Activating Circular Services in the Electric and Electronic Sector

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Deliverable 5.2.

Environmental analysis of C-SERVEES products and services: Life cycle assessment

Acronym: **C-SERVEES**

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<table>
<tr><td>Author(s)</td><td colspan="3">AIMPLAS</td></tr>
<tr><td rowspan="6">Version history</td><td>#</td><td>Reviewer</td><td>Comments</td></tr>
<tr><td>00</td><td>AIMPLAS</td><td>Document creation</td></tr>
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<tr><td>02</td><td>AIMPLAS</td><td>Final version</td></tr>
<tr><td></td><td></td><td></td></tr>
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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 were 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 were determined by means of life cycle sustainability assessment tools (LCSA), including environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA). Two different types of scenarios were 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 5.2 shows the life cycle assessment and material circularity index of each target product under the conventional scenario, called Reference product, and under the C-SERVEES scenario, called C-SERVEES product, and their comparison.

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.

Below are shown the main environmental indicators calculated for the four target products with their two scenarios and the relative improvement, referred to their functional unit, and excluding use energy and use consumables.

1) One washing cycle with an **ARÇELIK 7150370100 washing machine as Reference product and ARÇELIK 7150341600 as C-SERVEES product.**

Main life cycle cost indicators for one washing cycle of the washing machine.

Washing machine	Indicator	Unit	Reference	C-SERVEES	Relative improvement
	Global warming	kg CO_{2eq}	0.141	0.139	1.3%
	Human health	DALY	1.11E-06	1.11E-06	0.2%
	Ecosystems	species.yr	1.20E-09	1.20E-09	0.3%
	Resources	USD2013	1.27E-02	1.26E-02	0.8%
	Recycling credits, GWP	kg CO_{2eq}	-1.17E-02	-1.17E-02	0.0%
	Material Circularity Indicator		0.25	0.25	1.7%

2) 1,000 printed pages with a **LEXMARK CX860dte professional multifunctional laser printer**

Main life cycle cost indicators for 1000 printed pages of the multifunctional laser printer.

Multifunctional laser printer	Indicator	Unit	Reference	C-SERVEES	Relative improvement
	Global warming	kg CO_2 eq	2.779	2.558	8.0%
	Human health	DALY	1.08E-05	1.00E-05	7.1%
	Ecosystems	species.yr	1.64E-08	1.51E-08	7.7%
	Resources	USD2013	0.256	0.236	8.0%
	Recycling credits, GWP	kg CO_2 eq	-0.387	-0.331	-14.4%
	Material Circularity Indicator		0.484	0.543	12.3%

3) One hour of the **telecommunications equipment** monitoring composed by **an active ALM unit (ADVA 16ALM/#1650D/AC) and 50 passive sensors**

Main environmental indicators for one hour of the ALM product monitoring.

ALM product	**Indicator**	**Unit**	**Reference**	**C-SERVEES**	**Relative improvement**
	Global warming	kg CO_{2eq}	1.37E-03	9.27E-04	32.6%
	Human health	DALY	8.42E-09	4.70E-09	44.1%
	Ecosystems	species.yr	1.30E-11	7.57E-12	42.0%
	Resources	USD2013	7.38E-05	6.23E-05	15.5%
	Recycling credits, GWP	kg CO_{2eq}	-1.14E-04	-6.62E-05	-42.2%
	Material Circularity Indicator		0.41	0.71	73.1%

4) One watched hour of the **GRUNDIG G43C 891 5A 43" smart-TV set**

Main life cycle cost indicators for one watched hour of the TV set.

TV set	**Indicator**	**Unit**	**Reference**	**C-SERVEES**	**Relative improvement**
	Global warming	kg CO2eq	2.19E-02	1.40E-02	36.2%
	Human health	DALY	1.23E-07	7.49E-08	38.9%
	Ecosystems	species.yr	1.44E-10	9.01E-11	37.6%
	Resources	USD2013	1.64E-03	1.09E-03	33.6%
	Recycling credits, GWP	kg CO_{2eq}	-1.67E-03	-1.11E-03	-33.2%
	Material Circularity Indicator		0.37	0.56	52.1%

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).

The main conclusion of this Deliverable 5.2 is that the four target products, under the new circular economy models relying on the systemic eco-innovative services demonstrated in the project, and excluding electricity and consumables during the use phase**, have reduced global warming by 20%, human health and ecosystems quality by 22%, resources scarcity by 14% and improved circularity by 35%.**

Table of contents

List of figures

List of tables

List of acronyms and abbreviations

Acronym	Full form
3D	Three dimensions
ABS	Acrylonitrile-butadiene-styrene
AI	Artificial intelligence
ALM	Advanced link monitoring
B2B	Business-to-business
B2C	Business-to-customer
BoM	Bill of materials
CD	Compact disc
CE	Conformité Européenne
CF_e	Endpoint characterization factors
CF_m	Midpoint characterization factors
CMOS	Complementary metal-oxide-semiconductor
C_R	Waste fraction recycled
C-SERVEES	Activating circular services in the electrical and electronic sector
CSS	Country-Specific Sector
C_U	Waste fraction reuse
D2.2	Deliverable 2.2
DALY	Disability adjusted life years
DRAM	Dynamic random-access memory
DVD	Digital versatile disc or Digital video disc
E2N	Equal to new
E_C	Efficiency of the recycling process
Eco-PP	
ED	Ecosystems damage
EEE	Electric and electronic equipment
E_F	Efficiency of the recycling process
EI	Environmental impacts
EOFP	Ozone formation, terrestrial ecosystems, potential
EOL	End-of-life
EOL RR	End-of-life recycling rate
EPS	Expanded polystyrene
EU	European Union
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FFP	Fossil resource scarcity
F_R	Recycled feedstock
FS	Flat screens
FU	Functional unit
F_U	Reused feedstock
GB	Gigabyte
GF	Glass filled
GHG	Greenhouse gas
GHz	Gigahertz
GLO	Global
GWP	Global warming potential
HDD	Hard disk drive
HH	Human health
HIPS	Polystyrene, high impact
HOPF	Ozone formation, human health, potential
HTPc	Human carcinogenic toxicity
HTPnc	Human non-carcinogenic toxicity
IC	Integrated circuits
ICT	Information and communication technologies
IO	Input output

Acronym	Full form
IRP	Ionizing radiation potential
ISO	International Organization for Standardization
IT	Information technology
ITU	Intermediate transfer module
L	Lifetime
LCA	Life cycle assessment
LCC	Life cycle cost
LCCP	Lexmark cartridge collection programme
LCD	Liquid crystal display
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LDPE	Low-density polyethylene
LECP	Lexmark equipment collection programme
LED	Light emitting diode
LFI	Linear flow index
LHA	Large household appliances
LOP	Land use
LPA	Large professional appliances
MCI	Materials circularity index
MEP	Marine eutrophication potential
METP	Marine ecotoxicity potential
MLP	Multifunction laser printer
ODP	Stratospheric ozone depletion potential
OSR	Old scrap ratio
PA	Polyamide
PBT	Polybutylene terephtalate
PC	Polycarbonate
PCB	Printed writing board
PCBA	Printed circuit board assembly
PCR	Product category rules
PCU	Packet control unit
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PMP	Fine particulate matter formation
PMU	Power management unit
POM	Polyoxymethylene
PP	Polypropylene
PPO	Polyphenylene oxide
PPS	Polyphenylene sulphide
PR	Public relations
PS	Polystyrene
PSS	Product Service Systems
PSU	Power supply unit
PVC	Polyvinylchloride
PWB	Printed wiring board
QR	Quick response
RA	Resources scarcicity
RC	Recycled content
RER	Europe
RIR	Recycling input rate
RoW	Rest of the World
SD	Sensitivity dependence
S-LCA	Social life cycle assessment
SMD	Surface mount device
SOP	Mineral resource scarcity

Acronym	Full form
SPA	Small professional appliances
TAP	Terrestrial acidification
TE	Telecom equipment
TETP	Terrestrial ecotoxicity potential
tkm	Tonnes-km
TR	Percentage of time replaced
TV	Television
U	Functional unit
UK	United Kingdom
USA	United States of America
V	Virgin raw material
VAT	Value added tax
W	Waste
W_0	Waste going to landfill
W_C	Waste generated in the recycling process
WCP	Water consumption potential
WCR	Waste collected for recycling or refurbishment
WEEE	Waste of electric and electronic equipment
W_F	Waste generated to produce the recycled content used as feedstock
WM	Washing machine
WP	Work package
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 were 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 were 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.

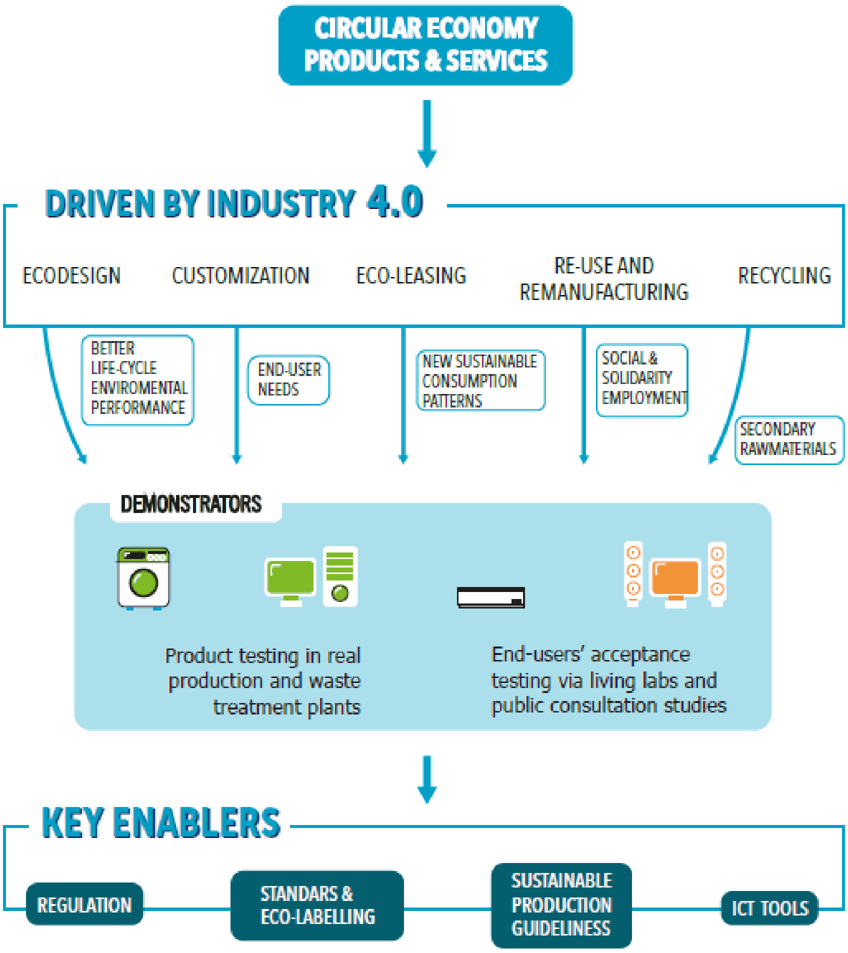

Figure 1. Schematic overview of the C-SERVEES project.

The environmental, economic and social viability of the target products and related eco-services were 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 scenarios were 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 5.2 shows the life cycle assessment and material circularity index of each target product under the conventional scenario, called Reference product, and under the C-SERVEES scenario, called C-SERVEES product, and their comparison.

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.

