internal and external costs (related to environmental externalities).
- Social life cycle assessment, including 5 social impact categories.

All these studies and results constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of the washing machine.

2 Goal and scope

The present study aimed to calculate the environmental, economic and social impacts of the washing machine ARÇELIK 9123 WF. It has 9 kg capacity, energy efficiency class A^{+++} and connectivity features. It is manufactured in Çayırova (Turkey) and currently sold worldwide. More details on the washing machine investigated are shown in A1-Table 1.

A1-Table 1. Technical specifications of the demo washing machine.

MODEL	**ARÇELIK 9123 WF**
Image	
Product number	7150370100
Colour	White
Size	840 mm × 600 mm × 610 mm
Weight	75 (±4) kg
Capacity	9.0 kg
Max. spin speed	1,200 rpm
Fascia	Grundig
Dynamic group	Large
Number of programs	16
Features	HomeWhiz, ProSmart (Brushless Motor with 10-year guarantee), Wi-Fi and BLE, Steam Function, Anticrease+
Energy class	A^{+++} (-30%)
Electricity consumption per year	148 kWh
Water consumption per year	10,318 L
Country of origin	Turkey

3 Life cycle assessment

3.1 Functional unit and system boundaries

The product function for the washing machine is washing clothes. The functional unit considered in the study is one washing machine ARÇELIK 9123 WF, which has 9 kg capacity and it results in 24,750 kg of clothes washed during its 12.5-year lifetime (assuming 220 washing cycles/year). A1-Table 2 shows the system boundaries considered for the washing machine, identifying the life cycle phases, processes and other elementary flows included and excluded in the study.

A1-Table 2. System boundaries considered for the washing machine.

Life cycle phase	Included	Excluded
Raw material extraction and processing	Extraction of natural resources Refining and raw material production Intermediate product manufacturing Waste treatment and transport	Infrastructure
Product manufacturing	Energy for product manufacturing/assembly Transport	Infrastructure Production losses
Product distribution	Transport	
Product use	Electricity consumption Water consumption Detergent consumption	Maintenance
End of life	Transport EoL treatments Landfilling of waste fraction not recycled	
Benefits and burdens beyond system boundaries	Recycling benefits (included as credits)	

3.2 Allocation and cut-off criteria

No multi-output foreground processes were identified during data collection. Inventories taken from Ecoinvent database were allocated according to the cut-off system model.[18]

The system boundary in the EoL phase was drawn just behind product waste collection and transportation to the recycling sites. WEEE from the washing machine was classified as waste by-product and environmental burdens associated with waste treatment were thus allocated completely to the waste-producing activity (as indicated in Section 3.1.3 of the main document). The environmental impacts of the EoL phase and the credits generated by recycling are both interesting for the comparative assessment between the baseline product system and the redesigned product system proposed in the C-SERVEES project. Product packaging was also included in the assessment (from cradle to packaging waste collection), but packaging waste treatment was excluded.

No available primary data were knowingly omitted or excluded.

3.3 Data quality

The data used to create the inventory model is as precise, complete, consistent and representative as possible with regard to the goal and scope of the study.

- Primary data was provided by ARÇELIK from the most recent BoM of the product. The data used for the study is considered to be of the highest precision. Ecoinvent database was the main secondary data source used to model the product system.

- Completeness was judged based on the completeness of both the inputs/outputs per unit process and the unit processes themselves.
- Consistency refers to modelling choices and data sources. The goal was to ensure that differences in results occur due to actual differences between product systems investigated and compared, and not due to inconsistencies in modelling choices, data sources, characterisation factors, etc.
- Representativeness expresses the degree to which the data matches the geographical, temporal and technological requirements:
    - The average electricity mix for Europe was considered for the use phase (as explained in Section 3.1.2 of the main document) using the most recent data published (year 2019).[16]
    - Ecoinvent database version used was updated in 2018.
    - Integrated circuits, PWB and capacitors were modelled based on recent literature data (as explained in Section 3.1.1 of the main document).
    - Distances for distribution of washing machines from ARÇELIK factory to retailers were obtained from Google Maps[60] and sea-distances.org[61] for road and water transport, respectively.

3.4 Assumptions and limitations

Other assumptions and limitations for the LCA study of the washing machine are listed below:

- No production losses were considered.
- Recycled content was assumed to be the worldwide average (Table 11).
- The road distance from ARÇELIK factory to the port of Istanbul was assumed to be negligible.
- Railway distances were assumed to be similar to those by road transport.
- Distances for product distribution within each country were assumed as 300 km, except for countries where the port is not within their territory and Maldives (due to the small dimensions of its islands).
- Retailers were assumed to be located in the centre of each country.
- The average lifetime and intensity of use of the target washing machine were assumed to be similar to industry-average values taken from literature (to determine the MCI).
- No maintenance was assumed during the lifetime of the product.
- Waste collection rate was assumed to be the European average for large household appliances (Table 8).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[20]

3.5 Life cycle inventory

This section describes the LCI developed for the target washing machine, including inputs/outputs inventoried for each life-cycle phase and the data sources used for their inventory modelling.

3.5.1 Manufacturing

The LCI of the washing machine manufacturing was obtained from the BoM provided by ARÇELIK. The washing machine consists of several modules, which in turn contain different components and materials. The packaging used for the washing machine was also included in product manufacturing. A final module accounting for the scrap generated in the manufacturing process was also included. The different modules inventoried and their total amounts are listed in A1-Table 3.

A1-Table 3. Modules of the target washing machine.

Modules in washing machine	Total amount (kg)
Packaging	1.22
Customer module	0.32
Control system	2.20
Terminal	0.24
Dynamic system	41.91
Cabinet	13.90
Isolation	0.28
Front door	3.42
Front cabinet	2.19
Accessories	1.84
Panel	1.30
Aqua system	4.01
Motor	3.50
Scrap	2.22
Total	**76.32**

Each module is made of different components and/or materials that are processed with certain manufacturing processes to attain the final shape and properties required for the product. The inventories for the components, materials and manufacturing processes required to produce the washing machine were mainly taken from the Ecoinvent database. These inventories are linked to their own functional unit (FU), so they show energy consumption, resource consumption, emissions, etc. for different basic activities, expressed per amount of materials extracted and/or processed (kg, m^2 or m^3), for example. The environmental impacts of the materials and components composing the washing machine modules were thus obtained by multiplying their amounts by the impacts calculated from the corresponding LCI datasets (for the defined FU). A list of the LCI datasets used for the manufacturing phase is given in A1-Table 4.

A1-Table 4. LCI datasets of material, components and processes for washing machine manufacturing.

Input	Dataset name	FU
	RAW MATERIALS	
Galvanized steel	Steel, low-alloyed, hot rolled + Zinc coat (64 m2/t)	1 kg
Polyester resin, unsaturated	Polyester resin, unsaturated {GLO}| market for | Cut-off, U	1 kg
Acrylate, polyacrylamide	Polyacrylamide {GLO}| market for | Cut-off, U	1 kg
Low-density polyethylene (LDPE)	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U	1 kg
Expanded polystyrene (EPS)	Polystyrene, expandable + Polymer foaming {RER}	1 kg
ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, U	1 kg
Brass	Brass {GLO}| market for | Cut-off, U	1 kg
Bronze	Bronze {GLO}| market for | Cut-off, U	1 kg
Blue pigment	Chromium oxide, flakes {GLO}| market for | Cut-off, U Blue pigment	1 kg
Float glass	Flat glass, uncoated {GLO}| market for | Cut-off, U	1 kg
Glass fibre	Glass fibre {GLO}| market for | Cut-off, U	1 kg
Low carbon steel bar/sheet	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U	1 kg
Masterbatch	30% Blue pigment + 70% PE	1 kg
PA 6.6	Nylon 6-6 {GLO}| market for | Cut-off, U	1 kg
PA 6.6-GF14	86% PA 6.6 + 14% Glass fibre	1 kg
PA 6.6-GF30	67% PA 6.6 + 30% Glass fibre	1 kg
Paper	Paper, newsprint {RER}| market for | Cut-off, U	1 kg
PC	Polycarbonate {GLO}| market for | Cut-off, U	1 kg
PC+ABS	60% PC + 40% ABS	1 kg

Input	Dataset name	FU
PET/PBT	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	1 kg
Polyester film (PET)	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	1 kg
Polyolefin	Polypropylene, granulate {GLO}| market for | Cut-off, U	1 kg
POM	Polyoxymethylene (POM)/EU-271	1 kg
PP	Polypropylene, granulate {GLO}| market for | Cut-off, U	1 kg
PP-GF20	80% PP + 20% Glass fibre	1 kg
PP-GF30	70% PP + 30% Glass fibre	1 kg
PP-CA40	60% PP + 40% Calcite	1 kg
PP-T20	PP-T20 Polypropylene + 20% talc	1 kg
PPO	Polystyrene, high impact {GLO}| market for | Cut-off, U PPO	1 kg
Stainless steel/Stainless steel spring wire/Steel bearing	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U	1 kg
Steel/Steel sheet	Steel, unalloyed {GLO}| market for | Cut-off, U	1 kg
Steel music wire/Steel wire rod	Steel, low-alloyed {GLO}| market for | Cut-off, U	1 kg
Thermoplastic polyurethane elastomer	Synthetic rubber {GLO}| market for | Cut-off, U	1 kg
Concrete	Concrete block {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg
PVC	Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg
Calcite	Calcium carbonate, precipitated {RER}| market for calcium carbonate, precipitated | Cut-off, U	1 kg
Zamak	Zamak	1 kg
Cast iron	Cast iron {GLO}| market for | Cut-off, U	1 kg
Felt cotton	Cotton fibre {GLO}| market for | Cut-off, U	1 kg
Chipboard, particle board	Particle board, for indoor use {GLO}| market for | Cut-off, U	1 m^3
Tin coating (64 m2/t)	Tin plating, pieces {RER}| processing | Cut-off, U	1 m^2
Tin coated brass	Brass + Tin plating pieces	1 kg
Paint	Alkyd paint, white, without solvent, in 60% solution state {RER}| market for alkyd paint, white, without solvent, in 60% solution state | Cut-off, U	1 kg
Paint Spirit/thinner	White spirit {GLO}| market for | Cut-off, U	1 kg
Paint hardener	Butyl acetate {RoW}| production | Cut-off, U	1 kg
Lubricating oil	Lubricating oil {RER}| market for lubricating oil | Cut-off, U	1 kg
	PROCESSING	
Metal processing	Sheet rolling, steel {GLO}| market for | Cut-off, U	1 kg
	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
	Metal working, average for copper product manufacturing {GLO}| market for | Cut-off, U	1 kg
	Metal working, average for metal product manufacturing {RER}| processing | Cut-off, U)	1 kg
	Phosphating (Zn i) 3.24 g/m2	1 m^2
	Section bar rolling, steel {GLO}| market for |Cut-off, U	1 kg
Plastic processing	Injection moulding {GLO}| market for | Cut-off, U	1 kg
Aluminium extrusion	Section bar extrusion, aluminium {GLO}| market for | Cut-off, U	1 kg
Metal stamping and bending	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	1 kg
Steel turning	Section bar rolling, steel {GLO}| market for | Cut-off, U	1 kg
Mirror finishing (polishing)	Polishing {RoW}| production | Cut-off, U	1 kg
Stainless steel sheet average metal working	Metal working, average for chromium steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Steel sheet average metal working	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Plastic injection moulding	Injection moulding {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
Plastic pipes extrusion	Extrusion, plastic pipes {GLO}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)	1 kg
	COMPONENTS	
Capacitor, ceramic SMD type (86 mg average weight)	Capacitor, for surface-mounting {GLO}| market for | Cut-off, U	1 kg
Resistor, SMD type (9.8 mg average weight)	Resistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
Connector, all types (9 g average weight)	Electric connector, wire clamp {GLO}| market for | Cut-off, U	1 kg
key switch tact (242mg) 6.2x6.3x1.8	Switch, toggle type {GLO}| market for | Cut-off, U	1 kg
Motor	Electric motor, for electric scooter {GLO}| production | Cut-off, U	1 kg
PCBA	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Cut-off, U	1 kg
PVC, Cu Cable	Cable, connector for computer, without plugs {GLO}| market for | Cut-off, U	1 kg
Resistor	Resistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
Plug	Plug, inlet and outlet, for computer cable {GLO}| market for | Cut-off, U	1 p
Ferrite	Ferrite {GLO}| market for | Cut-off, U	1 kg
LCD	Liquid crystal display, unmounted {GLO}| production | Cut-off, U	1 kg

3.5.2 Use

Distribution

The washing machine is distributed to a wide list of countries as shown in A1-Table 5.

A1-Table 5. Washing machine distribution by countries.

Country	Market share
Turkey	40.40%
UK	14.07%
France	6.29%
Germany	5.81%
Spain	5.48%
Italy	3.14%
Sweden	2.60%
Serbia	2.33%
Belgium	2.18%
Romania	1.71%
Austria	1.84%
Poland	1.73%
South Africa	1.45%
Rest of countries	10.95%

Product distribution is done by road (47.5%), water (51.6%), and railway (0.9%). The weight of one washing machine (in tonnes) was multiplied by the distance travelled through each transport mode (in km) to calculate the total amounts linked to each transport mode (in tonnes-km or tkm). The values are shown in A1-Table 6.

A1-Table 6. Estimated amounts for distribution of one washing machine by transport mode.

Transport mode	Amount (tkm)
Road	42
Water	196
Railway	1
Total	**239**

The environmental impacts due to the distribution of the washing machines from the ARÇELIK factory to retailers were obtained by multiplying the amounts transported (in tkm) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in A1-Table 7.

A1-Table 7. LCI datasets of transport modes for washing machine distribution.

Input	Dataset name	FU
Road transport	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1 tkm
Water transport	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, U	1 tkm
Railway transport	Transport, freight train {RER}| market group for transport, freight train | Cut-off, U	1 tkm

Product operation

The environmental impacts caused by the use of the washing machine are due to water, detergent and electricity consumption required for its operation. Considering an average lifetime of 12.5 years with an average water consumption of 10,318 litres/year, the total water consumed by the washing machine is 128,975 litres. The washing machine uses an average of 75 grams of detergent per washing cycle. The average use of the washing machine is 220 cycles/year, thus resulting in 206.25 kg of detergent consumed during the lifetime. Finally, the average consumption of electricity is 147.8 kWh/year, which corresponds to a total electricity consumption of 1,847.5 kWh for the entire lifetime. Data used for these estimates were obtained from literature.[15]

The environmental impacts derived from the use of the washing machine were obtained by multiplying the amounts of water, detergent and electricity consumed by the impacts calculated from the corresponding LCI datasets, which are shown in A1-Table 8.

A1-Table 8. LCI datasets of electricity, water and detergent for washing machine operation.

Input	Dataset name	FU
Electricity	Electricity, low voltage, production EUROPE, at grid/RER U, SCENARIO 2020	1 kWh
Water	Tap water {RER}| market group for | Cut-off, U	1 L
Detergent	Soap {GLO}| market for | Cut-off,	1 kg

3.5.3 End of life

Waste collection

Waste collection rate for washing machine at the end of life was assumed to be 46.3%, which is the average waste collection of large household appliances in Europe for the year 2017 (see Table 7 & Table 8).

Waste treatment

Material flows associated with the EoL treatment of the washing machine are classified in A1-Table 9 following the approach and data from the WEEE LCI project.[3] For each material flow, it states the mass in the product (as put on the market), the mass collected for recycling and the mass finally recycled. All the waste materials collected are treated following the take-back scheme available for large household appliances (LHA), while waste not collected was assumed to be landfilled. PCB materials are classified into copper, gold, lead, silver, platinoids, other metals and support materials (such as plastics, fibres, etc.).

A1-Table 9. Waste material flows related to washing machine EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
LHA | ABS without BFR, density < 1.3	2.717	1.257	0.000
LHA | Aluminium	2.202	1.019	0.916
LHA | Brass	0.039	0.018	0.000
LHA | Concrete	23.800	11.012	0.000
LHA | Copper within PCB	0.618	0.286	0.215
LHA | Copper within Wire	0.136	0.063	0.000
LHA | Copper	0.357	0.165	0.000
LHA | Glass	1.930	0.893	4.05E-04
LHA | Gold within PCB	1.34E-03	6.19E-04	4.83E-04
LHA | Lead within PCB	1.33E-03	6.16E-04	1.77E-04
LHA | Oil	0.054	0.025	0.025
LHA | PA without BFR, density < 1.3	0.023	0.010	0.000
LHA | PCB Other base metals	0.222	0.103	0.000
LHA | PCB Support	0.646	0.299	0.000
LHA | PE within wire	0.028	0.013	0.000
LHA | Platinoid within PCB	4.65E-04	2.15E-04	2.843E-05
LHA | PP without BFR, density < 1.3	1.830	0.847	0.408
LHA | PUR foam	0.589	0.272	0.000
LHA | PVC within wire	1.638	0.758	0.000
LHA | Rubber	1.812	0.839	0.000
LHA | Silver within PCB	0.006	0.003	3.80E-04
LHA | Steel	27.600	12.771	10.771
LHA | Wood	1.000	0.463	0.000
LPA| ABS-PC without BFR, density < 1.3	0.328	0.152	0.000
LPA| Glass fibres-plastics composites	6.875	3.181	0.000
LPA| PBT without BFR, density < 1.3	0.200	0.092	0.000
LPA| PC without BFR, density < 1.3	0.045	0.021	0.000
FS| Zinc	0.093	0.043	0.000
Total WEEE cut-off washing machine	**74.790**	**34.606**	**12.336**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one washing machine) is shown in A1-Table 9. The LCI datasets used for recycling of each material flow were obtained from WEEE LCI project.[3] These allow to calculate the environmental impacts of recycling according to two different accounting methods: impacts with benefits (including the impacts of recycling operations and the benefits from the substitution of primary raw materials with the recycled ones) and impacts without benefits (that only includes the impacts of recycling operations). Both accounting methods were applied herein to calculate both direct environmental impacts of recycling and environmental credits due to primary material substitution (calculated as the difference between impacts with and without benefits).

Landfill disposal

A fraction of the waste generated at the EoL of the washing machine is not recycled. It was assumed that this waste fraction is landfilled. Non-recycled waste were classified into three different waste material flows to model landfill disposal, namely aluminium, inert material and plastics. The amount of the washing machine that is finally landfilled classified by waste material flow is shown in A1-Table 10.

A1-Table 10. Waste material flows related to landfill disposal of washing machine.

Waste type	Mass landfilled (kg)
Plastics	9.018
Aluminium	1.183
Inert material	29.984
Total	**40.185**

The environmental impacts derived from landfill disposal were obtained by multiplying the amount of each waste material flow landfilled by the impacts calculated from the corresponding LCI datasets, which are shown in A1-Table 11.

A1-Table 11. LCI datasets of landfill disposal for washing machine EoL.

Input	Dataset name	FU
Landfill disposal for aluminium waste	Disposal, aluminium, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for inert waste	Disposal, inert material, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for plastic waste	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	1 kg

3.6 Life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2 of the main document). Life cycle environmental impacts of the washing machine were thus calculated for eighteen midpoint impact categories (including global warming and other) and three endpoint impact categories (damages to human health, ecosystem diversity and resource availability).

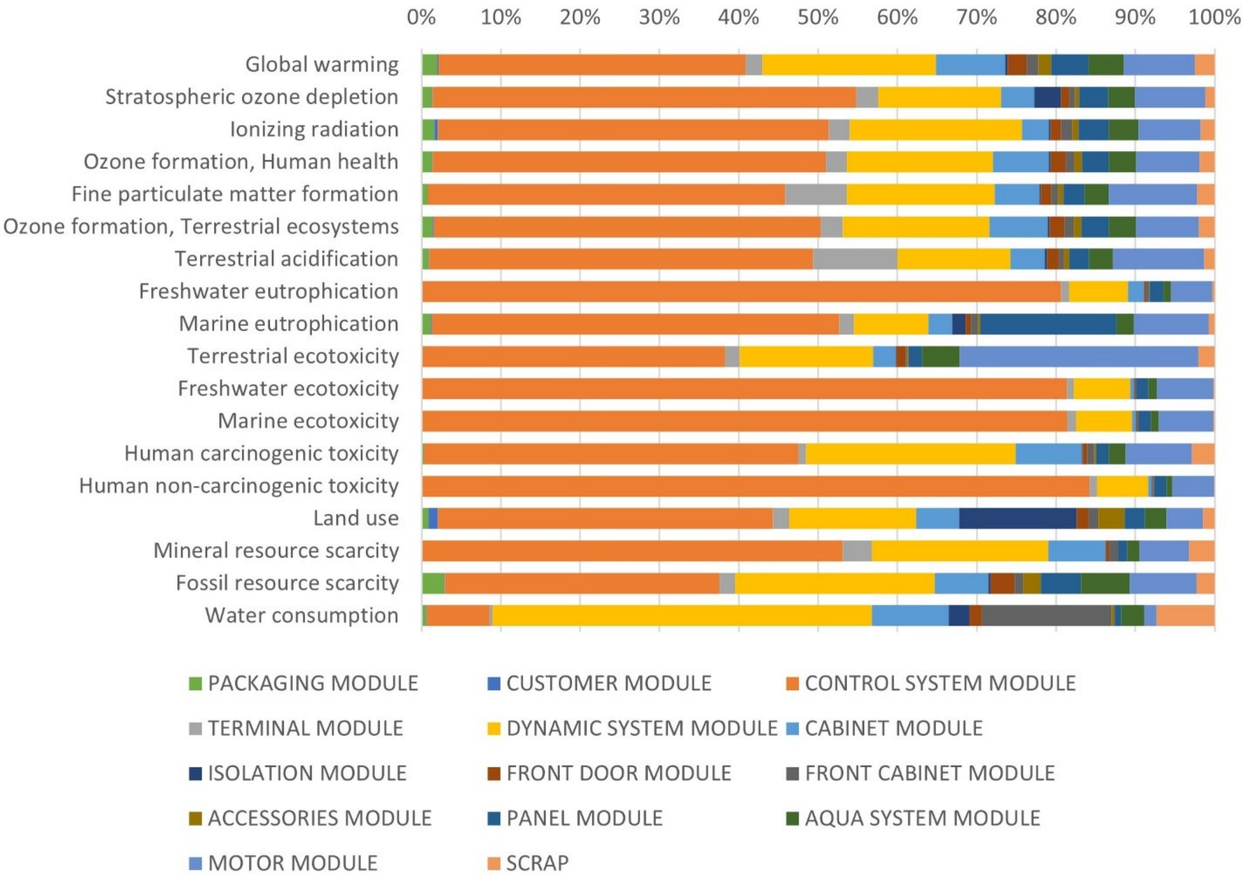
3.6.1 Manufacturing (cradle-to-gate)

A1-Table 12 shows the environmental impacts for the manufacturing of one washing machine (i.e., the functional unit used in the study), including the global warming impact and endpoint impacts. The total cradle-to-gate impacts are broken down by the various modules composing the washing machine.

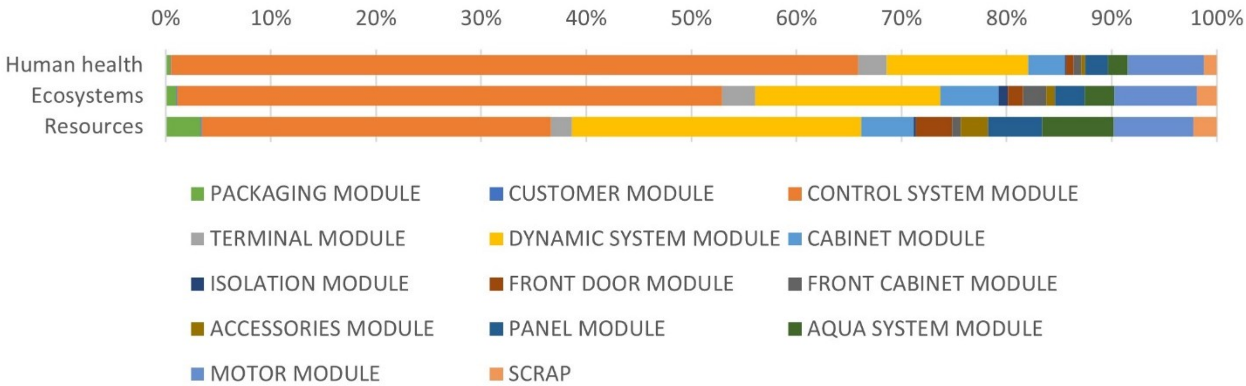
A1-Table 12. Global warming and endpoint impacts for the manufacturing of one washing machine (cradle-to-gate).

Modules in washing machine	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Packaging	7.13	1.36E-05	3.06E-08	1.06
Customer module	0.43	1.06E-06	3.76E-09	0.04
Control system	137.43	1.94E-03	1.63E-06	10.69
Terminal	7.63	8.00E-05	9.86E-08	0.64
Dynamic system	77.60	4.01E-04	5.54E-07	8.84
Cabinet	30.91	1.03E-04	1.74E-07	1.61
Isolation	0.99	3.26E-06	2.91E-08	0.07
Front door	8.58	2.21E-05	4.44E-08	1.12
Front cabinet	5.29	2.17E-05	6.92E-08	0.25
Accessories	5.68	1.12E-05	2.70E-08	0.84
Panel	16.78	6.33E-05	8.91E-08	1.65
Aqua system	15.77	5.62E-05	8.91E-08	2.20
Motor	31.82	2.16E-04	2.46E-07	2.43
Scrap	8.90	3.63E-05	6.02E-08	0.72
Total manufacturing	**354.93**	**2.97E-03**	**3.14E-06**	**32.15**

In addition, the contribution of each module to the total impact of washing machine manufacturing for every midpoint and endpoint category assessed is described in A1-Figure 1 and A1-Figure 2, respectively. The results show that the control system module generates the highest impact for all endpoint categories and almost all midpoint categories. It is only surpassed the dynamic system module in the water footprint. The dynamic system module is indeed the second most environmental detrimental module for all impact categories, except for terrestrial ecotoxicity, in which the motor module is the second most harmful module.



A1-Figure 1. Midpoint impacts for washing machine manufacturing (cradle-to-gate) by modules.



A1-Figure 2. Endpoint impacts for washing machine manufacturing (cradle-to-gate) by modules.

3.6.2 Use

A1-Table 13 shows the global warming impact and endpoint impacts for the use of one washing machine during its entire lifetime, as well as the breakdown of total impacts by the different causes generating them, including product distribution (by transport mode) and consumption of electricity, water and detergent. In addition, two different scenarios are included for electricity consumption: one where the electricity mix is assumed to be constant over time (year 2020 used as basis for calculation) and other where the electricity mix variation with time is modelled for the period 2020-2032 (see Figure 8 & Figure 9).

It can be found that electricity and detergent consumed by the washing machine have by far the highest environmental impacts for the use phase, while the contributions of product distribution and water consumption are comparatively very limited. In addition, when comparing both scenarios for electricity consumption, it is clear the important role that the increase of renewable sources in the electricity mix can play in the coming years. The scenario with variable electricity mix for the whole product lifetime means a decrease for all impact categories (compared to the constant electricity mix scenario) except for terrestrial ecotoxicity (increased by 0.57%), land use (increased by 0.02%) and mineral resource scarcity (increased by 0.85%). The impact increase for these categories is explained by the amount of land occupied by renewable energy sources and the raw materials needed. The impact category with lower reduction is marine eutrophication (0.30%), whereas the category that reaches the highest reduction is ozone formation impact on human health (9.71%). Global warming is reduced by 7.19%, while endpoint impacts are reduced as follows: human health damage by 3.11%, ecosystem diversity damage by 2.53% and resource availability by 6.00%.

A1-Table 13. Global warming and endpoint impacts for the use of one washing machine.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution (road)	5.36	1.10E-05	2.65E-08	0.84
Product distribution (water)	2.17	9.78E-06	1.79E-08	0.29
Product distribution (railway)	5.92E-02	1.63E-07	3.45E-10	0.01
Electricity (variable mix - 2020-2032)	956.04	2.80E-02	1.59E-04	41.31
Electricity (constant mix - 2020)	1,137.56	2.91E-02	1.64E-04	46.54
Water	45.80	4.44E-04	1.97E-06	2.40
Detergent	959.52	1.78E-03	1.09E-05	20.26
Total Use (variable elect. mix - 2020-2032)	**1,969.10**	**3.02E-02**	**1.72E-04**	**64.10**
Total Use (constant elect. mix - 2020)	**2,150.63**	**3.13E-02**	**1.77E-04**	**70.33**

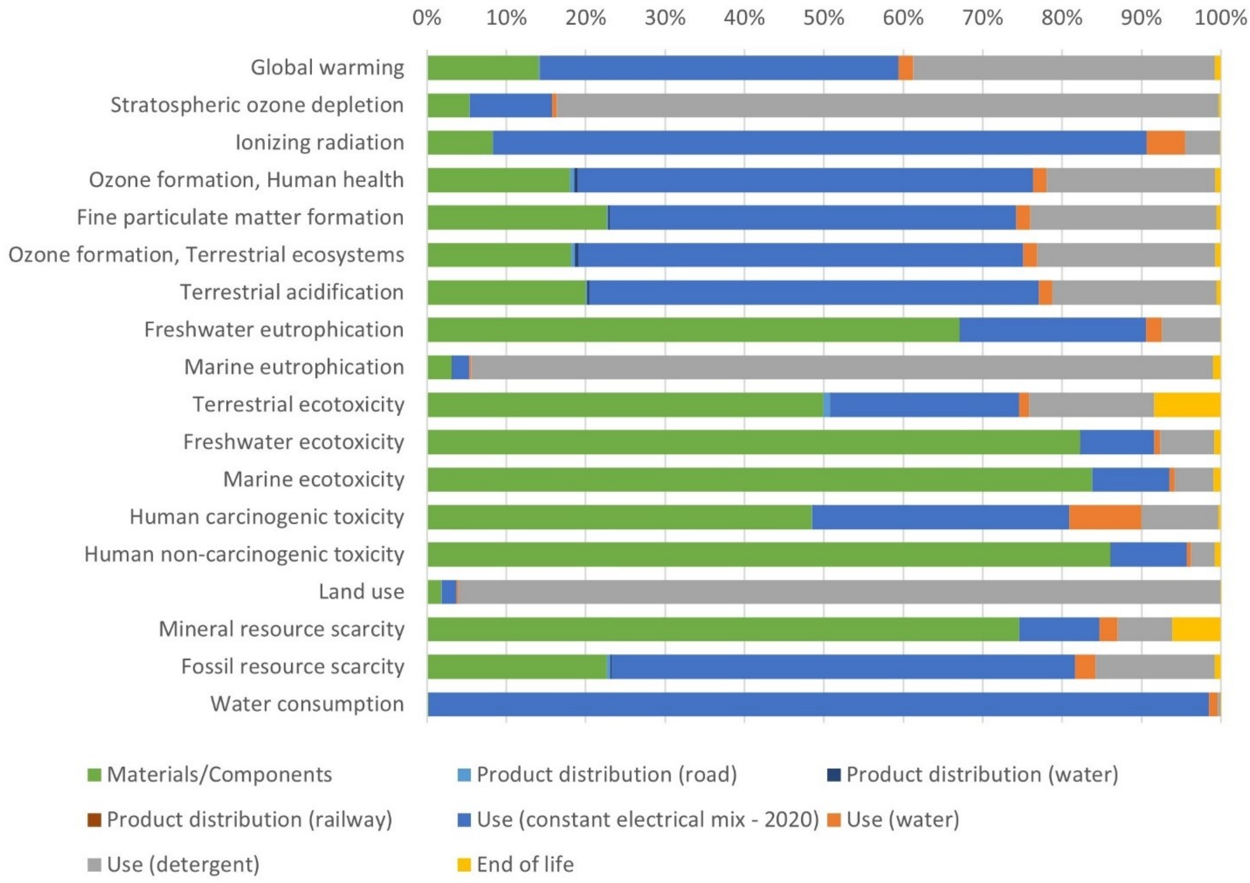
3.6.3 Total (cradle-to-grave)

A1-Table 14 collects the global warming impact and endpoint impacts for the whole life cycle of one washing machine. The total cradle-to-grave impacts for the washing machine are broken down by life cycle phases. In addition, the contribution of each life cycle phase to the total environmental impacts of washing machine for every midpoint and endpoint category assessed is shown in A1-Figure 3 and A1-Figure 4, respectively.

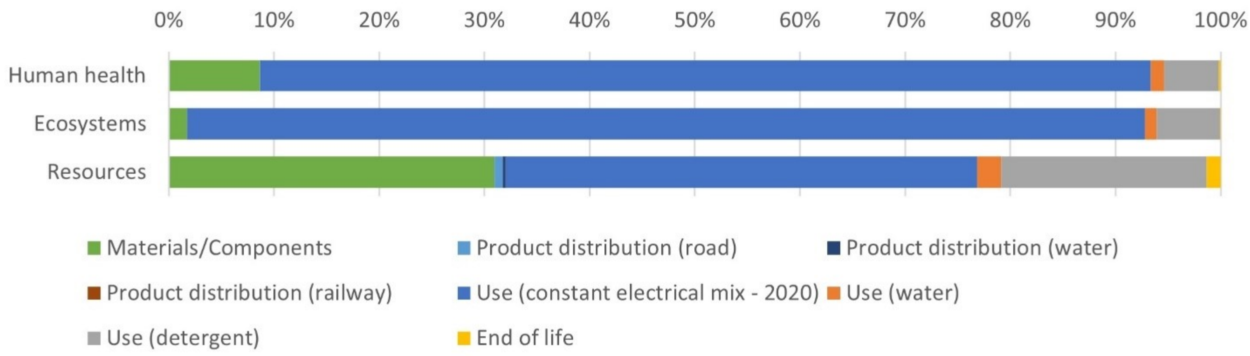
A1-Table 14. Global warming and endpoint impacts for the whole life cycle of one washing machine (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	354.93	2.97E-03	3.14E-06	32.15
Use (variable elect. mix - 2020-2032)	1,969.10	3.02E-02	1.72E-04	64.10
Use (constant elect. mix - 2020)	2,150.63	3.13E-02	1.77E-04	70.33
EoL (waste collected for recycling)	18.27	3.72E-05	8.73E-08	1.36
EoL (waste landfilled)	1.69	1.85E-05	2.66E-08	0.03
TOTAL (variable elect. mix)	**2,343.83**	**3.33E-02**	**1.76E-04**	**97.64**
TOTAL (constant elect. mix)	**2,525.36**	**3.43E-02**	**1.80E-04**	**103.86**
Credits from recycling	-32.17	-1.06E-04	-2.07E-07	-2.40

The use stage has the highest contribution to the total impact both for global warming and for all endpoint categories, as well as for many midpoint categories. Specifically, the electricity consumed during the use has the most harmful impact for every endpoint category and for some midpoint categories, such as global warming, ionizing radiation, ozone formation, fine particulate matter formation, terrestrial acidification, fossil resource scarcity and water consumption. Indeed, the electricity consumed holds nearly all the impact for water consumption. The use of detergent is also a major contributor for many impact categories, showing the largest impact for stratospheric ozone depletion, marine eutrophication and land use. The manufacturing of the washing machine also has a predominant impact for several midpoint categories, such as freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human toxicity (both carcinogenic and non-carcinogenic) and mineral resource scarcity. End-of-life impacts are very low and are rewarded totally with the credits given by 12.34 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).