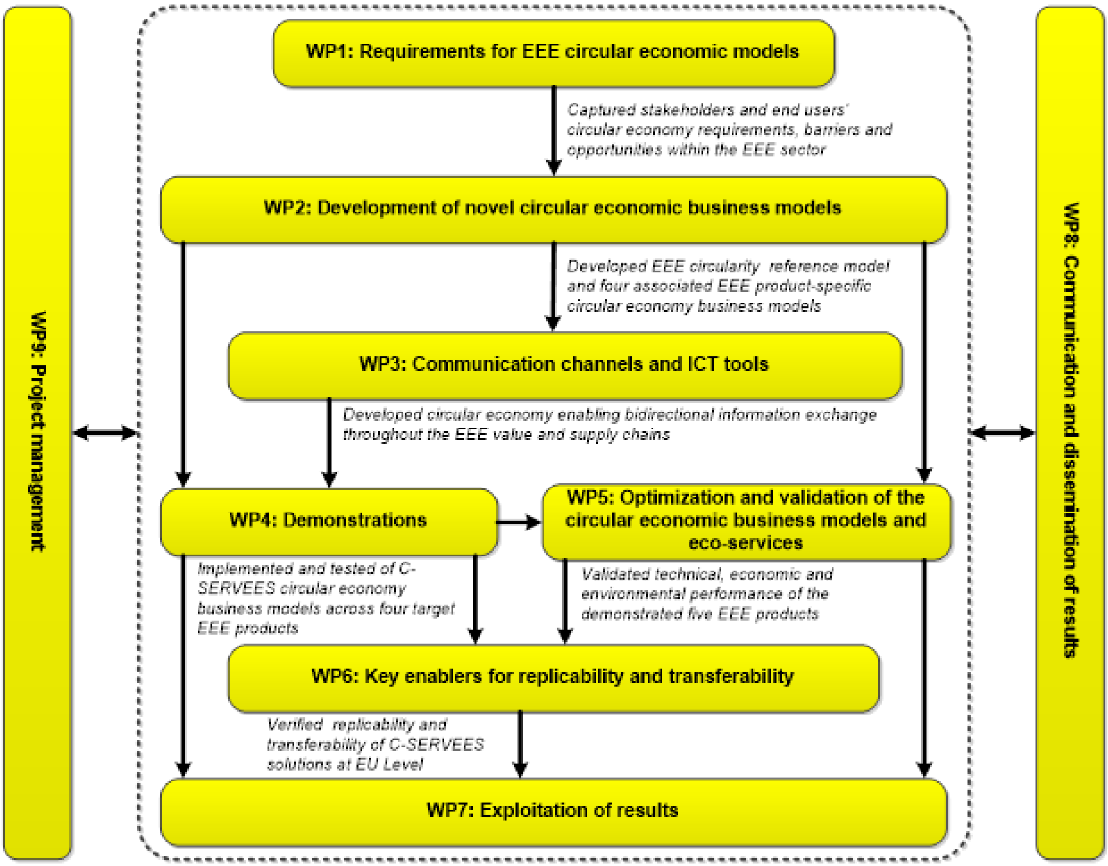

Figure 2. WP structure of the C-SERVEES project.

This Deliverable 5.2 is part of WP5, whose main objective is to validate the new circular business models by verifying their total costs (internal and external cots). The relationship of WP5 (and Deliverable 5.2 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 leaded 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 were 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 were relied on QR codes (requiring product labelling), providing access to end users via their smartphones, while WEEE managers can use QR code scanners. Functionalities included product life-cycle tracking and feedback to producers, as well as interactive user manuals, repair manuals, warranty tracking or consumables management.

The ICT tools were developed in sprints with industry partners that tested them to validate and optimise their features and functionalities. They were 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 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 initially selected for each target product (as for the WP2 and related deliverables D2.2, D2.3, D2.4 and D2.5) were implemented through the demonstrations for the 'Design and Production' phase (presented in Deliverable 4.1). These potential actions for increasing circularity from WP2 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) were explored by EEE producers for possible progression outside the confines of the project.

Table 1. Demonstration circular economy actions to be conducted along the C-SERVEES project for Washing Machines.

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 washing machines' components • Use novel formula to increase recycled PET content in the washing machines' tub to make it more durable • Use QR codes to provide information about materials and company's circularity to all the value chain
		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 • Obtain feedback from washing machines' B2B customers via questionnaires • Develop new corporate B2B sales channels in Europe for renting washing machines • Develop a washing machine rental business model • Assess the feasibility of washing machines' leasing/renting options • Target low income customers for the sale or rent of refurbished washing machines' (students, pensioners, house shares, etc.)
	End of life	Expand and improve repair & refurbishment operations	• Collect end of life products from B2B customers, refurbish them and provide refurbished products to B2B customers as a new business line • Enable collection of end-of use-washing machines' back from customers with a partner in Europe • Explore the use of 3D printing for spare parts and/or customisation • Reuse motors and electrical cards from returned washing machines as spare parts in Turkey • Develop dismantling and repair training programmes • Create awareness in relation to washing machines' circularity among B2B consumers via the help of QR codes inserted in products, which include examples of Arçelik's best practices in terms of circularity • Expand partnerships with Arçelik dealers and retailers to sell remanufactured B2C washing machines'
		Improve recycling process/recovering of the washing machine	• Use a QR code on washing machines' components to track their service call rate • Initiate a take back collection system for end of use washing machines in Europe with a partner • Develop circular end-of-life recovery strategies for collected washing machines outside Turkey

Table 2. Demonstration circular economy actions to be conducted along the C-SERVEES project for Laser Printers.

Demo product (producer)	Life-cycle stage	Circular economy action	Action description
Printer products, incl. laser printers and toner cartridges (LEXMARK) 	Design & production	Eco-design of the printer	• Identify levers to reduce dismantling and refurbishing cost by setting various operating models • Provide information about printers to LEXMARK recycling partners • Use materials that recyclers can easily and profitably recycle • Use ICT to support information sharing across the supply chain related to recycled content • Devise an eco-design strategy for printers during dismantling activities
		Increase circularity in the printer's life cycle	• Expand LCCP and/merge with LECP program (collecting and refurbishing whole printers and key components) • Assess options to reuse material from EOL/WEEE printers • Learn from recyclers what materials can be recycled better or more profitably to use more of them instead of low-recycle value or efficiency materials
	Use	Improve data collection and management	• Reduce the number of unnecessary and incorrect shipments • Salvage working and repairable parts from collected/return printers and use on E2N (Equal to New) printers • Increase the flow of returned end-of-life printers by reducing the associated time and cost • Explore the competitiveness of 3D printing for spare plastic parts • Engage with key customer to understand their needs and requirements as it relates to refurbished products • Active lobbying at EU and/or national level for wider acceptance and promotion of circular business models • Active media/PR campaign on refurbished printers • Promote refurbished printers • Use QR code to inform customers about options to return their unused products to the manufacturer • Investigate economics of more CE suitable materials coming from end-of-life cartridges or printers
	End of life	Improve the LCCP	• Expand LCCP and/merge with LECP program (collecting and refurbishing whole printers and key components) • Implement ICT tools for improvement in logistics
		Improve the recycling of printers and cartridges	• Maintain highest levels of data security by ensuring that customers' documents are erased from refurbished (E2N) printers

Table 3. Demonstration circular economy actions to be conducted along the C-SERVEES project for ALM product.

Demo product (producer)	Life-cycle stage	Circular economy action	Action description
Telecom equipment (ADVA) 	Design & production	Eco-design of ALM system	• Design for longevity, in particular better maintainability • Design for better recycling, in particular related to plastics • Improve energy efficiency in the use phase by at least 20% • Devise an eco-design approach in production and Design for Recycling • Reduce costs of manual disassembly for recycling
		Improve circularity in ALM production	• Perform LCA to detect improvement areas in production
	Use	Improvements in performance	• Implement eco-design strategies across the life cycle of ALM products and the subsequent reduction of energy use
		Explore feasibility of renting/shared use/PSS	• In-depth PSS analysis considering lifetime and other ICT product • Introduce options for leasing, renting or sharing products • Expand the scope of PSS (moving toward vendor ownership) • Move towards a rental model for B2B customers • Demonstration of leasing/renting with selected stakeholder
	End of life	Improve repair and refurbishment operations	• Carry out a feasibility analysis of AI for predictive maintenance • Assess components' reuse • Provide an analysis of part-exchange options as part of repair and maintenance
		Improve recycling of the ALM system	• Assign components to most efficient recycling pathways • Provide an analysis of how recycling needs to be changed to become more efficient • Define which level of material data is suitable for recyclers • Improve the proportion of components, parts and/or materials recovered • Reduce volume of packaging and develop plastic-free packaging

Table 4. Demonstration circular economy actions to be conducted along the C-SERVEES project for ALM product.

Demo product (producer)	Life-cycle stage	Circular economy action	Action description
TV sets (ARÇELIK) 	Design & production	Eco-design of the TV set	• Increase recycled plastic content in TV components • Increase the durability of LED panel and mainboard • Use QR codes to provide information about materials and company's circularity to all the value chain
		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 • Use 3D printing for TV components • Obtain feedback from TV B2B customers via questionnaires and living labs • Develop new corporate B2B sales channels in Europe for renting TVs • Develop a TV rent business model for Smart Boards and Digital Signage products • Assess the feasibility of TV renting options
	End of life	Expand and improve repair and refurbishment operations	• Collecting and remanufacturing end of use TV sets • Enable traceability of remanufactured TV parts • Develop dismantling and repair training programmes • Create awareness among TV B2B consumers via the help of QR codes inserted in products • Expand partnerships with ARÇELIK TV dealers and retailers to sell remanufactured B2C TVs • Target low-income customers for the sale or rent of refurbished TVs (students, pensioners, house shares, etc.) • Initiate a take back collection system in Europe with a partner
		Improve recycling process of the TV set	• Decrease packaging waste • Increase circularity of TV waste plastics • Develop circular end-of-life recovery strategies for end of use TVs outside Turkey

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

The main objective of this WP was 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 was 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 scenarios were assessed and compared for each target product to validate the sustainability of the new circular business models:

- 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).

A preliminary LCSA was included in D5.1. However, during the development of the C-SERVEES project and in accordance with the definition of the circular models, some changes were introduced in some parts of the linear product in order to achieve a more representative comparison.

This Deliverable 5.2 shows the life cycle assessment and circularity of each target product under the conventional scenario, called Reference product, and under the C-SERVEES scenario, called C-SERVEES product. The impacts of the C-SERVEES scenario are also compared to those for the conventional scenario, also compiled here and replacing Deliverable 5.1, to calculate the sustainability benefits that can be achieved with the solutions developed in the project.

1.2 Structure of the Deliverable

Deliverable 5.2 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.
- Methodology of the life cycle assessment.
- One chapter for each target product containing a comprehensive LCA of the reference product, the C-SERVEES product and a comparative assessment.
- Conclusions.

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

The sustainability analysis is performed on the Telecommunication equipment (TE) which central device is called Advanced link monitoring (ALM).

These products and their main characteristics are described below.

Different Product Category Rules[1] aimed for stablishing different Environmental Product Declarations for similar EEE products showed that the functional unit is defined by two approaches:

1. A unit of the product, or/and
2. Dedicated function of the product

The first approach was justified in the way that each product is “marketed and sold in such units”. This is intended to cover the end-user acceptance. On the other hand, comparison among the different products seems not straightforward when functionalities change. For that reason, each product was evaluated also against the functional unit defined for them.

This means that the assessment of each product was conducted for a unit of the product/system. Results are presented then both as per unit of the product but also as per the functional unit the product is intended for.

This Deliverable 5.2 shows the life cycle assessment and circularity assessment of each target product under the conventional scenario, called Reference product, and under the C-SERVEES scenario, called C-SERVEES product, and their comparison.

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.

[1] Several references like UL, Environdec or Environment and Development Foundation were consulted. Main PCRs are no longer in force.

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.

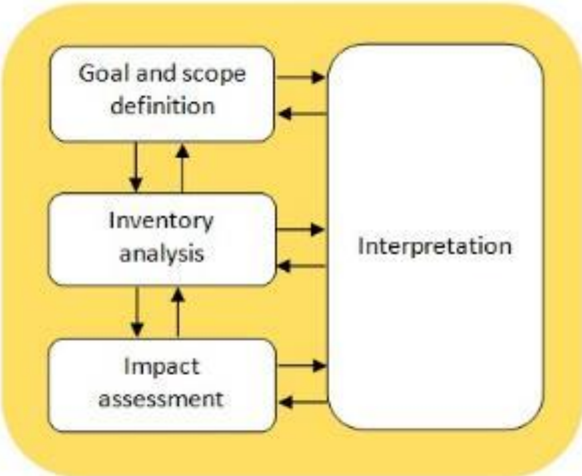

Figure 4. Framework of the LCA methodology.

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 and the two scenarios 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 as explained in ANNEX A1.1.

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.[4–6] 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,[7] which provides figures for the years 2016 and 2050 (Figure 5), while the electricity mix for intermediate years was modelled by linear interpolation.

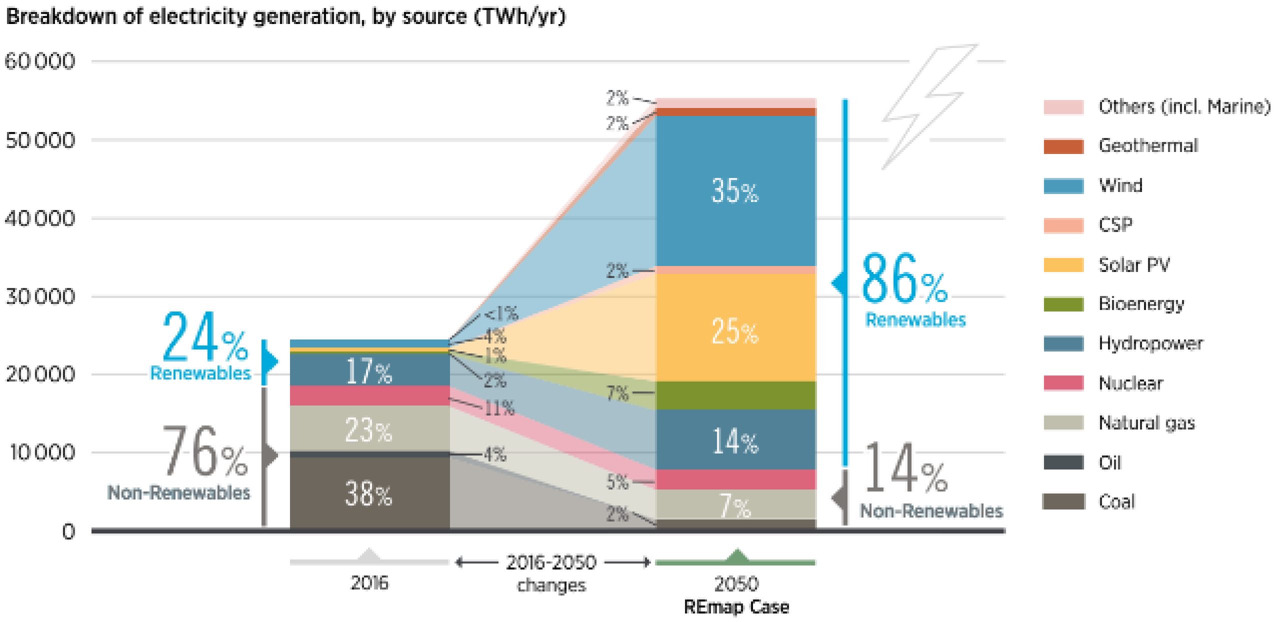

Figure 5. Evolution of the European electricity mix.[7]

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 6 shows the decrease in the estimated Global Warming Potential of the modelled European electricity mix over 20 years.

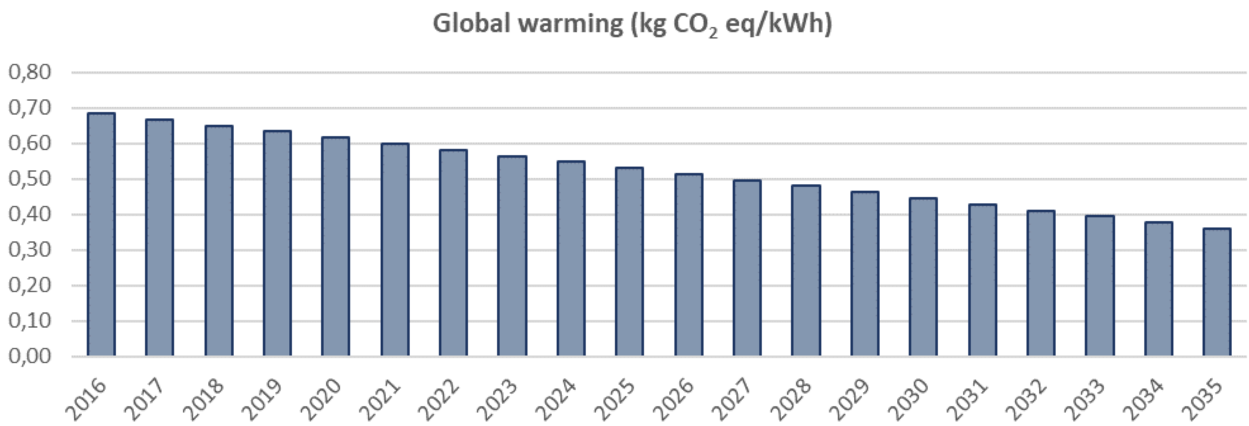

Figure 6. Global Warming Potential for low-voltage electricity production for the period 2016-2035 according to the European electricity mix evolution.

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[8] for the year 2017 (Table 5).

Table 5. EEE products and their wastes in the EU-27 for the year 2017. Source: Eurostat.[8]

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 6 shows the waste collection rates assumed for the EEE products targeted in the project. EU average collection rates (from Table 5) were considered for those products for which specific collection rates were not available.

Table 6. 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 6) 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.

Recycling waste is modelled with data of the project WEEE LCI[3], as explained in ANNEX A1.2. 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[9] 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 7).

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 7).

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 8). 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).

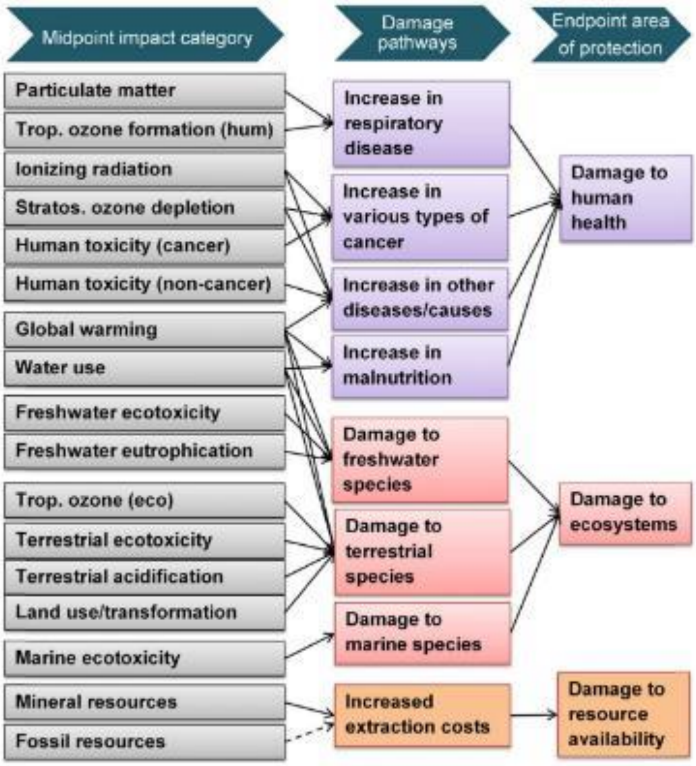

Figure 7. Impact categories covered in the ReCiPe2016 method.

Table 7. 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 8. 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. A more detailed explanation of the modelling of the MCI is in the ANNEX A1.3.

4 Washing machine

The washing machine selected for demonstration as the Reference product is GRUNDING C-SERVEES (7150370100), which has 9 kg capacity, energy efficiency class A^{+++} and connectivity features. It is manufactured in Çayırova (Turkey) and currently sold in Europe (especially Spain) and Turkey. 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 had a chance to collect data and learn customer usage habits to improve customers' experience and offer maintenance and repair services to extend product life. More details on the current washing machine selected for demonstration are shown in Table 9.

Table 9. 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

The activities conducted in the LCSA were derived from the WASH-CIRCMODE short-term actions validated in WP2. The table below presents the WASH-CIRCMODE canvas sub-components and their validated short-term CE actions, as presented in Table 24 in D2.2, and the selected strategies implemented in WP5 as C-SERVEES product (Product number 7150341600).

Table 10. Validated short-term WASH-CIRCMODE Canvas Key Circular sub-components and their associated Circular Economy Actions relevant for the LCSA.

WASH-CIRCMODE Canvas Sub-Component	WASH-CIRCMODE validated short-term Circular Economy Actions	LCSA implemented
WASH_C1.1 Diversify circular activities	WASH_A1.1.1 Increase recycled plastic content in washing machine's components	Eco-PP inner cover and detergent box group
WASH_C1.2 Embrace eco design to ensure products circularity across life-cycle ages	WASH_A1.2.1 Use novel formula to increase recycled PET content in the washing machine's tub to make it more durable	Recycled PET TUB
WASH_C2.3 Introduce and/or expand the use of ICT to foster circular economy	WASH_A2.3.2 Use QR codes to provide information about washing machine's materials and company's circularity	
WASH_A1.3.1 Enhance the integration of circular strategies into the production process	Blowing agent inner cover and detergent box group	Mass reduction in tub, inner cover and detergent box group

4.1 Scope

4.1.1 Functional unit and system boundaries

The product function for the washing machine is washing clothes, 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). The assessment was initially performed for one product and at the end converted to the functional unit. Table 11 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.

Table 11. 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)	

4.1.2 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.[10]

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). 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.

4.1.3 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) using the most recent data published (year 2019).[7]
    - 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[11] and sea-distances.org[12] for road and water transport, respectively.

4.1.4 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 148).
- 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 6).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[13]

4.2 Reference 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.

4.2.1 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 Table 12.

Table 12. Modules of the Reference WM.

Modules in washing machine	Total amount (kg)
Packaging	1.22
Customer module	0.32
Control system	2.20
Terminal	0.24
Dynamic system	43.01
Cabinet	13.90
Isolation	0.28
Front door	3.42
Front cabinet	2.19
Accessories	1.84
Panel	1.30
Aqua system	3.99
Motor	3.50
Scrap	2.22
Total	**77.41**

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 Table 13.