A1-Figure 3. Midpoint impacts for the washing machine (cradle-to-grave) by life cycle phases.



A1-Figure 4. Endpoint impacts for the washing machine (cradle-to-grave) by life cycle phases.

3.7 Material circularity indicator

Material flows associated with the washing machine were grouped into the following categories (see A1-Table 9): steel, aluminium, copper, gold, silver, lead, platinoid metals, other metals, plastics, glass and others. The recycled feedstock (F_R) in the washing machine was estimated in order to allow for further calculation of the virgin feedstock (V). The recycled feedstock was based on average recycled content for each material category, which was determined using industry databases and literature data (Table 11). The washing machine does not contain reused feedstock (F_U = 0).

The amount of waste collected for recycling was assumed to be the same as the waste collection rate for large household appliances (see Table 8). It was assumed to be the same for all material categories included in the washing machine (C_R = 46.3%). It was assumed that no waste fraction is collected for reuse (C_U = 0). The amount of waste going to landfill or energy recovery (W_0) was therefore deducted directly from the waste collection rate.

The efficiency of the recycling process (E_C) for each material category was calculated as the ratio between waste collected and recycled (using values in A1-Table 9). It was then used to calculate the amount of waste generated in the recycling process (W_C). The amount of waste generated to produce the recycled content used as feedstock (W_F) was obtained from the average efficiency of the recycling process (E_F) for each material, which was assumed to be 75% for plastics and 90% for other materials (metals, glass and others).

Feedstock and wastes were thus calculated taking into account all the above data and using formulae described in Section 3.3 of the main document. Results for feedstock and waste are collected in A1-Table 15.

A1-Table 15. Feedstock and waste for one washing machine used for MCI calculation.

Material	Mass M (kg)	Virgin feedstock V (kg)	Unrecoverable waste W (kg)	Unrecoverable waste to disposal W_0 (kg)	Unrecoverable waste from recycling parts W_C (kg)	Unrecoverable waste from recycled feedstock W_F (kg)
Steel	27.600	19.646	16.272	14.830	2.000	0.884
Aluminium	2.202	1.730	1.261	1.183	0.103	0.052
Copper	1.111	0.722	0.768	0.597	0.299	0.043
Gold	1.34E-03	0.001	8.06E-04	7.19E-04	1.36E-04	3.72E-05
Silver	6.34E-03	0.005	4.73E-03	3.41E-03	2.55E-03	9.79E-05
Lead	1.33E-03	0.001	9.75E-04	7.16E-04	4.39E-04	7.99E-05
Platinoid metals	4.65E-04	0.000	3.49E-04	2.50E-04	1.87E-04	1.31E-05
Other metals	0.353	0.308	0.274	0.190	1.64E-01	5.11E-03
Plastic	16.730	14.756	12.985	8.989	7.333	0.658
Glass	1.930	1.814	1.490	1.037	0.893	0.013
Others	24.854	24.854	19.092	13.354	11.475	0.000
TOTAL	**74.790**	**63.838**	**52.147**	**40.185**	**22.269**	**1.656**

MCI calculation for the washing machine was then conducted (A1-Table 16). The average lifetime and intensity of use for the target washing machine investigated herein were assumed to be the same as for the industry-average products (L/Lav = U/Uav = 1). Therefore, the value of the utility function for the washing machine was 0.9. The linear flow index, considering feedstock and waste results (A1-Table 15), was 0.83. The MCI for the washing machine was finally calculated as 0.25.

A1-Table 16. MCI calculation for the washing machine.

Parameter	Value
Actual average lifetime of product L (years)	12.5
Actual average lifetime of industry-average product L_{av} (years)	12.5
Average number of functional units (FUs) during the use phase of product U (cycles/year)	220
Average number of FUs during the use phase of industry-average product U_{av} (cycles/year)	220
Utility of the product X	1.00
Utility factor F(X)	0.90
Linear Flow Index LFI	0.83
Material Circularity Indicator of the product MCI_P	**0.25**

4 Life cycle costing

4.1 Internal costs

The internal costs assessed for the washing machine includes the costs for:

(i) Acquisition of raw materials and components, including related transport operations.

(ii) Manufacturing of the product.

(iii) Distribution of the product to retailers or final customers.

(iv) Use, including product operation and required consumables.

(v) End of life, including WEEE management.

A1-Table 17 shows the breakdown of the internal costs of the washing machine by life cycle phase, namely manufacturing (including i, ii and iii), use (iv) and end of life (v).

Retail price provided by ARÇELIK was assumed herein to consider manufacturing costs. The retail price covers all the costs related to raw materials and components, product manufacturing and distribution, as well as other any other costs for product development (like R&D costs) and net revenues from sales.

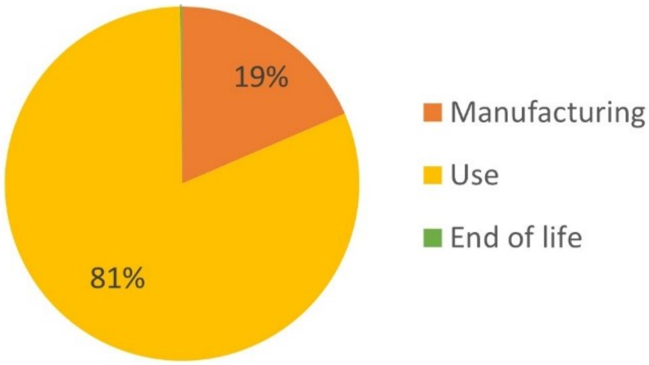
The use phase includes the costs for electricity, water and detergent consumed by the washing machine for operation during its whole lifetime (as detailed in Section 3.5.2 of this Annex). Total consumption values were therefore estimated at 1,847.5 kWh of electricity, 128,975 litres of water and 206.25 kg of detergent. The average market prices for these consumables were assumed as follows (see Section 4.1.2 of the main document): 0.216 €/kWh of electricity for year 2019, with a sustained annual growth factor of 1.022 for the following years; 0.0016 €/litre of water (constant value assumed for the whole lifetime) and 5.6 €/kg of detergent.

The costs for WEEE management was estimated at 3.86 € (for one washing machine), which corresponds to the fee paid by producers for the EoL management of each washing machine they put on the market.

A1-Table 17. Internal costs for the whole life cycle of one washing machine (cradle-to-grave).

Life cycle phase	Concept	Cost (€)	Total cost (€)
Manufacturing	Retail price (incl. costs for materials/components, manufacturing, distribution, other product development costs and net revenues)	414.01	414.01
Use	Electricity consumption	453.93	1,816.89
	Water consumption	207.79	
	Detergent consumption	1,155.17	
End of life	WEEE management fee	3.86	3.86
TOTAL	**Manufacturing + Use + EoL**	-	**2,234.75**

A1-Figure 5 graphically shows the contribution of each life cycle phase to the total internal cost of the washing machine. It can be found that the use phase is the most expensive by far, while the contribution of end-of-life phase is negligible.



A1-Figure 5. Contribution of each life cycle phase to the total internal costs for the washing machine.

4.2 External costs

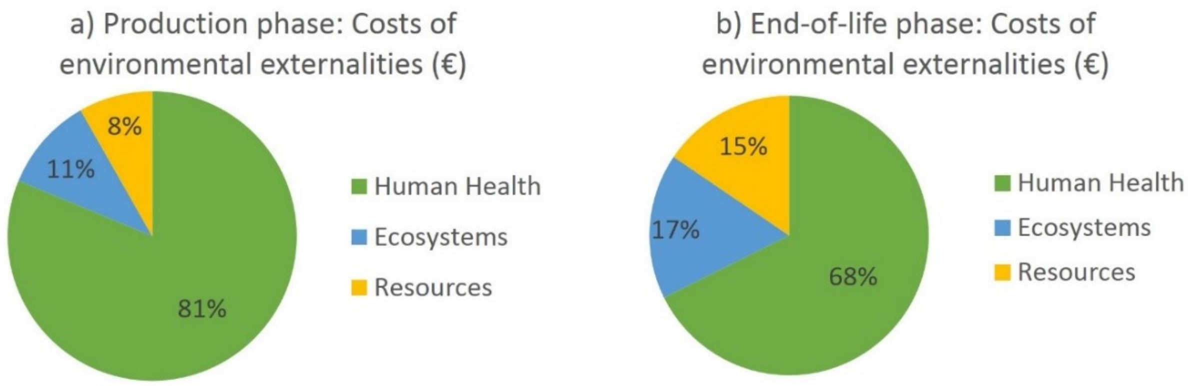
Monetary valuation of environmental impacts was applied to assess the costs of environmental externalities. To this end, LCA results obtained for the washing machine (see Section 3.6 of this Annex) were combined with monetisation factors given for different environmental impact categories (see Section 4.2 of the main document). External costs were estimated using two different approaches for monetary valuation: (1) monetisation of global warming impact and (2) monetisation of endpoint impacts. It should be noted that the economic costs obtained in each case cannot be added together since the global warming impact (as well as the other midpoint impacts) is included in the endpoint impacts.

The results from the monetary valuation of environmental impacts are collected in A1-Table 18. These are broken down by life cycle phases and impact categories monetized.

A1-Table 18. External costs for the whole life cycle of one washing machine (cradle-to-grave).

Life cycle phase	Impact category	Total amount	Monetisation factor	Economic cost (€)
Manufacturing	Human health	2.97E-03 DALY	101,311 €/DALY	301.09
	Ecosystems	3.14E-06 species.yr	1.23E+07 €/species.yr	38.75
	Resources	32.15 USD2013	0.929 €/USD2013	29.88
	Sub-total endpoint impacts	-	-	**369.72**
	Global warming	354.93 kg CO_2 eq	130 €/tonne CO_2 eq	46.19
Use	Human health	3.13E-02 DALY	101,311 €/DALY	3171.06
	Ecosystems	1.77E-04 species.yr	1.23E+07 €/species.yr	2179.91
	Resources	70.33 USD2013	0.929 €/USD2013	65.37
	Sub-total endpoint impacts	-	-	**5416.34**
	Global warming	2,150.63 kg CO_2 eq	130 €/tonne CO_2 eq	279.85
End of life	Human health	5.56E-05 DALY	101,311 €/DALY	5.63
	Ecosystems	1.14E-07 species.yr	1.23E+07 €/species.yr	1.40
	Resources	1.39 USD2013	0.929 €/USD2013	1.29
	Sub-total endpoint impacts	-	-	**8.33**
	Global warming	19.96 kg CO_2 eq	130 €/ tonne CO_2 eq	2.60
TOTAL	Human health	3.43E-02 DALY	101,311 €/DALY	3477.79
	Ecosystems	1.80E-04 species.yr	1.23E+07 €/species.yr	2220.06
	Resources	103.86 USD2013	0.929 €/USD2013	96.54
	Total endpoint impacts	-	-	**5794.39**
	Total global warming	2,525.52 kg $CO_{2\,eq}$	130 €/tonne CO_2 eq	328.63

A1-Figure 6 graphically shows the contribution of each endpoint impact to the total external costs for the manufacturing and end of life, since these are the life cycle phases in which the project is expected to achieve higher improvements. Most of the external costs are due to human health damages, while the costs of damages to ecosystem diversity and resource availability are lower and comparable with each other.



A1-Figure 6. Contribution of each endpoint impact to total external costs of manufacturing and end-of-life phases for the washing machine.

4.3 Total life cycle costs

Concluding, A1-Table 19 shows the total life cycle cost including internal and external costs. Clearly, the cost of environmental externalities, and especially the external cost for the use stage, is the highest cost element. In contrast, the product waste management in the end-of-life phase is the one with the lowest cost, both for internal and external costs.

A1-Table 19. Total costs for the whole life cycle of one washing machine (cradle-to-grave).

Life cycle phase	Internal cost (€)	External cost (€)	Total cost (€)
Manufacturing	414.01	369.72	783.73
Use	1,816.89	5,416.34	7,233.23
End of life	3.86	8.33	12.19
TOTAL	**2,234.75**	**5,794.39**	**8,029.15**

5 Social life cycle assessment

5.1 Social life cycle inventory

Primary data provided by ARÇELIK was used as the starting point to carry out the S-LCA. Specifically, it provided economic data describing the supply chain composition and location, identifying all the economic costs required to produce the washing machine and the cost breakdown by countries and economic sectors. A1-Table 20 shows the percentage breakdown of total production costs by countries and sectors.

A1-Table 20. Production cost breakdown for the washing machine by countries and economic sectors.

Country/Sector	Plastic products	Ferrous metals	Non-ferrous metals	Paper products	Mineral products	Electronic equipment	Oil	Manufacturing process
TOTAL	28.591%	13.461%	3.955%	0.391%	2.748%	31.573%	0.031%	19.251%
Turkey	26.575%	10.645%	3.955%	0.391%	1.299%	27.947%	0.031%	19.251%
Germany						0.234%		
China		1.937%				0.752%		
Poland	0.955%							
Slovenia		0.878%				0.540%		
Italy					1.449%			
Taiwan	0.411%					2.100%		
UK	0.650%							

The sectors included in the assessment comprise those related to every material and/or component required to produce the washing machine, as well as the sector linked to the manufacturing process at ARÇELIK facilities (i.e., electronic equipment sector in Turkey). Electronic equipment and plastics are the most complex sectors in the supply chain since the related components come from 5 and 4 different countries, respectively. Turkey is clearly the most important country in the washing machine value chain, since 90% of the total production costs is spent there.

The SHDB method and datasets were then used to calculate the social impacts for each sector in each country (as explained in Section 5 of the main document). The Social Hotspot 2019 Category Method with Weights (which is available for SimaPro software) was used. The social impacts derived from the washing machine were obtained by allocating the production costs (in USD) to the corresponding social LCI datasets for every country-specific sector involved in the washing machine supply chain. The social LCI datasets used are listed in A1-Table 21.

A1-Table 21. Social LCI datasets for the country-specific sectors linked to the washing machine.

Social Hotspot Database (SHDB)	Reference Unit
Chemical, rubber, plastic products/TUR S	USD
Chemical, rubber, plastic products/POL S	USD
Chemical, rubber, plastic products/TWN S	USD
Chemical, rubber, plastic products/GBR S_UK	USD
Ferrous metals/TUR S	USD
Ferrous metals/CHN S_China	USD
Ferrous metals/SVN S	USD
Metal products/TUR S	USD
Paper products, publishing/TUR S	USD
Mineral products nec/TUR S	USD
Mineral products nec/ITA S	USD
Electronic equipment/TUR S	USD
Electronic equipment/DEU S_Germany	USD
Electronic equipment/CHN S_China	USD
Electronic equipment/SVN S	USD

Social Hotspot Database (SHDB)	Reference Unit
Electronic equipment/TWN S	USD
Oil/TUR S	USD
Manufactures nec/TUR S	USD

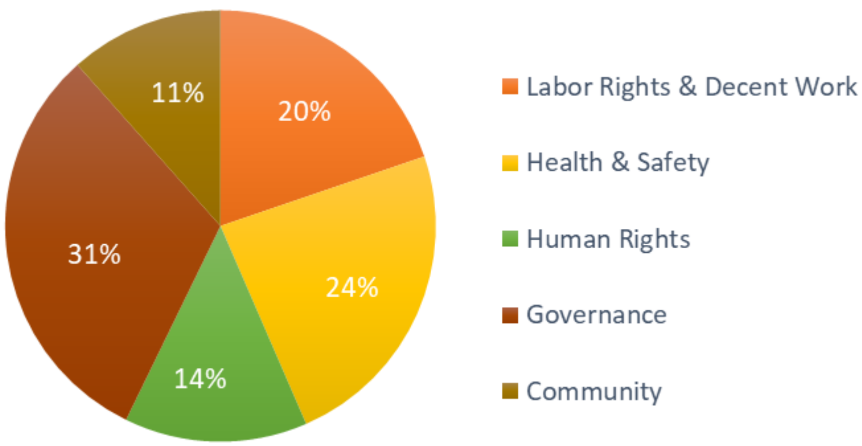
5.2 Social life cycle impact assessment

The social footprint of the washing machine was calculated by aggregating the social impacts associated with each country-specific sector listed in A1-Table 21 into a single social impacts indicator, namely the so-called Social Hotspot Index (SHI). A1-Table 22 shows the SHI obtained for the washing machine, as well as its breakdown into the different social impact categories that contribute to the total social footprint.

A1-Table 22. Social impacts of the washing machine by impact category.

Social category	Total impact (Pt)
Labour Rights & Decent Work	662.99
Health & Safety	794.55
Human Rights	460.75
Governance	1,045.95
Community	387.92
TOTAL: SHI	**3,352.16**

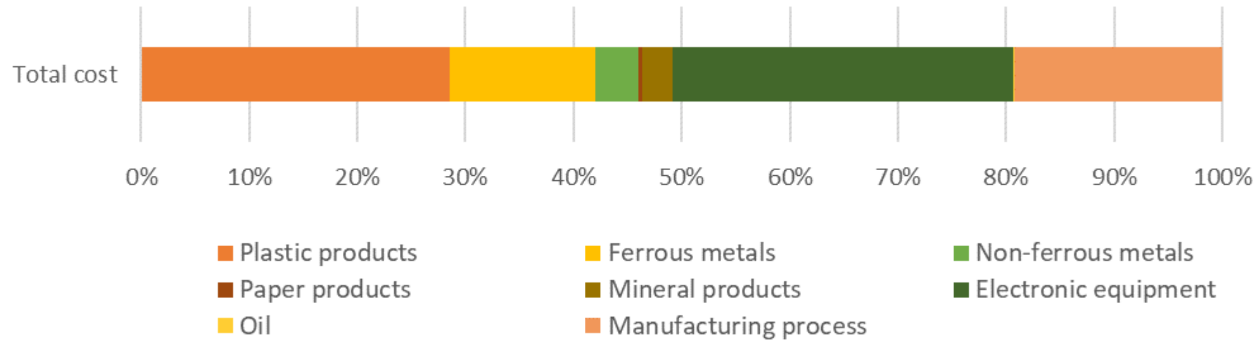
A1-Figure 7 shows graphically the contribution of each social impact category to the total social footprint of the washing machine. It can be found that the greatest social impacts are due to Governance and Health & Safety issues, while social impacts affecting Community have the lowest contribution.



A1-Figure 7. Percentage of impact categories in the social life cycle assessment for the washing machine.

5.2.1 Social impacts by economic sectors

A1-Figure 8 shows the economic share of each productive sector in the washing machine supply chain. The economic sector with the highest contribution (i.e., that in which the company spent more money to produce the washing machine) is the electronic equipment sector, followed by the plastics sector and the EEE manufacturing process (performed in ARÇELIK facilities). In contrast, oil and paper products are the economic sectors where expenditures are the lowest.

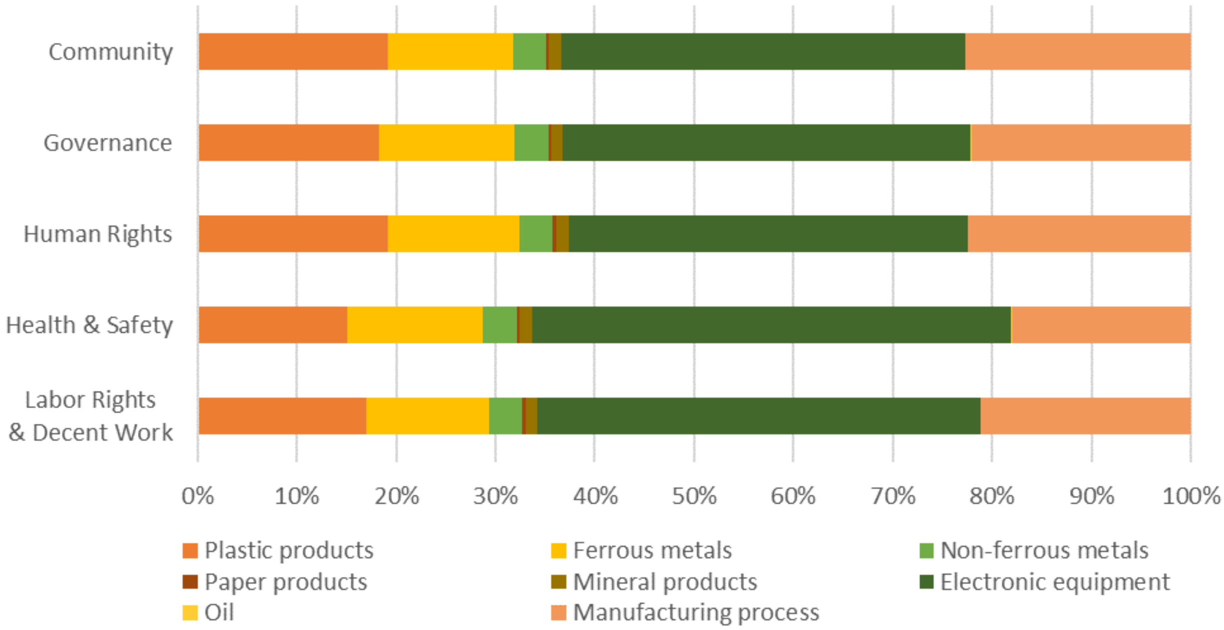


A1-Figure 8. Production cost breakdown for the washing machine by economic sectors.

The social impacts were assessed for every economic sector. A1-Table 23 shows the impacts for each social category obtained for each sector involved in the washing machine supply chain, while A1-Figure 9 shows graphically the contribution by each sector to the total impact in each social category. The results show that the electronic equipment sector, which is related to the electronic components used in the washing machine, comprises most of the impact for every social category, ranging between 41% and 48% of total social impact depending on the social category. The impact contribution of the electronic equipment sector is high compared to its economic share in total production costs, which is around 32%, meaning that the social risk levels in this sector are high compared with other sectors in the washing machine supply chain. The social impacts of the plastic products, ferrous metals and manufacturing process conducted in ARÇELIK facilities (Turkey) also have relevant contributions to social impacts. However, it should be noted that the impact contribution of these sectors are aligned with their economic shares in total production costs, so their social risk levels are acceptable. Oil, paper and mineral products have negligible social impacts when compared to the other economic sectors composing the washing machine supply chain.

A1-Table 23. Social impacts of the washing machine by economic sectors.

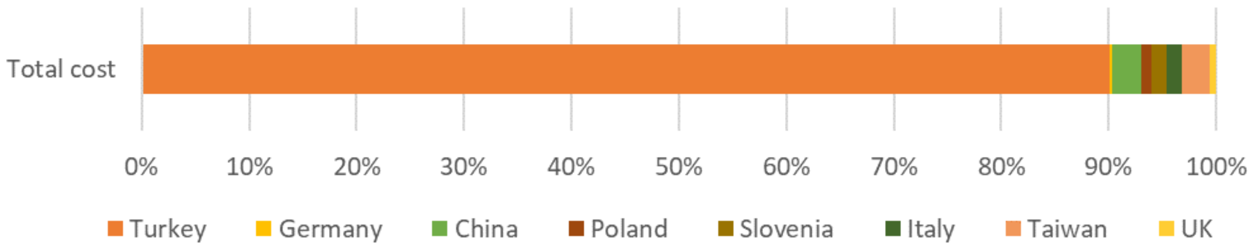
Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Plastic products	112.71	120.03	88.31	191.47	74.08
Ferrous metals	82.12	108.06	61.11	141.99	49.25
Non-ferrous metals	22.18	27.28	15.43	35.73	12.70
Paper products	1.85	2.01	1.28	2.92	1.14
Mineral products	7.65	10.62	5.89	12.46	4.79
Electronic equipment	296.39	382.93	185.18	429.80	157.70
Oil	0.09	0.15	0.07	0.18	0.07
Manufacturing	140.01	143.46	103.48	231.42	88.20
TOTAL	**662.99**	**794.55**	**460.75**	**1,045.95**	**387.92**



A1-Figure 9. Contribution of each economic sector to the total social impacts of the washing machine by social category.

5.2.2 Social impacts by countries

A1-Figure 10 shows the economic share of each country in the washing machine supply chain. The country with the highest contribution by far is Turkey, comprising about 90% of the total washing machine production costs. It includes both the manufacturing costs at ARÇELIK facilities and also the purchasing costs of various materials and components (especially plastic products, ferrous metals and electronic components) from other companies located in Turkey as well. The expenditure in the rest of countries is very low in comparison; e.g., China and Taiwan are the second and third countries with the largest contributions to total production costs, but these are less than 3% each.



A1-Figure 10. Production cost breakdown for the washing machine by country.

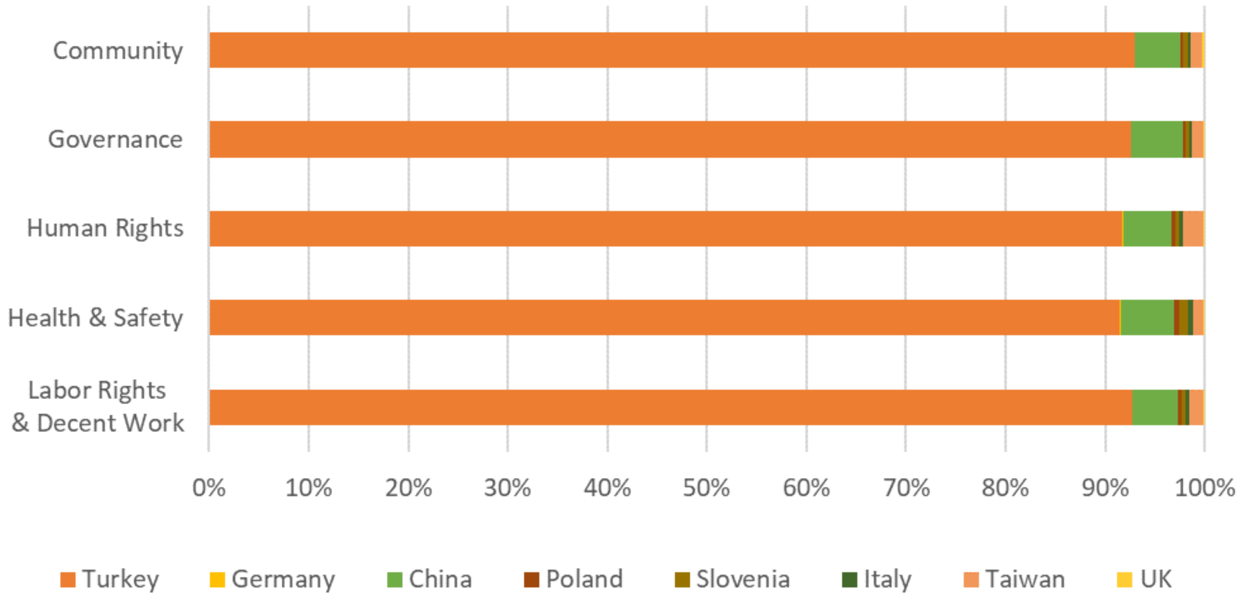
The social impacts were also assessed for every country in the washing machine supply chain. A1-Table 24 shows the impacts for each social category obtained for each country, while A1-Figure 11 shows graphically the contribution by each country to the total impact in each social category.

The results show that Turkey is the country with the highest social impacts for all social categories, ranging between 91% and 93% of the total washing machine impacts depending on the social category assessed. These results were expected since 90% of the total washing machine production costs take place there, either in ARÇELIK factory or in the facilities of other Turkish companies supplying materials or components. ARÇELIK should therefore prioritise opportunities and measures together its Turkish suppliers (especially those in electronic equipment sector) to apply social improvements there, which could in turn derive in a decrease of the social footprint of the washing machine.

China also shows relevant contributions to total social impacts, although these are much lower than those from Turkey. Despite China and Taiwan have similar shares in total production costs, the social impacts in China are between 2 and 5 times greater than in Taiwan. This reveals that social risk levels in the Chinese productive sectors supplying ARÇELIK are high, so they can be identified as social hotspots of the washing machine. ARÇELIK could also investigate opportunities and measures for social improvements there.

A1-Table 24. Social impacts of the washing machine by country.

Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Turkey	614.48	726.56	422.81	968.02	360.70
Germany	0.49	0.89	0.38	0.62	0.24
China	30.35	43.09	22.30	54.51	17.79
Poland	2.11	3.49	1.72	2.92	0.94
Slovenia	3.04	7.53	1.89	3.49	1.61
Italy	2.14	3.42	1.89	3.12	1.33
Taiwan	9.37	8.15	9.06	12.01	4.52
UK	1.01	1.42	0.69	1.27	0.79
TOTAL	**662.99**	**794.55**	**460.75**	**1,045.95**	**387.92**



A1-Figure 11. Contribution of each country to the total social impacts of the washing machine by social category.

Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.1. Results of environmental, economic and social preliminary analyses.
Annex 2 – Multifunctional laser printer

Acronym: **C-SERVEES**

Project title: **Activating Circular Services in the Electric and Electronic Sector**

Contract Nº: **776714**

Start date: **1st May 2018**

Duration: **48 months**

Deliverable number	D5.1 – Annex 2
Deliverable title	Results of environmental, economic and social preliminary analyses. Annex 2 – Multifunctional laser printer
Submission due date	31/10/2020 (M30)
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Dissemination Level	Public
Version	04
Deliverable Lead Beneficiary	AIMPLAS

1 Introduction

This Annex includes the comprehensive documentation related to the life cycle sustainability assessment of the current professional multifunctional laser printer used for demonstration in the C-SERVEES project. It includes more details on the methodological aspects and assumptions done, life cycle inventory developed and detailed results for the following studies:

- Life cycle assessment, including midpoint and endpoint environmental impact categories and material circularity indicator.
- Life cycle costing, including internal and external costs (related to environmental externalities).
- Social life cycle assessment, including 5 social impact categories.

All these studies and results constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of the multifunctional laser printer.

2 Goal and scope

The present study aimed to calculate the environmental, economic and social impacts of the multifunctional laser printer LEXMARK CX860dte. It is a professional multi-function device with standard 2-sided printing and scanning that prints at up to 60 ppm black and colour. It is manufactured in China and currently sold in the EU market. The printer product delivered to the customer consists of the printer, a power cord, printed setup instructions, a CD/DVD with User Guide & Printer Drivers and an initial set of product supplies, such as toner cartridges, imaging kits and the fusing mechanism. The imaging kit and the fuser are installed at the factory, while the toner cartridges must be installed by the customer. More details on the multifunctional laser printer investigated are shown in A2-Table 1.

A2-Table 1. Technical specifications of the demo multifunctional laser printer.

MODEL	LEXMARK CX860dte
Image	
Product number	42K0071
Print technology	Colour Laser
Functions	Colour copying, colour faxing, colour printing, colour scanning, colour network scanning
Display	Lexmark e-Task 10-inch (25 cm) class colour touch screen
Size / Packaged size	1162 x 559 x 588 mm / 1380 x 762 x 830 mm
Weight / Packaged weight	131.3 kg / 157.4 kg
Print speed (up to)	Black: 60 ppm / Colour: 60 ppm (pages per minute)
Recommended monthly page volume	5,000 - 50,000 pages
Laser cartridges yield (up to)	55,000-page Black and Colour (CMYK) Ultra High Yield Cartridges 22,000-page Colour (CMY) Extra High Yield Cartridges 33,000-page Black Extra High Yield Cartridge 17,000-page Colour (CMY) High Yield Cartridges 8,000-page Black and Colour (CMYK) Cartridges
Photoconductor estimated yield (up to)	175,000 pages, based on 3 average letter/A4-size pages per print job and ~ 5% coverage
Developer unit(s) estimated yield (up to)	300,000 pages, based on 3 average letter/A4-size pages per print job and ~ 5% coverage
Cartridge(s) Shipping with Product	8,000-page Black Return Program Toner Cartridge 17,000-page Colour (CMY) High Yield Return Program Toner Cartridges
Electricity consumption	0.391 kWh/1,000 pages (ENERGY STAR Certified)
Average power	0.3 W (Hibernate Mode), 3.3 W (Sleep Mode), 125 W (Ready Mode), 870 W (Printing), 650 W (Copying), 115 W (Scanning)
Country of origin	China

3 Life cycle assessment

3.1 Functional unit and system boundaries

The main product function for the multifunctional laser printer is to create hard copy images from electronic or hard copy originals by fusing different colours to a medium like paper. The functional unit considered in this study is one multifunctional laser printer LEXMARK CX860dte, which has a maximum printing speed of 60 pages per minute and results in 390,000 pages printed during its 5-year lifetime (assuming a standard business usage of 260 days/year and 300 pages per day).

A2-Table 2 shows the system boundaries considered for the laser printer, identifying the life cycle phases, processes and other elementary flows included and excluded in the study.

A2-Table 2. System boundaries considered for the laser printer.

Life cycle phase	Included	Excluded
Raw material extraction and processing	Extraction of natural resources Refining and raw material production Intermediate product manufacturing Waste treatment and transport	Infrastructure
Product manufacturing	Energy for product manufacturing/assembly Transport	Infrastructure Production losses Packaging
Product distribution	Transport	
Product use	Electricity consumption Paper consumption Consumption of toner cartridges (including manufacturing and transport) Maintenance, including other replacements like imaging kit, fuser kit and toner bottles (including manufacturing and transport)	Infrastructure Production losses Packaging Trips for maintenance
End of life	Transport EoL treatments for laser printer EOL treatments for replacements Landfilling of waste fraction not recycled	
Benefits and burdens beyond system boundaries	Recycling benefits (included as credits)	

3.2 Allocation and cut-off criteria

No multi-output foreground processes were identified during data collection. Inventories taken from Ecoinvent database were allocated according to the cut-off system model.[18]

The system boundary in the EoL phase was drawn just behind product waste collection and transportation to the recycling sites. WEEE from the laser printer was classified as waste by-product and environmental burdens associated with waste treatment were thus allocated completely to the waste-producing activity (as indicated in Section 3.1.3 of the main document). The environmental impacts of the EoL phase and the credits generated by recycling are both interesting for the comparative assessment between the baseline product system and the redesigned product system proposed in the C-SERVEES project. Paper consumed by the laser printer was considered as a recyclable by-product, so the environmental burdens associated with paper waste recycling were excluded from the system boundaries in the present study, but they must be allocated to the recycled paper (for further secondary uses). Product packaging was excluded from the assessment since its impact was predicted as negligible (compared to that of the whole laser printer), while this exclusion will have no effect on the comparative results (between current and C-SERVEES scenarios).

No available primary data were knowingly omitted or excluded.

3.3 Data quality

The data used to create the inventory model is as precise, complete, consistent and representative as possible with regard to the goal and scope of the study.