Table 13. LCI datasets of material, components and processes for Reference WM 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
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

Input	Dataset name	FU
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
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

4.2.2 Use

Distribution

The washing machine is distributed to a wide list of countries as shown in Table 14.

Table 14. Reference WM 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 Table 15.

Table 15. Estimated amounts for distribution of one Reference WM 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 Table 16.

Table 16. LCI datasets of transport modes for Reference WM 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.[6]

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 Table 17.

Table 17. 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

4.2.3 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the washing machine are classified in Table 18 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.). Note, packaging is not included in Table 18.

Table 18. Waste material flows related to one Reference WM 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	7.972	3.689	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	**75.875**	**35.107**	**12.333**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one washing machine) is shown in Table 18. 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 was 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 Table 19.

Table 19. Waste material flows related to landfill disposal of one Reference WM.

Waste type	Mass landfilled (kg)
Plastics	9.601
Aluminium	1.183
Inert material	29.984
Total	**40.767**

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 Table 20.

Table 20. LCI datasets of landfill disposal for Reference WM 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

4.3 Reference life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

4.3.1 Manufacturing (cradle-to-gate)

Table 21 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.

Table 21. Global warming and endpoint impacts for the manufacturing of one Reference WM (cradle-to-gate).

Modules in washing machine	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Packaging	7.13E+00	1.36E-05	3.06E-08	1.06E+00
Customer module	0.43	1.06E-06	3.76E-09	3.73E-02
Control system	137.43	1.94E-03	1.63E-06	1.07E+01
Terminal	7.63	8.00E-05	9.86E-08	6.37E-01
Dynamic system	8.12E+01	4.05E-04	5.62E-07	8.95E+00
Cabinet	30.91	1.03E-04	1.74E-07	1.61E+00
Isolation	0.99	3.26E-06	2.91E-08	6.66E-02
Front door	9.07	2.25E-05	4.41E-08	1.21E+00
Front cabinet	5.29	2.17E-05	6.92E-08	2.53E-01
Accessories	5.68	1.12E-05	2.70E-08	8.44E-01
Panel	16.78	6.33E-05	8.91E-08	1.65E+00
Aqua system	16.27	5.65E-05	8.84E-08	2.28E+00
Motor	31.82	2.16E-04	2.46E-07	2.43E+00
Scrap	8.90	3.63E-05	6.02E-08	7.17E-01
Total manufacturing	**359.55**	**2.98E-03**	**3.15E-06**	**3.24E+01**

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 Figure 8 and Figure 9, 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.

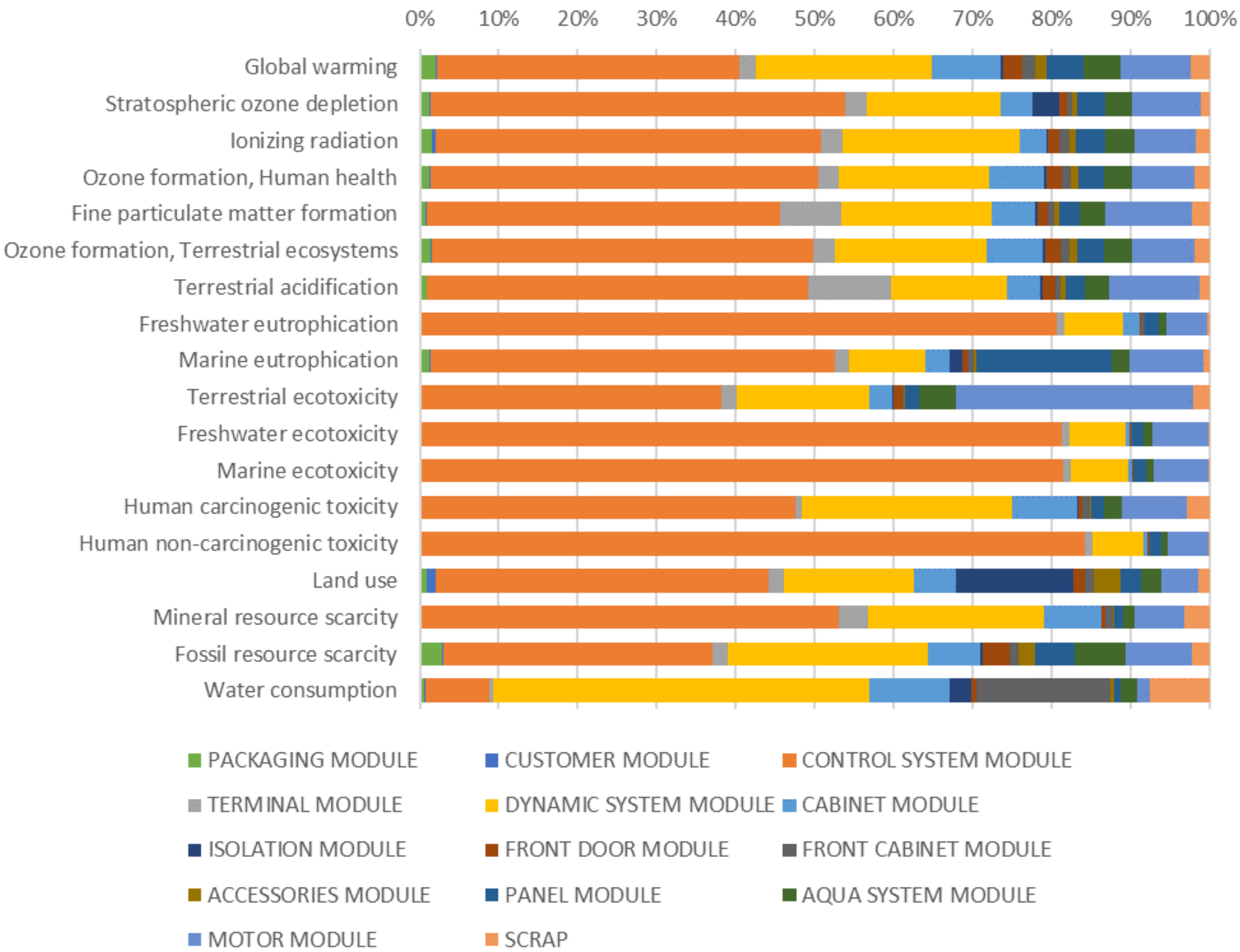

Figure 8. Midpoint impacts for Reference WM manufacturing (cradle-to-gate) by modules

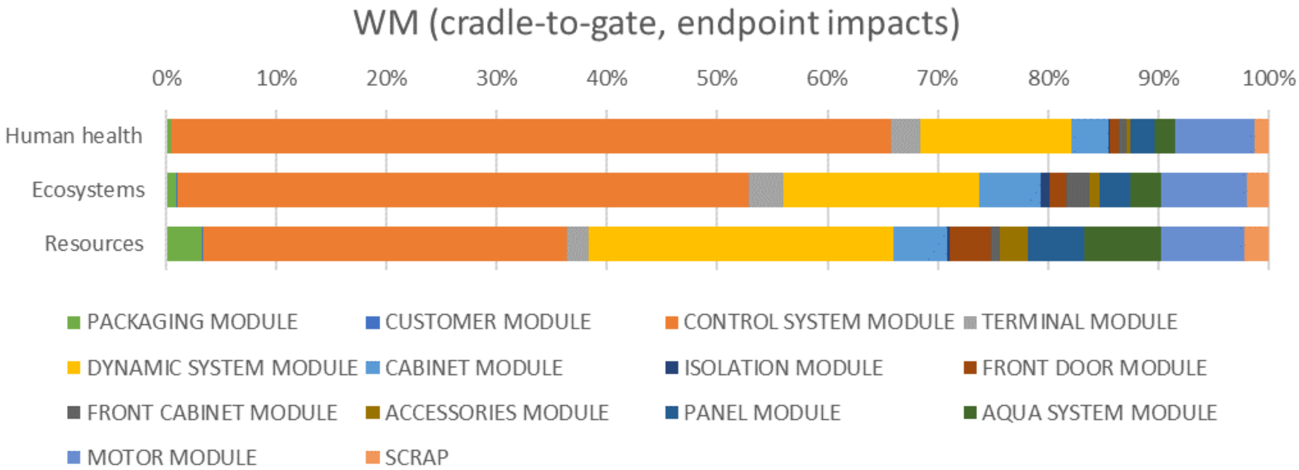

Figure 9 Endpoint impacts for Reference WM manufacturing (cradle-to-gate) by modules

4.3.2 Use

Table 22 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 5 & Figure 6).

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%.

Table 22. 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)	5.46E+00	1.12E-05	2.71E-08	8.37E-01
Product distribution (water)	2.22E+00	9.98E-06	1.83E-08	2.87E-01
Product distribution (railway)	6.04E-02	1.66E-07	3.52E-10	5.57E-03
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**

4.3.3 Total (cradle-to-grave)

Table 23 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 Figure 10 and Figure 11, respectively.

Table 23. Global warming and endpoint impacts for the whole life cycle of one Reference WM (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	358.82	2.98E-03	3.15E-06	3.27E+01
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).

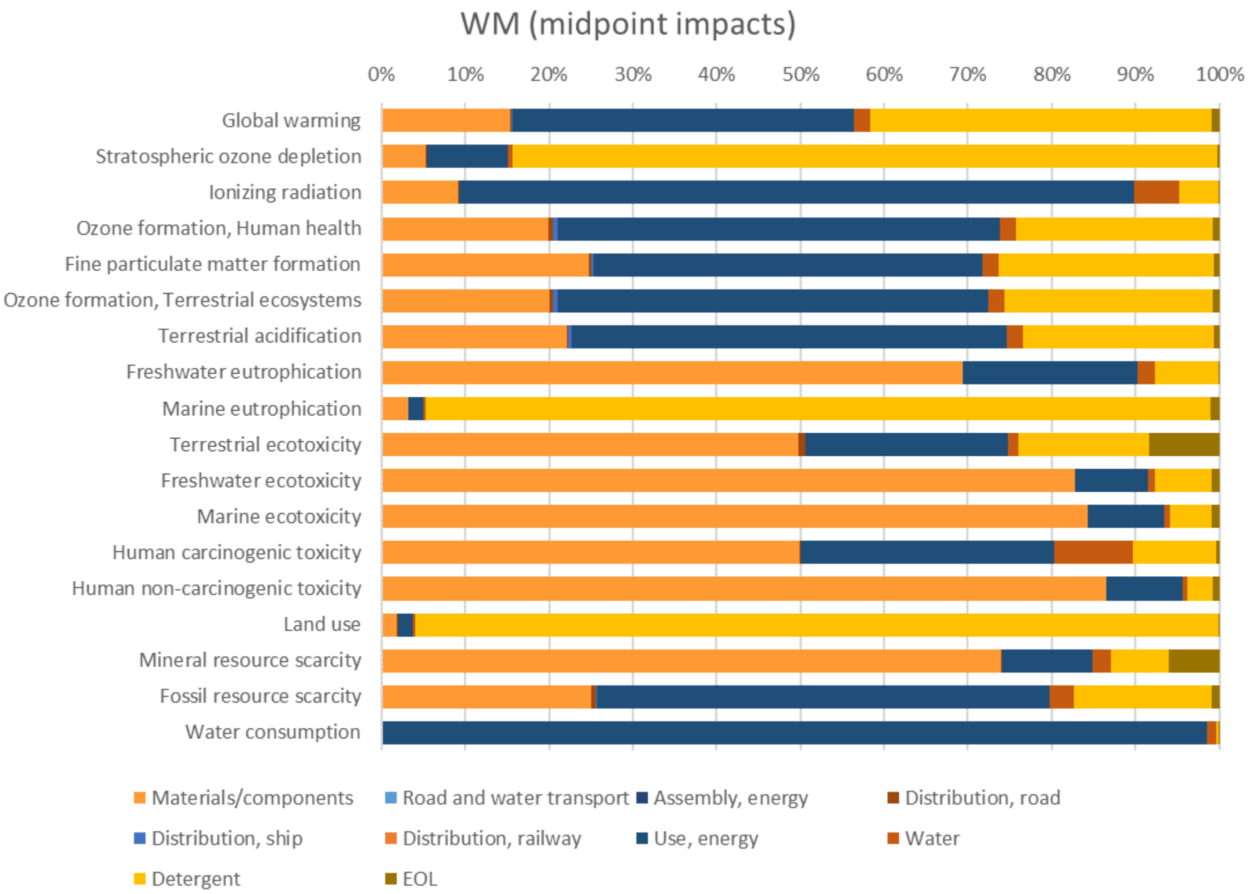

Figure 10. Midpoint impacts for the Reference WM (cradle-to-grave) by life cycle phases

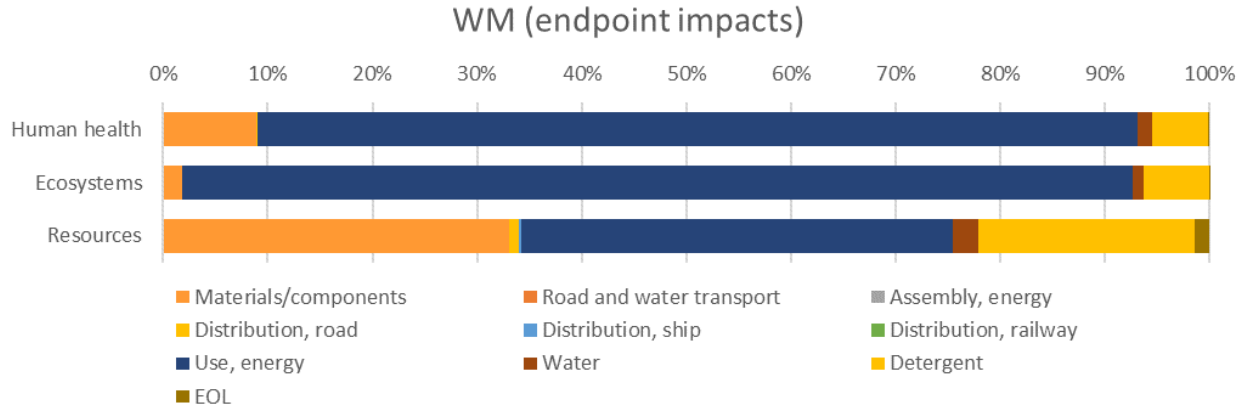

Figure 11 Endpoint impacts for the Reference WM (cradle-to-grave) by life cycle phases.

4.4 Reference material circularity indicator

Material flows associated with the washing machine were grouped into the following categories: 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 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 148). 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 6). 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 Table 148). 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 considering all the above data and using formulae described in A1.3. Results for feedstock and waste are collected in Table 24.

Table 24. 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	17.814	15.712	13.841	9.572	7.838	0.701

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)
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	**75.875**	**64.794**	**53.004**	**40.767**	**22.774**	**1.698**

MCI calculation for the washing machine was then conducted, Table 25. 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 (Table 24), was 0.83. The MCI for the washing machine was finally calculated as 0.25.

Table 25. MCI calculation for the Reference WM.

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**

4.5 C-SERVEES life cycle inventory

4.5.1 Redesign changes

Redesign changes implemented in the LCSA as described in Table 10 are detailed in Table 26. Recycled materials are included for the inner door (64%), the detergent box (64%) and the tub (10%), as well as mass reduction of the tub, 1.021 kg, and some less reductions in the inner cover and the detergent box.

Table 26 C-SERVEES WM changes.

	Reference	C-SERVEES
Product:	7150370100	7150341600
Lifetime	12.5 years	12.5 years
Functional units	2750	2750
Recycled content	No recycled materials	Inner door: 64% recycled Detergent box: 64% recycled Tub: 10% recycled
Mass reduction	No	Reduction of 1 .09 kg in tub Reduction of 17 g in inner cover Reduction of 21 g in Detergent box

4.5.2 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 Table 27.

Table 27. Modules of the C-SERVEES WM.

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	3.97
Motor	3.50
Scrap	2.22
Total	**76.29**

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 Table 28.

Table 28. LCI datasets of material, components and processes for C-SERVEES WM.

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

4.5.3 Use

Distribution

The washing machine is distributed to a wide list of countries as shown in Table 29.

Table 29. C-SERVEES WM 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 Table 30.

Table 30. Estimated amounts for distribution of one C-SERVEES WM 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 Table 31.

Table 31. LCI datasets of transport modes for C-SERVEES WM 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.[6]

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 Table 32.

Table 32. LCI datasets of electricity, water and detergent for C-SERVEES WM 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

4.5.4 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the washing machine are classified in Table 33 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.).

Table 33. Waste material flows related to C-SERVEES WM 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	1,778	0,823	0,396
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	**74.738**	**34.581**	**12.325**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one washing machine) is shown in Table 33. 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 was 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 Table 34. Compared with Reference WM (Table 19), 0.61 kg of plastic are reduced from landfill disposal.

Table 34. Waste material flows related to landfill disposal of C-SERVEES WM.

Waste type	Mass landfilled (kg)
Plastics	8.99
Aluminium	1.183
Inert material	29.984

Total	40.157

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 Table 35.

Table 35. LCI datasets of landfill disposal for C-SERVEES WM 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

4.6 C-SERVEES life cycle assessment

4.6.1 Manufacturing (cradle-to-gate)

Table 36 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.

Table 36. Global warming and endpoint impacts for the manufacturing of one C-SERVEES WM (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	1.06E+00
Customer module	0.43	1.06E-06	3.76E-09	3.73E-02
Control system	137.43	1.94E-03	1.63E-06	1.07E+01
Terminal	7.63	8.00E-05	9.86E-08	6.37E-01
Dynamic system	77.60	4.01E-04	5.54E-07	8.84E+00
Cabinet	30.91	1.03E-04	1.74E-07	1.61E+00
Isolation	0.99	3.26E-06	2.91E-08	6.66E-02
Front door	8.54	2.20E-05	4.42E-08	1.11E+00
Front cabinet	5.29	2.17E-05	6.92E-08	2.53E-01
Accessories	5.68	1.12E-05	2.70E-08	8.44E-01
Panel	16.78	6.33E-05	8.91E-08	1.65E+00
Aqua system	15.69	5.60E-05	8.86E-08	2.19E+00
Motor	31.82	2.16E-04	2.46E-07	2.43E+00
Scrap	8.90	3.63E-05	6.02E-08	7.17E-01
Total manufacturing	**354.82**	**2.97E-03**	**3.14E-06**	**3.21E+01**

In addition, the contribution of each module to the total impact of washing machine manufacturing for every midpoint and endpoint category assessed is described Figure 12 and Figure 13, 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.

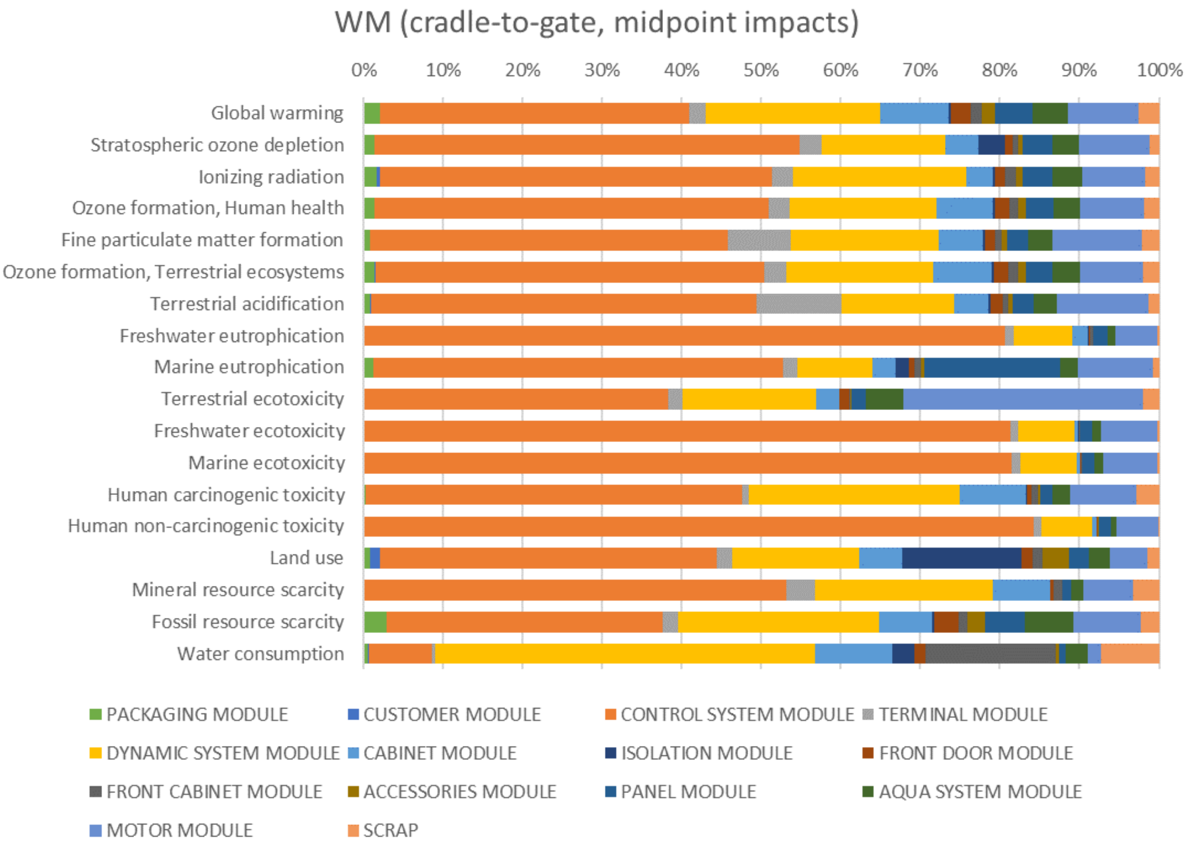

Figure 12. Midpoint impacts for C-SERVEES WM manufacturing (cradle-to-gate) by modules.

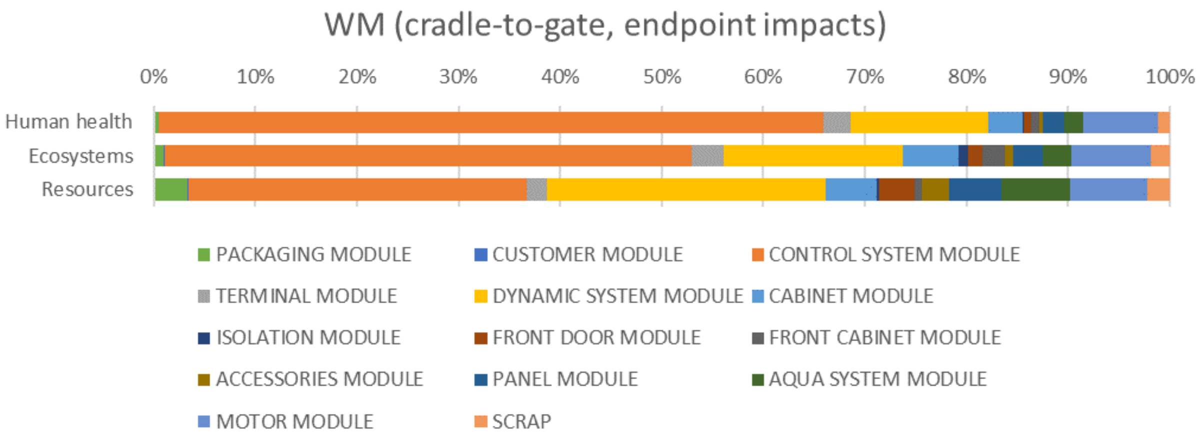

Figure 13 Endpoint impacts for C-SERVEES WM manufacturing (cradle-to-gate) by modules.