- Primary data was provided by LEXMARK from the most recent BoM of the product. The data used for the study is considered to be of the highest precision. Ecoinvent database was the main secondary data source used to model the product system.
- Completeness was judged based on the completeness of both the inputs/outputs per unit process and the unit processes themselves.
- Consistency refers to modelling choices and data sources. The goal was to ensure that differences in results occur due to actual differences between product systems investigated and compared, and not due to inconsistencies in modelling choices, data sources, characterisation factors, etc.
- Representativeness expresses the degree to which the data matches the geographical, temporal and technological requirements:
    - The average electricity mix for Europe was considered for the use phase (as explained in Section 3.1.2 of the main document) using the most recent data published (year 2019).[16]
    - Ecoinvent database version used was updated in 2018.
    - Integrated circuits, PWB and capacitors were modelled based on recent literature data (as explained in Section 3.1.1 of the main document).
    - Distances for distribution of laser printers from LEXMARK factory to retailers were obtained from Google Maps[60] and sea-distances.org[61] for road and water transport, respectively.

3.4 Assumptions and limitations

Assumptions were based on the LEXMARK confidential report "EPD System for Printer & Multi-Functional Devices" (version 2.0, 10/10/2018), which in turn is based on the UL Environment Standard that defines the Product Category Rules (PCR) for printers and multi-function printing units. Other assumptions and limitations for the LCA study of the multifunctional laser printer are listed below:

Manufacturing

- No production losses were considered.
- No packaging was considered.
- Recycled content was assumed to be the worldwide average (Table 11).
- Transports for materials/components from suppliers to LEXMARK factory were assumed to be 402 km by road transport and 11,668 by water transport.
- Manufacturing energy for assembly is pending.
- Refurbished parts were defined by LEXMARK, including the replacement frequency (i.e., percentage of times they can be reused). Refurbished parts reduce the mass of primary materials/components used in the laser printer proportionally to the corresponding replacement frequency.
- Burdens for the refurbishment operations are pending.

Use

- Total printed pages for lifetime were assumed as 390,000 (assuming 5-year lifetime and a standard business usage of 260 days/year and 300 pages per day).
- Distances for distribution of laser printers and replacements were estimated as follows: 2,672 km of road transport for laser printer, 5,765 km of road transport and 11,668 km of water transport for cartridges, and 2,763 km of road transport for toner bottles.
- Electricity consumption for printing was estimated at 0.391 kWh/1,000 pages (according to standard calculation method defined in ENERGY STAR Program Requirements for Imaging Equipment).
- Paper consumption was estimated at 3.39 kg/1,000 pages. LCI dataset for paper was taken from Ecoinvent database.
- Lifetime for toner cartridges and other parts requiring maintenance (replacement) was estimated as follows: 41,500 and 21,900 printed pages for black and colour cartridges, respectively (market average); 254,966 printed pages for imaging kit; 300,000 printed pages for fuser kit; and 115,000 printed pages for toner bottle.
- Trips for maintenance were not considered.
- According to LEXMARK data, used toner cartridges in the industry are evenly distributed between recycling, remanufacturing (refilling) and landfilling (one third each). It should be noted that LEXMARK has a zero-landfill policy.
- The weight for toner cartridges (filled and packaged) was assumed to be 1.768 kg and 1.408 kg for black and colour cartridges, respectively (market average). LCI datasets for black and colour toner cartridges were taken from Ecoinvent database.
- The industry-average lifetime and intensity of use for laser printers were taken from literature (to determine the MCI). Lifetime was thus estimated at 5 years (like for LEXMARK CX860dte) and intensity of use was 50 ppm (instead of 60 ppm for LEXMARK CX860dte).

End of life

- Rate for waste collection for refurbishment/recycling was estimated by LEXMARK at 66.7% (Table 8). The rest of products/materials not collected for refurbishment/recycling were assumed to be landfilled.
- The EoL inventories for laser printer and replacements were assumed to be as the ones modelled in the WEEE LCI project.[20]
- The impacts of the end of life for replacements was included in the general end-of-life phase for the product.
- Road distances for recycling of laser printer and replaced parts were estimated as follows: 1,207 km for laser printer and fuser kits; 2,063 km for cartridges, imaging kits and toner bottles.

3.5 Life cycle inventory

This section describes the LCI developed for the target laser printer, including inputs/outputs inventoried for each life-cycle phase and the data sources used for their inventory modelling.

3.5.1 Manufacturing

The LCI of the laser printer manufacturing was obtained from the BoM provided by LEXMARK. The laser printer consists of several modules, which in turn contain different components and materials. The different modules inventoried and their total amounts are listed in A2-Table 3.

A2-Table 3. Modules of the target laser printer.

Modules in laser printer	Total amount (kg)
Tray (Input 550 sheet Asm)	2.08
21K2300	36.36
Caster	10.64
Developer	2.27
Fuser	2.34
Imaging unit	0.19
ITU (Intermediate transfer module)	2.67
Laser printhead	2.63
PCU	3.42
Power cord	0.40
Power supply	1.82
Printer module	47.97
Scanner module	14.55
Toner cartridge	1.26
Waste toner bottle	1.16
Total	**129.75**

Each module is made of different components and/or materials that are processed with certain manufacturing processes to attain the final shape and properties required for the product. The inventories for the components, materials and manufacturing processes required to produce the laser printer were mainly taken from the Ecoinvent database. These inventories are linked to their own functional unit (FU), so they show energy consumption, resource consumption, emissions, etc. for different basic activities, expressed per amount of materials extracted and/or processed (kg), for example. The environmental impacts of the materials and components composing the laser printer modules were thus obtained by multiplying their amounts by the impacts calculated from the corresponding LCI datasets (for the defined FU). A list of the LCI datasets used for the manufacturing phase is given in A2-Table 4.

A2-Table 4. LCI datasets of material, components and processes for laser printer manufacturing.

Input	Dataset name	FU
	RAW MATERIALS	
ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, U	1 kg
ABS+PMMA	60% ABS + 40% PMMA	1 kg
ABS-GF20	80% ABS + 20% Glass fibre	1 kg
AlNiCo	Ferronickel, 25% Ni {GLO}| production | Cut-off, U	1 kg
Aluminium alloy	Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	1 kg
Brass	Brass {GLO}| market for | Cut-off, U	1 kg
Bronze	Bronze {GLO}| market for | Cut-off, U	1 kg
Copper	Copper {GLO}| market for | Cut-off, U	1 kg
Nickel silver	65.8% Copper + 16.7% Nickel (99.5%) + 17.5% Zinc	1 kg
Glass fibre	Glass fibre {GLO}| market for | Cut-off, U	1 kg
Nylon 6-6	Nylon 6-6 {GLO}| market for | Cut-off, U	1 kg
PBT-GF30	70% PET + 30% Glass fibre	1 kg
PC	Polycarbonate {GLO}| market for | Cut-off, U	1 kg
PC+ABS	60% PC + 40% ABS	1 kg
LCP-GF40	60% Unsaturated polyester resin + 40% Glass fibre	1 kg
PE, LDPE	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
PMMA	Polymethyl methacrylate, beads {GLO}| market for | Cut-off, U	1 kg
Polyester film (PET)	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	1 kg
Polyester resin, unsaturated	Polyester resin, unsaturated {GLO}| market for | Cut-off, U	1 kg
Polyolefin	Polypropylene, granulate {GLO}| market for | Cut-off, U	1 kg
Polyurethane foam	Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | Cut-off, U	1 kg
POM	Polyoxymethylene (POM)/EU-271	1 kg
PP	Polypropylene, granulate {GLO}| market for | Cut-off, U	1 kg
PPS	Polyphenylene sulphide {GLO}| market for | Cut-off, U	1 kg
PS	Polystyrene, general purpose {GLO}| market for | Cut-off, U	1 kg
Expanded polystyrene (EPS)	Polystyrene, expandable + Polymer foaming {RER}	1 kg
PS	Polystyrene, general purpose {GLO}| market for | Cut-off, U	1 kg
HIPS	Polystyrene, high impact {GLO}| market for | Cut-off, U	1 kg
PVC	Polyvinylchloride, at regional storage/RER U	1 kg
Stainless steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U	1 kg
Galvanized steel	Steel, low-alloyed, hot rolled + Zinc coat (64 m2/t)	1 kg
Low carbon steel bar/sheet	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U	1 kg
Thermoplastic polyurethane elastomer	Synthetic rubber {GLO}| market for | Cut-off, U	1 kg
Water	Tap water {RER}| market group for | Cut-off, U	1 kg
Zinc	Zinc {GLO}| market for | Cut-off, U	1 kg
	PROCESSING	
Aluminium extrusion	Section bar extrusion, aluminium {GLO}| market for | Cut-off, U	1 kg
Brass casting (used for zinc as well)	Casting, brass {GLO}| market for | Cut-off, U	1 kg
Bronze casting	Casting, bronze {GLO}| market for |Cut-off, U	1 kg
Copper average metal working	Metal working, average for copper product manufacturing {GLO}| market for | Cut-off, U	1 kg
Plastic extrusion	Extrusion, plastic pipes {GLO}| market for | Cut-off, U	1 kg
Plastic recycling	348MJ/ton	1 kg
Plastic injection moulding	Injection moulding {GLO}| market for | Cut-off, U	1 kg
Stainless steel sheet average metal working	Metal working, average for chromium steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Steel sheet average metal working	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Steel turning	Section bar rolling, steel {GLO}| market for | Cut-off, U	1 kg
Metal stamp and bending	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	1 kg
Wire copper	Wire drawing, copper/RER U	1 kg
	COMPONENTS	
Battery cell	Battery cell, Li-ion {GLO}| market for | Cut-off, U	1 kg
Capacitor MLC	Capacitor, for surface-mounting {GLO}| market for | Cut-off, U	1 kg
Capacitor MLC SMD precious metals	Modelled from MLC 1210 gold	1 kg
Capacitor, film type	Capacitor, film type, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Capacitor Al-Elko radial THT	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Cut-off, U	1 kg
Diode power THT	Diode, glass-, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Diode signal	Diode, glass-, for surface-mounting {GLO}| market for | Cut-off, U	1 kg
HDD	Hard disk drive, for laptop computer {GLO}| production | Cut-off, U (Weight: 0.118 kg)	1 p
Inductor, coil miniature	Inductor, miniature radio frequency chip {GLO}| market for | Cut-off, U	1 kg
Inductor, coil multilayer chip	Inductor, low value multilayer chip {GLO}| market for | Cut-off, U	1 kg
Ring Core Coil	Inductor, ring core choke type {GLO}| market for | Cut-off, U	1 kg
LCD	Liquid crystal display, unmounted {GLO}| production | Cut-off, U	1 kg

Input	Dataset name	FU
LED SMD high-efficiency	Light emitting diode {GLO}| market for | Cut-off, U	1 kg
Resistor	Resistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
Switch module	Switch, toggle type {GLO}| market for | Cut-off, U	1 kg
Transistor signal	Transistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
PCB PSU	Printed wiring board, for power supply unit, Pb containing {GLO}| production | Cut-off, U	1 kg
PCB SMD	Printed wiring board, for surface mounting, Pb containing surface {GLO}| market for | Cut-off, U (1.6 mm thick 6-layer PWB with HALS and Sn-Pb mixture with a square weight of 3.26 kg)	1 m2
PCB THT	Printed wiring board, for through-hole mounting, Pb containing surface {GLO}| market for | Cut-off, U (1.6 mm thick 2-layer PWB with HALS and Sn-Pb mixture with a square weight of 3.08 kg)	1 m2
IC (modelled)	IC BGA 144 (181mg) 10x10mm MPU generic (130 nm node)	1 kg
	IC BGA 144 (360mg) 13X13mm MPU generic (130 nm node)	1 kg
	IC BGA 256 (4g) 27x27 mm CMOS logic (45 nm node)	1 kg
	IC PLCC 20 (751mg) 9x9 mm CMOS logic (250 nm node)	1 kg
	IC QFP 32 (184mg) 7x7 mm CMOS logic (90 nm node)	1 kg
	IC QFP 240 (6.20g) 32x32x3.5	1 kg
	IC SO 8 (76mg) 4.9x3.9 mm CMOS logic (90 nm node)	1 kg
	IC SO 20 (530mg) 12.8x7.5 mm CMOS logic (90nm node)	1 kg
	IC SSOP 14 (120mg) 6.0x5.3x1.75	1 kg
	IC SSOP 24 (123mg) 8.2x5.3 mm CMOS logic (65 nm node)	1 kg
	IC TQFP 32 (146mg) 5x5 mm MPU generic (130 nm node)	1 kg
	IC TQFP 44 (272mg) 10x10 mm MPU generic (130 nm node)	1 kg
	IC TSSOP 8 (23mg) 3x3 mm DRAM (57 nm node)	1 kg
	IC TSSOP 16 (59mg) 4.4x5.0 mm DRAM (57 nm node)	1 kg
	IC TSOP 28 (232mg) 8x13.4 mm DRAM (57 nm node)	1 kg
	IC TSSOP 48 (187mg) 6.1x12.5 mm DRAM (57 nm node)	1 kg

Refurbished parts

LEXMARK also provided a list of parts suitable for refurbishment, including the replacement frequency for each part, expressed as the percentage of times they can be reused to replace virgin parts (A2-Table 5). Refurbished parts reduce the mass of primary materials/components in the laser printer by 10.3% (from 129.75 kg to 116.36 kg). The mass of primary materials/components linked to these parts that was finally accounted for the environmental impact assessment was calculated considering the percentage of time replaced (TR) and the waste collection rate for the EoL laser printers (WCR = 66.7%), as follows:

$$Mass\ for\ impacts = Mass \cdot [1 - WCR \cdot (1 - TR)] \quad (14)$$

A2-Table 5. Refurbished parts in the laser printer.

Part name	BoM part number	Percentage of time replaced (%)
Board 10.1" UICC	17X7101	20
Shield Controller	21K1191	30
Cover Rear left	21K2829	35
Cover Right	21K2809	35
Cover Connector access	21K2806	25
Doors Left door	21K2830	35
Rollers Transfer	21K3985	100
Tray Insert Media	21K1600, 21K1624, 21K2196	40
Other General SVC MPF tray	21K1520	35
Cover Standard bin	21K2951	35
Cover HTU attach	21K2975	35
Cover Rear upper	21K2936	30
Cover Left upper	21K2969	35

Part name	BoM part number	Percentage of time replaced (%)
Cover Front column upper	21K2956	30
Doors Front	21K2801, 21K2988	60
Cover Scanner left	21K2953	40
Cover Scanner right	21K2952	40
Cover Scanner front	21K2961	40
Cover Scanner left upper	21K2967	40
Cover Scanner right upper	21K2966	40
Cover Scanner front upper	21K2965	40
CS82x SVC Maint Kit	21K3985	100
CS82x SVC Fuser 230V	21K1264, 21K1270	100
Support Scanner	21K2868, 21K2869	5
Cover FB scanner top	25B9160	10
Cover Left lower	21K8568	25
Scanner Flatbed	21K9000	10
Cover Front	21K8801	50
Cover Rear	21K8804	50
Pad ADF		15
Tray Input	21K8201	55
Scanner Complete ADF	21K8021	20
Rollers ADF pick	21K8305	100
Belt ADF feed	21K8304	100
Rollers ADF separator	24T1274	100
Bezel 10.1	3079274	45
Cover Top door	21K8567	50
Bezel CX860	21K4211	45
Maint Kit	41X0360, 41X0359, 41X0358	100
Feeder pick	21K2309	100
Rollers Pick roller and separator	21K2309, 21K1610	100

3.5.2 Use

The environmental impacts of the use phase are due to laser printer distribution, electricity consumption required for its operation, paper consumed for printing, toner cartridges and other printer components that need to be replaced several times during the printer lifetime. The amounts related to all these environmental burdens were estimated for the whole lifetime of the printer based on the assumptions explained in Section 3.4 of this Annex. The values are shown in A2-Table 6.

A2-Table 6. Estimated amounts of inputs for the use of one laser printer.

Input	No of units consumed	Mass (kg)	Distance	Total amount	Unit
Electricity	-	-	-	152.49	kWh
Paper	390,000	1,322.10	-	1,322.10	kg
Black toner	9	6.27	-	6.27	kg
Colour toner	17	5.74	-	5.74	kg
Replacement of toner cartridges	26	8.18	-	26	Unit
Toner bottle	3	3.49	-	3	Unit
Imaging kit: Imaging unit	1	0.19	-	1	Unit
Imaging kit: Developer	1	2.27	-	1	Unit
Imaging kit: PCU	1	3.42	-	1	Unit
Fuser kit	1	2.34	-	1	Unit
Road transport, printer	-	129.75	2,672	346.64	tkm
Road transport, cartridge + imaging kit + fuser kit	-	20.24	5,765	116.68	tkm
Road transport, toner bottle	-	3.49	2,763	9.65	tkm
Water transport, toner + fuser kit + imaging kit	-	20.24	11,668	236.15	tkm

Distribution

The amounts related to product distribution and transport of replacements were estimated (in tonnes-km or tkm) by multiplying the weight of the laser printer and replacements (in tonnes) by the distance travelled through each transport mode (in km). The environmental impacts due to the distribution of the laser printers and their components were then obtained by multiplying the amounts transported (in tkm, as shown in A2-Table 6) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in A2-Table 7.

A2-Table 7. LCI datasets of transport modes for laser printer distribution.

Input	Dataset name	FU
Road transport	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1 tkm
Water transport	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, U	1 tkm

Product operation

The environmental impacts derived from the use of the laser printer were obtained by multiplying the total amounts of electricity, paper and other consumables (collected in A2-Table 6) by the impacts calculated from the corresponding LCI datasets, which are shown in A2-Table 8.

A2-Table 8. LCI datasets of electricity, paper, toner cartridges and other replacements for laser printer operation.

Input	Dataset name	FU
Electricity	Electricity, low voltage, production EUROPE, at grid/RER U, SCENARIO 2020	1 kWh
Paper	Paper, wood free, coated {RER}| market for | Cut-off, U	1 kg
Black toner	Toner, black, powder {GLO}| production | Cut-off, U	1 kg
Colour toner	Toner, colour, powder {GLO}| production | Cut-off, U	1 kg

3.5.3 End of life

The impacts of the end of life encompasses herein both the impacts of the laser printer and the impacts of the used parts that need to be replaced during the lifetime of the printer, including toner cartridges, imaging kits, fuser kits and toner bottles.

Waste collection

Waste collection rate for laser printer at the end of life was assumed to be 66.7%, according to primary data provided by LEXMARK.

Waste treatment

Material flows associated with the EoL treatment of the laser printer are classified in A2-Table 9 following the approach from the WEEE LCI project.[3] For each material flow, it states the mass in the product (as put on the market), the mass collected for reuse and for recycling, and the mass finally recycled. The waste materials collected are treated following the LEXMARK take-back scheme, which was assumed to have similar efficiencies and environmental burdens (and benefits) as typical take-back schemes for large professional electrical equipment (LPA). Waste not collected was assumed to be landfilled. PCB materials are classified into copper, gold, lead, silver, platinoids, other metals and support materials (such as plastics, fibres, etc.).

Datasets	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
LPA| ABS-PC without BFR, density < 1.3	1.647	1.098	0.564	0.535	0.000
LPA| ABS without BFR, density < 1.3	29.521	19.690	4.804	14.886	0.000
LPA| Aluminium	0.852	0.568	0.013	0.555	0.534
LPA| Brass	4.06E-03	2.71E-03	1.12E-03	1.59E-03	1.10E-03
LPA| Bronze	0.447	0.298	0.021	0.277	0.211
LPA| Copper within Wire	1.020	0.681	0.091	0.590	0.418
LPA| Copper	0.407	0.272	0.000	0.272	0.163
LPA| Glass fibres-plastics composites	8.888	5.929	0.664	5.264	0.000
LPA| PA without BFR, density < 1.3	0.211	0.141	0.001	0.140	0.000
LPA| PBT without BFR, density < 1.3	4.861	3.242	0.527	2.716	0.000
LPA| PC without BFR, density < 1.3	1.458	0.972	0.029	0.944	0.000
LPA| PMMA	0.121	0.081	0.025	0.056	0.000
LPA| PP without BFR, density < 1.3	0.506	0.337	0.002	0.335	0.104
LPA| Copper within PCB	0.785	0.524	0.116	0.407	0.306
LPA| Gold within PCB	1.17E-03	7.78E-04	5.75E-05	7.20E-04	5.62E-04
LPA| Lead within PCB	6.96E-03	4.65E-03	4.89E-04	4.16E-03	1.19E-03
LPA| PCB Other base metals	0.941	0.628	0.054	0.574	0.000
LPA| PCB Support	1.422	0.949	0.316	0.633	0.000
LPA| Platinoid within PCB	2.13E-05	1.42E-05	2.97E-06	1.12E-05	1.48E-06
LPA| Silver within PCB	5.97E-03	3.98E-03	1.59E-04	3.82E-03	4.95E-04
LPA| PS without BFR, density < 1.3	0.220	0.147	1.29E-04	0.147	0.000
LPA| PUR foam	0.383	0.255	0.002	0.253	0.000
LPA| PVC within wire	1.546	1.031	0.131	0.900	0.000
LPA| Steel	74.506	49.695	6.045	43.650	36.851
LHA | Glass	6.77E-04	4.52E-04	0.00E+00	4.52E-04	0.00E+00
Total WEEE laser printer	**129.761**	**86.551**	**13.407**	**73.144**	**38.591**

Material flows associated with the EoL treatment for the replaced parts generated as waste during the whole lifetime of the printer were modelled following the same approach, as shown in A2-Table 10.

A2-Table 10. Waste material flows related to EoL of replacements for laser printer (toners, imaging kits, fuser kits and toner bottles).

Datasets	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
LPA| ABS-PC without BFR, density < 1.3	0.057	0.038	0.000	0.038	0.000
LPA| ABS without BFR, density < 1.3	7.086	4.726	2.102	2.624	0.000
LPA| Aluminium	0.071	0.048	0.000	0.048	0.046
LPA| Bronze	0.085	0.056	0.000	0.056	0.043
LPA| Copper within Wire	0.004	0.003	0.000	0.003	0.002
LPA| Copper	0.007	0.005	0.000	0.005	0.003
LPA| Glass fibres-plastics composites	0.536	0.357	0.040	0.317	0.000
LPA| PA without BFR, density < 1.3	0.008	0.006	0.000	0.006	0.000
LPA| PBT without BFR, density < 1.3	0.909	0.606	0.240	0.366	0.000
LPA| Copper within PCB	0.017	0.012	0.005	0.007	0.005
LPA| Gold within PCB	7.91E-06	5.28E-06	1.03E-06	4.25E-06	3.32E-06
LPA| Lead within PCB	6.19E-05	4.13E-05	1.03E-05	3.10E-05	8.91E-06
LPA| PCB Other base metals	0.113	0.075	0.000	0.075	0.000
LPA| PCB Support	0.015	0.010	0.003	0.007	0.000
LPA| Platinoid within PCB	4.47E-07	2.98E-07	1.14E-07	1.84E-07	2.44E-08
LPA| Silver within PCB	1.04E-04	6.92E-05	2.53E-05	4.39E-05	5.69E-06
LPA| PS without BFR, density < 1.3	0.051	0.034	0.001	0.033	0.000

LPA| PUR foam	0.006	0.004	0.000	0.004	0.000
LPA| PVC within wire	2.262	1.509	0.336	1.173	0.990
LPA| Steel	0.000	0.000	0.000	0.000	0.000
Total WEEE laser printer replacements	**11.228**	**7.489**	**2.73**	**4.762**	**1.089**

A2-Table 11 summarises the total amounts of waste materials linked to the EoL treatment for one laser printer, including both the printer itself and the replacements consumed during its whole lifetime.

A2-Table 11. Total waste material flows related to laser printer EoL (including replacements).

Input	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
Laser printer	129.761	86.551	13.407	73.144	38.591
Replacements	11.228	7.489	2.73	4.762	1.089
Total WEEE	**140.989**	**94.040**	**16.134**	**77.906**	**39.680**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one laser printer) is shown in A2-Table 9 and A2-Table 10. The LCI datasets used for recycling of each material flow were obtained from WEEE LCI project.[3] These allow to calculate the environmental impacts of recycling according to two different accounting methods: impacts with benefits (including the impacts of recycling operations and the benefits from the substitution of primary raw materials with the recycled ones) and impacts without benefits (that only includes the impacts of recycling operations). Both accounting methods were applied herein to calculate both direct environmental impacts of recycling and environmental credits due to primary material substitution (calculated as the difference between impacts with and without benefits).

Landfill disposal

A fraction of the waste generated at the EoL of the laser printer is not recycled. It was assumed that this waste fraction is landfilled. Non-recycled waste were classified into three different waste material flows to model landfill disposal, namely aluminium, inert material and plastics. The amount of the laser printer, including EoL replacements, that is finally landfilled classified by waste material flow is shown in A2-Table 12.

A2-Table 12. Waste material flows related to landfill disposal of laser printer (including replacements).

Waste type	Mass landfilled (kg)
Plastics	19.797
Aluminium	0.307
Inert material	26.845
Total	**46.949**

The environmental impacts derived from landfill disposal were obtained by multiplying the amount of each waste material flow landfilled by the impacts calculated from the corresponding LCI datasets, which are shown in A2-Table 13.

A2-Table 13. LCI datasets of landfill disposal for laser printer EoL.

Input	Dataset name	FU
Landfill disposal for aluminium waste	Disposal, aluminium, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for inert waste	Disposal, inert material, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for plastic waste	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	1 kg

3.6 Life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2 of the main document). Life cycle environmental impacts of the laser printer were thus calculated for eighteen midpoint impact categories (including global warming and other) and three endpoint impact categories (damages to human health, ecosystem diversity and resource availability).

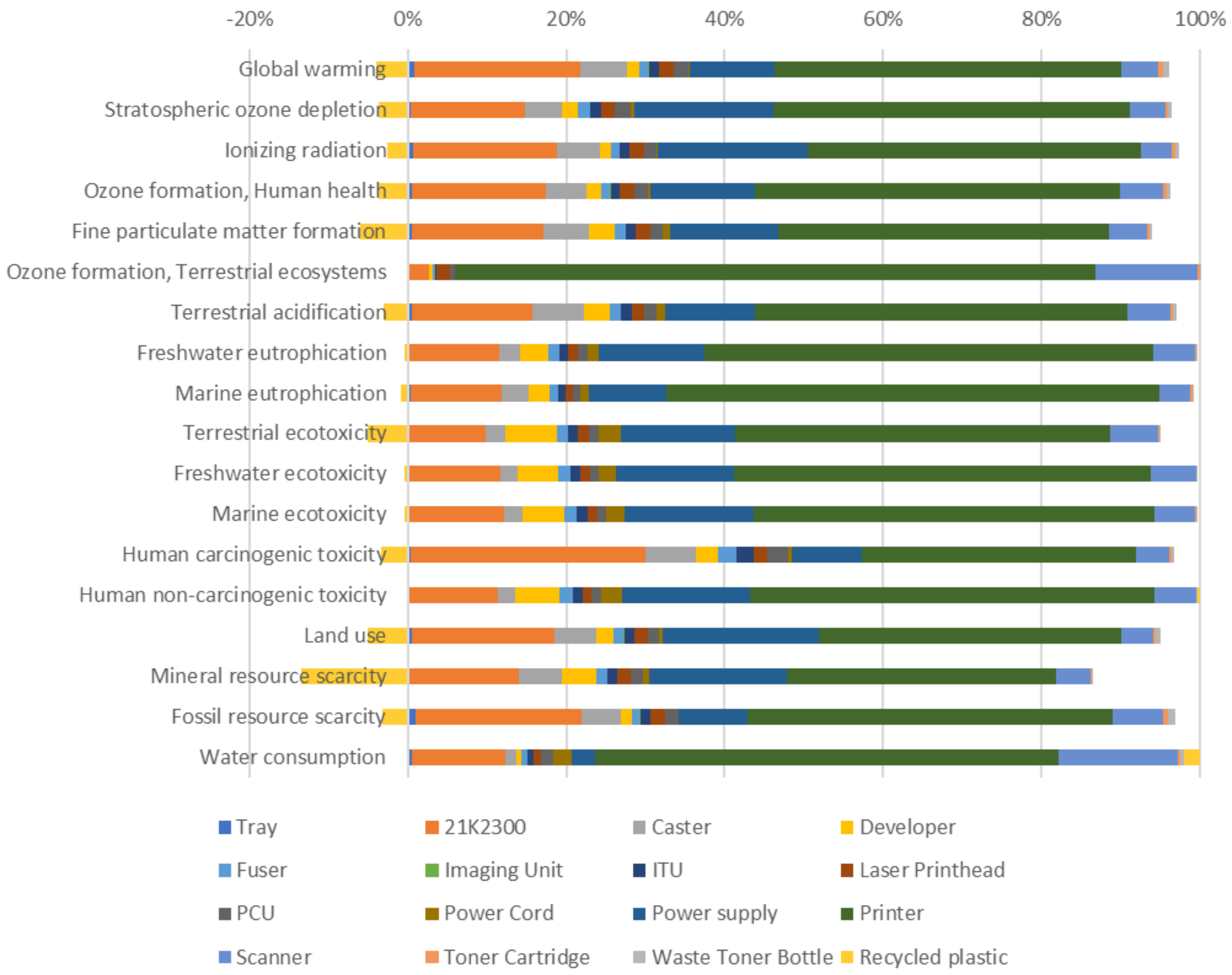
3.6.1 Manufacturing (cradle-to-gate)

A2-Table 14 shows the environmental impacts for the manufacturing of one laser printer (i.e., the functional unit used in the study), including the global warming impact and endpoint impacts. The total cradle-to-gate impacts are broken down by the various modules composing the laser printer. Recycled plastics were included as an additional module that considers the total recycled plastic content in the laser printer and its benefits (expressed as negative values) resulting from the substitution of virgin plastics.

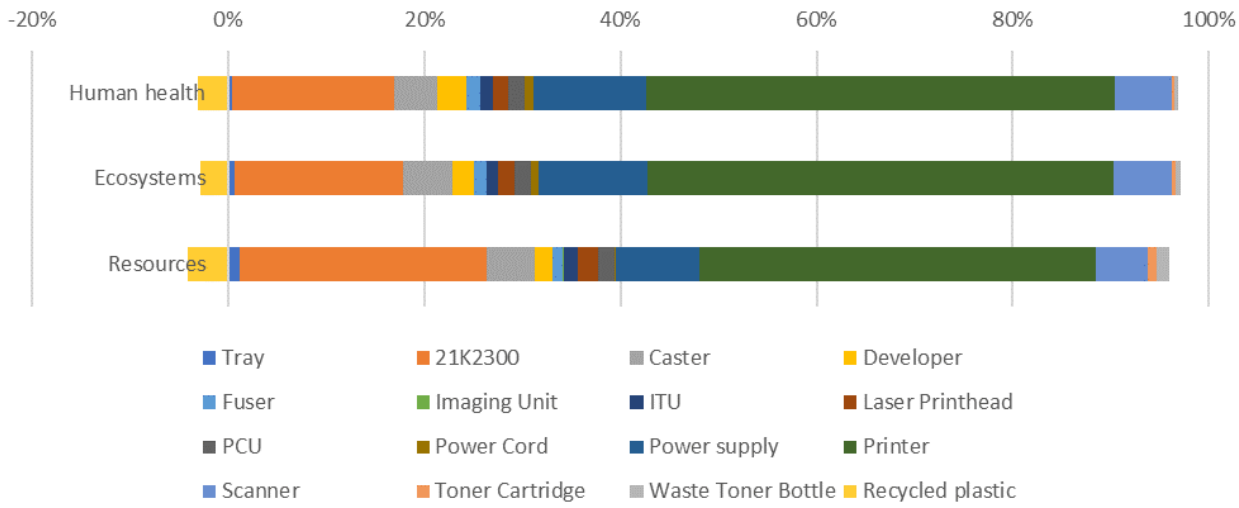
A2-Table 14. Global warming and endpoint impacts for the manufacturing of one laser printer (cradle-to-gate).

Modules in laser printer	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Tray (Input 550 sheet Asm)	7.00	1.45E-05	3.03E-08	0,85
21K2300	172.56	5.54E-04	8.28E-07	17,84
Caster	48.05	1.48E-04	2.42E-07	3,53
Developer	12.17	1.01E-04	1.06E-07	1,26
Fuser	9.33	4.49E-05	5.72E-08	0,72
Imaging unit	1.01	1.81E-06	4.10E-09	0,17
ITU (Intermediate transfer module)	10.35	4.30E-05	5.73E-08	0,97
Laser printhead	14.97	5.33E-05	7.87E-08	1,45
PCU	15.56	5.45E-05	7.97E-08	1,23
Power cord	1.28	3.23E-05	3.73E-08	0,12
Power supply	88.69	3.85E-04	5.33E-07	6,04
Printer module	358.81	1.61E-03	2.28E-06	28,65
Scanner module	38.77	1.94E-04	2.84E-07	3,82
Toner cartridge	4.98	1.14E-05	2.14E-08	0,66
Waste toner bottle	6.59	1.31E-05	2.75E-08	0,85
Recycled plastic	-32.30	-1.05E-04	-1.35E-07	-2.90
Transport of components	24.01	9.12E-05	1.75E-07	3.26
Total manufacturing	**781.84**	**3.24E-03**	**4.71E-06**	**68.53**

In addition, the contribution of each module to the total impact of laser printer manufacturing for every midpoint and endpoint category assessed is described in A2-Figure 1 and A2-Figure 2, respectively. The results show that the so-called printer module generates the highest impact for all impact categories, both at the midpoint and endpoint level. It should be noted that this is the heaviest module in the laser printer, representing about 37% of total product weight. In addition, it includes several PWB and other electronic components that show significant environmental impacts. There are other two modules that can also be highlighted because of their relevant contributions to total manufacturing impacts, namely the 21K2300 and the power supply.



A2-Figure 1. Midpoint impacts for laser printer manufacturing (cradle-to-gate) by modules.



A2-Figure 2. Endpoint impacts for laser printer manufacturing (cradle-to-gate) by modules.

3.6.2 Use

A2-Table 15 shows the global warming impact and endpoint impacts for the use of one laser printer during its lifetime, as well as the breakdown of total impacts by the different causes, including product distribution and consumption of electricity, paper, toner cartridges and other components replaced several times during the printer lifetime. In addition, two different scenarios are included for electricity consumption: one where the electricity mix is assumed to be constant over time (year 2020 used as basis for calculation) and other where the electricity mix variation with time is modelled for period 2020-2032 (see Figure 8 & Figure 9).

It can be found that paper consumed for printing has by far the highest global warming and endpoint impacts for the use phase, contributing to total use impacts as follows: 80% for global warming, 54% for human health damages, 59% for ecosystem diversity damages and 79% for resource availability damages. Electricity consumption also has relevant environmental impacts, especially for human health damages (36%) and ecosystem diversity damages (37%), while its contribution is more limited for global warming (5%) and resource availability damages (2%). Finally, the toners and other replacements required during the use phase contribute significantly to global warming (12%), human health (9%) and resource availability damages (14%).

In addition, when comparing both scenarios for electricity consumption, it can be found that the increase of renewable sources in the electricity mix contributes to reduce the impacts from the laser printers over lifetime. The scenario with variable electricity mix for the whole product lifetime means a decrease for global warming and all endpoint impacts (compared to the constant electricity mix scenario).