4.6.2 Use

Table 37 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 5 & Figure 6).

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%.

Table 37. Global warming and endpoint impacts for the use of one C-SERVEES WM.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution (road)	5.46	1.12E-05	2.71E-08	8.37E-01
Product distribution (water)	2.22	9.98E-06	1.83E-08	2.87E-01
Product distribution (railway)	6.04	1.66E-07	3.52E-10	5.57E-03
Electricity (variable mix - 2020-2032)	956.04	2.80E-02	1.59E-04	40.31
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)	2343.85	3.02E-02	1.72E-04	97.6

4.6.3 Total (cradle-to-grave)

Table 38 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 Figure 14 and Figure 15, respectively.

Table 38. Global warming and endpoint impacts for the whole life cycle of one C-SERVEES WM (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	354.82	2.97E-03	3.14E-06	3.21E+01
Use (variable elect. mix - 2020-2032)	1,969.10	3.02E-02	1.72E-04	64.10
EoL (waste collected for recycling)	18.24	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)	**2,343.85**	**3.33E-02**	**1.76E-04**	**97.62**
Credits from recycling	-32.16	-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 12.33 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).

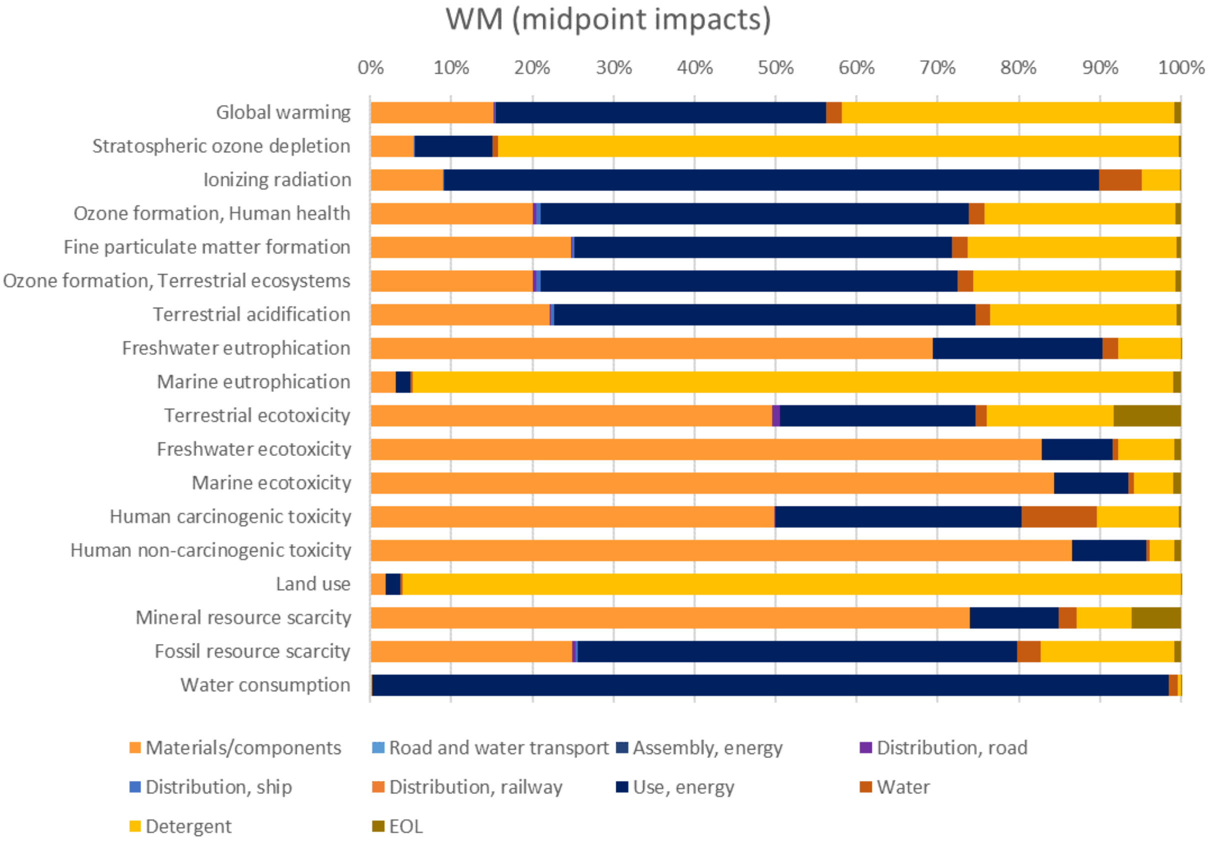

Figure 14. Midpoint impacts for the C-SERVEES WM (cradle-to-grave) by life cycle phases

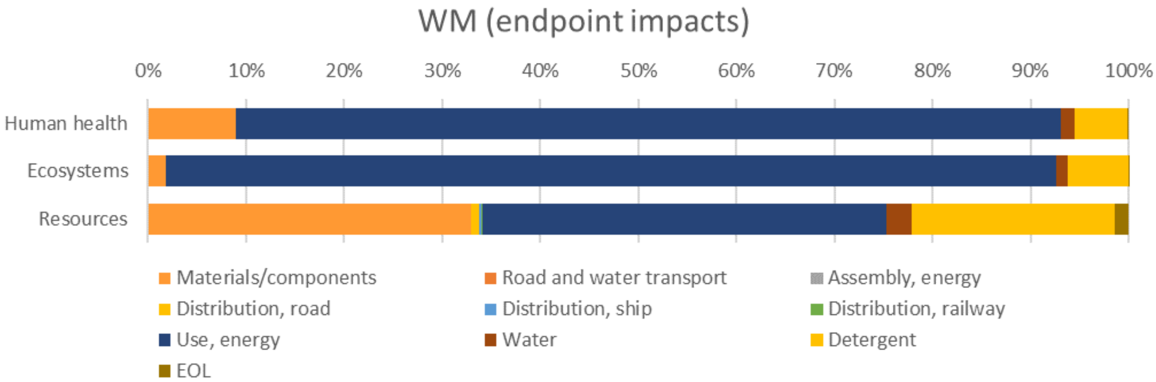

Figure 15. Endpoint impacts for the C-SERVEES WM (cradle-to-grave) by life cycle phases.

4.7 C-SERVEES material circularity indicator

Material flows associated with the washing machine were grouped into the following: 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 148). 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 6). 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 Table 33). 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 Table 39.

Table 39. Feedstock and waste for one C-SERVEES WM 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	16,678	14.241	13,028	8.961	7.321	0.812
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	**74.738**	**63.323**	**52.190**	**40.157**	**22.257**	**1.810**

MCI calculation for the washing machine was then conducted. 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, Table 40, was 0.83. The MCI for the washing machine was finally calculated as 0.25.

Table 40. MCI calculation for the C-SERVEES WM.

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**

4.8 Comparative life cycle assessment

Environmental enhancement of the washing machine is performed with recycled materials for the inner door, the detergent box and the tub, as well as mass reduction of the tub and some less reductions in the inner cover and the detergent box. These improvements reduce the environmental impact in almost all impact categories to a maximum of 0.3% (Resources endpoint) and an average of 0.08% for the life cycle of the washing machine, including electricity, detergent and water, see Figure 16.

These improvements are clearer if we only consider the washing machine, without taking into account electricity, water and detergent during use. In this case, the environmental improvement is an average of 0.25% across all impact categories. The largest impact reduction occurs in the impact category of ionising radiation (2.51% for WM only) and, in contrast, two impact categories worsen for WM with recycled materials, water consumption and stratospheric ozone depletion. For the remaining impact categories, the values are more homogeneous, within the range 0-1.3%.

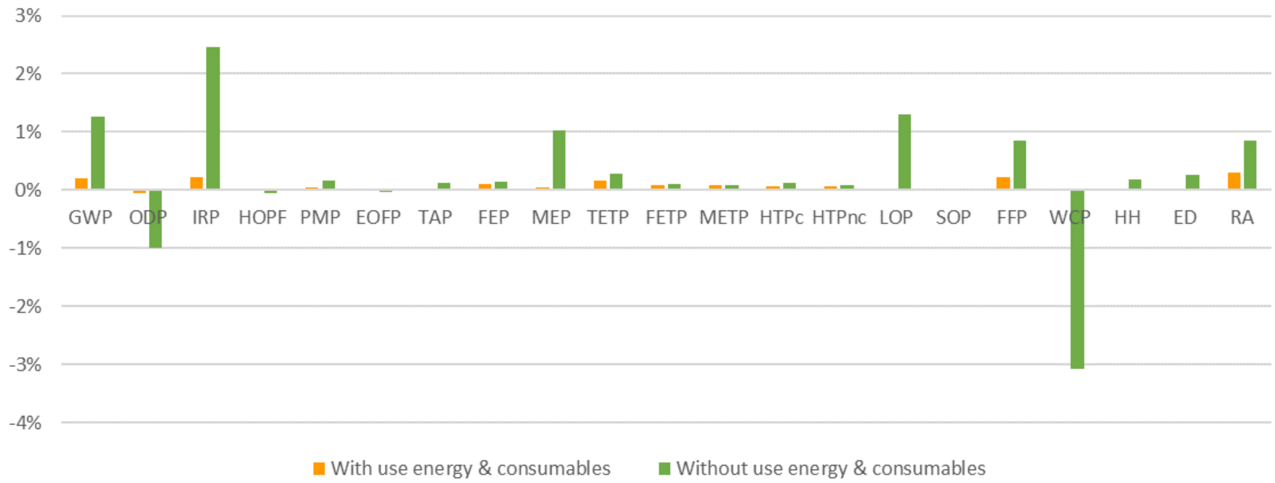

Figure 16. WM relative environmental impact reductions.

Considering global warming impact category, the environmental impact is reduced during component manufacture and at the end of life by 1.3% and 0.9%, respectively, see Table 41 and *Figure 17*. However, energy and detergent, the most impactful, remain unchanged, leaving a total reduction for the whole life cycle by 0.2%. No change is produced in the recycling benefits.

Table 41. Comparative GWP for washing machine, including electricity and consumables during use, for one washing cycle.

Units: kg CO_{2eq}		**Reference**	**CSERVEES**	**Relative improvement**
Manufacturing	Components	0.131	0.129	1.3%
Use	Distribution	0.003	0.003	0.0%
	Electricity	0.348	0.348	0.0%
	Water	0.017	0.017	0.0%
	Detergent	0.349	0.349	0.0%
EOL	End-of-life	0.007	0.007	0.9%
TOTAL		**0,854**	**0.852**	**0.2%**
Recycling	Benefits	-0.012	-0.012	0.0%

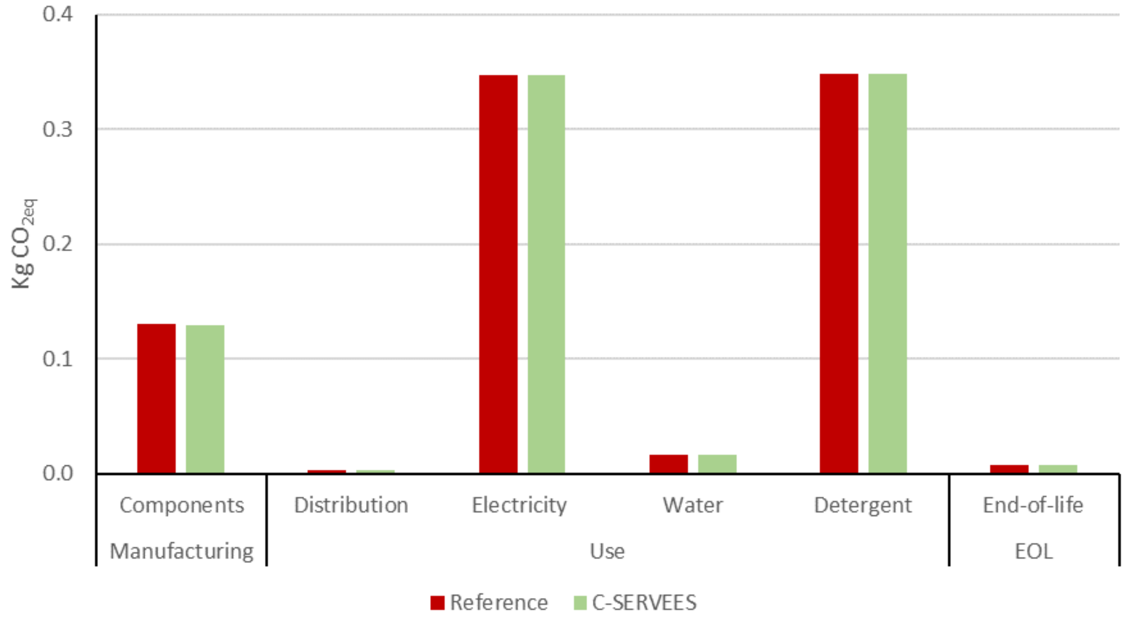

Figure 17. WM comparative GWP, including electricity and consumables during use, for one washing cycle.

4.9 Comparative material circularity

Circularity enhancement of the washing machine is performed with recycled materials for the inner door, the detergent box and the tub, as well as mass reduction of the tub and some less reductions in the inner cover and the detergent box. All these improvements increase the material circularity 1.7%, from 0.249 to 0.253, see Figure 18.

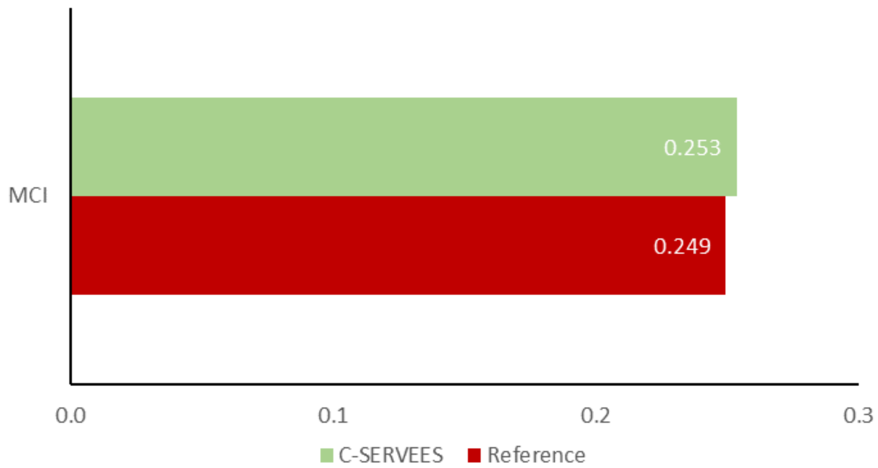

Figure 18. WM comparative MCI

5 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 42.

The functional unit considered in the present study is 1,000 printed pages with the one multifunctional laser printer LEXMARK CX860dte. The performance of this laser printer is 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. The assessment was initially performed for one product and at the end converted to the functional unit.

Table 42. 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

The activities conducted in the LCSA were derived from the PRINT-CIRCMODE short-term actions validated in WP2. The table below presents the PRINT-CIRCMODE canvas sub-components and their validated short-term CE actions, as presented in Table 24 in D2.3, and the selected strategies implemented in WP5 as C-SERVEES product.

Table 43. Validated short-term PRINT-CIRCMODE Canvas Key Circular sub-components and their associated Circular Economy Actions relevant for the LCSA.

PRINT-CIRCMODE Canvas Sub-Component	PRINT-CIRCMODE validated short-term Circular Economy Actions	LCSA implemented
PRINT_C2.3 Introduce and/or expand the use of ICT to foster circular economy	PRINT_A2.3.1 Use ICT to support information sharing across the supply chain related to recycled content	Remanufacturing
PRINT_C1.1 Diversify circular activities	PRINT_A1.1 2 Identify levers to reduce dismantling and refurbishing cost by setting various operating models	
PRINT_C1.5 Provide repair and maintenance services, including new technologies such as 3D printing	PRINT_A1.5.2 Salvage working and repairable parts from collected/return printers and use on E2N (Equal to New) printers	
PRINT_C1.6 Optimize end-of-life circularity	PRINT_A1.6.1 increase the flow of returned end-of-life printers by reducing the associated time and cost	
PRINT_C2.3 Introduce and/or expand the use of ICT to foster circular economy	PRINT_A2.3.1 Use ICT to support information sharing across the supply chain related to recycled content	
PRINT_C9.4 Implement and/or enhance strategies and/or practices to address the challenges of promoting options with lower lifetime rather than lower initial costs	PRINT_A9.4.2 Investigate economics of more CE suitable materials coming from end-of-life cartridges or printers	Remanufacturing toner cartridges

5.1 Scope

5.1.1 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).

Table 44 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.

Table 44. 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)	

5.1.2 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.

5.1.3 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) 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 Annex A1.1).
    - 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.

5.1.4 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 148).
- 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.
- 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 6). 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.

5.2 Reference life cycle inventory

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

5.2.1 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 Table 45.

Table 45. Modules of the Reference MLP.

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 Table 46.

Table 46. LCI datasets of material, components and processes for Reference MLP.

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
PMMA	Polymethyl methacrylate, beads {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
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
LED SMD high-efficiency	Light emitting diode {GLO}| market for | Cut-off, U	1 kg

Input	Dataset name	FU
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

5.2.2 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 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 5.1.4. The values are shown in Table 47.

Table 47. Estimated amounts of inputs for the use of one Reference MLP.

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 Table 47) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in Table 48.

Table 48. LCI datasets of transport modes for the Reference MLP.

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 Table 47) by the impacts calculated from the corresponding LCI datasets, which are shown in Table 49.

Table 49. LCI datasets of electricity, paper, toner cartridges and other replacements for the Reference MLP.

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

5.2.3 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 Table 50 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 by local recyclers. 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.).

Table 50. Waste material flows related to one Reference MLP EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
LPA| ABS-PC without BFR, density < 1.3	1.647	1.098	0.00
LPA| ABS without BFR, density < 1.3	29.521	19.690	0.00
LPA| Aluminium	0.852	0.568	0.55
LPA| Brass	0.004	0.003	1.87E-03
LPA| Bronze	0.447	0.298	0.23
LPA| Copper within Wire	1.020	0.681	0.48
LPA| Copper	0.407	0.272	0.16
LPA| Glass fibres-plastics composites	8.888	5.929	0.00
LPA| PA without BFR, density < 1.3	0.211	0.141	0.00
LPA| PBT without BFR, density < 1.3	4.861	3.242	0.00
LPA| PC without BFR, density < 1.3	1.458	0.972	0.00
LPA| PMMA	0.121	0.081	0.000
LPA| PP without BFR, density < 1.3	0.506	0.337	0.105
LPA| Copper within PCB	0.750	0.500	0.376
LPA| Gold within PCB	1.17E-03	7.78E-04	0.001
LPA| Lead within PCB	6.96E-03	4.65E-03	0.001
LPA| PCB Other base metals	0.941	0.628	0.000
LPA| PCB Support	1.422	0.949	0.000
LPA| Platinoid within PCB	2.13E-05	1.42E-05	1.88E-06
LPA| Silver within PCB	5.97E-03	3.98E-03	5.16E-04
LPA| PS without BFR, density < 1.3	0.220	0.147	0.000
LPA| PUR foam	0.383	0.255	0.000
LPA| PVC within wire	1.546	1.031	0.000
LPA| Steel	74.506	49.695	41.954
LHA | Glass	0.001	0.000	0.000
Total WEEE laser printer	**129.726**	**86.527**	**43.859**

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 Table 51.

Table 51. Waste material flows related to EoL of replacements for one Reference MLP (toners, imaging kits, fuser kits and toner bottles).

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
LPA| ABS-PC without BFR, density < 1.3	0.057	0.038	0.000
LPA| ABS without BFR, density < 1.3	7.086	4.726	0.000
LPA| Aluminium	0.071	0.048	0.046
LPA| Bronze	0.085	0.056	0.043
LPA| Copper within Wire	0.004	0.003	0.002
LPA| Copper	0.007	0.005	0.003
LPA| Glass fibres-plastics composites	0.536	0.357	0.000
LPA| PA without BFR, density < 1.3	0.008	0.006	0.000
LPA| PBT without BFR, density < 1.3	0.909	0.606	0.000
LPA| Copper within PCB	0.017	0.012	0.005
LPA| Gold within PCB	7.91E-06	5.28E-06	3.32E-06
LPA| Lead within PCB	6.19E-05	4.13E-05	8.91E-06
LPA| PCB Other base metals	0.113	0.075	0.000
LPA| PCB Support	0.015	0.010	0.000
LPA| Platinoid within PCB	4.47E-07	2.98E-07	2.44E-08
LPA| Silver within PCB	1.04E-04	6.92E-05	5.69E-06
LPA| PS without BFR, density < 1.3	0.051	0.034	0.000
LPA| PUR foam	0.006	0.004	0.000
LPA| PVC within wire	2.262	1.509	1.274

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
LPA| Steel	0.000	0.000	0.000
Total WEEE laser printer replacements	**11.228**	**7.489**	**1.376**

Table 52 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.

Table 52. Total waste material flows related to one Reference MLP EoL (including replacements).

Input	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
Laser printer	129.726	86.527	43.859
Replacements	11.228	7.489	1.376
Total WEEE	**140.953**	**94.016**	**39.680**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one laser printer) is shown in Table 50 and Table 51. 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 was 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 are finally landfilled classified by waste material flow is shown in Table 53.

Table 53. Waste material flows related to landfill disposal of one Reference MLP (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 Table 54.

Table 54. LCI datasets of landfill disposal for the Reference MLP 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

5.3 Reference life cycle impact assessment

Life cycle impact assessment for the Reference laser printer was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

5.3.1 Manufacturing (cradle-to-gate)

Table 55 shows the environmental impacts for the manufacturing of one laser printer, 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.