A2-Table 15. Global warming and endpoint impacts for the use of one laser printer.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution	45.32	9.28E-05	2.24E-07	6.94
Electricity (variable mix - 2020-2032)	88.69	2.37E-03	1.34E-05	3.66
Electricity (constant mix - 2020)	93.89	2.40E-03	1.35E-05	3.84
Paper	1,347.75	3.54E-03	2.14E-05	128.87
Toners	85.06	2.06E-04	3.78E-07	10.22
Maintenance (replacements, incl. transport)	109.42	3.61E-04	5.73E-07	13.12
Total Use (variable elect. mix - 2020-2032)	**1,676.23**	**6.56E-03**	**3.60E-05**	**162.82**
Total Use (constant elect. mix - 2020)	**1,681.44**	**6.59E-03**	**3.61E-05**	**162.99**

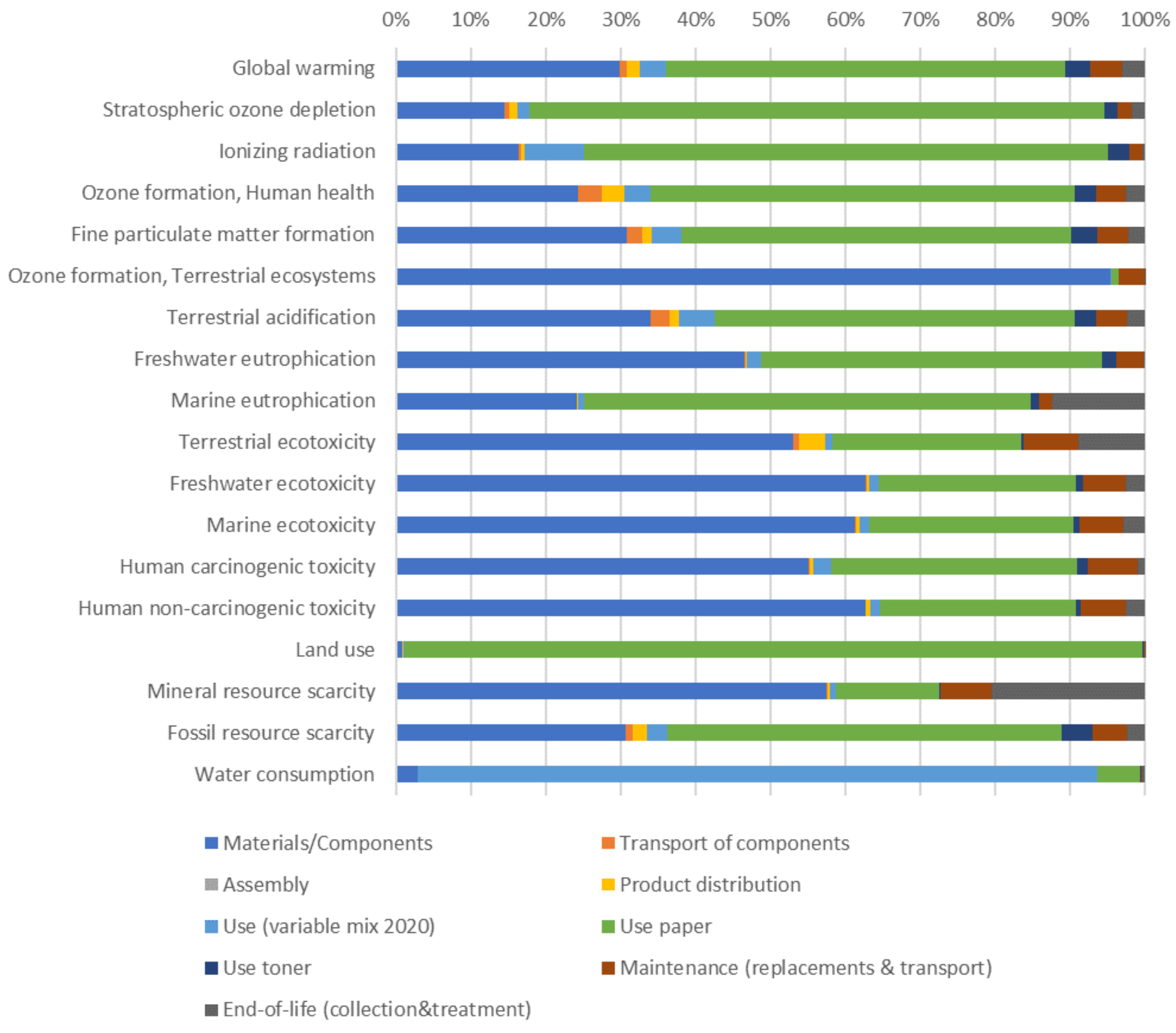
3.6.3 Total (cradle-to-grave)

A2-Table 16 collects the global warming impact and endpoint impacts for the whole life cycle of one laser printer. The total cradle-to-grave impacts for the laser printer are broken down by life cycle phases. In addition, the contribution of each life cycle phase to the total environmental impacts of laser printer for every midpoint and endpoint category assessed is shown in A2-Figure 3 and A2-Figure 4, respectively.

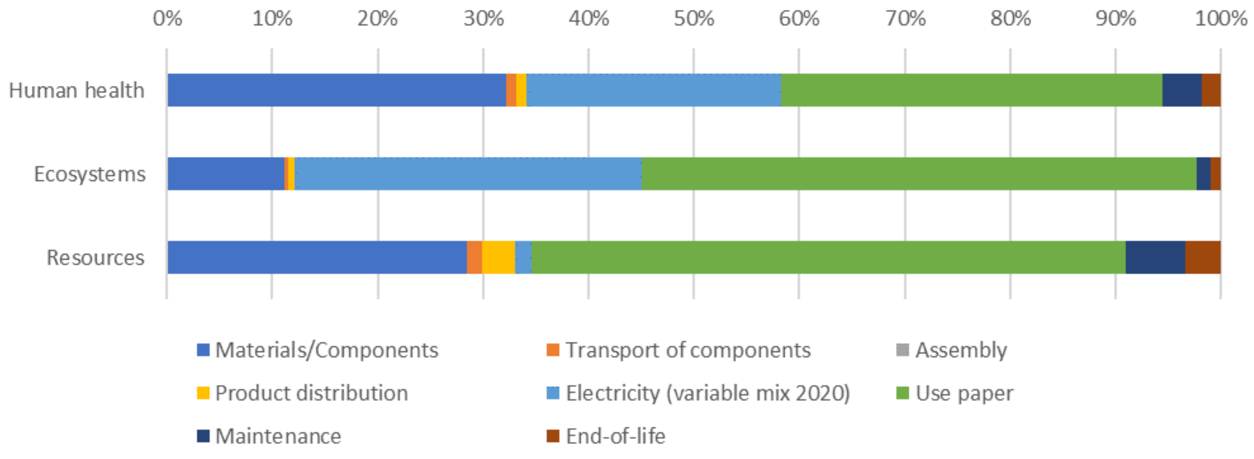
A2-Table 16. Global warming and endpoint impacts for the whole life cycle of one laser printer (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	781.84	3.24E-03	4.71E-06	68.53
Product distribution	45.32	9.28E-05	2.24E-07	6.94
Use (variable elect. mix - 2020-2032)	88.69	2.37E-03	1.34E-05	3.66
Use, paper	1,347.75	3.54E-03	2.14E-05	128.87
Use, toners	85.06	2.06E-04	3.78E-07	10.22
Maintenance (replacements, incl. transport)	109.42	3.61E-04	5.73E-07	13.12
EoL (waste treatment)	76.67	1.86E-04	3.87E-07	7.72
TOTAL (variable elect. mix)	**2,534.74**	**9.99E-03**	**4.11E-05**	**239.07**
Credits from recycling	-129.19	-4.95E-04	-9.29E-07	-10.70

The use stage has the highest contribution to the total impact both for global warming and for all endpoint categories, as well as for many midpoint categories. The impacts of the use phase are mainly due to paper consumption, although the consumption of electricity and replacements are also relevant to a lesser extent. Electricity consumption indeed encompasses almost all the water consumption impact. The manufacturing phase also has significant contribution to total life-cycle impacts, especially for some midpoint categories, such as ozone formation impact on terrestrial ecosystems; terrestrial, freshwater, marine and human ecotoxicities; and mineral resource scarcity. End-of-life impacts are limited compared to the impacts of other life cycle phases and they are rewarded with the credits given by materials recycled (including gold, aluminium, steel, copper, silver and others).



A2-Figure 3. Midpoint impacts for the laser printer (cradle-to-grave) by life cycle phases.



A2-Figure 4. Endpoint impacts for the laser printer (cradle-to-grave) by life cycle phases.

3.7 Material circularity indicator

Material flows associated with the laser printer were grouped into the following categories (see A2-Table 9): steel, aluminium, copper, gold, silver, lead, platinoid metals, other metals and plastics. The recycled feedstock (F_R) in the laser printer was estimated in order to allow for further calculation of the virgin feedstock (V). The recycled feedstock for plastics was based on primary data provided by LEXMARK, while average recycled content was used for other material categories, which was determined using industry databases and literature data (Table 11). The laser printer also contains reused feedstock coming from refurbished parts, which was estimated for each material category using primary data provided by LEXMARK (F_U ranging between 0.9% and 13.8% depending on the material category, with 9.9% weighted average).

The amount of waste collected for recycling and reuse was assumed to be the same as the waste collection rate for large household appliances (see Table 8). It was assumed to be the same for all material categories included in the laser printer and it was distributed between recycling (C_R = 56.8% weighted average) and reuse (C_R = 9.9% weighted average) taking into account the waste treatment figures in A2-Table 9 and A2-Table 10. The amount of waste going to landfill or energy recovery (W_0) was therefore deducted directly from the waste collection rate.

The efficiency of the recycling process (E_C) for each material category was calculated as the ratio between waste collected for recycling and mass recycled (using values in A2-Table 9 and A2-Table 10). It was then used to calculate the amount of waste generated in the recycling process (W_C). The amount of waste generated to produce the recycled content used as feedstock (W_F) was obtained from the average efficiency of the recycling process (E_F) for each material, which was assumed to be 75% for plastics and 90% for metals.

Feedstock and wastes were thus calculated taking into account all the above data and using formulae described in Section 3.3 of the main document. Results for feedstock and waste are collected in A2-Table 17.

MCI calculation for the laser printer (including its consumables and replacements) was then conducted (A2-Table 18). The average lifetime for the target laser printer investigated herein was assumed to be the same as for the industry-average products (L/Lav = 1). However, the intensity of use was assumed to be higher for the target laser printer (60 ppm against 50 ppm for industry-average products, resulting in U/Uav = 1.20). Therefore, the value of the utility function for the laser printer was 0.75. The linear flow index, considering feedstock and waste results (A2-Table 17), was 0.61. The MCI for the laser printer was finally calculated as 0.54.

A2-Table 17. Feedstock and waste for one laser printer used for MCI calculation.

Material	Mass M (kg)	Virgin feedstock V (kg)	Unrecoverable waste W (kg)	Unrecoverable waste to disposal W_0 (kg)	Unrecoverable waste from recycling parts W_C (kg)	Unrecoverable waste from recycled feedstock W_F (kg)
Steel	76.768	48.261	30.284	25.564	6.982	2.458
Aluminium	0.923	0.713	0.330	0.307	0.023	0.022
Copper	2.242	1.245	0.983	0.746	0.385	0.087
Gold	1.17E-03	8.22E-04	4.87E-04	3.91E-04	1.59E-04	3.26E-05
Silver	6.07E-03	5.04E-03	3.75E-03	2.02E-03	3.36E-03	9.37E-05
Lead	7.03E-03	2.73E-03	4.04E-03	2.34E-03	2.98E-03	4.22E-04
Platinoid metals	2.17E-05	1.30E-05	1.25E-05	7.23E-06	9.89E-06	6.22E-07
Other metals	1.591	1.308	0.906	0.530	0.729	0.023
Plastic	59.451	41.488	36.265	19.797	30.099	2.837
TOTAL	**140.988**	**93.024**	**68.776**	**46.949**	**38.226**	**5.428**

A2-Table 18. MCI calculation for the laser printer.

Parameter	Value
Actual average lifetime of product L (years)	5
Actual average lifetime of industry-average product L_{av} (years)	5
Average number of functional units (FUs) during the use phase of product U (ppm max.)	60
Average number of FUs during the use phase of industry-average product U_{av} (ppm max.)	50
Utility of the product X	1.20
Utility factor F(X)	0.75
Linear Flow Index LFI	0.61
Material Circularity Indicator of the product MCI_P	**0.54**

4 Life cycle costing

The economic study for the multifunctional laser printer LEXMARK CX860dte was performed considering both internal and external costs and assuming two different scenarios in relation to the product use:

- Scenario 1 – Standard use: it is based on an average standard business customer that uses the printer 260 days/year for printing 300 pages/day, thus resulting in 390,000 pages printed during the 5-year lifetime.
- Scenario 2 – Low-intensive use: it is based on a business customer that uses the printer 260 days/year for printing 150 pages/day, thus resulting in 195,000 pages printed during the 5-year lifetime.

These scenarios were defined according to market analysis data provided by LEXMARK. The internal costs, external environmental costs and total costs for each scenario are detailed and compared below.

4.1 Internal costs

The internal costs assessed for the laser printer includes the costs for:

(i) Acquisition of raw materials and components, including related transport operations.

(ii) Manufacturing of the product.

(iii) Distribution of the product to retailers or final customers.

(iv) Use, including product operation and required consumables (paper and toner cartridges).

(v) Maintenance, including the production and transport of replacements (toner bottles, imaging kits and fuser kits).

(vi) End of life, including WEEE management for the laser printer, consumables and replaced parts.

4.1.1 Scenario 1 – Standard use

A2-Table 19 shows the breakdown of the internal costs of the laser printer by life cycle phase, namely manufacturing (including i, ii and iii), use (iv and v) and end of life (vi), according to the standard use scenario.

Retail price provided by LEXMARK was assumed herein to consider manufacturing costs. The retail price covers all the costs related to raw materials and components, product manufacturing and distribution, as well as other any other costs for product development (like R&D costs) and net revenues from sales.

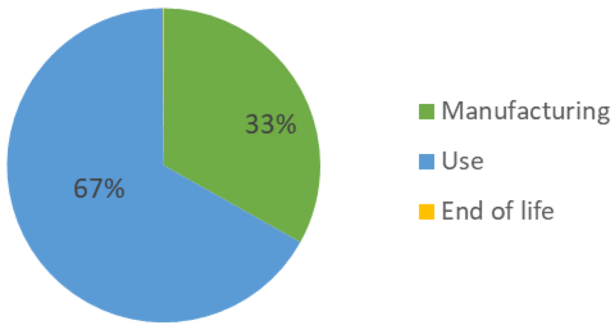
The use phase includes the costs for electricity, consumables (paper and toner cartridges) and other parts replaced during maintenance throughout the printer lifetime (as detailed in Section 3.5.2 of this Annex). Total linked amounts were therefore estimated at 152.49 kWh of electricity, 390 thousand pages (1,322 kg paper), 9 black toners, 17 colour toners, 3 toner bottles, 1 imaging kit and 1 fuser kit. The average market prices for these consumables were assumed as follows: 0.117 €/kWh of electricity for year 2019, with a sustained annual growth factor of 1.022 for the following years; 9.20 €/1,000 paper pages; 458.51 €/black toner; 465.40 €/colour toner, 44.95 €/toner bottle; 511.59 €/imaging kit; 762.87 €/fuser kit.

The costs for WEEE management was estimated at 15.00 € for one laser printer, which corresponds to the fee paid by producers for the EoL management of each laser printer they put on the market. In addition, the costs for waste management of consumables and components were estimated similarly.

A2-Table 19. Internal costs for the whole life cycle of one laser printer (cradle-to-grave) according to scenario 1.

Life cycle phase	Concept	Cost (€)	Total cost (€)
Manufacturing	Retail price (incl. costs for materials/components, manufacturing, distribution, other product development costs and net revenues)	8,459.00	8,459.00
Use	Electricity consumption	18.70	17,054.40
	Paper consumption	3,588.00	
	Toner cartridges	12,038.39	
	Toner bottle	134.85	
	Imaging kit	511.59	
	Fuser kit	762.87	
End of life	WEEE management fee, printer	15.00	24.06
	WEEE management fee, toner cartridges	7.28	
	WEEE management fee, replacements	1.78	
TOTAL	**Manufacturing + Use + EoL**	-	**25,537.46**

A2-Figure 5 graphically shows the contribution of each life cycle phase to the total internal cost of the laser printer. It can be found that the use phase represents two-thirds of the total internal costs, while the remaining third is attributable to the manufacturing phase. The contribution of end of life to internal costs is negligible.



A2-Figure 5. Contribution of each life cycle phase to the total internal costs for the laser printer according to scenario 1.

4.1.2 Scenario 2 – Low-intensive use

A2-Table 20 shows the breakdown of the internal costs of the laser printer by life cycle phase according to the low-intensive use scenario. While manufacturing costs remain the same as in the standard use scenario, the costs for the use phase are decreased due to lower consumption of electricity, paper, toners and replacements. The same happens for the end-of-life phase since the amounts of waste from consumables and replaced parts to be managed is lower.

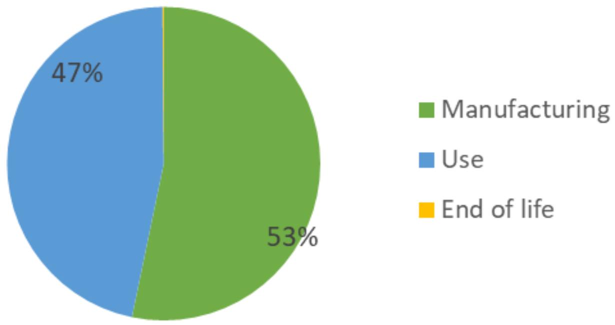
The total amounts consumed during the use phase for the low-intensive use scenario were estimated at 76.25 kWh of electricity, 195 thousand pages (661 kg paper), 4 black toner, 8 colour toner and 1 toner bottles and 1 imaging kit. Replacement of imaging kit and fuser kit is not required under this scenario due to the lower use of the printer. The average market prices for these consumables were also used in this case to calculate the total internal costs.

The costs for WEEE management was estimated at 15.00 € for one laser printer, which corresponds to the fee paid by producers for the EoL management of each laser printer they put on the market. In addition, the costs for waste management of consumables and components were estimated similarly.

A2-Table 20. Internal costs for the whole life cycle of one laser printer (cradle-to-grave) according to scenario 2.

Life cycle phase	Concept	Cost (€)	Total cost (€)
Manufacturing	Retail price (incl. costs for materials/components, manufacturing, distribution, other product development costs and net revenues)	8,459.00	8,459.00
Use	Electricity consumption	9.35	7,405.54
	Paper consumption	1,794.00	
	Toner cartridges	5,557.24	
	Toner bottle	44.95	
	Imaging kit	0.00	
	Fuser kit	0.00	
End of life	WEEE management fee, printer	15.00	18.68
	WEEE management fee, toner cartridges	3.36	
	WEEE management fee, replacements	0.32	
TOTAL	**Manufacturing + Use + EoL**	-	**15,883.22**

A2-Figure 6 graphically shows the contribution of each life cycle phase to the total internal cost of the laser printer. The manufacturing phase represents a little more than half of the total internal costs in this scenario, while the remaining internal costs are attributable to the use phase. The contribution of end of life to internal costs is also negligible for this scenario.



A2-Figure 6. Contribution of each life cycle phase to the total internal costs for the laser printer according to scenario 2.

4.2 External costs

Monetary valuation of environmental impacts was applied to assess the costs of environmental externalities. To this end, LCA results obtained for the laser printer (see section 3.6 of this Annex) were combined with monetisation factors given for different environmental impact categories (see Section 4.2 of the main document). External costs were estimated using two different approaches for monetary valuation: (1) monetisation of global warming impact and (2) monetisation of endpoint impacts. It should be noted that the economic costs obtained in each case cannot be added together since the global warming impact (as well as the other midpoint impacts) is included in the endpoint impacts.

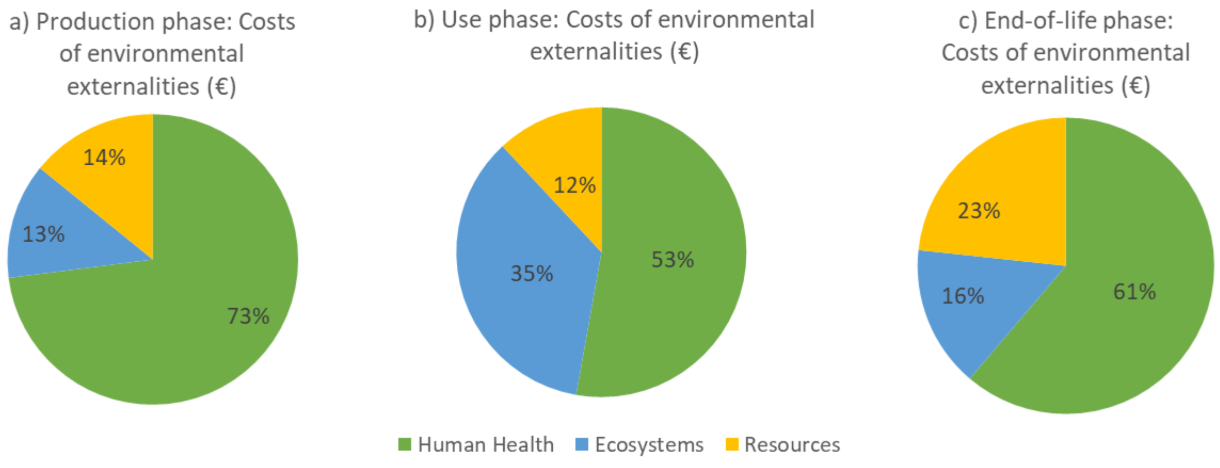
4.2.1 Scenario 1 – Standard use

The results from the monetary valuation of environmental impacts for the standard use scenario are collected in A2-Table 21. These are broken down by life cycle phases and impact categories monetized. It can be found that the use phase is the main responsible for the external costs, followed by the manufacturing phase. The costs of end-of-life phase are comparatively negligible.

A2-Table 21. External costs for the whole life cycle of one laser printer (cradle-to-grave) according to scenario 1.

Life cycle phase	Impact category	Total amount	Monetisation factor	Economic cost (€)
Manufacturing	Human health	3.24E-03 DALY	101,311 €/DALY	328.47
	Ecosystems	4.71E-06 species.yr	1.23E+07 €/species.yr	58.00
	Resources	68.53 USD2013	0.929 €/USD2013	63.70
	Sub-total endpoint impacts	-	-	**450.17**
	Global warming	781.84 kg CO_2 eq	130 €/tonne CO_2 eq	101.74
Use	Human health	6.56E-03 DALY	101,311 €/DALY	665.00
	Ecosystems	3.60E-05 species.yr	1.23E+07 €/species.yr	443.22
	Resources	162.82 USD2013	0.929 €/USD2013	151.33
	Sub-total endpoint impacts	-	-	**1,259.55**
	Global warming	1,665.46 kg CO_2 eq	130 €/tonne CO_2 eq	218.12
End of life	Human health	1.86E-04 DALY	101,311 €/DALY	18.85
	Ecosystems	3.87E-07 species.yr	1.23E+07 €/species.yr	4.77
	Resources	7.72 USD2013	0.929 €/USD2013	7.18
	Sub-total endpoint impacts	-	-	**30.80**
	Global warming	76.67 kg CO_2 eq	130 €/tonne CO_2 eq	9.98
TOTAL	Human health	9.99E-03 DALY	101,311 €/DALY	1,012.33
	Ecosystems	4.11E-05 species.yr	1.23E+07 €/species.yr	505.99
	Resources	239.07 USD3013	0.929 €/USD2013	222.20
	Total endpoint impacts	-	-	**1,740.52**
	Total global warming	2,534.74 kg CO_2 eq	130 €/tonne CO_2 eq	329.83

A2-Figure 7 graphically shows the contribution of each endpoint impact to the total external costs for each life-cycle phase. Most of the external costs are due to human health damages. The costs of damages to ecosystem diversity are especially relevant for the use phase, while the costs of damages to resource availability are important for the end-of-life phase.



A2-Figure 7. Contribution of each endpoint impact to total external costs of manufacturing and end-of-life phases for the laser printer according to scenario 1.

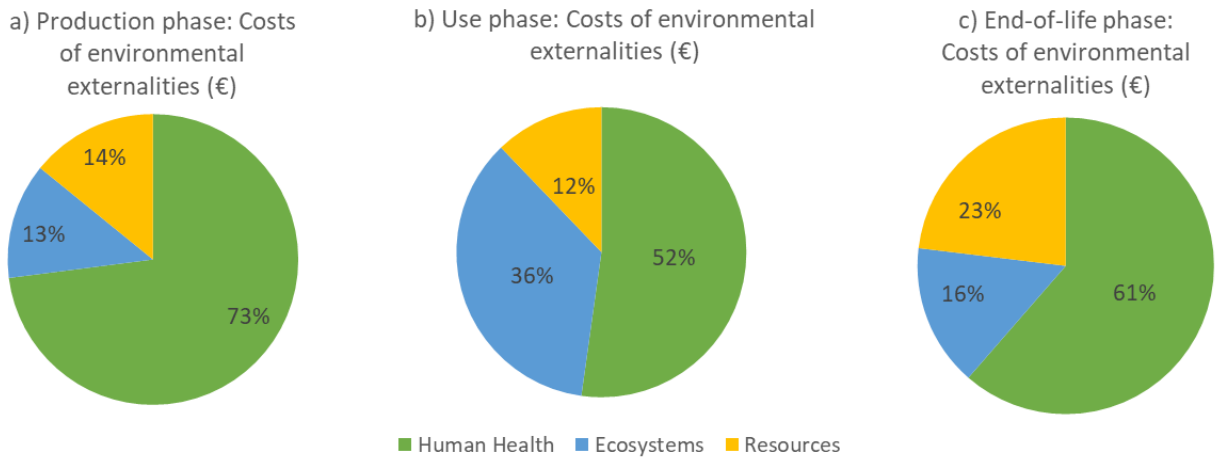
4.2.2 Scenario 2 – Low-intensive use

The results from the monetary valuation of environmental impacts for the low-intensive use scenario are collected in A2-Table 22. These are broken down by life cycle phases and impact categories monetized. Even though the external costs of the use phase are lower in this scenario, they still have the largest contribution to total external costs. The manufacturing phase also contributes heavily to total external costs, while the external costs of end-of-life phase are comparatively negligible.

A2-Table 22. External costs for the whole life cycle of one laser printer (cradle-to-grave) according to scenario 2.

Life cycle phase	Impact category	Total amount	Monetisation factor	Economic cost (€)
Manufacturing	Human health	3.24E-03 DALY	101,311 €/DALY	328.47
	Ecosystems	4.71E-06 species.yr	1.23E+07 €/species.yr	58.00
	Resources	68.53 USD2013	0.929 €/USD2013	63.70
	Sub-total endpoint impacts	-	-	**450.17**
	Global warming	781.84 kg CO_2 eq	130 €/tonne CO_2 eq	101.74
Use	Human health	3.20E-03 DALY	101,311 €/DALY	324.06
	Ecosystems	1.79E-05 species.yr	1.23E+07 €/species.yr	220.75
	Resources	81.52 USD2013	0.929 €/USD2013	75.77
	Sub-total endpoint impacts	-	-	**620.58**
	Global warming	829.24 kg CO_2 eq	130 €/tonne CO_2 eq	107.90
End of life	Human health	1.75E-04 DALY	101,311 €/DALY	17.70
	Ecosystems	3.63E-07 species.yr	1.23E+07 €/species.yr	4.47
	Resources	7.16 USD2013	0.929 €/USD2013	6.66
	Sub-total endpoint impacts	-	-	**28.83**
	Global warming	71.76 kg CO_2 eq	130 €/ tonne CO_2 eq	9.34
TOTAL	Human health	6.62E-03 DALY	101,311 €/DALY	670.23
	Ecosystems	2.30E-05 species.yr	1.23E+07 €/species.yr	283.22
	Resources	157.21 USD2013	0.929 €/USD2013	146.12
	Total endpoint impacts	-	-	**1,099.57**
	Total global warming	1,682.84 kg CO_2 eq	130 €/tonne CO_2 eq	218.98

A2-Figure 8 graphically shows the contribution of each endpoint impact to the total external costs for each life-cycle phase. Most of the external costs are due to human health damages, while the costs of ecosystem diversity and resource availability damages are especially relevant for the use and end-of-life phases, respectively.



A2-Figure 8. Contribution of each endpoint impact to total external costs of manufacturing and end-of-life phases for the laser printer according to scenario 2.

4.3 Total life cycle costs

Concluding, A2-Table 23 shows the total life cycle cost for both scenarios assessed, including internal and external costs. The internal costs are by far the highest cost element for both scenarios. In the standard use scenario these costs are mainly dominated by the use phase, while in the low-intensive use scenario the intensity of use of the laser printer is lower and the manufacturing phase becomes the most relevant in terms of internal costs. Manufacturing and use phases together comprises most of the costs, both for internal and external costs in both scenarios, while the costs of end-of-life phases is comparatively negligible.

A2-Table 23. Total costs for the whole life cycle of one laser printer (cradle-to-grave): comparison between scenarios.

Life cycle phase	Scenario 1 – Standard use			Scenario 2 – Low-intensive use		
	Internal cost (€)	External cost (€)	Total cost (€)	Internal cost (€)	External cost (€)	Total cost (€)
Manufacturing	8,459.00	450.17	8,909.17	8,459.00	450.17	8,909.17
Use	17,054.40	1,259.55	18,313.95	7,405.54	620.58	8,026.11
End of life	24.06	30.80	54.86	18.68	28.83	47.51
TOTAL	**25,537.46**	**1,740.52**	**27,277.97**	**15,883.22**	**1,099.57**	**16,982.79**

5 Social life cycle assessment

5.1 Social life cycle inventory

Primary data provided by LEXMARK was used as the starting point to carry out the S-LCA. Specifically, it provided economic data describing the supply chain composition and location, identifying all the economic costs required to produce the laser printer and the cost breakdown by countries and economic sectors. LEXMARK provided primary data for a series of components that account all together for 95 kg, so the social impacts were linearly extrapolated considering the total weight of the laser printer (130 kg approximately). A2-Table 24 shows the percentage breakdown of total production costs by countries and sectors.

A2-Table 24. Production cost breakdown for the laser printer by countries and economic sectors.

Country/Sector	Plastic products	Ferrous metals	Non-ferrous metals	Paper products	Mineral products	Electronic equipment	Manufacturing process
TOTAL	23.564%	13.172%	0.754%	0.209%	2.227%	34.019%	26.053%
China	21.273%	12.870%	0.754%	0.209%	1.415%	24.295%	26.053%
USA	0.063%	0.016%				4.854%	
Japan	2.181%					0.587%	
Germany		0.101%				0.012%	
Philippines						2.376%	
South Korea					0.812%	1.610%	
Thailand		0.185%				0.285%	
Singapore	0.047%						

The sectors included in the assessment comprise those related to every material and/or component required to produce the laser printer, as well as the sector linked to the manufacturing process at LEXMARK facilities (i.e., electronic equipment sector in China). Electronic equipment is the most complex sector in the supply chain since the related components come from 7 different countries, being China the country where more money is spent in electronic components. By countries, China is by far the most important in the acquisition of materials and components, representing around 87% of total production costs for the laser printer. It is followed by USA, although its contribution is much more limited with about 5% of total production costs.

The SHDB method and datasets were then used to calculate the social impacts for each sector in each country (as explained in Section 5 of the main document). The Social Hotspot 2019 Category Method with Weights (which is available for SimaPro software) was used. The social impacts derived from the laser printer were obtained by allocating the production costs (in USD) to the corresponding social LCI datasets for every country-specific sector involved in the laser printer supply chain. The social LCI datasets used are listed in A2-Table 25.

A2-Table 25. Social LCI datasets for the country-specific sectors linked to the laser printer.

Social Hotspot Database (SHDB)	Reference Unit
Chemical, rubber, plastic products/CHN S	USD
Chemical, rubber, plastic products/USA S	USD
Chemical, rubber, plastic products/JPN S	USD
Chemical, rubber, plastic products/SGP S	USD
Electronic equipment/CHN S China	USD
Electronic equipment/USA S	USD
Electronic equipment/JPN S Japan	USD
Electronic equipment/DEU S Germany	USD
Electronic equipment/PHL S	USD
Electronic equipment/KOR S SouthKorea	USD
Electronic equipment/THA S Thailand	USD
Ferrous metals/CHN S China	USD

Social Hotspot Database (SHDB)	Reference Unit
Ferrous metals/USA S	USD
Ferrous metals/DEU S Germany	USD
Ferrous metals/THA S	USD
Metals nec/CHN S China	USD
Paper products, publishing/CHN S China	USD
Mineral products nec/CHN S China	USD
Mineral products nec/KOR S	USD
Manufactures nec/CHN S	USD

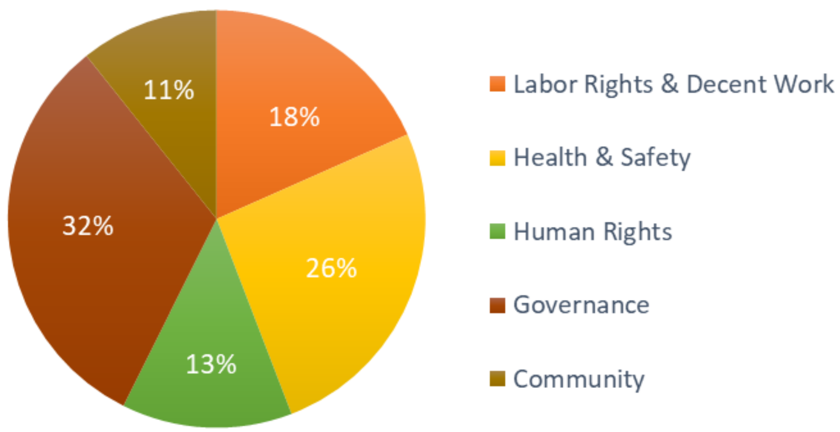
5.2 Social life cycle impact assessment

The social footprint of the laser printer was calculated by aggregating the social impacts associated with each country-specific sector listed in A2-Table 25 into a single social impacts indicator, namely the so-called Social Hotspot Index (SHI). A2-Table 26 shows the SHI obtained for the laser printer, as well as its breakdown into the different social impact categories that contribute to the total social footprint.

A2-Table 26. Social impacts of the laser printer by impact category.

Social category	Total impact (Pt)
Labour Rights & Decent Work	16,651.75
Health & Safety	23,400.89
Human Rights	11,977.73
Governance	28,937.41
Community	9,724.92
TOTAL: SHI	**90,692.69**

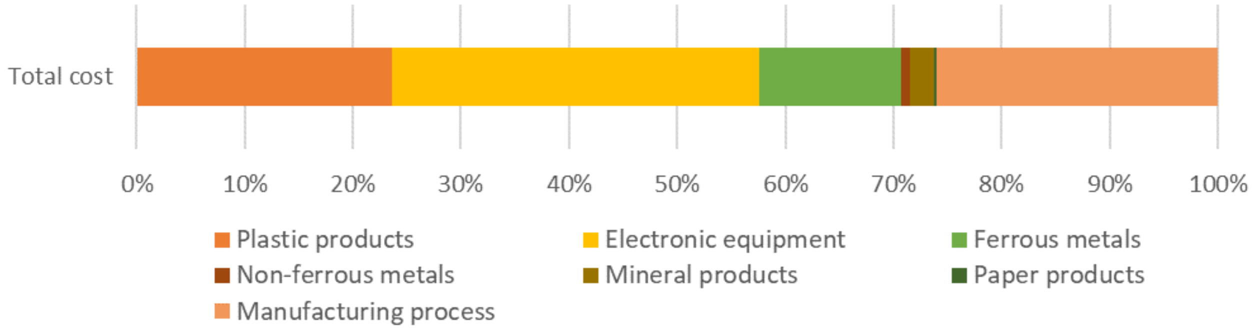
A2-Figure 9 shows graphically the contribution of each social impact category to the total social footprint of the laser printer. It can be found that the greatest social impacts are due to Governance and Health & Safety issues, while social impacts affecting Community have the lowest contribution.



A2-Figure 9. Percentage of impact categories in the social life cycle assessment for the laser printer.

5.2.1 Social impacts by economic sectors

A2-Figure 10 shows the economic share of each productive sector in the laser printer supply chain. The economic sector with the highest contribution (i.e., that in which the company spent more money to produce the laser printer) is the electronic equipment sector, followed by the EEE manufacturing process (performed in LEXMARK facilities) and the sectors related to plastic products and ferrous metals. In contrast, paper products and non-ferrous metals are the economic sectors where expenditures are the lowest.



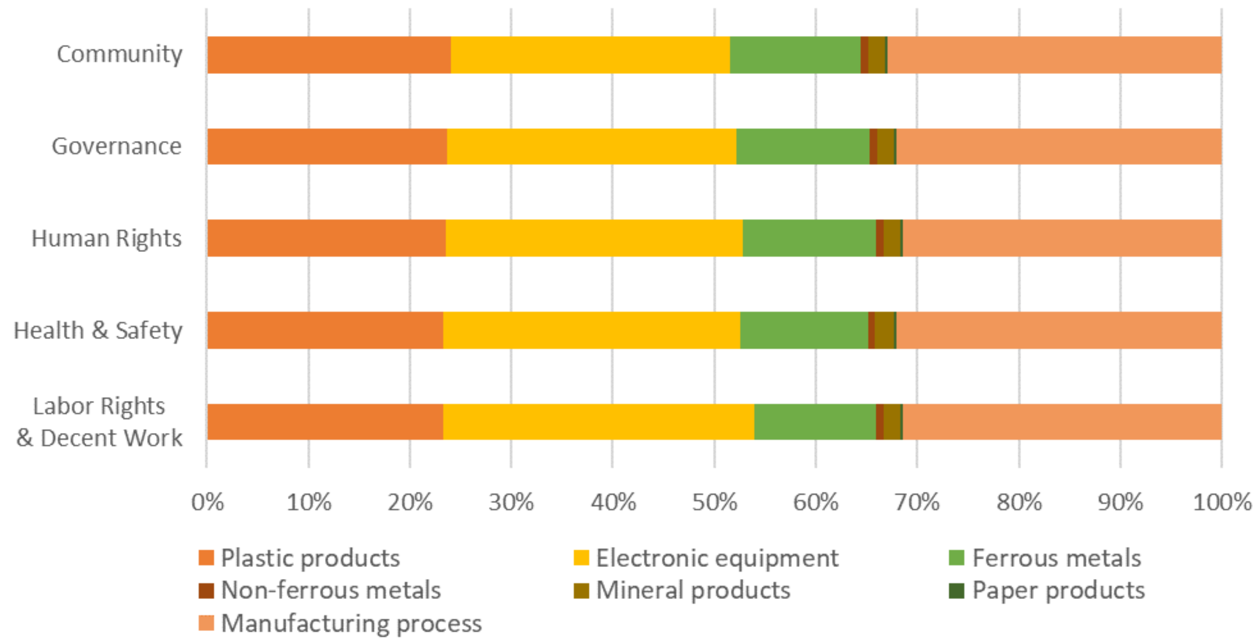
A2-Figure 10. Production cost breakdown for the laser printer by economic sectors.

The social impacts were assessed for every economic sector. A2-Table 27 shows the impacts for each social category obtained for each sector involved in the laser printer supply chain, while A2-Figure 11 shows graphically the contribution by each sector to the total impact in each social category. The results show that the manufacturing process used to produce the laser printer comprises most of the impact for every social category, ranging between 31% and 33% of total social impacts depending on the social category assessed. The impact contribution of the manufacturing process is therefore slightly higher than its economic share in total production costs, which is around 26%. This means that the laser printer manufacturing process, which takes place in China, constitutes a social hotspot to be prioritised when planning measures to improve social conditions and reduce the social footprint of the laser printer.

There are other economic sectors showing relevant contributions to total social impacts, such as electronic equipment (28-32% contribution to total impacts), plastic products (23-24%) and ferrous metals (12-13%). The impact contributions of these sectors are completely aligned to their respective economic shares in total production costs, so their social risk levels are tolerable (i.e., social improvements could be applied there due to their large contribution to social impacts, but the priority is lower). Minera products, non-ferrous metals and paper products have negligible social impacts when compared to the other economic sectors composing the laser printer supply chain.

A2-Table 27. Social impacts of the laser printer by economic sectors.

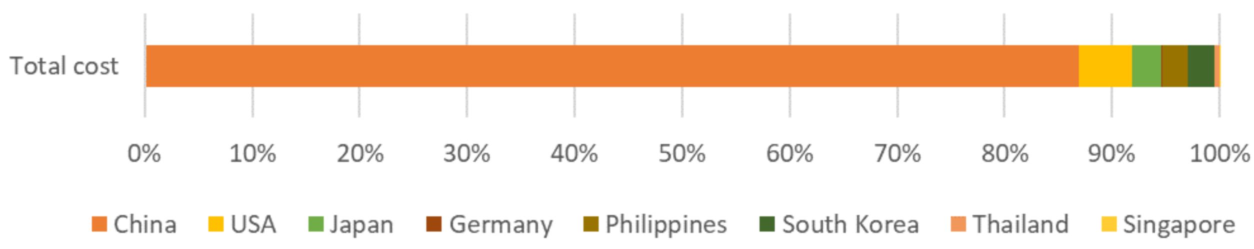
Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Plastic products	3,882.18	5,441.42	2,823.77	6,860.10	2,334.11
Electronic equipment	5,108.77	6,864.22	3,500.50	8,250.36	2,678.98
Ferrous metals	1,992.48	2,937.28	1,567.28	3,778.69	1,256.61
Non-ferrous metals	116.09	167.06	89.64	213.94	72.66
Mineral products	284.80	429.47	197.36	484.28	154.15
Paper products	43.87	63.18	31.12	77.83	25.63
Manufacturing	5,223.55	7,498.26	3,768.06	9,272.22	3,202.78
TOTAL	**16,651.75**	**23,400.89**	**11,977.73**	**28,937.41**	**9,724.92**



A2-Figure 11. Contribution of each economic sector to the total social impacts of the laser printer by social category.

5.2.2 Social impacts by countries

A2-Figure 12 shows the economic share of each country in the laser printer supply chain. The country with the highest contribution is China, comprising about 87% of the total laser printer production costs. It includes both the manufacturing costs at LEXMARK facilities and also the purchasing costs of various materials and components (especially plastic products, ferrous metals and electronic components) from other companies located in China as well. The expenditure in the rest of countries involved in the supply chain is very low in comparison. Nonetheless, the contribution to total production costs of some countries is still relevant, such as USA (4.9%), Japan (2.8%), Philippines (2.4%) and South Korea (2.4%), whereas the contribution of other countries is negligible.



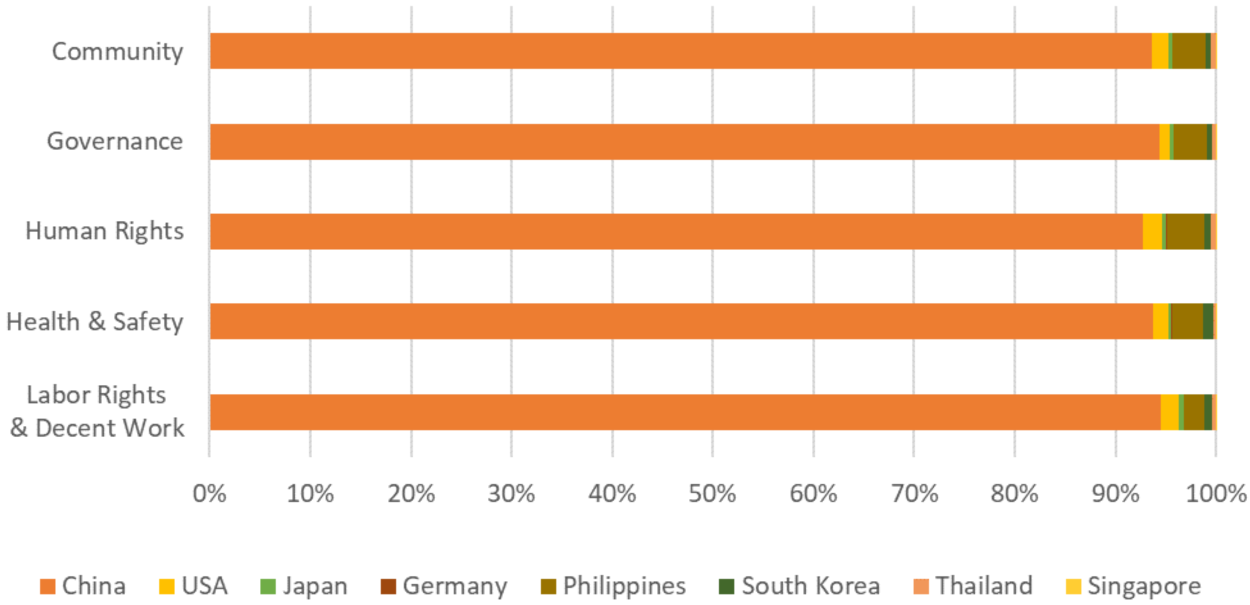
A2-Figure 12. Production cost breakdown for the laser printer by country.

The social impacts were also assessed for every country in the laser printer supply chain. A2-Table 28 shows the impacts for each social category obtained for each country, while A2-Figure 13 shows graphically the contribution by each country to the total impact in each social category. The results show that China is the country with the highest social impacts for all social categories. Despite China represents 87% of total production costs, the social impacts there encompass between 93% and 95% of the total laser printer impacts depending on the social category assessed. This reveals that social risk levels in the Chinese productive sectors supplying LEXMARK are high, so they can be identified as social hotspots of the laser printer. LEXMARK could therefore investigate opportunities and measures there to apply social improvements, not only at its production factory in China but also collaborating with its Chinese suppliers. This could result in a decrease of the social footprint of the laser printer.

Philippines was also identified as a social hotspot, although with a lower priority given its minor social impacts in absolute terms. The reason is that the contributions of Philippines to total social impacts are between 2 and 4 greater than its share in total production costs, which means that social risk levels are important there. There are then great opportunities to implement social improvements in Philippines by working together with suppliers located there.

A2-Table 28. Social impacts of the laser printer by country.

Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
China	15,748.31	21,950.25	11,108.10	27,326.84	9,104.50
USA	284.09	356.61	223.91	296.02	159.72
Japan	78.45	62.57	56.50	84.26	40.18
Germany	2.39	4.15	2.07	3.49	1.44
Philippines	345.44	734.91	444.05	962.87	320.56
South Korea	126.24	226.11	75.40	151.53	53.05
Thailand	64.96	64.72	66.36	110.08	44.25
Singapore	1.86	1.57	1.34	2.32	1.22
TOTAL	**16,651.75**	**23,400.89**	**11,977.73**	**28,937.41**	**9,724.92**



A2-Figure 13. Contribution of each country to the total social impacts of the laser printer by social category.

Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.1. Results of environmental, economic and social preliminary analyses.

Annex 3 – Telecom equipment

Acronym: **C-SERVEES**

Project title: **Activating Circular Services in the Electric and Electronic Sector**

Contract Nº: **776714**

Start date: **1st May 2018**

Duration: **48 months**

Deliverable number	D5.1 – Annex 3
Deliverable title	Results of environmental, economic and social preliminary analyses. Annex 3 – Telecom equipment
Submission due date	31/10/2020 (M30)
Actual submission date	30/11/2020 (M31)
Work Package	WP5
WP Leader	AIMPLAS
Dissemination Level	Public
Version	04
Deliverable Lead Beneficiary	AIMPLAS

1 Introduction

This Annex includes the comprehensive documentation related to the life cycle sustainability assessment of the current telecom equipment used for demonstration in the C-SERVEES project. It includes more details on the methodological aspects and assumptions done, life cycle inventory developed and detailed results for the following studies:

- Life cycle assessment, including midpoint and endpoint environmental impact categories and material circularity indicator.
- Life cycle costing, including internal and external costs (related to environmental externalities).
- Social life cycle assessment, including 5 social impact categories.

All these studies and results constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of the telecom equipment.

2 Goal and scope

The present study aimed to calculate the environmental, economic and social impacts of the telecom equipment ADVA 16ALM/#1650D/AC. It is an Advanced Link Monitoring (ALM) product that splits into an (electrically) active unit and passive fibre-optic sensors for the monitoring optical networks, including tasks like collection of real-time information on fibre integrity, fast and easy localization of user traffic and remote passive fire detection in sites that are accessed with a fibre. It is manufactured in Germany and currently sold worldwide. More details on the ALM product investigated are shown in A3-Table 1.

A3-Table 1. Technical specifications of the demo telecom equipment.

MODEL	ADVA 16ALM/#1650D/AC
Image	
Product number	1043709841-02
Description	Advanced Link Monitor (ALM), 16 ports with LC/APC connectors, AC powered
Colour	Grey
Size	44 × 215 × 213 mm
Weight / Packaged weight	< 2 kg / 11.6 kg
Power typical / maximum	10 W / 13 W
Country of origin	Germany

3 Life cycle assessment

3.1 Functional unit and system boundaries

The product function for the ALM product is fibre monitoring. The functional unit considered in the study is one ALM product, including the active unit (ADVA 16ALM/#1650D/AC) and fourteen passive fibre-optic sensors, which offers continuous monitoring throughout its 8-year lifetime (i.e., 365 days/year and 24 h/day).

A3-Table 2 shows the system boundaries considered for the ALM product, identifying the life cycle phases, processes and other elementary flows included and excluded in the study.

A3-Table 2. System boundaries considered for the ALM product.

Life cycle phase	Included	Excluded
Raw material extraction and processing	Extraction of natural resources Refining and raw material production Intermediate product manufacturing Waste treatment and transport	Infrastructure
Product manufacturing	Energy for product manufacturing/assembly Transport	Infrastructure Production losses Packaging
Product distribution	Transport	
Product use	Electricity consumption	Maintenance
End of life	Transport EoL treatments Landfilling of waste fraction not recycled	
Benefits and burdens beyond system boundaries	Recycling benefits (included as credits)	

3.2 Allocation and cut-off criteria

No multi-output foreground processes were identified during data collection. Inventories taken from Ecoinvent database were allocated according to the cut-off system model.[18]

The system boundary in the EoL phase was drawn just behind product waste collection and transportation to the recycling sites. WEEE from the ALM product was classified as waste by-product and environmental burdens associated with waste treatment were thus allocated completely to the waste-producing activity (as indicated in Section 3.1.3 of the main document). The environmental impacts of the EoL phase and the credits generated by recycling are both interesting for the comparative assessment between the baseline product system and the redesigned product system proposed in the C-SERVEES project. Product packaging was excluded from the assessment since its impact was predicted as negligible (compared to that of the whole ALM product), while this exclusion will have no effect on the comparative results (between current and C-SERVEES scenarios).

No available primary data were knowingly omitted or excluded.

3.3 Data quality

The data used to create the inventory model is as precise, complete, consistent and representative as possible with regard to the goal and scope of the study.

- Primary data was provided by ADVA. The data used for the study is considered to be of the highest precision. Ecoinvent database was the main secondary data source used to model the product system.

- Completeness was judged based on the completeness of both the inputs/outputs per unit process and the unit processes themselves.
- Consistency refers to modelling choices and data sources. The goal was to ensure that differences in results occur due to actual differences between product systems investigated and compared, and not due to inconsistencies in modelling choices, data sources, characterisation factors, etc.
- Representativeness expresses the degree to which the data matches the geographical, temporal and technological requirements:
  - The average electricity mix for Europe was considered for the use phase (as explained in Section 3.1.2 of the main document) using the most recent data published (year 2019).[16]
  - Ecoinvent database version used was updated in 2018.
  - Integrated circuits, PWB and capacitors were modelled based on recent literature data (as explained in Section 3.1.1 of the main document).

3.4 Assumptions and limitations

Other assumptions and limitations for the LCA study of the ALM product are listed below:

- No production losses were considered.
- No packaging was considered.
- Recycled content was assumed to be the worldwide average (Table 11).
- The origins for water and air transport were assumed to be the Hamburg port and Munich airport, respectively.
- Distances for product distribution within each country were assumed as 300 km, except for USA, where 2,000 km were assumed.
- The average lifetime and intensity of use of the target ALM product were assumed to be similar to industry-average values (to determine the MCI).
- No maintenance was considered during the lifetime of the product.
- Waste collection rate was assumed to be the European average for IT and telecommunications equipment (Table 8).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[20]

3.5 Life cycle inventory

This section describes the LCI developed for the target ALM product, including inputs/outputs inventoried for each life-cycle phase and the data sources used for their inventory modelling.

3.5.1 Manufacturing

The LCI of the ALM product manufacturing was obtained from primary data provided by ADVA. The ALM product consists of several components. The different components inventoried and their total amounts are listed in A3-Table 3. Fourteen passive sensors were also included in the LCI, seven with a certain configuration and the other seven with a different one, as inventoried in A3-Table 4.

A3-Table 3. Components of the target ALM product.

Components in ALM product	Part/Material	Total amount	Unit
Chassis	Zinc-coated steel sheet (ASTM A653)	1.230	kg
Heatsink	Aluminium alloy 6063	0.267	kg
Small mechanical parts	Fastener, cage and others	0.134	kg
Printed wiring board (PWB)	14-layers PWB	0.035	m^2
Power supply unit (PSU)	PSU 26 W 240 V AC	0.359	kg
Power cable	Cable, loom 20 AWG, UL 1015	0.320	m
Integrated circuits (IC)	ICs (BGA, QFP, SO, SSOP, TQFP, TSOP, TSSOP)	15.711	g
Capacitors	Ceramic and tantalum capacitors	8.327	g
Resistors	Thick film flat chips and SMD thermistor	0.632	g
Transistors	Transistors SOT23	1.046	g
Diodes	Diodes (MELF, SOD123/323/523, SOD323)	0.199	g
Inductor	Coil miniatures and coil multilayer chips	4.159	g
LED	SMD LEDs	1.349	g
Lightpipe	Polycarbonate	27.000	g
Oscillator	Oscillator crystal	0.200	g
Connectors	Various configurations	47.755	g
Coin cell battery	Cell BR Series (Li/Poly-carbon monofluoride)	2.800	g
Optical fibre	Glass fibre bare	26.000	g
Optical switch module	Key switch tact	0.242	g
Optical jumper	Optical jumper	0.500	m
Optical receiver	Photodiode RX PIN SIX ARRAY	4.000	g
Optical coupler and circulator	Coupler xx/yy SM C	6.000	g
Optical laser diode	LAS 980 360MW PUMP	4.000	g
Optical adapter	ADPT/LC/DUP/45/M	96.544	g
Variable optical attenuator	Attenuator ATT/xxxdB/LC	4.640	g
Passive units, configuration 1	see A3-Table 4	7	units
Passive units, configuration 2	see A3-Table 4	7	units
Total, without passive units	**-**	**2.492**	**kg**

A3-Table 4. Components of the passive units.

Components/Materials in passive units	Total amount (g/unit)	
	Configuration 1	Configuration 2
Fibre, glass fibre	0.015	0.015
Fibre coating, polyacrylamide	0.021	0.021
Mechanical parts, aluminium alloy 6061	3.622	13.942
Compression spring, low-alloyed steel	0.250	0.499
Integrated circuits	**3.908**	**14.478**

Each component is in turn made of different components and/or materials that are processed with certain manufacturing processes to attain the final shape and properties required for the product. The inventories for the components, materials and manufacturing processes required to produce the ALM product were mainly taken from the Ecoinvent database. These inventories are linked to their own functional unit (FU), so they show energy consumption, resource consumption, emissions, etc. for different basic activities, expressed per amount of materials extracted and/or processed (kg, m, m^2 or unit), for example. The environmental impacts of the materials and components composing the ALM product modules were thus obtained by multiplying their amounts by the impacts calculated from the corresponding LCI datasets (for the defined FU). A list of the LCI datasets used for the manufacturing phase is given in A3-Table 5.

A3-Table 5. LCI datasets of material, components and processes for ALM product manufacturing.

Input	Dataset name	FU
	RAW MATERIALS	
Aluminium alloy	Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	1 kg
Copper	Copper {GLO}| market for | Cut-off, U	1 kg
Nickel silver	65.8% Copper + 16.7% Nickel (99.5%) + 17.5% Zinc	1 kg
Optical fibre	Glass fibre bare, modelled as ADVA | Cut-off, U	1 kg
Glass fibre	Glass fibre {GLO}| market for | Cut-off, U	1 kg
Glass fibre reinforced plastic, polyamide, injection moulded	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Cut-off, U	1 kg
Nickel	Nickel, 99.5% {GLO}| market for | Cut-off, U	1 kg
Nylon 6-6	Nylon 6-6 {GLO}| market for | Cut-off, U	1 kg
Polyester resin, unsaturated	Polyester resin, unsaturated {GLO}| market for | Cut-off, U	1 kg
Polycarbonate	Polycarbonate {GLO}| market for | Cut-off, U	1 kg
Acrylate, polyacrylamide	Polyacrylamide {GLO}| market for | Cut-off, U	1 kg
Expanded polystyrene (EPS)	Polystyrene, expandable + Polymer foaming {RER}	1 kg
Stainless steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U	1 kg
Galvanized steel	Steel, low-alloyed, hot rolled + Zinc coat (64 m2/t)	1 kg
Low carbon steel bar/sheet	Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U	1 kg
Tin	Tin {GLO}| market for | Cut-off, U	1 kg
Zinc	Zinc {GLO}| market for | Cut-off, U	1 kg
	PROCESSING	
Injection plastics	Injection moulding {GLO}| market for | Cut-off, U	1 kg
Steel processing	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Rolling steel	Sheet rolling, steel {GLO}| market for | Cut-off, U	1 kg
Rolling chromium steel	Sheet rolling, chromium steel {GLO}| market for | Cut-off, U	1 kg
Rolling aluminium	Sheet rolling, aluminium {GLO}| market for | Cut-off, U	1 kg
Rolling copper	Sheet rolling, copper {GLO}| market for | Cut-off, U	1 kg
	COMPONENTS	
Battery cell	Battery cell, Li-ion {GLO}| market for | Cut-off, U	1 kg
Cable 0.036 kg/m	Cable, network cable, category 5, without plugs {GLO}| market for | Cut-off, U 0.036 kg/m	1 m
Capacitor, ceramic SMD type (86 mg average weight)	Capacitor, for surface-mounting {GLO}| market for | Cut-off, U	1 kg
Capacitor, film type (0.7 g average weight)	Capacitor, film type, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Capacitor, electrolytic type, small < 2 cm height (1.29 g average weight)	Capacitor, electrolyte type, < 2cm height {GLO}| market for | Cut-off, U	1 kg
Capacitor, electrolytic type, big > 2 cm height (50.5 g average weight)	Capacitor, electrolyte type, > 2cm height {GLO}| market for | Cut-off, U	1 kg
Capacitor, tantalum (0.254 g average weight)	Capacitor, tantalum-, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Connector, all types (9 g average weight)	Electric connector, wire clamp {GLO}| market for | Cut-off, U	1 kg
CONN FP 2X3 THT IEEE1394	Connector, CONN FP 2X3 THT IEEE1394, modelled as ADVA | U	1 unit
Connector mainly Cu and PET	Connector, mainly Cu and PET, modelled as ADVA | U	1 kg
CONN RJ45 THT	Connector, CONN RJ45 THT, modelled as ADVA | U	1 unit
Connector with fibre glass	Connector, with fibre glass, modelled as ADVA | U	1 kg
Diode, SMD glass type (32 mg average weight)	Diode, glass-, for surface-mounting {GLO}| market for | Cut-off, U	1 kg
Diode, THT glass type (0,596 g average weight)	Diode, glass-, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
Electronic component unspecified	Electronic component, passive, unspecified {GLO}| market for | Cut-off, U	1 kg
Inductor, coil miniature wound (16.8 mg average weight)	Inductor, miniature radio frequency chip {GLO}| market for | Cut-off, U	1 kg
Inductor, coil multilayer chip (2.1 mg average weight)	Inductor, low value multilayer chip {GLO}| market for | Cut-off, U	1 kg
IC Logic: rest of materials	Integrated circuit, logic type No energy No wafer	1 kg
IC Memory: rest of materials	Integrated circuit, memory type {GLO}| production | No energy No wafer	1 kg
LED (350 mg average weight)	Light emitting diode {GLO}| market for | Cut-off, U	1 kg
Modelled MLC1210 (43 mg)	MLC 1210 (gold)	1 unit
Optical receiver, photodiode	Optical receiver, photodiode, RX PIN SIX ARRAY, modelled as ADVA | U	1 kg
Optical coupler and circulator	Optical coupler and circulator, Coupler xx/yy SM C, modelled as ADVA | U	1 kg
Optical laser diode	Optical laser diode, LAS 980 360MW PUMP, modelled as ADVA | U	1 kg
Optical adapter	Optical adapter, ADPT/LC/DUP/45/M, modelled as ADVA | U	1 unit
Optical jumper	Optical jumper, modelled as ADVA | U	1 m
Optical switch module, toggle type switch (29 g average weight)	Switch, toggle type {GLO}| market for | Cut-off, U	1 kg
PCB SMD	Printed wiring board, for surface mounting, Pb containing surface {GLO}| market for | Cut-off, U (1.6 mm thick 6-layer PWB with HALS and Sn-Pb mixture with a square weight of 3.26 kg)	1 m^2
PCB THT	Printed wiring board, for through-hole mounting, Pb containing surface {GLO}| market for | Cut-off, U (1.6 mm thick 2-layer PWB with HALS and Sn-Pb mixture with a square weight of 3.08 kg)	1 m^2
Resistor, metal film type (0.48 g average weight)	Resistor, metal film type, through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Resistor, SMD type (9.8 mg average weight)	Resistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
Si	Single-Si wafer, for electronics {RoW}| production | Alloc Rec, U	1 m^2
Transistor, SMD type (0.593 g average weight)	Transistor, surface-mounted {GLO}| market for | Cut-off, U	1 kg
Transistor, small type (0.818 g average weight)	Transistor, wired, small size, through-hole mounting {GLO}| market for | Cut-off, U	1 kg
Variable optical attenuator	Variable optical attenuator, modelled as ADVA | U	1 unit

3.5.2 Use

Distribution

The ALM product is distributed mostly to three countries, namely UK (38%), Germany (28%) and USA (27%). Product distribution is done by road (36.4%), water (16.4%) and air (47.3%). The weight of one ALM product (in tonnes) was multiplied by the distance travelled through each transport mode (in km) to calculate the total amounts associated with each transport mode (in tonnes-km or tkm). These values are shown in A3-Table 6.

A3-Table 6. Estimated amounts for distribution of one ALM product by transport mode.

Transport mode	Amount (tkm)
Road	2.12
Water	1.30
Air	4.63
Total	**8.05**

The environmental impacts due to the distribution of the ALM products from the ADVA factory to customers were obtained by multiplying the amounts transported (in tkm) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in A3-Table 7.

A3-Table 7. LCI datasets of transport modes for ALM product distribution.

Input	Dataset name	FU
Road transport	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1 tkm
Water transport	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, U	1 tkm
Air transport	Transport, freight, aircraft {GLO}| market for | Cut-off, U	1 tkm

Product operation

The environmental impacts caused by the use of the ALM product are only due to electricity consumption required for its operation. Considering that this product has an average lifetime of 8 years with full operation (365 days/year and 24 h/day) and typical power consumption of 10 W, the total electricity consumed during its whole lifetime is 700.8 kWh.

The environmental impacts derived from the use of the ALM product were obtained by multiplying the amount of electricity consumed by the impacts calculated from the corresponding LCI dataset, which is shown in A3-Table 8. In addition, a factor of 0.79 was applied in this case to consider an electricity mix with higher share of renewable energies than the European average (since this is the case for the network operators being the ALM product users).

A3-Table 8. LCI datasets of electricity for ALM product operation.

Input	Dataset name	FU
Electricity	Electricity, low voltage, production EUROPE, at grid/RER U, SCENARIO 2020	1 kWh

3.5.3 End of life

Waste collection

Waste collection rate for ALM product at the end of life was assumed to be 59.2%, which is the average waste collection of IT and telecommunications equipment in Europe for the year 2017 (see Table 7 & Table 8).

Waste treatment

Material flows associated with the EoL treatment of the ALM product are classified in A3-Table 9 following the approach and data from the WEEE LCI project.[3] For each material flow, it states the mass in the product (as put on the market), the mass collected for recycling and the mass finally recycled. All the waste materials collected are treated following the take-back scheme available for small professional electric equipment (SPA), while waste not collected was assumed to be landfilled. PCB materials are classified into copper, gold, lead, silver, platinoids, other metals and support materials (such as plastics, fibres, etc.).

A3-Table 9. Waste material flows related to ALM product EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
SPA | Aluminium	0.415	0.246	0.246
SPA | Copper within PCB	1.29E-01	0.0763	0.057
SPA | Copper within Wire	2.66E-03	0.0016	0.001
SPA | Copper	0.030	0.0178	0.014
SPA | Gold within PCB	3.27E-04	1.93E-04	1.51E-04
SPA | Lead within PCB	1.45E-03	0.001	2.46E-04
SPA | PA without BFR, density < 1.3	0.020	0.012	0.000
SPA | PC without BFR, density < 1.3	0.027	0.016	0.000
SPA | PCB Other base metals	0.126	0.075	0.000
SPA | PCB Support	0.192	0.114	0.000
SPA | Platinoid within PCB	3.64E-06	2.15E-06	2.85E-07
SPA | PVC within wire	0.002	0.001	0.000
SPA | Silver within PCB	1.08E-03	6.41E-04	8.31E-05
SPA | Steel	1.464	0.867	0.720
LPA| Glass fibres-plastics composites	0.001	0.001	0.000
LPA| PET without BFR, density < 1.3	0.072	0.043	0.000
Total WEEE cut-off ALM product	**2.485**	**1.471**	**1.039**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one ALM product) is shown in A3-Table 9. The LCI datasets used for recycling of each material flow were obtained from WEEE LCI project.[3] These allow to calculate the environmental impacts of recycling according to two different accounting methods: impacts with benefits (including the impacts of recycling operations and the benefits from the substitution of primary raw materials with the recycled ones) and impacts without benefits (that only includes the impacts of recycling operations). Both accounting methods were applied herein to calculate both direct environmental impacts of recycling and environmental credits due to primary material substitution (calculated as the difference between impacts with and without benefits).

Landfill disposal

A fraction of the waste generated at the EoL of the ALM product is not recycled. It was assumed that this waste fraction is landfilled. Non-recycled waste were classified into three different waste material flows to model landfill disposal, namely aluminium, inert material and plastics. The amount of the ALM product that is finally landfilled classified by waste material flow is shown in A3-Table 10.

A3-Table 10. Waste material flows related to landfill disposal of ALM product.

Waste type	Mass landfilled (kg)
Plastics	0.129
Aluminium	0.170
Inert material	0.716
Total	**1.014**

The environmental impacts derived from landfill disposal were obtained by multiplying the amount of each waste material flow landfilled by the impacts calculated from the corresponding LCI datasets, which are shown in A3-Table 11.

A3-Table 11. LCI datasets of landfill disposal for ALM product EoL.

Input	Dataset name	FU
Landfill disposal for aluminium waste	Disposal, aluminium, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for inert waste	Disposal, inert material, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for plastic waste	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	1 kg

3.6 Life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2 of the main document). Life cycle environmental impacts of the ALM product were thus calculated for eighteen midpoint impact categories (including global warming and other) and three endpoint impact categories (damages to human health, ecosystem diversity and resource availability).

3.6.1 Manufacturing (cradle-to-gate)

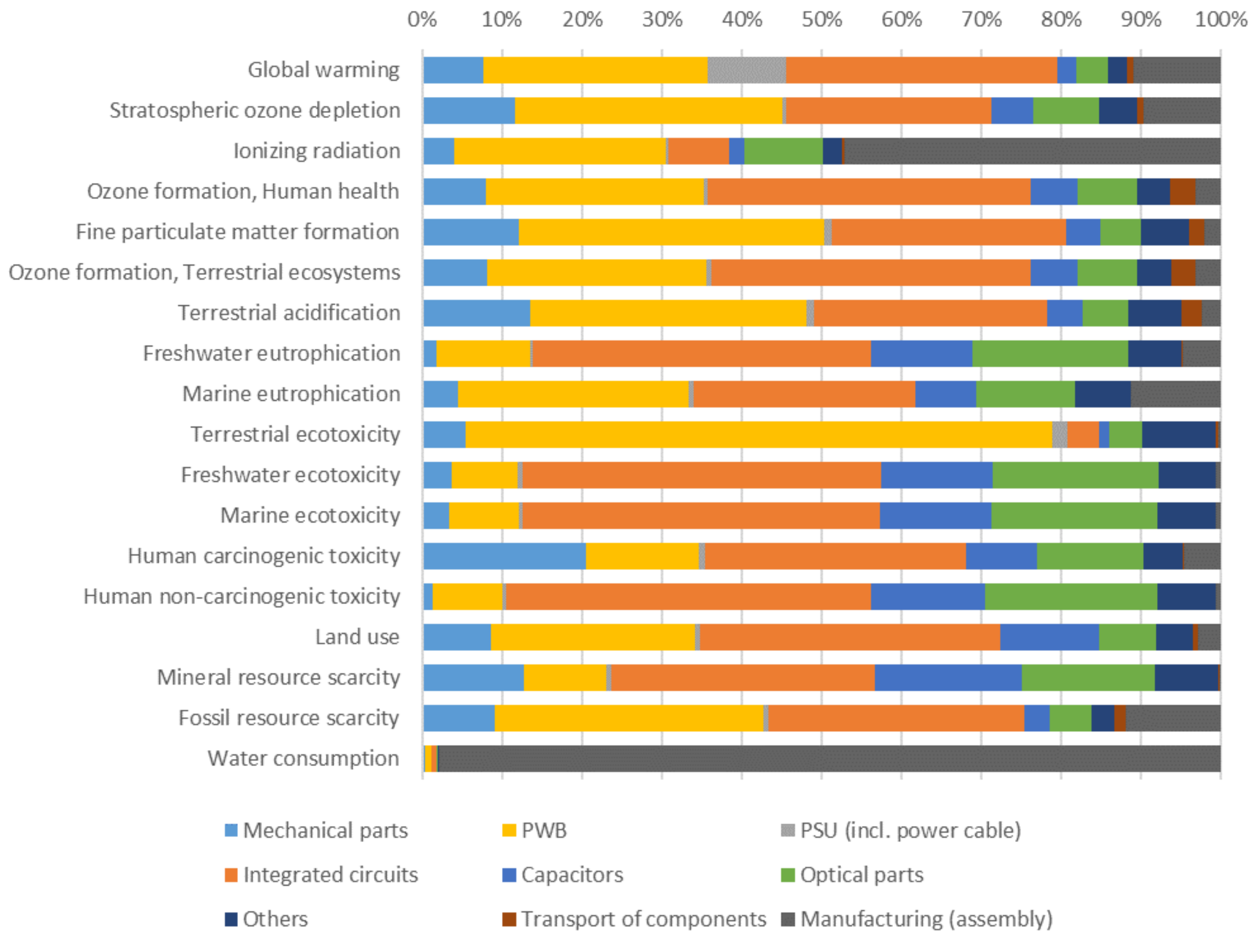
A3-Table 12 shows the environmental impacts for the manufacturing of one ALM product (i.e., the functional unit used in the study), including the global warming impact and endpoint impacts for every ALM component.

A3-Table 12. Global warming and endpoint impacts for the manufacturing of one ALM product (cradle-to-gate).

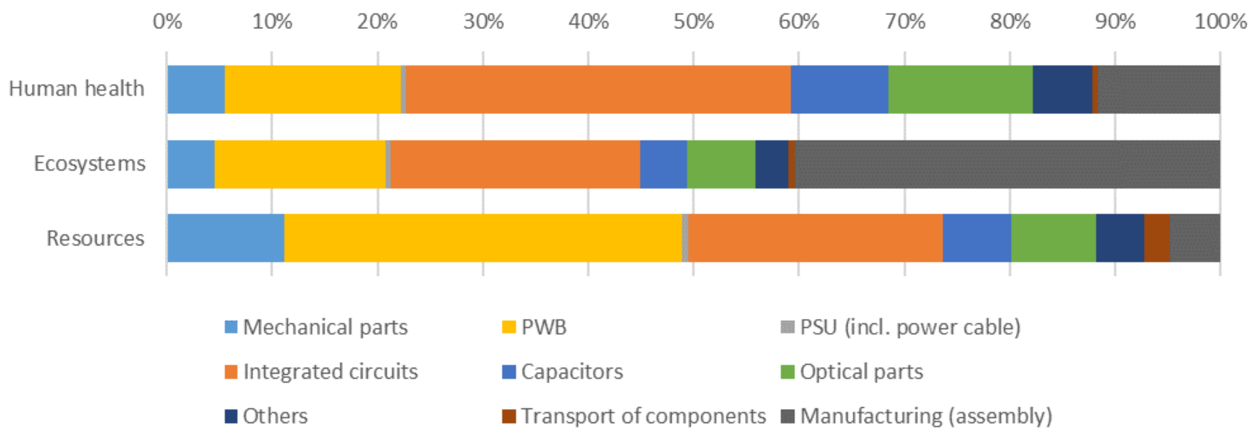
Components in ALM product	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Chassis	3.279	1.89E-05	2.03E-08	0.214
Heatsink	2.125	6.54E-06	1.03E-08	0.093
Small mechanical parts	1.095	5.52E-06	8.45E-09	0.133
Printed wiring board (PWB)	23.729	9.42E-05	1.40E-07	1.481
Power supply unit (PSU)	8.179	8.48E-07	1.36E-09	0.013
Power cable	0.159	1.96E-06	1.95E-09	0.012
Integrated circuits (IC)	28.812	2.05E-04	2.04E-07	0.946
Capacitors	2.004	5.21E-05	3.80E-08	0.255
Resistors	0.096	3.73E-06	2.63E-09	0.011
Transistors	0.198	1.03E-06	1.33E-09	0.011
Diodes	0.060	2.77E-07	3.44E-10	0.003
Inductor	0.470	5.68E-06	5.13E-09	0.043
LED	0.375	1.24E-06	1.86E-09	0.021
Lightpipe	0.269	4.63E-07	1.02E-09	0.024
Oscillator	0.012	1.24E-07	1.17E-10	0.001
Connectors	0.493	1.93E-05	1.46E-08	0.062
Coin cell battery	0.016	1.63E-07	1.72E-10	0.001
Optical fibre	1.180	2.59E-06	5.70E-09	0.066
Optical switch module	0.004	1.09E-07	8.12E-11	0.000
Optical jumper	0.004	6.94E-09	1.62E-11	0.001
Optical receiver	0.031	4.70E-07	4.16E-10	0.003
Optical coupler and circulator	0.033	7.71E-08	1.64E-10	0.003
Optical laser diode	0.721	3.78E-05	2.37E-08	0.104
Optical adapter	0.723	3.12E-06	4.54E-09	0.046
Variable optical attenuator	0.660	3.33E-05	2.09E-08	0.096
Transport of components	0.705	2.73E-06	5.21E-09	0.095
Energy for assembly	9.299	6.56E-05	3.47E-07	0.190
Passive units, configuration 1	0.207	6.45E-07	1.00E-09	0.009
Passive units, configuration 2	0.786	2.44E-06	3.82E-09	0.035
Total manufacturing, without passive units	**84.731**	**5.63E-04**	**8.59E-07**	**3.929**
Total manufacturing, with passive units	**85.724**	**5.66E-04**	**8.64E-07**	**3.972**

In addition, the contribution of each component to the total impact of ALM product manufacturing for every midpoint and endpoint category assessed is graphically showed in A3-Figure 1 and A3-Figure 2, respectively. The breakdown of the total cradle-to-gate impacts shows that PWB and IC have the highest contributions for al midpoint impacts, except for ionising radiation and water consumption that are dominated by the energy consumer for product assembly. Other components, such as mechanical and optical parts, show significant contributions as well, but these are limited compared to PWB and IC. Regarding endpoint impacts, PWB and

IC are the components with highest impacts on human health and resource availability, while energy for assembly is the main contributor to ecosystem diversity damages.



A3-Figure 1. Midpoint impacts for ALM product manufacturing (cradle-to-gate) by modules.



A3-Figure 2. Endpoint impacts for ALM product manufacturing (cradle-to-gate) by modules.

3.6.2 Use

A3-Table 13 shows the global warming impact and endpoint impacts for the use of one ALM product during its entire lifetime, as well as the breakdown of total impacts by the different causes generating them, including product distribution and electricity consumption. It includes two different scenarios for electricity consumption: one where the electricity mix is assumed to be constant over time (year 2020 used as basis for calculation) and other where the electricity mix variation with time is modelled for the period 2020-2032 (see Figure 8 & Figure 9).

It can be found that electricity consumed by the ALM product have by far the highest environmental impacts for the use phase, while the contributions of product distribution are comparatively very limited. In addition, when comparing both scenarios for electricity consumption, it is clear the important role that the increase of renewable sources in the electricity mix can play in the coming years. The scenario with variable electricity mix for the whole product lifetime means a decrease for all impact categories (compared to the constant electricity mix scenario) except for terrestrial ecotoxicity (increased by 1.44%), land use (increased by 0.66%) and mineral resource scarcity (increased by 5.08%). The impact increase for these categories is explained by the amount of land occupied by renewable energy sources and the raw materials needed. The impact category with lower reduction is water consumption (1.41%), whereas the category that reaches the highest reduction is terrestrial acidification (10.32%). Global warming is reduced by 9.52%, while endpoint impacts are reduced as follows: human health damage by 2.23%, ecosystem diversity damage by 1.69% and resource availability by 7.66%.

A3-Table 13. Global warming and endpoint impacts for the use of one ALM product.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution	5.456	8.69E-06	2.24E-08	0.811
Electricity (variable mix - 2020-2027)	307.835	8.51E-03	4.83E-05	12.812
Electricity (constant mix - 2020)	340.889	8.71E-03	4.92E-05	13.946
Total Use (variable elect. mix - 2020-2032)	**313.291**	**8.52E-03**	**4.83E-05**	**13.623**
Total Use (constant elect. mix - 2020)	**346.345**	**8.71E-03**	**4.92E-05**	**14.756**

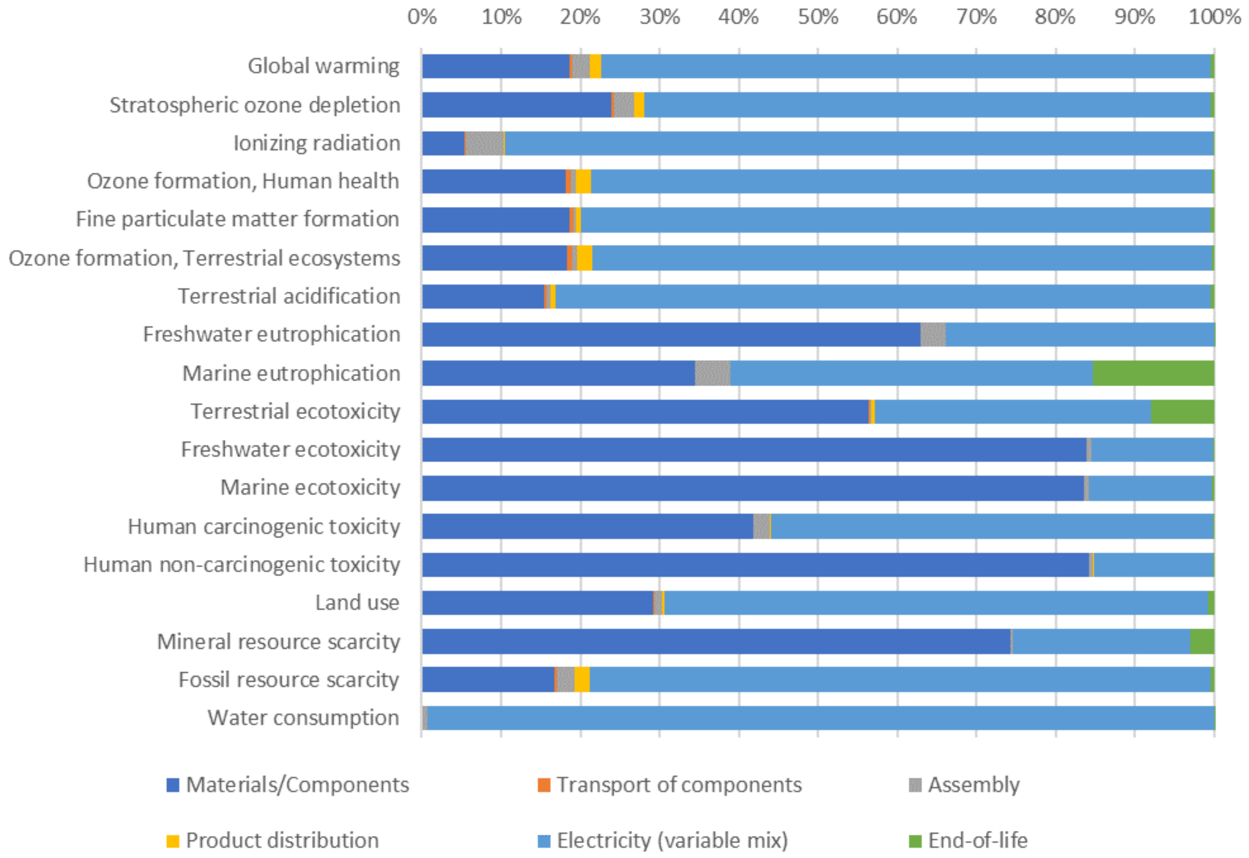
3.6.3 Total (cradle-to-grave)

A3-Table 14 collects the global warming impact and endpoint impacts for the whole life cycle of one ALM product. The total cradle-to-grave impacts for the ALM product are broken down by life cycle phases. In addition, the contribution of each life cycle phase to the total environmental impacts of ALM product for every midpoint and endpoint category assessed is shown in A3-Figure 3 and A3-Figure 4, respectively.

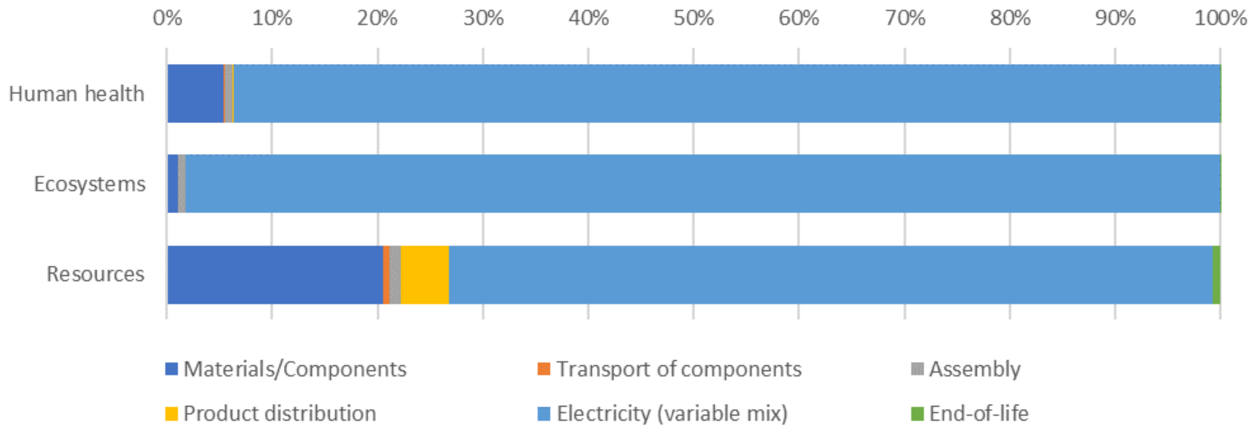
A3-Table 14. Global warming and endpoint impacts for the whole life cycle of one ALM product (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	84.73	5.63E-04	8.59E-07	3.93
Use (variable elect. mix - 2020-2032)	313.29	8.52E-03	4.83E-05	13.62
Use (constant elect. mix - 2020)	346.35	8.71E-03	4.92E-05	14.76
EoL	1.43	4.76E-06	1.02E-08	0.14
TOTAL, without passive units (variable elect. mix)	**399.45**	**9.09E-03**	**4.92E-05**	**17.70**
TOTAL, with passive (variable elect. mix)	**406.40**	**9.11E-03**	**4.92E-05**	**18.00**
Credits from recycling	-6.89	-2.94E-05	-7.41E-08	-0.66

The use stage has the highest contribution to the total impact both for global warming and for all endpoint categories, as well as for most of the midpoint categories. Specifically, the electricity consumed during the use has the most harmful impact for every endpoint category and for all midpoint impact categories, except for freshwater eutrophication; terrestrial, freshwater and marine ecotoxicities; human non-carcinogenic toxicity; and mineral resource scarcity. For these midpoint impact categories, the materials and components used for manufacturing the ALM product has the highest contribution to the total life-cycle impact. . End-of-life impacts are very low and are rewarded with the credits given by 1.04 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).



A3-Figure 3. Midpoint impacts for the ALM product (cradle-to-grave) by life cycle phases.



A3-Figure 4. Endpoint impacts for the ALM product (cradle-to-grave) by life cycle phases.

3.7 Material circularity indicator

Material flows associated with the ALM product were grouped into the following categories (see A3-Table 9): steel, aluminium, copper, gold, silver, lead, platinoid metals, other metals and plastics. The recycled feedstock (F_R) in the ALM product was estimated in order to allow for further calculation of the virgin feedstock (V). The recycled feedstock was based on average recycled content for each material category, which was determined using industry databases and literature data (Table 11). The ALM product does not contain reused feedstock (F_U = 0).

The amount of waste collected for recycling was assumed to be the same as the waste collection rate for IT and telecommunications equipment (see Table 8). It was assumed to be the same for all material categories included in the ALM product (C_R = 59.2%). It was assumed that no waste fraction is collected for reuse (C_U = 0). The amount of waste going to landfill or energy recovery (W_0) was therefore deducted directly from the waste collection rate.

The efficiency of the recycling process (E_C) for each material category was calculated as the ratio between waste collected and recycled (using values in A3-Table 9). It was then used to calculate the amount of waste generated in the recycling process (W_C). The amount of waste generated to produce the recycled content used as feedstock (W_F) was obtained from the average efficiency of the recycling process (E_F) for each material, which was assumed to be 75% for plastics and 90% for metals.

Feedstock and wastes were thus calculated taking into account all the above data and using formulae described in Section 3.3 of the main document. Results for feedstock and waste are collected in A3-Table 15.

A3-Table 15. Feedstock and waste for one ALM product used for MCI calculation.

Material	Mass M (kg)	Virgin feedstock V (kg)	Unrecoverable waste W (kg)	Unrecoverable waste to disposal W_0 (kg)	Unrecoverable waste from recycling parts W_C (kg)	Unrecoverable waste from recycled feedstock W_F (kg)
Steel	1.464	1.042	0.694	0.598	0.146	0.047
Aluminium	0.415	0.326	0.174	0.170	0.000	0.010
Copper	0.162	0.105	0.105	0.066	0.073	0.006
Gold	3.27E-04	2.45E-04	1.59E-04	1.33E-04	4.25E-05	9.07E-06
Silver	1.08E-03	9.32E-04	7.29E-04	4.42E-04	5.58E-04	1.67E-05
Lead	1.45E-03	6.65E-04	9.38E-04	5.90E-04	6.10E-04	8.67E-05
Platinoid metals	3.64E-06	2.72E-06	2.47E-06	1.48E-06	1.87E-06	1.02E-07
Other metals	0.126	0.110	0.090	0.051	0.075	0.002
Plastic	0.315	0.278	0.228	0.129	0.186	0.012
TOTAL	**2.485**	**1.863**	**1.294**	**1.014**	**0.481**	**0.077**

MCI calculation for the ALM product was then conducted (A3-Table 16). No values were found in literature for the lifetime and intensity of use of industry-average ALM products. The lifetime and intensity of use for industry-average ALM products were thus assumed to be the same as for the target ALM product investigated herein (L/Lav = U/Uav = 1). Therefore, the value of the utility function for the ALM product was 0.9. The linear flow index, considering feedstock and waste results (A3-Table 15), was 0.66. The MCI for the ALM product was finally calculated as 0.40.

A3-Table 16. MCI calculation for the ALM product.

Parameter	Value
Actual average lifetime of product L (years)	8
Actual average lifetime of industry-average product L_{av} (years)	8
Average number of functional units (FUs) during the use phase of product U (h/year)	8,760
Average number of FUs during the use phase of industry-average product U_{av} (h/year)	8,760
Utility of the product X	1.00
Utility factor F(X)	0.90
Linear Flow Index LFI	0.66
Material Circularity Indicator of the product MCI_P	**0.40**

4 Life cycle costing

4.1 Internal costs

The internal costs assessed for the ALM product includes the costs for:

(i) Acquisition of raw materials and components, including related transport operations.

(ii) Manufacturing of the product.

(iii) Distribution of the product to retailers or final customers.

(iv) Use, including product operation.

(v) End of life, including WEEE management.

A3-Table 17 shows the breakdown of the internal costs of the ALM product by life cycle phase, namely manufacturing (including i, ii and iii), use (iv) and end of life (v).

Retail price provided by ADVA was assumed herein to consider manufacturing costs. The retail price covers all the costs related to raw materials and components, product manufacturing and distribution, as well as other any other costs for product development (like R&D costs) and net revenues from sales.

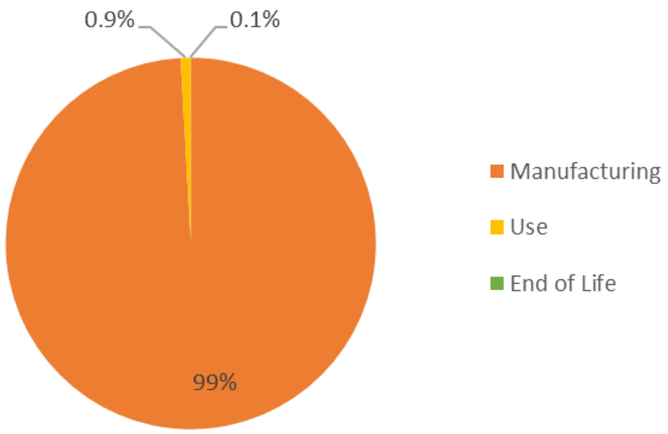
The use phase includes the costs for the electricity consumed by the ALM product for operation during its whole lifetime (as detailed in Section 3.5.2 of this Annex). Total electricity consumption was estimated at 700.8 kWh. The average market price of electricity for non-household customers was assumed as 0.117 €/kWh for the year 2019, while a sustained annual growth factor of 1.022 was applied for the following years (see Section 4.1.2 of the main document). No maintenance operations were considered for the ALM product.

The costs for WEEE management was estimated at 0.19 € (for one ALM product), which corresponds to the fee paid by producers for the EoL management of each ALM product they put on the market.

A3-Table 17. Internal costs for the whole life cycle of one ALM product (cradle-to-grave).

Life cycle phase	Concept	Total cost (€)
Manufacturing	Retail price (incl. costs for materials/components, manufacturing, distribution, other product development costs and net revenues)	16,368.00
Use	Electricity consumption	88.85
End of life	WEEE management fee	0.19
TOTAL	**Manufacturing + Use + EoL**	**16,457.04**

A3-Figure 5 graphically shows the contribution of each life cycle phase to the total internal cost of the ALM product. It can be found that the manufacturing phase is the most expensive by far, comprising 99% of the total internal cost.



A3-Figure 5. Contribution of each life cycle phase to the total internal costs for the ALM product.

4.2 External costs

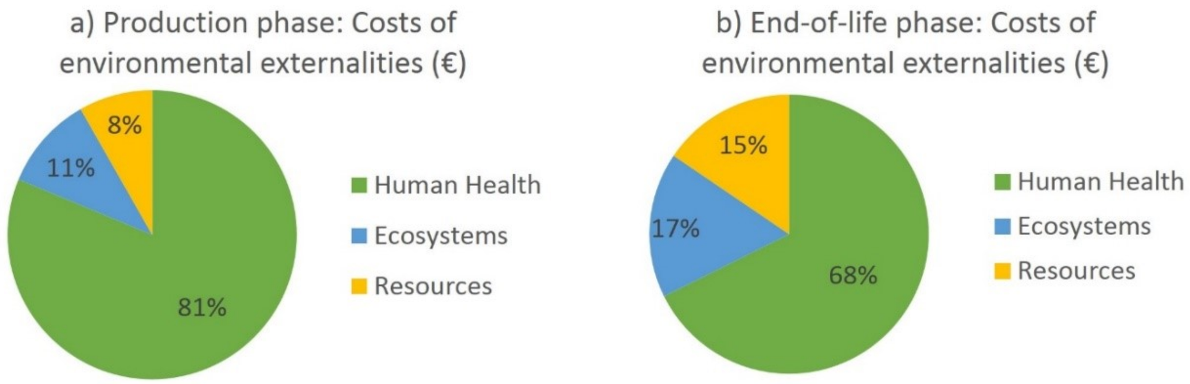
Monetary valuation of environmental impacts was applied to assess the costs of environmental externalities. To this end, LCA results obtained for the ALM product (see Section 3.6 of this Annex) were combined with monetisation factors given for different environmental impact categories (see Section 4.2 of the main document). External costs were estimated using two different approaches for monetary valuation: (1) monetisation of global warming impact and (2) monetisation of endpoint impacts. It should be noted that the economic costs obtained in each case cannot be added together since the global warming impact (as well as the other midpoint impacts) is included in the endpoint impacts.

The results from the monetary valuation of environmental impacts are collected in A3-Table 18. These are broken down by life cycle phases and impact categories monetized.

A3-Table 18. External costs for the whole life cycle of one ALM product (cradle-to-grave).

Life cycle phase	Impact category	Total amount	Monetisation factor	Economic cost (€)
Manufacturing	Human health	5.63E-04 DALY	101,311 €/DALY	57.07
	Ecosystems	8.59E-07 species.yr	1.23E+07 €/species.yr	10.59
	Resources	3.93 USD	0.929 €/USD2013	3.65
	Sub-total endpoint impacts	-	-	**71.31**
	Global warming	85 kg CO_2 eq	130 €/tonne CO_2 eq	11.03
Use	Human health	7.40E-08 DALY	101,311 €/DALY	0.01
	Ecosystems	4.83E-05 species.yr	1.23E+07 €/species.yr	595.65
	Resources	13.62 USD	0.929 €/ USD2013	12.66
	Sub-total endpoint impacts	-	-	**608.32**
	Global warming	313 kg CO_2 eq	130 €/tonne CO_2 eq	40.77
End of life	Human health	4.76E-06 DALY	101,311 €/DALY	0.48
	Ecosystems	1.02E-08 species.yr	1.23E+07 €/species.yr	0.13
	Resources	0.14 USD	0.929 €/USD2013	0.13
	Sub-total endpoint impacts	-	-	**0.74**
	Global warming	1.43 kg CO_2 eq	130 €/tonne CO_2 eq	0.19
TOTAL	Human health	5.68E-04 DALY	101,311 €/DALY	57.56
	Ecosystems	4.92E-05 species.yr	1.23E+07 €/species.yr	606.37
	Resources	17.70 USD	0.929 €/USD2013	16.45
	Total endpoint impacts	-	-	**680.38**
	Total global warming	399.45 kg CO_2 eq	130 €/tonne CO_2 eq	51.98

A3-Figure 6 graphically shows the contribution of each endpoint impact to the total external costs for the manufacturing and end of life, since these are the life cycle phases in which the project is expected to achieve higher improvements. Most of the external costs are due to human health damages, while the costs of damages to ecosystem diversity and resource availability are lower and comparable with each other.



A3-Figure 6. Contribution of each endpoint impact to total external costs of manufacturing and end-of-life phases for the ALM product.

4.3 Total life cycle costs

Concluding, A3-Table 19 shows the total life cycle cost including internal and external costs. The internal cost is in this case much higher than the cost of environmental externalities. The internal cost is clearly dominated by the product manufacturing cost, while the use phase shows the highest contribution to external cost. The product waste management in the end-of-life phase is the one with the lowest cost, which is negligible both for internal and external costs.

A3-Table 19. Total costs for the whole life cycle of one ALM product (cradle-to-grave).

Life cycle phase	Internal cost (€)	External cost (€)	Total cost (€)
Manufacturing	16,368.00	71.31	16,439.31
Use	88.85	608.32	697.17
End of life	0.19	0.74	0.93
TOTAL	**16,457.04**	**680.38**	**17,137.42**

5 Social life cycle assessment

5.1 Social life cycle inventory

Primary data provided by ADVA was used as the starting point to carry out the S-LCA. Specifically, it provided economic data describing the supply chain composition and location, identifying all the economic costs required to produce the ALM product and the cost breakdown by countries and economic sectors. A3-Table 20 shows the percentage breakdown of total production costs by countries and sectors.

A3-Table 20. Production cost breakdown for the ALM product by countries and economic sectors.

Country/Sector	Plastic products	Ferrous metals	Non-ferrous metals	Paper products	Mineral products	Electronic equipment	Manufacturing process
TOTAL	0.264%	1.531%	0.461%	0.037%	56.702%	12.106%	28.899%
Germany	0.054%	0.280%		0.034%	2.635%	4.249%	28.899%
Japan		0.038%	0.117%		20.265%	0.0002%	
China		0.974%	0.343%	0.004%	20.875%	1.309%	
Hong Kong		0.181%					
USA	0.0001%			0.002%	12.928%	5.502%	
UK	0.196%					0.098%	
Taiwan	0.014%					0.381%	
Switzerland		0.013%				0.029%	
South Korea						0.006%	
Singapore						0.001%	
Thailand						0.002%	
The Netherlands						0.053%	

The sectors included in the assessment comprise those related to every material and/or component required to produce the ALM product, as well as the sector linked to the manufacturing process at ADVA facilities (i.e., electronic equipment sector in Germany). Electronic equipment is the most complex sector in the supply chain since the related components come from 11 different countries, being USA and Germany those where more money is spent in electronic components. By countries, Germany, Japan, China and USA are the most important in the acquisition of materials and components. It would be advisable to check the actual origin of some minerals, which may be different from the countries where mineral products are purchased.

The SHDB method and datasets were then used to calculate the social impacts for each sector in each country (as explained in Section 5 of the main document). The Social Hotspot 2019 Category Method with Weights (which is available for SimaPro software) was used. The social impacts derived from the ALM product were obtained by allocating the production costs (in USD) to the corresponding social LCI datasets for every country-specific sector involved in the ALM product supply chain. The social LCI datasets used are listed in A3-Table 21.

A3-Table 21. Social LCI datasets for the country-specific sectors linked to the ALM product.

Social Hotspot Database (SHDB)	Reference Unit
Chemical, rubber, plastic products/DEU S_Germany	USD
Chemical, rubber, plastic products/GBR S_UK	USD
Chemical, rubber, plastic products/TWN S	USD
Chemical, rubber, plastic products/USA S	USD
Electronic equipment/CHE S_Switzerland	USD
Electronic equipment/CHN S_China	USD
Electronic equipment/DEU S_Germany	USD
Electronic equipment/GBR S_UK	USD
Electronic equipment/JPN S_Japan	USD
Electronic equipment/KOR S_SouthKorea	USD

Social Hotspot Database (SHDB)	Reference Unit
Electronic equipment/NLD S_Netherlands	USD
Electronic equipment/SGP S_Singapore	USD
Electronic equipment/THA S_Thailand	USD
Electronic equipment/TWN S	USD
Electronic equipment/USA S	USD
Ferrous metals/CHE S_Switzerland	USD
Ferrous metals/CHN S_China	USD
Ferrous metals/DEU S_Germany	USD
Ferrous metals/GBR S_UK	USD
Ferrous metals/HKG S_HongKong	USD
Ferrous metals/JPN S_Japan	USD
Metals nec/CHN S_China	USD
Metals nec/JPN S_Japan	USD
Mineral products nec/CHN S	USD
Mineral products nec/DEU S	USD
Mineral products nec/JPN S	USD
Mineral products nec/USA S	USD
Paper products, publishing/CHN S	USD
Paper products, publishing/DEU S	USD
Paper products, publishing/USA S	USD

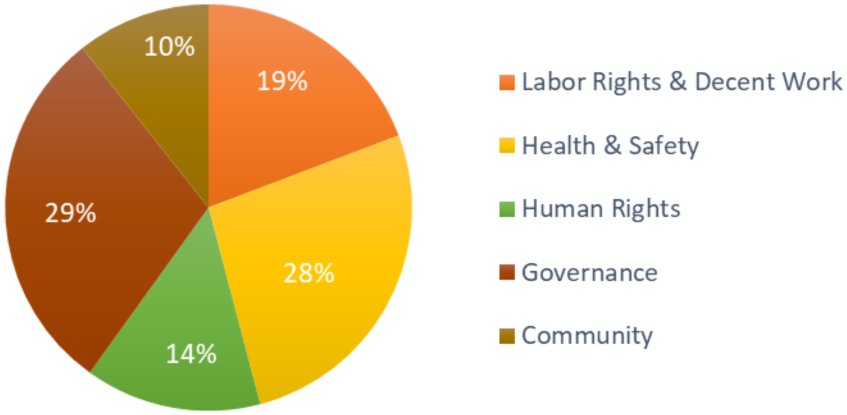
5.2 Social life cycle impact assessment

The social footprint of the ALM product was calculated by aggregating the social impacts associated with each country-specific sector listed in A3-Table 21 into a single social impacts indicator, namely the so-called Social Hotspot Index (SHI). A3-Table 22 shows the SHI obtained for the ALM product, as well as its breakdown into the different social impact categories that contribute to the total social footprint.

A3-Table 22. Social impacts of the ALM product by impact category.

Social category	Total impact (Pt)
Labour Rights & Decent Work	5,369.25
Health & Safety	7,802.17
Human Rights	3,981.75
Governance	8,027.94
Community	2,959.06
TOTAL: SHI	**28,140.17**

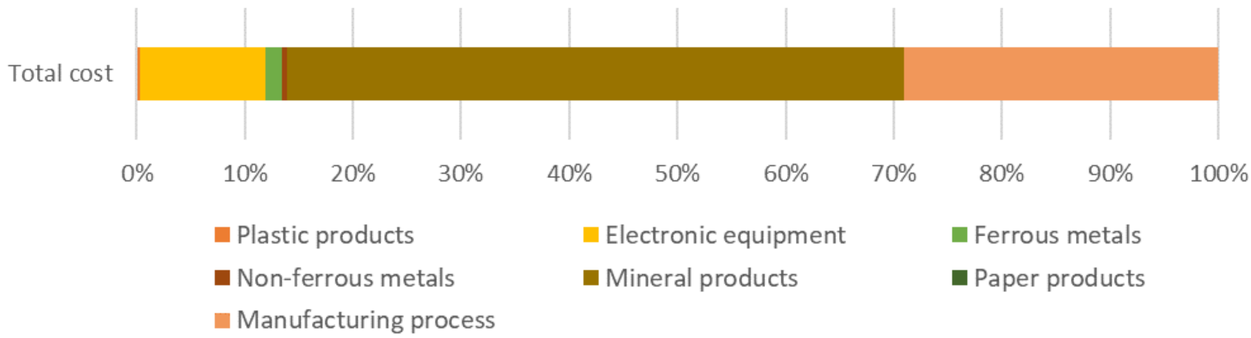
A3-Figure 7 shows graphically the contribution of each social impact category to the total social footprint of the ALM product. It can be found that the greatest social impacts are due to Governance and Health & Safety issues, while social impacts affecting Community have the lowest contribution.



A3-Figure 7. Percentage of impact categories in the social life cycle assessment for the ALM product.

5.2.1 Social impacts by economic sectors

A3-Figure 8 shows the economic share of each productive sector in the ALM product supply chain. The economic sector with the highest contribution (i.e., that in which the company spent more money to produce the ALM product) is the mineral products sector, followed by the EEE manufacturing process (performed in ADVA facilities) and the electronic equipment sector. In contrast, paper and plastic products and non-ferrous metals are the economic sectors where expenditures are the lowest.

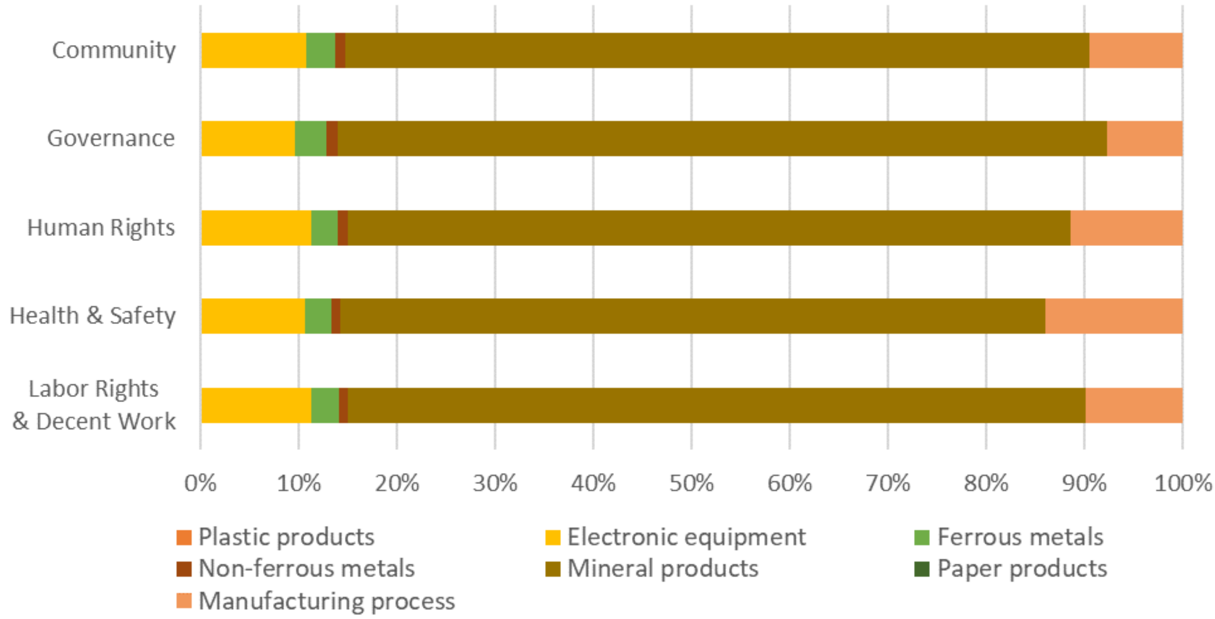


A3-Figure 8. Production cost breakdown for the ALM product by economic sectors.

The social impacts were assessed for every economic sector. A3-Table 23 shows the impacts for each social category obtained for each sector involved in the ALM product supply chain, while A3-Figure 9 shows graphically the contribution by each sector to the total impact in each social category. The results show that the mineral products used in the ALM product comprises most of the impact for every social category (with over 70% of total impacts). It is followed by electronic equipment sector related to the electronic components acquired by the company to produce the ALM product. The social impacts of the manufacturing process conducted in ADVA facilities (Germany) also have a relevant contribution, which ranges between 8% and 14% depending on the social category. However, it should be noted that the impact contribution of the manufacturing process is low compared to the economic share that it has in total production costs, which is around 29%. The reason is that social risk levels in the electronic equipment sector in Germany are lower than those in many other sectors and countries where ADVA is purchasing the materials and components. Plastic and paper products have negligible social impacts when compared to the other economic sectors composing the ALM product supply chain.

A3-Table 23. Social impacts of the ALM product by economic sectors.

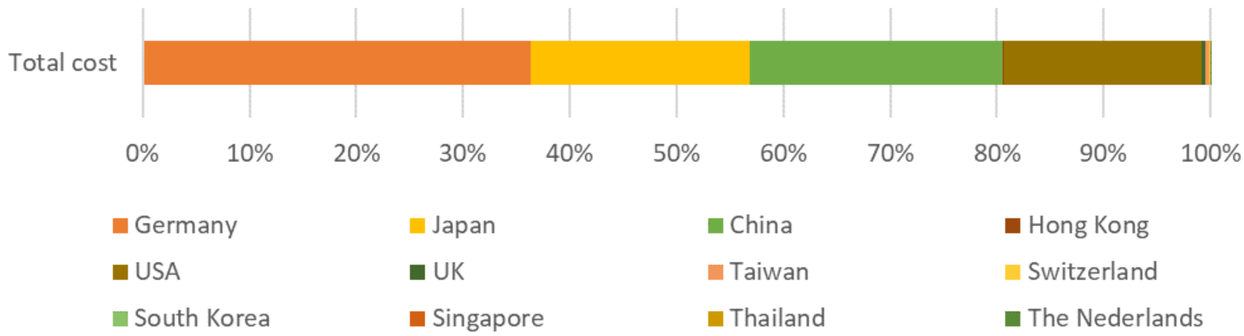
Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Plastic products	5.21	6.92	3.92	6,57	3.90
Electronic equipment	603.10	819.40	445.83	765.95	315.00
Ferrous metals	147.07	218.39	109.37	260.96	87.66
Non-ferrous metals	49.25	68.78	38.39	89.53	31.32
Mineral products	4,031.16	5,596.19	2,926.81	6,280.98	2,239.00
Paper products	1.19	2.08	0.93	1.73	0.65
Manufacturing	532.28	1,090.43	456.50	622.22	281.54
TOTAL	**5,369.25**	**7,802.17**	**3,981.75**	**8,027.94**	**2,959.06**



A3-Figure 9. Contribution of each economic sector to the total social impacts of the ALM product by social category.

5.2.2 Social impacts by countries

A3-Figure 10 shows the economic share of each country in the ALM product supply chain. The country with the highest contribution is Germany, comprising about 36% of the total ALM production costs. It includes both the manufacturing costs at ADVA facilities and also the purchasing costs of various materials and components (plastic and paper products, ferrous metals, mineral products and electronic components) from other companies located in Germany as well. Other countries with relevant contributions are China (24%), Japan (20%) and USA (18%), whereas the expenditure in the rest of countries is very low in comparison.



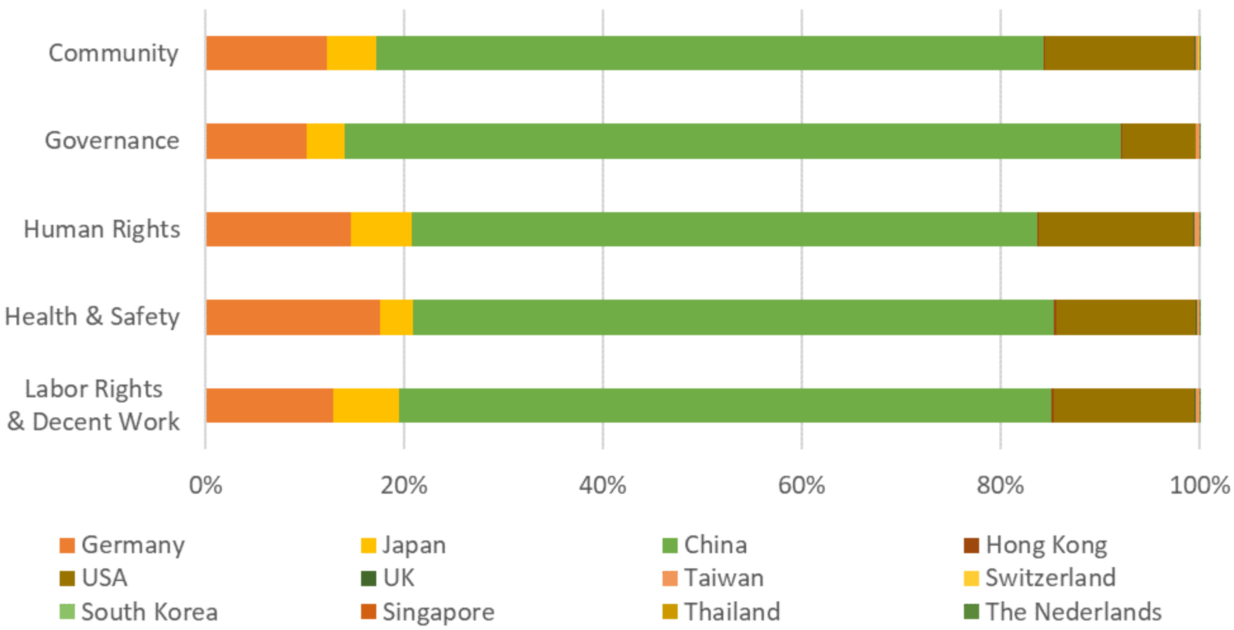
A3-Figure 10. Production cost breakdown for the ALM product by country.

The social impacts were also assessed for every country in the ALM product supply chain. A3-Table 24 shows the impacts for each social category obtained for each country, while A3-Figure 11 shows graphically the contribution by each country to the total impact in each social category. The results show that China is the country with the highest social impacts for all social categories. Despite China represents only 24% of total production costs associated with the ALM product, the social impacts there encompass between 63% and 70% of the total ALM product impacts depending on the social category assessed. This reveals that social risk levels in the Chinese productive sectors supplying ADVA are high, so they can be identified as social hotspots of the ALM product. ADVA could therefore investigate opportunities and measures together its Chinese suppliers to apply social improvements there, which could in turn derive in a decrease of the social footprint of the ALM product.

Germany, USA and Japan also shows relevant contributions to total social impacts, although these are much lower than those from China. As already anticipated previously, the case of Germany is positively remarkable since it covers 36% of total ALM production costs, including both product manufacturing and supplies purchased there, but it only causes between 10% and 18% of total social impacts.

A3-Table 24. Social impacts of the ALM product by country.

Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Germany	689.16	1,370.08	581.14	821.08	361.23
Japan	358.88	254.85	244.73	306.04	148.64
China	3,521.51	5,031.49	2,505.53	6,264.24	1,986.80
Hong Kong	13.85	20.40	4.67	10.62	3.80
USA	758.36	1,095.11	621.45	590.29	443.40
UK	6.37	9.41	4.22	7.93	4.74
Taiwan	18.00	16.40	17.42	23.40	8.27
Switzerland	1.23	1.50	1.08	1.84	1.07
South Korea	0.28	0.48	0.17	0.35	0.12
Singapore	0.05	0.05	0.03	0.07	0.03
Thailand	0.17	0.18	0.17	0.29	0.11
The Netherlands	1.39	2.21	1.12	1.80	0.83
TOTAL	**5,369.25**	**7,802.17**	**3,981.75**	**8,027.94**	**2,959.06**



A3-Figure 11. Contribution of each country to the total social impacts of the ALM product by social category.

Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.1. Results of environmental, economic and social preliminary analyses. Annex 4 – TV set

Acronym:	**C-SERVEES**
Project title:	**Activating Circular Services in the Electric and Electronic Sector**
Contract Nº:	**776714**
Start date:	**1st May 2018**
Duration:	**48 months**

Deliverable number	D5.1 – Annex 4
Deliverable title	Results of environmental, economic and social preliminary analyses. Annex 4 – TV set
Submission due date	31/10/2020 (M30)
Actual submission date	30/11/2020 (M31)
Work Package	WP5
WP Leader	AIMPLAS
Dissemination Level	Public
Version	04
Deliverable Lead Beneficiary	AIMPLAS

1 Introduction

This Annex includes the comprehensive documentation related to the life cycle sustainability assessment of the current TV set used for demonstration in the C-SERVEES project. It includes more details on the methodological aspects and assumptions done, life cycle inventory developed and detailed results for the following studies:

- Life cycle assessment, including midpoint and endpoint environmental impact categories and material circularity indicator.
- Life cycle costing, including internal and external costs (related to environmental externalities).
- Social life cycle assessment, including 5 social impact categories.

All these studies and results constitute the sustainability baseline against which to compare the improvements implemented and tested in the C-SERVEES project to increase the circularity of the TV set.

2 Goal and scope

The present study aimed to calculate the environmental, economic and social impacts of the TV GRUNDIG G43C 891 5A. It is a 43” smart-TV model with energy efficiency class A$^+$ and connectivity features. It is manufactured in Tekirdağ (Turkey) and currently on sale in Turkey and the EU. More details on the TV set investigated are shown in A4-Table 1.

A4-Table 1. Technical specifications of the demo TV set.

MODEL	GRUNDIG G43C 891 5A
Image	
Product (EAN) number	8690842398605
Description	43" / 108 cm, UHD (3.840 x 2.160), 50 Hz, HEVC/H.265, Smart
Colour	Black
Size	625 × 231 × 976 mm
Weight / Packaged weight	9.2 kg / 12.0 kg
Features	Picture features: Picture Noise Reduction, DLTI , DCTI, DNR, Digital Comb Filter (3D) Colour system: Multisystem USB supported files: .mp3, .m4a, .aac, .jpg, .jpe, .bmp, .png, .mov, .mpg, .mpe, .vob, .dat, .trp, .ts, .avi, .mp4, .mkv, .div
Energy class	A$^+$
Electricity consumption per year	53.3 kWh
Average power	0.15 W (Stand-by), 38.8 W (Nominal)
Country of origin	Turkey

3 Life cycle assessment

3.1 Functional unit and system boundaries

The product function for the TV set is to play multimedia content with image and sound. The functional unit considered in the study is one 43” TV set (GRUNDIG G43C 891 5A) with 10,784 hours of viewing during its 8-year lifetime (assuming an average use of 337 days/year and 4 h/day).[13]

A4-Table 2 shows the system boundaries considered for the TV, identifying the life cycle phases, processes and other elementary flows included and excluded in the study.

A4-Table 2. System boundaries considered for the TV set.

Life cycle phase	Included	Excluded
Raw material extraction and processing	Extraction of natural resources Refining and raw material production Intermediate product manufacturing Waste treatment and transport	Infrastructure
Product manufacturing	Energy for product manufacturing/assembly Transport	Infrastructure Production losses
Product distribution	Transport	
Product use	Electricity consumption Batteries for remote control	Maintenance
End of life	Transport EoL treatments Landfilling of waste fraction not recycled	
Benefits and burdens beyond system boundaries	Recycling benefits (included as credits)	

3.2 Allocation and cut-off criteria

No multi-output foreground processes were identified during data collection. Inventories taken from Ecoinvent database were allocated according to the cut-off system model.[18]

The system boundary in the EoL phase was drawn just behind product waste collection and transportation to the recycling sites. WEEE from the TV set was classified as waste by-product and environmental burdens associated with waste treatment were thus allocated completely to the waste-producing activity (as indicated in Section 3.1.3 of the main document). The environmental impacts of the EoL phase and the credits generated by recycling are both interesting for the comparative assessment between the baseline product system and the redesigned product system proposed in the C-SERVEES project. Product packaging was also included in the assessment (from cradle to packaging waste collection), but packaging waste treatment was excluded.

No available primary data were knowingly omitted or excluded.

3.3 Data quality

The data used to create the inventory model is as precise, complete, consistent and representative as possible with regard to the goal and scope of the study.

- Primary data was provided by ARÇELIK from the most recent BoM of the product. The data used for the study is considered to be of the highest precision. Ecoinvent database was the main secondary data source used to model the product system.

- Completeness was judged based on the completeness of both the inputs/outputs per unit process and the unit processes themselves.
- Consistency refers to modelling choices and data sources. The goal was to ensure that differences in results occur due to actual differences between product systems investigated and compared, and not due to inconsistencies in modelling choices, data sources, characterisation factors, etc.
- Representativeness expresses the degree to which the data matches the geographical, temporal and technological requirements:
  - The average electricity mix for Europe was considered for the use phase (as explained in Section 3.1.2 of the main document) using the most recent data published (year 2019).[16]
  - Ecoinvent database version used was updated in 2018.
  - Distances for distribution of TV sets from ARÇELIK factory to retailers were obtained from Google Maps[60] and sea-distances.org[61] for road and water transport, respectively.

3.4 Assumptions and limitations

Other assumptions and limitations for the LCA study of the TV set are listed below:

- No production losses were considered.
- Recycled content was assumed to be the worldwide average (Table 11).
- The road distance from ARÇELIK factory in Tekirdağ (Turkey) to the port of Istanbul was assumed to be 70 km.
- Railway distances were assumed to be similar to those by road transport.
- Distances for product distribution within each country were assumed as 300 km, except for countries where the port is not within their territory.
- Retailers were assumed to be located in the centre of each country.
- The average lifetime and intensity of use of the target TV set were assumed to be similar to industry-average values taken from literature (to determine the MCI).
- No maintenance was assumed during the lifetime of the product.
- Waste collection rate was assumed to be the European average for consumer equipment (Table 8).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[20]

3.5 Life cycle inventory

This section describes the LCI developed for the target TV set, including inputs/outputs inventoried for each life-cycle phase and the data sources used for their inventory modelling.

3.5.1 Manufacturing

The LCI of the TV manufacturing was obtained from the BoM provided by ARÇELIK. The TV consists of several modules, which in turn contain different components and materials. The packaging used for the TV was also included in product manufacturing. The different modules inventoried and their total amounts are listed in A4-Table 3.

A4-Table 3. Modules of the target TV set.

Modules in TV set	Total amount (kg)
Packaging	1.98
Cabinet	3.01
Display Assembly	5.53
Remote Control	0.10
Stand	0.38
Total	**10.99**

Each module is made of different components and/or materials that are processed with certain manufacturing processes to attain the final shape and properties required for the product. The inventories for the components, materials and manufacturing processes required to produce the TV were mainly taken from the Ecoinvent database. These inventories are linked to their own functional unit (FU), so they show energy consumption, resource consumption, emissions, etc. for different basic activities, expressed per amount of materials extracted and/or processed (kg), for example. The environmental impacts of the materials and components composing the TV modules were thus obtained by multiplying their amounts by the impacts calculated from the corresponding LCI datasets (for the defined FU). A list of the LCI datasets used for the manufacturing phase is given in A4-Table 4.

A4-Table 4. LCI datasets of material, components and processes for TV set manufacturing.

Input	Dataset name	FU
	RAW MATERIALS	
ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, U	1 kg
Acrylate, polyacrylamide	Polyacrylamide {GLO}| market for | Cut-off, U	1 kg
Cardboard	Corrugated board box {RER}| market for corrugated board box | Cut-off, U	1 kg
Copper	Copper {GLO}| market for | Cut-off, U	1 kg
Expanded polystyrene (EPS)	Polystyrene, expandable + Polymer foaming {RER}	1 kg
Galvanized steel	Steel, low-alloyed, hot rolled + Zinc coat (64 m2/t)	1 kg
Glass fibre	Glass fibre {GLO}| market for | Cut-off, U	1 kg
PA 6.6	Nylon 6-6 {GLO}| market for | Cut-off, U	1 kg
Paper	Paper, newsprint {RER}| market for | Cut-off, U	1 kg
PC	Polycarbonate {GLO}| market for | Cut-off, U	1 kg
PC+%10GF	PC+%10GF	1 kg
PC+ABS	60% PC + 40% ABS	1 kg
PC+ABS+%10GF	PC+ABS+%10GF	1 kg
PC+ABS+%15GF	PC+ABS+%15GF	1 kg
PE, LDPE	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U	1 kg
PET/PBT	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	1 kg
PMMA	Polymethyl methacrylate, beads {GLO}| market for | Cut-off, U	1 kg
Polyester film (PET)	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	1 kg
PP	Polypropylene, granulate {GLO}| market for | Cut-off, U	1 kg
PS	Polystyrene, general purpose {GLO}| market for | Cut-off, U	1 kg
PVC	Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	1 kg
Stainless steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U	1 kg
Steel/Steel sheet	Steel, unalloyed {GLO}| market for | Cut-off, U	1 kg
Thermoplastic polyurethane elastomer	Synthetic rubber {GLO}| market for | Cut-off, U	1 kg
	PROCESSING	
Metal processing	Sheet rolling, steel {GLO}| market for | Cut-off, U	1 kg
	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
	Metal working, average for copper product manufacturing {GLO}| market for | Cut-off, U	1 kg
	Metal working, average for metal product manufacturing {RER}| processing | Cut-off, U)	1 kg
Metal stamping and bending	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	1 kg
Plastic injection moulding	Injection moulding {GLO}| market for | Cut-off, U	1 kg
Plastic pipes extrusion	Extrusion, plastic pipes {GLO}| market for | Cut-off, U	1 kg
Plastic processing	Injection moulding {GLO}| market for | Cut-off, U	1 kg
Stainless steel sheet average metal working	Metal working, average for chromium steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Steel sheet average metal working	Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1 kg
Steel turning	Section bar rolling, steel {GLO}| market for | Cut-off, U	1 kg
	COMPONENTS	
PCBA	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Cut-off, U	1 kg
Electronic component, active	Electronic component, active, unspecified {GLO}| market for | Cut-off, U	1 kg
Electronic component, passive	Electronic component, passive, unspecified {GLO}| market for | Cut-off, U	1 kg
Label	Printed paper {GLO}| market for | Cut-off, U	1 kg
LCD	Liquid crystal display, unmounted {GLO}| production | Cut-off, U	1 kg
LED SMD	Light emitting diode {GLO}| market for | Cut-off, U	1 kg
Cable	Cable, connector for computer, without plugs {GLO}| market for | Cut-off, U	1 kg

ARCÇELIK also provided information on the location of its main suppliers of materials/components and transport modes used to deliver them from the suppliers to the ARÇELIK factory in Tekirdağ (Turkey). The weight of materials and components (in tonnes) were multiplied by the distances travelled through each transport mode (in km) to calculate the total amounts associated with each transport mode (in tonnes-km or tkm). These values are shown in A4-Table 5.

A4-Table 5. Estimated amounts for transport of materials/components for one TV set.

Transport mode	Amount (tkm)
Road	1.63
Water	22.51
Railway	0.28
Total	**24.42**

The environmental impacts caused by transportation of materials and components were obtained by multiplying the amounts transported (in tkm) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in A4-Table 6.

A4-Table 6. LCI datasets of transport modes for TV set (both for transport of materials/components and for product distribution).

Input	Dataset name	FU
Road transport	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	1 tkm
Water transport	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, U	1 tkm
Railway transport	Transport, freight train {RER}| market group for transport, freight train | Cut-off, U	1 tkm

3.5.2 Use

Distribution

The TV set is distributed to a wide list of countries as shown in A4-Table 7.

A4-Table 7. TV set distribution by countries.

Country	Market share
Turkey	66.21%
Germany	15.82%
United Arab Emirates	9.85%
Serbia	3.50%
Spain	1.64%
France	1.17%
Portugal	0.42%
Rest of countries	1.37%

Product distribution is done by road (58.2%), water (25.8%), and railway (16.0%). The weight of one TV was multiplied by the distance travelled through each transport mode to calculate the total amounts associated with each transport mode as shown in A4-Table 8. The environmental impacts due to the distribution of the TV sets from the ARÇELIK factory to retailers were obtained by multiplying the amounts transported by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in A4-Table 6.

A4-Table 8. Estimated amounts for distribution of one TV set by transport mode.

Transport mode	Amount (tkm)
Road	11.0
Water	4.9
Railway	3.0
Total	**18.9**

Product operation

The environmental impacts caused by the use of the TV are due to electricity consumed for its operation and batteries required for the remote control. The TV was assumed to have an average lifetime of 8 years with an average use of 337 days/year and 4 h/day. Under these assumptions, the average consumption of electricity was estimated at 426 kWh, including 418 kWh for power-on mode and 8 kWh for stand-by mode. Power data taken from the TV technical datasheet were used to calculate the electricity consumption. In addition, the total number of batteries consumed by the remote control during the 8-year lifetime was estimated at 6, considering the battery drain when the remote control is clicked 32 times a day (On, Off, 10 times for changing channels and 20 times for volume up/down).

The environmental impacts associated with the TV use were obtained by multiplying the amounts of electricity and batteries consumed by the impacts calculated from the corresponding LCI datasets, which are shown in A4-Table 9.

A4-Table 9. LCI datasets of electricity and batteries for TV set operation.

Input	Dataset name	FU
Electricity	Electricity, low voltage, production EUROPE, at grid/RER U, SCENARIO 2020	1 kWh
AA cell battery (Alkaline)	AA cell battery (Alkaline) - IDEMAT	1p

3.5.3 End of life

Waste collection

Waste collection rate for TV set at the end of life was assumed to be 84.2%, which is the average waste collection of consumer equipment in Europe for the year 2017 (see Table 7 & Table 8).

Waste treatment

Material flows associated with the EoL treatment of the TV are classified in A4-Table 10 following the approach and data from the WEEE LCI project.[3] For each material flow, it states the mass in the product (as put on the market), the mass collected for recycling and the mass finally recycled. All the waste materials collected are treated following the take-back scheme available for flat screens (FS), while waste not collected was assumed to be landfilled. PCB materials are classified into copper, gold, lead, silver, platinoids, other metals and support materials (such as plastics, fibres, etc.).

A4-Table 10. Waste material flows related to TV set EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
FS| ABS-PC without BFR, density < 1.3	1.958	1.648	0.000
FS| ABS without BFR, density < 1.3	0.023	0.019	0.000
FS| Copper within PCB	0.208	0.176	0.132
FS| Copper within Wire	0.072	0.061	0.047
FS| Gold within PCB	4.91E-04	4.13E-04	3.22E-04
FS| LCD panel	0.989	0.833	0.000
FS| Lead within PCB	1.81E-03	1.53E-03	4.38E-04
FS| PCB Other base metals	0.440	0.370	0.000
FS| PCB Support	0.340	0.286	0.000
FS| PE	0.043	0.037	0.000
FS| PET without BFR, density < 1.3	0.453	0.381	0.000
FS| Platinoid within PCB	3.85E-05	3.24E-05	4.28E-06
FS| PMMA	0.088	0.074	0.000
FS| PS without BFR, density < 1.3	0.614	0.517	0.000
FS| PVC within wire	0.065	0.055	0.000
FS| Silver within PCB	8.97E-03	7.55E-03	9.79E-04
FS| Steel	2.945	2.480	2.020
LPA| Glass fibres-plastics composites	0.603	0.508	0.000
LPA| PA without BFR, density < 1.3	0.059	0.049	0.000
LPA| PUR foam	0.031	0.026	0.000
Total WEEE cut-off TV	**8.943**	**7.528**	**2.201**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one TV set) is shown in A4-Table 10. The LCI datasets used for recycling of each material flow were obtained from WEEE LCI project.[3] These allow to calculate the environmental impacts of recycling according to two different accounting methods: impacts with benefits (including the impacts of recycling operations and the benefits from the substitution of primary raw materials with the recycled ones) and impacts without benefits (that only includes the impacts of recycling operations). Both accounting methods were applied herein to calculate both direct environmental impacts of recycling and environmental credits due to primary material substitution (calculated as the difference between impacts with and without benefits).

Landfill disposal

A fraction of the waste generated at the EoL of the TV is not recycled. It was assumed that this waste fraction is landfilled. Non-recycled waste were classified into two different waste material flows to model landfill disposal, namely inert material and plastics. The amount of the TV that is finally landfilled classified by waste material flow is shown in A4-Table 11.

A4-Table 11. Waste material flows related to landfill disposal of TV set.

Waste type	Mass landfilled (kg)
Plastics	0.676
Inert material	0.738
Total	**1.414**

The environmental impacts associated with landfill disposal were obtained by multiplying the amount of each waste material flow landfilled by the impacts calculated from the corresponding LCI datasets, which are shown in A4-Table 12.

A4-Table 12. LCI datasets of landfill disposal for TV set EoL.

Input	Dataset name	FU
Landfill disposal for inert waste	Disposal, inert material, 0% water, to sanitary landfill/CH U	1 kg
Landfill disposal for plastic waste	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	1 kg

3.6 Life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2 of the main document). Life cycle environmental impacts of the TV set were thus calculated for eighteen midpoint impact categories (including global warming and other) and three endpoint impact categories (damages to human health, ecosystem diversity and resource availability).

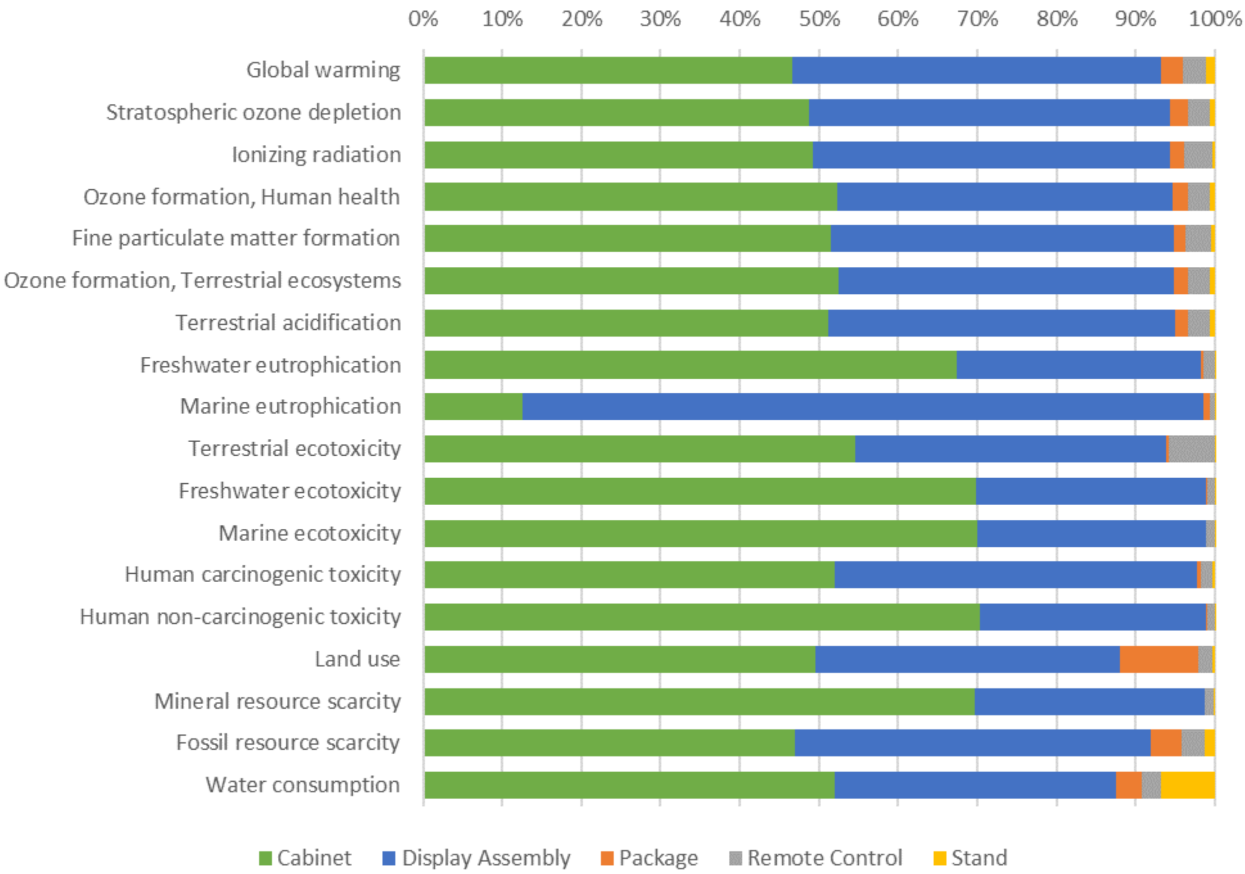
3.6.1 Manufacturing (cradle-to-gate)

A4-Table 13 shows the environmental impacts for the manufacturing of one TV set (i.e., the functional unit used in the study), including the global warming impact and endpoint impacts. The total cradle-to-gate impacts are broken down by the various modules composing the TV. The impacts also include the transport of materials and components from the suppliers to the TV factory.

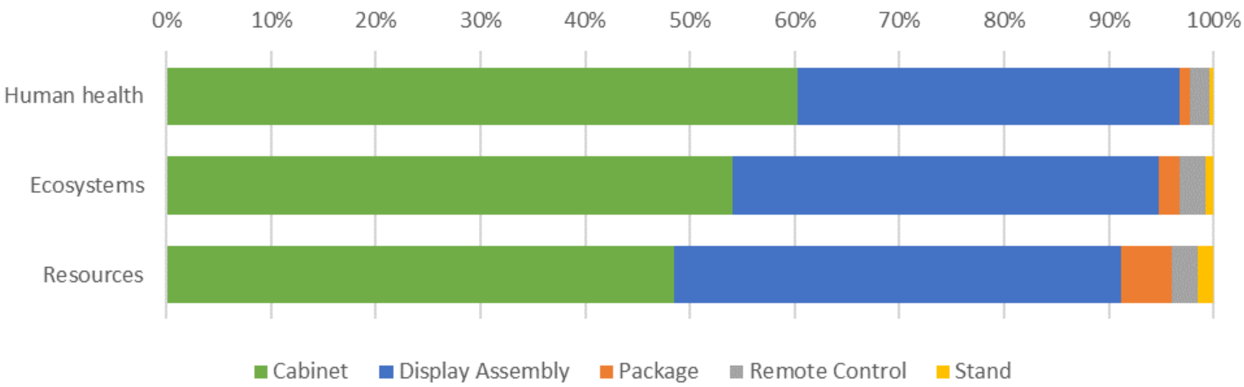
A4-Table 13. Global warming and endpoint impacts for the manufacturing of one TV set (cradle-to-gate).

Modules in TV set	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Packaging	6.29	1.16E-05	2.94E-08	0.80
Cabinet	104.66	7.80E-04	8.10E-07	8.10
Display Assembly	104.32	4.74E-04	6.11E-07	7.14
Remote Control	6.59	2.49E-05	3.67E-08	0.42
Stand	2.61	5.09E-06	1.22E-08	0.26
Transport of materials/components	1.27	3.35E-06	7.22E-09	0.13
Total manufacturing	**225.74**	**1.30E-03**	**1.51E-06**	**16.85**

In addition, the contribution of each module to the total impact of TV manufacturing for every midpoint and endpoint category assessed is described in A4-Figure 1 and A4-Figure 2, respectively. The results show that the cabinet and display modules generate most of the impact for all midpoint and endpoint categories, representing both together over 90% of the total manufacturing impact for all categories except for land use and water consumption. The contribution of other TV modules to the total manufacturing impact is comparatively negligible.



A4-Figure 1. Midpoint impacts for TV set manufacturing (cradle-to-gate) by modules.



A4-Figure 2. Endpoint impacts for TV set manufacturing (cradle-to-gate) by modules.

3.6.2 Use

A4-Table 14 shows the global warming impact and endpoint impacts for the use of one TV during its entire lifetime, as well as the breakdown of total impacts by the different causes generating them, including product distribution (by transport mode) and consumption of electricity and remote control batteries. Two different scenarios are included for electricity consumption: one where the electricity mix is assumed to be constant over time (year 2020 used as basis for calculation) and other where the electricity mix variation with time is modelled for the period 2020-2027 (see Figure 8 & Figure 9).

It can be found that electricity consumed by the TV totally dominates the impacts for the use phase, while the contributions of product distribution and batteries are negligible. It is therefore clear the key role that the increase of renewable sources in the electricity mix can play in the coming years. The scenario with variable electricity mix for the whole product lifetime means a reduction for all impact categories (compared to the constant electricity mix scenario) except for terrestrial ecotoxicity (increased by 0.24%), land use (increased by 0.21%) and mineral resource scarcity (increased by 0.38%). The impact increase for these categories is explained by the amount of land occupied by renewable energy sources and the raw materials needed. The other impact categories decrease from 0.20% for human non-carcinogenic toxicity up to 6.04% for terrestrial acidification. Global warming is reduced by 5.11%, while endpoint impacts are reduced as follows: human health damage by 1.87%, ecosystem diversity damage by 1.62% and resource availability by 3.08%.

A4-Table 14. Global warming and endpoint impacts for the use of one TV set.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution (road)	1.44	2.95E-06	7.13E-09	0.22
Product distribution (water)	0.23	6.27E-07	1.33E-09	0.02
Product distribution (railway)	0.03	1.55E-07	2.84E-10	0.00
Electricity (variable mix - 2020-2027)	236.85	6.55E-03	3.72E-05	9.86
Electricity (constant mix - 2020)	262.28	6.70E-03	3.78E-05	10.73
Batteries for remote control	0.14	3.84E-07	7.66E-10	0.01
Total Use (variable elect. mix - 2020-2032)	**238.69**	**6.55E-03**	**3.72E-05**	**10.11**
Total Use (constant elect. mix - 2020)	**264.13**	**6.70E-03**	**3.78E-05**	**10.99**

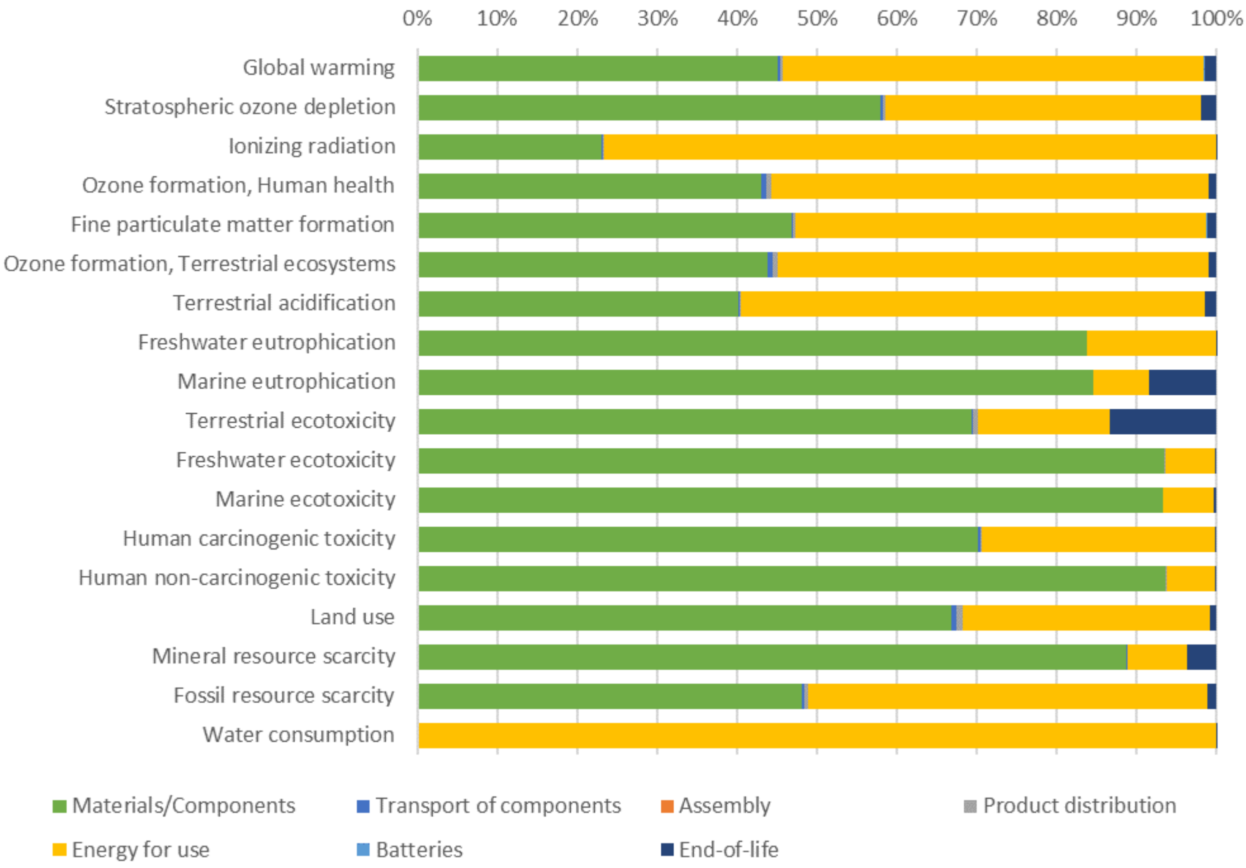
3.6.3 Total (cradle-to-grave)

A4-Table 15 collects the global warming impact and endpoint impacts for the whole life cycle of one TV. The total cradle-to-grave impacts for the TV are broken down by life cycle phases. In addition, the contribution of each life cycle phase to the total environmental impacts of the TV set for every midpoint and endpoint category assessed is shown in A4-Figure 3 and A4-Figure 4, respectively.

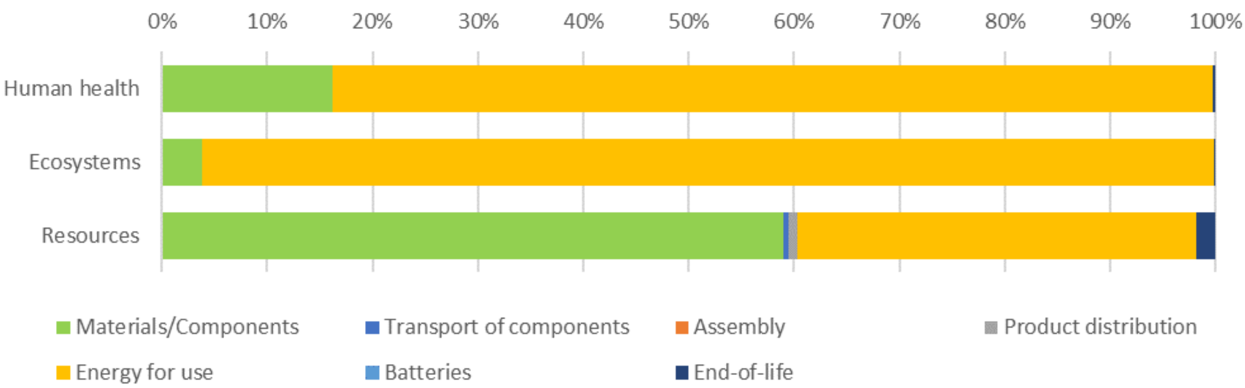
A4-Table 15. Global warming and endpoint impacts for the whole life cycle of one TV set (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	225.74	1.30E-03	1.51E-06	16.85
Use (variable elect. mix - 2020-2032)	238.69	6.55E-03	3.72E-05	10.11
Use (constant elect. mix - 2020)	264.13	6.70E-03	3.78E-05	10.99
EoL (waste treatment)	7.69	1.85E-05	4.00E-08	0.51
TOTAL (variable elect. mix)	**472.13**	**7.87E-03**	**3.87E-05**	**27.47**
TOTAL (constant elect. mix)	**497.56**	**8.02E-03**	**3.94E-05**	**28.35**
Credits from recycling	-17.86	-7.80E-05	-1.94E-07	-1.77

The use stage has the highest contribution to the total impact for global warming and several midpoint impact categories, as well as for human health and ecosystem diversity damages. Specifically, the electricity consumed during the use is responsible for most of these midpoint and endpoint impacts. The TV manufacturing also has a predominant impact for the damage to resource availability and for several midpoint categories, especially for impacts on freshwater and marine environments, human toxicity, land use and mineral resource scarcity. End-of-life impacts are very low and are rewarded with the credits given by 2.20 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).



A4-Figure 3. Midpoint impacts for the TV set (cradle-to-grave) by life cycle phases.



A4-Figure 4. Endpoint impacts for the TV set (cradle-to-grave) by life cycle phases.

3.7 Material circularity indicator

Material flows associated with the TV were grouped into the following categories (see A4-Table 10): steel, copper, gold, silver, lead, platinoid metals, other metals, plastics and glass. The recycled feedstock (F_R) in the TV was estimated in order to allow for further calculation of the virgin feedstock (V). The recycled feedstock was based on average recycled content for each material category, which was determined using industry databases and literature data (Table 11). The TV does not contain reused feedstock (F_U = 0).

The amount of waste collected for recycling was assumed to be the same as the waste collection rate for flat screens (see Table 8). It was assumed to be the same for all material categories included in the TV set (C_R =

84.2%). It was assumed that no waste fraction is collected for reuse (C_U = 0). The amount of waste going to landfill or energy recovery (W_0) was therefore deducted directly from the waste collection rate.

The efficiency of the recycling process (E_C) for each material category was calculated as the ratio between waste collected and recycled (using values in A4-Table 10). It was then used to calculate the amount of waste generated in the recycling process (W_C). The amount of waste generated to produce the recycled content used as feedstock (W_F) was obtained from the average efficiency of the recycling process (E_F) for each material, which was assumed to be 75% for plastics and 90% for metals and glass.

Feedstock and wastes were thus calculated taking into account all the above data and using formulae described in Section 3.3 of the main document. Results for feedstock and waste are collected in A4-Table 16.

A4-Table 16. Feedstock and waste for one TV set used for MCI calculation.

Material	Mass M (kg)	Virgin feedstock V (kg)	Unrecoverable waste W (kg)	Unrecoverable waste to disposal W_0 (kg)	Unrecoverable waste from recycling parts W_C (kg)	Unrecoverable waste from recycled feedstock W_F (kg)
Steel	2.945	2.096	0.743	0.466	0.459	0.094
Copper	0.281	0.183	0.079	0.044	0.058	0.011
Gold	4.91E-04	3.68E-04	1.30E-04	7.76E-05	9.08E-05	1.36E-05
Silver	8.97E-03	7.72E-03	4.77E-03	1.42E-03	6.57E-03	1.38E-04
Lead	1.81E-03	8.33E-04	8.84E-04	2.86E-04	1.09E-03	1.09E-04
Platinoid metals	3.85E-05	2.87E-05	2.07E-05	6.08E-06	2.81E-05	1.08E-06
Other metals	0.440	0.382	0.258	0.070	0.370	6.35E-03
Plastic	4.276	3.772	2.560	0.676	3.600	0.168
Glass	0.989	0.930	0.576	0.156	0.833	6.60E-03
TOTAL	**8.943**	**7.372**	**4.221**	**1.414**	**5.328**	**0.287**

MCI calculation for the TV set was then conducted (A4-Table 17). The average lifetime and intensity of use for the target TV set investigated herein were assumed to be the same as for the industry-average products (L/Lav = U/Uav = 1). Therefore, the value of the utility function for the TV set was 0.9. The linear flow index, considering feedstock and waste results (A4-Table 16), was 0.75. The MCI for the TV set was finally calculated as 0.32.

A4-Table 17. MCI calculation for the TV set.

Parameter	Value
Actual average lifetime of product L (years)	8
Actual average lifetime of industry-average product L_{av} (years)	8
Average number of functional units (FUs) during the use phase of product U (h/day)	4
Average number of FUs during the use phase of industry-average product U_{av} (h/day)	4
Utility of the product X	1.00
Utility factor F(X)	0.90
Linear Flow Index LFI	0.75
Material Circularity Indicator of the product MCI_P	**0.32**

4 Life cycle costing

4.1 Internal costs

The internal costs assessed for the TV set includes the costs for:

(i) Acquisition of raw materials and components, including related transport operations.

(ii) Manufacturing of the product.

(iii) Distribution of the product to retailers or final customers.

(iv) Use, including product operation and required consumables.

(v) End of life, including WEEE management.

A4-Table 18 shows the breakdown of the internal costs of the TV set by life cycle phase, namely manufacturing (including i, ii and iii), use (iv) and end of life (v).

Retail price provided by ARÇELIK was assumed herein to consider manufacturing costs. The retail price covers all the costs related to raw materials and components, product manufacturing and distribution, as well as other any other costs for product development (like R&D costs) and net revenues from sales.

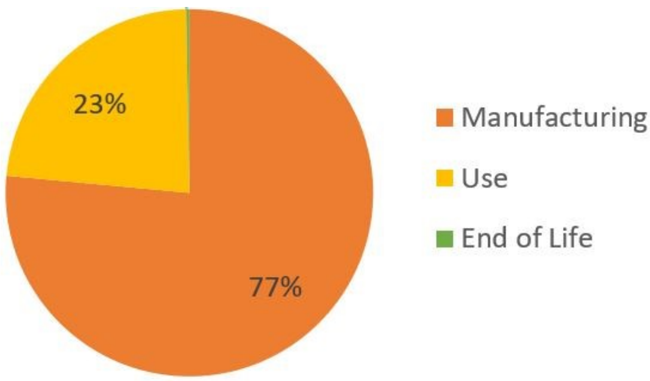
The use phase includes the costs for electricity and for remote control batteries consumed for the whole lifetime of the TV (as detailed in Section 3.5.2 of this Annex). Total consumption values were therefore estimated at 426 kWh of electricity and 6 AA-type batteries. The average market prices for electricity was assumed as 0.216 €/kWh of electricity for year 2019, with a sustained annual growth factor of 1.022 for the following years (see Section 4.1.2 of the main document). The cost for the 6 batteries was assumed to be 5 €, considering average market price.

The costs for WEEE management was estimated at 1.20 € (for one TV set), which corresponds to the fee paid by producers for the EoL management of each TV set they put on the market.

A4-Table 18. Internal costs for the whole life cycle of one TV set (cradle-to-grave).

Life cycle phase	Concept	Cost (€)	Total cost (€)
Manufacturing	Retail price (incl. costs for materials/components, manufacturing, distribution, other product development costs and net revenues)	343.59	343.59
Use	Electricity consumption Batteries for remote control	99.43 5.00	104.43
End of life	WEEE management fee	1.20	1.20
TOTAL	**Manufacturing + Use + EoL**	-	**449.22**

A4-Figure 5 graphically shows the contribution of each life cycle phase to the total internal cost of the TV set. It can be found that the manufacturing phase is the most expensive, followed by the use phase, whereas the contribution of end-of-life phase is negligible.



A4-Figure 5. Contribution of each life cycle phase to the total internal cost for the TV set.

4.2 External costs

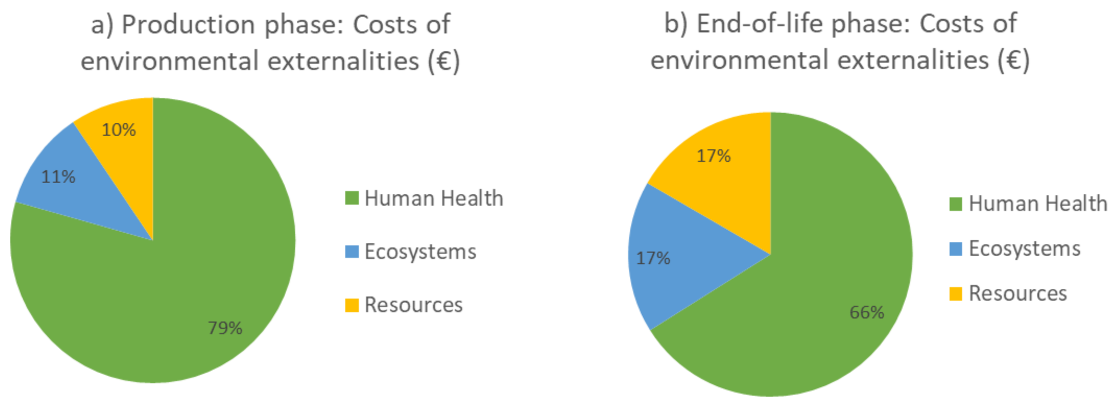
Monetary valuation of environmental impacts was applied to assess the costs of environmental externalities. To this end, LCA results obtained for the TV set (see Section 3.6 of this Annex) were combined with monetisation factors given for different environmental impact categories (see Section 4.2 of the main document). External costs were estimated using two different approaches for monetary valuation: (1) monetisation of global warming impact and (2) monetisation of endpoint impacts. It should be noted that the economic costs obtained in each case cannot be added together since the global warming impact (as well as the other midpoint impacts) is included in the endpoint impacts.

The results from the monetary valuation of environmental impacts are collected in A4-Table 19. These are broken down by life cycle phases and impact categories monetized.

A4-Table 19. External costs for the whole life cycle of one TV set (cradle-to-grave).

Life cycle phase	Impact category	Total amount	Monetisation factor	Economic cost (€)
Manufacturing	Human health	1.30E-03 DALY	101,311 €/DALY	131.65
	Ecosystems	1.51E-06 species.yr	1.23E+07 €/species.yr	18.55
	Resources	16.85 USD2013	0.929 €/USD2013	15.56
	Sub-total endpoint impacts	-	-	**165.86**
	Global warming	226 kg CO_2 eq	130 €/tonne CO_2 eq	29.37
Use	Human health	6.70E-03 DALY	101,311 €/DALY	678.99
	Ecosystems	3.78E-05 species.yr	1.23E+07 €/species.yr	466.08
	Resources	10.99 USD2013	0.929 €/USD2013	10.21
	Sub-total endpoint impacts	-	-	**1,155.29**
	Global warming	264 kg CO_2 eq	130 €/tonne CO_2 eq	34.37
End of life	Human health	1.85E-05 DALY	101,311 €/DALY	1.88
	Ecosystems	4.00E-08 species.yr	1.23E+07 €/species.yr	0.49
	Resources	0.51 USD2013	0.929 €/USD2013	0.47
	Sub-total endpoint impacts	-	-	**2.84**
	Global warming	8 kg CO_2 eq	130 €/ tonne CO_2 eq	1.00
TOTAL	Human health	8.02E-03 DALY	101,311 €/DALY	812.52
	Ecosystems	3.94E-05 species.yr	1.23E+07 €/species.yr	485.13
	Resources	28.34 USD2013	0.929 €/USD2013	26.34
	Total endpoint impacts	-	-	**1,323.99**
	Total global warming	498 kg CO_2 eq	130 €/tonne CO_2 eq	64.74

A4-Figure 6 graphically shows the contribution of each endpoint impact to the total external costs for the manufacturing and end of life, since these are the life cycle phases in which the project is expected to achieve higher improvements. Most of the external costs are due to human health damages, while the costs of damages to ecosystem diversity and resource availability are lower and comparable with each other.



A4-Figure 6. Contribution of each endpoint impact to total external costs of manufacturing and end-of-life phases for the TV set.

4.3 Total life cycle costs

Concluding, A4-Table 20 shows the total life cycle cost including internal and external costs. The cost of environmental externalities, and especially the external cost for the use stage, is the highest cost element. In contrast, the product waste management in the end-of-life phase is the one with the lowest cost, both for internal and external costs.

A4-Table 20. Total costs for the whole life cycle of one TV set (cradle-to-grave).

Life cycle phase	Internal cost (€)	External cost (€)	Total cost (€)
Manufacturing	343.59	165.86	509.45
Use	104.43	1,155.29	1,259.71
End of life	1.20	2.84	4.04
TOTAL	**449.22**	**1,323.99**	**1,773.21**

5 Social life cycle assessment

5.1 Social life cycle inventory

Primary data provided by ARÇELIK was used as the starting point to carry out the S-LCA. Specifically, it provided economic data describing the supply chain composition and location, identifying all the economic costs required to produce the TV set and the cost breakdown by countries and economic sectors. A4-Table 21 shows the percentage breakdown of total production costs by countries and sectors.

A4-Table 21. Production cost breakdown for the TV set by countries and economic sectors.

Country/Sector	Plastic products	Ferrous metals	Paper products	Mineral products	Electronic equipment	Manufacturing process
TOTAL	10.268%	3.700%	0.837%	44.871%	21.863%	18.461%
China	2.181%			44.871%	4.656%	
Hong Kong	0.089%				0.255%	
Germany	0.009%				1.781%	
Turkey	7.918%	3.700%	0.837%		13.009%	18.461%
Taiwan	0.014%				1.649%	
Poland					0.027%	
Singapore					0.486%	
South Korea	0.057%					

The sectors included in the assessment comprise those related to every material and/or component required to produce the TV, as well as the sector linked to the manufacturing at ARÇELIK facilities (i.e., electronic equipment sector in Turkey). Electronic equipment and plastics are the most complex sectors in the supply chain since the related components come from 7 and 6 different countries, respectively, being Turkey and China those where more money is spent. By countries, China and Turkey are indeed the most important in the acquisition of materials and components, accounting both together for over 95% of total TV production costs.

The SHDB method and datasets were then used to calculate the social impacts for each sector in each country (as explained in Section 5 of the main document). The Social Hotspot 2019 Category Method with Weights (which is available for SimaPro software) was used. The social impacts derived from the TV set were obtained by allocating the production costs (in USD) to the corresponding social LCI datasets for every country-specific sector involved in the TV supply chain. The social LCI datasets used are listed in A4-Table 22.

A4-Table 22. Social LCI datasets for the country-specific sectors linked to the TV set.

Social Hotspot Database (SHDB)	Reference Unit
Chemical, rubber, plastic products/CHN S	USD
Chemical, rubber, plastic products/HKG S	USD
Chemical, rubber, plastic products/DEU S	USD
Chemical, rubber, plastic products/TUR S	USD
Chemical, rubber, plastic products/TWN S	USD
Chemical, rubber, plastic products/KOR S	USD
Ferrous metals/TUR S	USD
Paper products, publishing/TUR S	USD
Mineral products nec/CHN S_China	USD
Electronic equipment/CHN S_China	USD
Electronic equipment/HKG S	USD
Electronic equipment/DEU S_Germany	USD
Electronic equipment/TUR S	USD
Electronic equipment/TWN S	USD
Electronic equipment/POL S	USD
Electronic equipment/SGP S_Singapore	USD
Manufactures nec/TUR S	USD

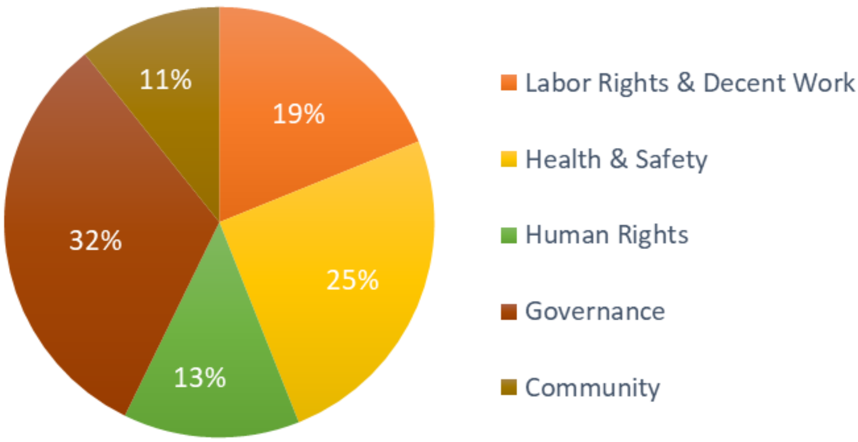
5.2 Social life cycle impact assessment

The social footprint of the TV set was calculated by aggregating the social impacts associated with each country-specific sector listed in A4-Table 22 into a single social impacts indicator, namely the so-called Social Hotspot Index (SHI). A4-Table 23 shows the SHI obtained for the TV, as well as its breakdown into the different social impact categories that contribute to the total social footprint.

A4-Table 23. Social impacts of the TV set by impact category.

Social category	Total impact (Pt)
Labour Rights & Decent Work	1,276.99
Health & Safety	1,698.46
Human Rights	897.25
Governance	2,166.93
Community	726.69
TOTAL: SHI	**6,766.32**

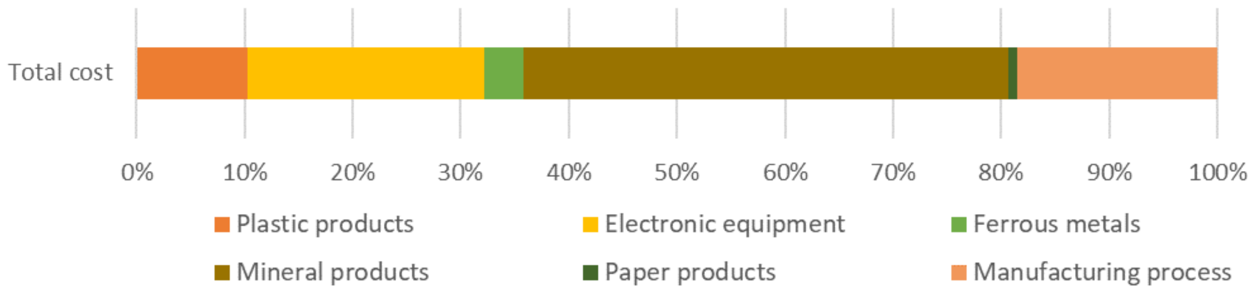
A4-Figure 7 shows graphically the contribution of each social impact category to the total social footprint of the TV. It can be found that the greatest social impacts are due to Governance and Health & Safety issues, while social impacts affecting Community have the lowest contribution.



A4-Figure 7. Percentage of impact categories in the social life cycle assessment for the TV set.

5.2.1 Social impacts by economic sectors

A4-Figure 8 shows the economic share of each productive sector in the TV supply chain. The economic sector with the highest contribution (i.e., that in which the company spent more money to produce the TV) is the mineral products sector, followed by the electronic equipment sector and the EEE manufacturing process (at ARÇELIK facilities). Paper and ferrous metals are the economic sectors where expenditures are the lowest.

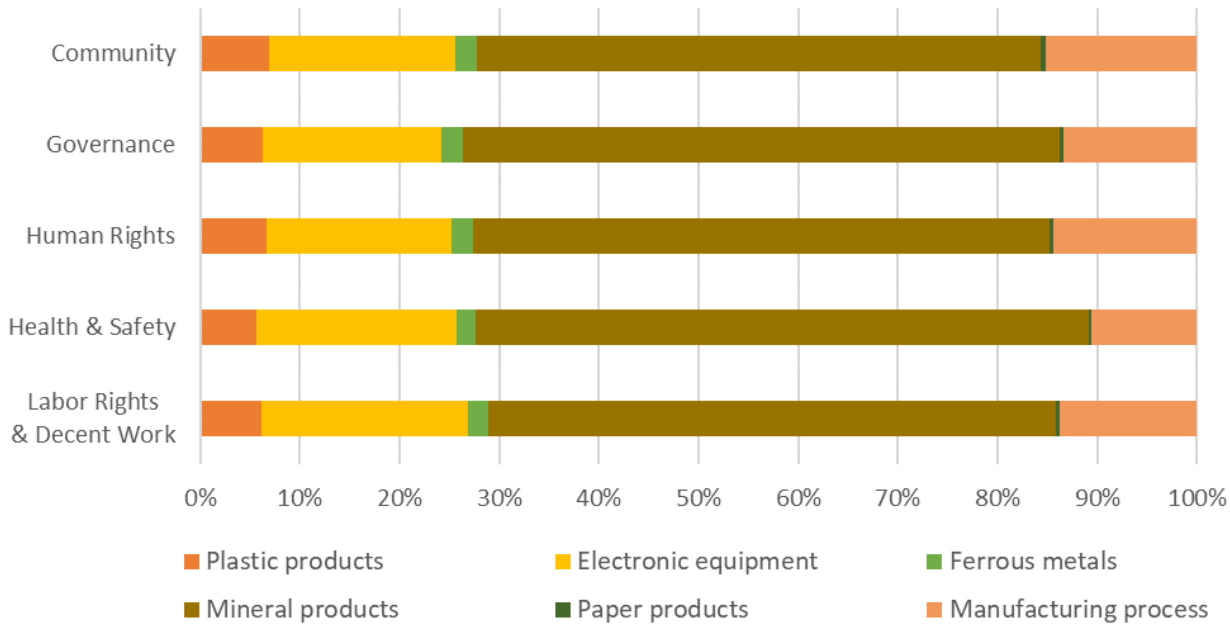


A4-Figure 8. Production cost breakdown for the TV set by economic sectors.

The social impacts were assessed for every economic sector. A4-Table 24 shows the impacts for each social category obtained for each sector involved in the TV supply chain, while A4-Figure 9 shows graphically the contribution by each sector to the total impact in each social category. The results show that the mineral products used in the TV set comprises most of the impact for every social category (with over 57% of total impacts). The impact contribution of the mineral products acquired is high compared to their economic share in total production costs, which is around 45%. This means that the social risk levels in this sector, which is totally located in China, are high compared with other sectors in the TV supply chain, so it presents a social hotspot to be considered when planning measures to improve social conditions and reduce the social footprint of the TV set. The electronic equipment sector, the manufacturing process conducted in ARÇELIK facilities (Turkey) and the plastics sector also have relevant contributions to social impacts. However, it should be noted that the impact contribution of these sectors are lower than their economic shares in total production costs, so their social risk levels are acceptable. Paper products and ferrous metals have negligible social impacts when compared to the other economic sectors composing the TV supply chain.

A4-Table 24. Social impacts of the TV set by economic sectors.

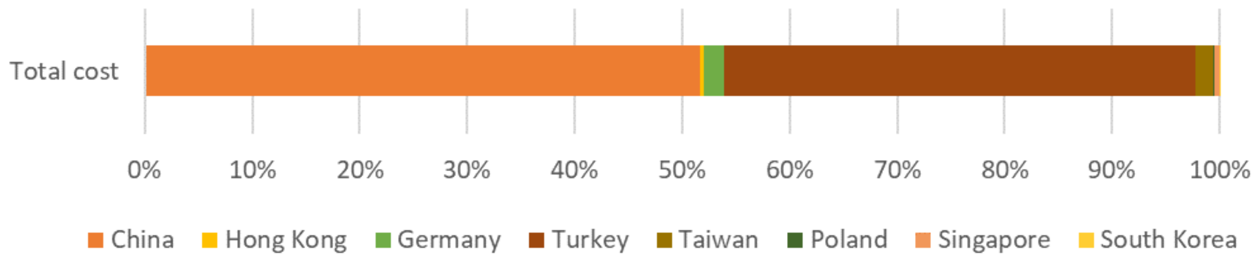
Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
Plastic products	79.16	96.75	59.49	137.11	49.81
Electronic equipment	263.29	339.34	166.44	387.50	136.29
Ferrous metals	27.00	33.14	19.81	45.49	15.96
Mineral products	727.37	1,044.29	518.58	1,299.39	411.19
Paper products	5.15	5.60	3.58	8.16	3.18
Manufacturing	175.02	179.33	129.35	289.28	110.26
TOTAL	**1,276.99**	**1,698.46**	**897.25**	**2,166.93**	**726.69**



A4-Figure 9. Contribution of each economic sector to the total social impacts of the TV set by social category.

5.2.2 Social impacts by countries

A4-Figure 10 shows the economic share of each country in the TV supply chain. The country with the highest contribution is China, comprising about 52% of the total TV production costs. It is followed by Turkey, which accounts for around 44% of the total TV production costs, including both the manufacturing costs at ARÇELIK facilities and the purchasing costs of various materials and components from other companies located in Turkey. The expenditure in the rest of countries is very low in comparison; e.g., Germany and Taiwan are the third and fourth countries with the largest contributions to total production costs, but these are less than 2% each.



A4-Figure 10. Production cost breakdown for the TV set by country.

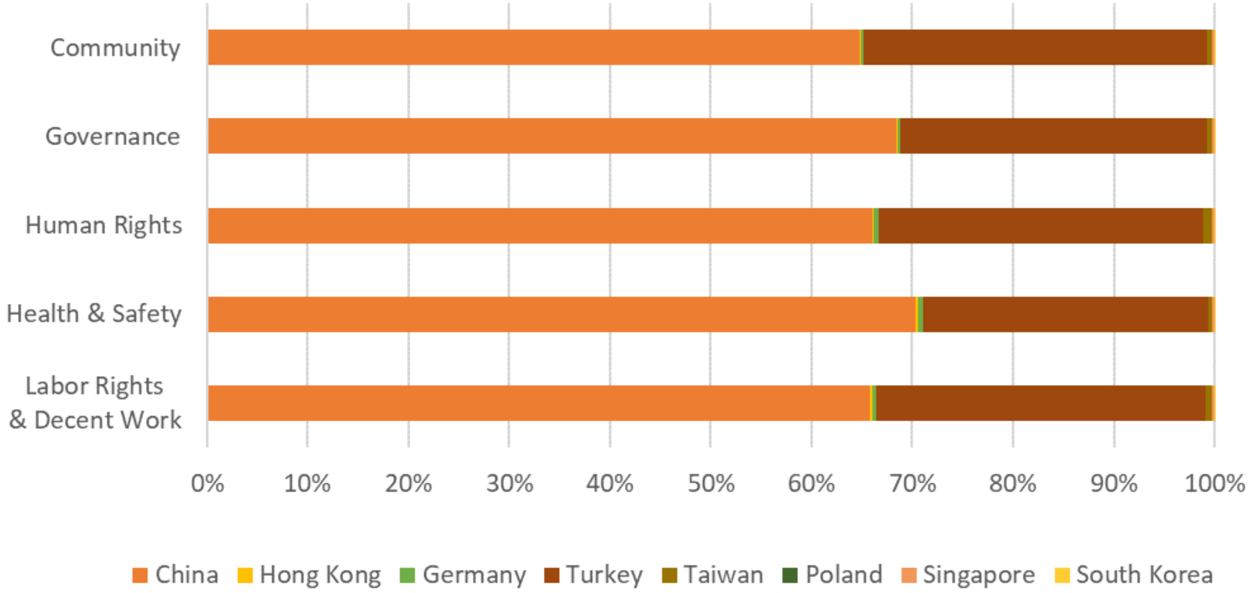
The social impacts were also assessed for every country in the TV supply chain. A4-Table 25 shows the impacts for each social category obtained for each country, while A4-Figure 11 shows graphically the contribution by each country to the total impact in each social category. The results clearly show that China is the country with the highest social impacts for all social categories. It comprises two-thirds of the total social impacts, while the remaining third is mainly attributable to Turkey. The social impacts of the other countries involved in the TV supply china are comparatively negligible.

Despite China represents 52% of the total TV production costs, the social impacts there encompass between 65% and 70% of the total TV impacts depending on the social category assessed. This reveals that social risk levels in the Chinese productive sectors supplying ARÇELIK are high, so they can be identified as social hotspots of the TV set. ARÇELIK should therefore investigate opportunities and measures together its Chinese suppliers (especially those providing mineral products) to apply social improvements there, which could in turn derive in a decrease of the social footprint of the TV.

Turkey also represents a social hotspot due to its large contribution to total social impacts. ARÇELIK could devise measures for social improvement together its Turkish suppliers, although these should have a second order of priority behind the measures for China.

A4-Table 25. Social impacts of the TV set by country.

Economic sector	Labour Rights & Decent Work	Health & Safety	Human Rights	Governance	Community
China	839.92	1,193.42	592.97	1,483.51	470.46
Hong Kong	2.97	4.11	1.13	2.51	0.86
Germany	4.87	8.85	3.81	6.21	2.36
Turkey	417.33	480.32	288.91	659.20	247.24
Taiwan	8.15	7.50	7.89	10.63	3.70
Poland	0.12	0.19	0.08	0.15	0.05
Singapore	3.39	3.70	2.31	4.42	1.90
South Korea	0.24	0.37	0.16	0.30	0.12
TOTAL	**1,276.99**	**1,698.46**	**897.25**	**2,166.93**	**726.69**



A4-Figure 11. Contribution of each country to the total social impacts of the TV set by social category.