Table 55. Global warming and endpoint impacts for the manufacturing of one Reference MLP (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)	11.67	2.42E-05	5.06E-08	1.42
21K2300	180.31	5.68E-04	8.60E-07	18.88
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 print head	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	393.85	1.73E-03	2.46E-06	31.89
Scanner module	65.38	3.14E-04	4.90E-07	6.14
Toner cartridge	7.47	1.71E-05	3.21E-08	0.99
Waste toner bottle	6.59	1.31E-05	2.75E-08	0.85
Recycled plastic	-44.32	-6.06E-05	-1.01E-07	-6.81
Transport of components	24.01	9.12E-05	1.75E-07	3.26
Total manufacturing	**846.39**	**3.56E-03**	**5.19E-06**	**72.12**

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 Figure 19 and Figure 20, 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.

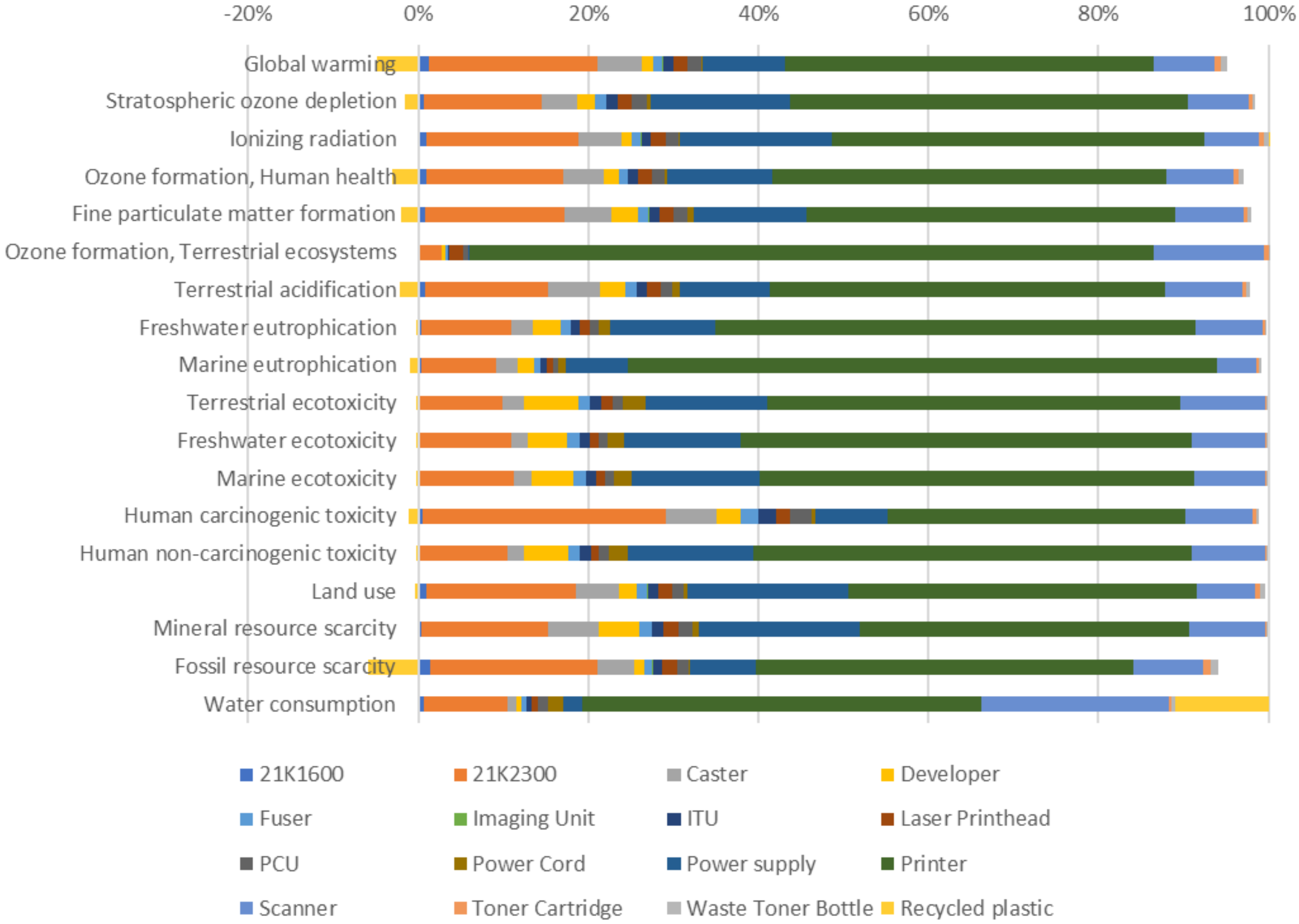

Figure 19. Midpoint impacts for the Reference MLP manufacturing (cradle-to-gate).

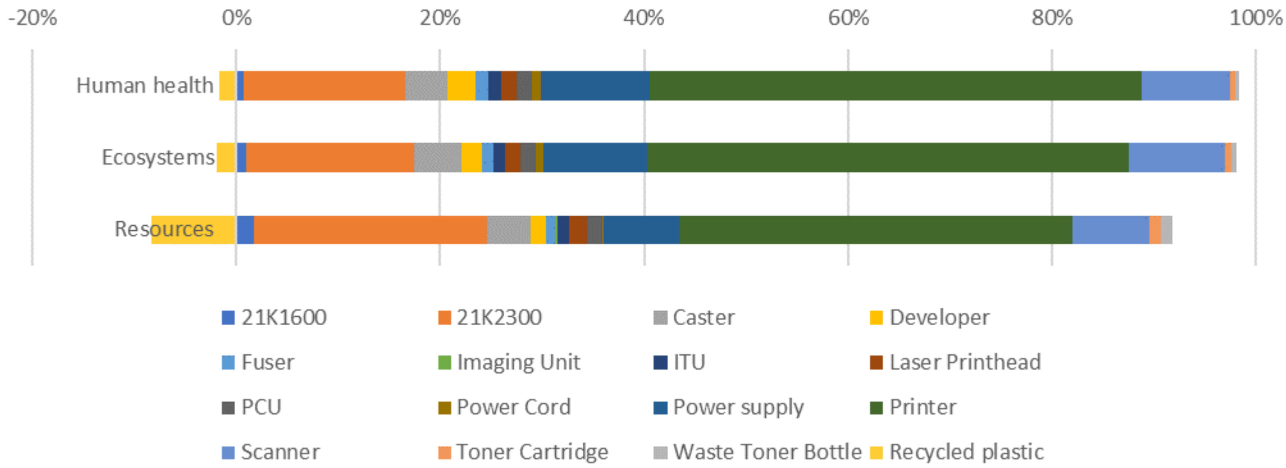

Figure 20. Endpoint impacts for the Reference MLP manufacturing (cradle-to-gate)

5.3.2 Use

Table 56 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 5 & Figure 6).

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).

Table 56. Global warming and endpoint impacts for the use of one Reference MLP.

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)	125.60	3.98E-04	6.42E-07	15.27
Total Use (variable elect. mix - 2020-2032)	**1692.42**	**6.60E-03**	**3.60E-05**	**164.97**
Total Use (constant elect. mix - 2020)	**1697.62**	**6.63E-03**	**3.62E-05**	**165.15**

5.3.3 Total (cradle-to-grave)

Table 57 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 Figure 21 and Figure 22, respectively.

Table 57. Global warming and endpoint impacts for the whole life cycle of one Reference MLP (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	846.39	3.56E-03	5.19E-06	72.12
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	1347.75	3.54E-03	2.14E-05	128.87
Use, toners	85.06	2.06E-04	3.78E-07	10.22
Maintenance (replacements, incl. transport)	125.60	3.98E-04	6.42E-07	15.27
EoL (waste treatment)	66.65	1.64E-04	3.33E-07	5.58
TOTAL (variable elect. mix)	**2605.46**	**1.03E-02**	**4.16E-05**	**242.66**
Credits from recycling	-150.99	-5.67E-04	-1.07E-06	-12.81

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).

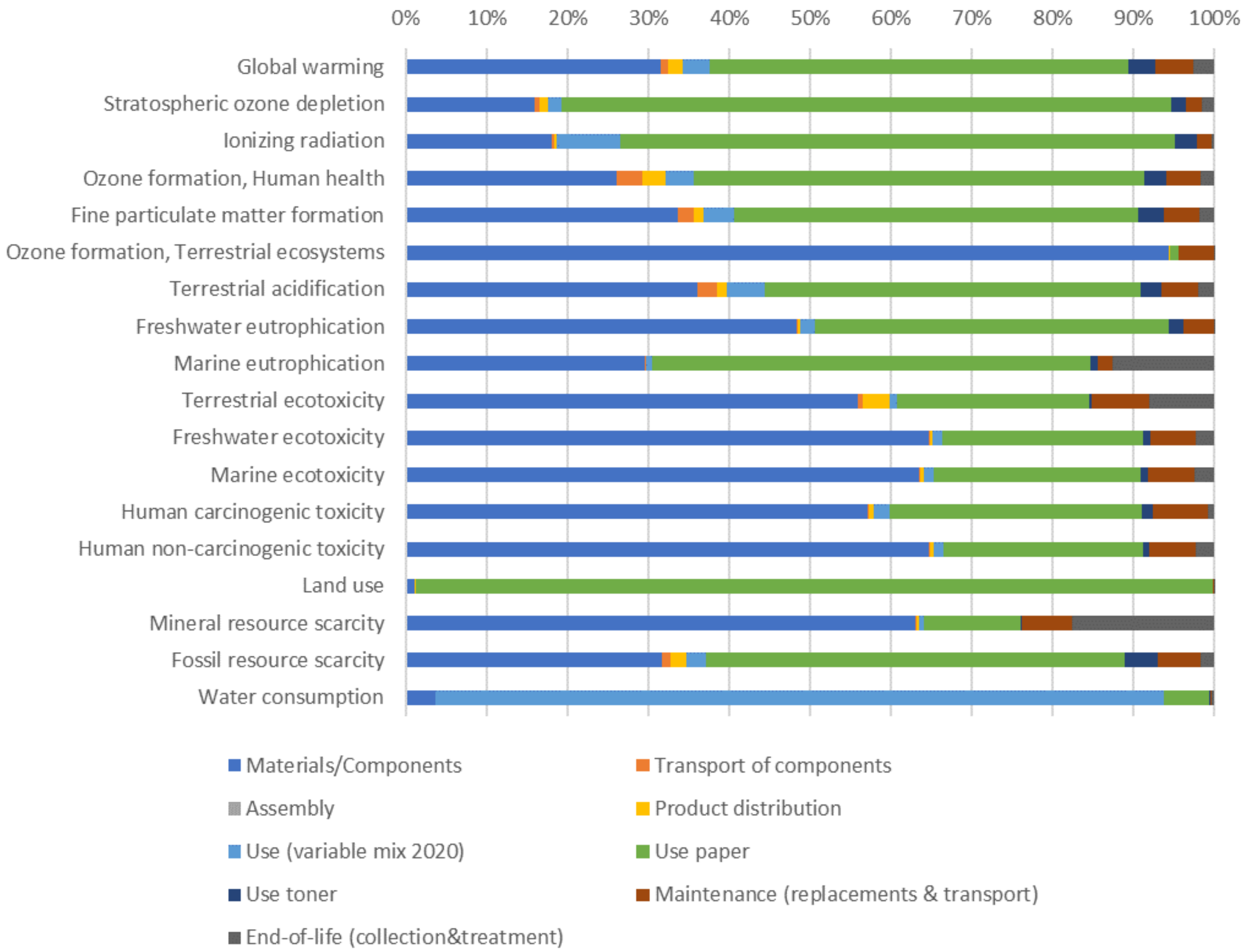

Figure 21. Midpoint impacts for the Reference MLP (cradle-to-grave).

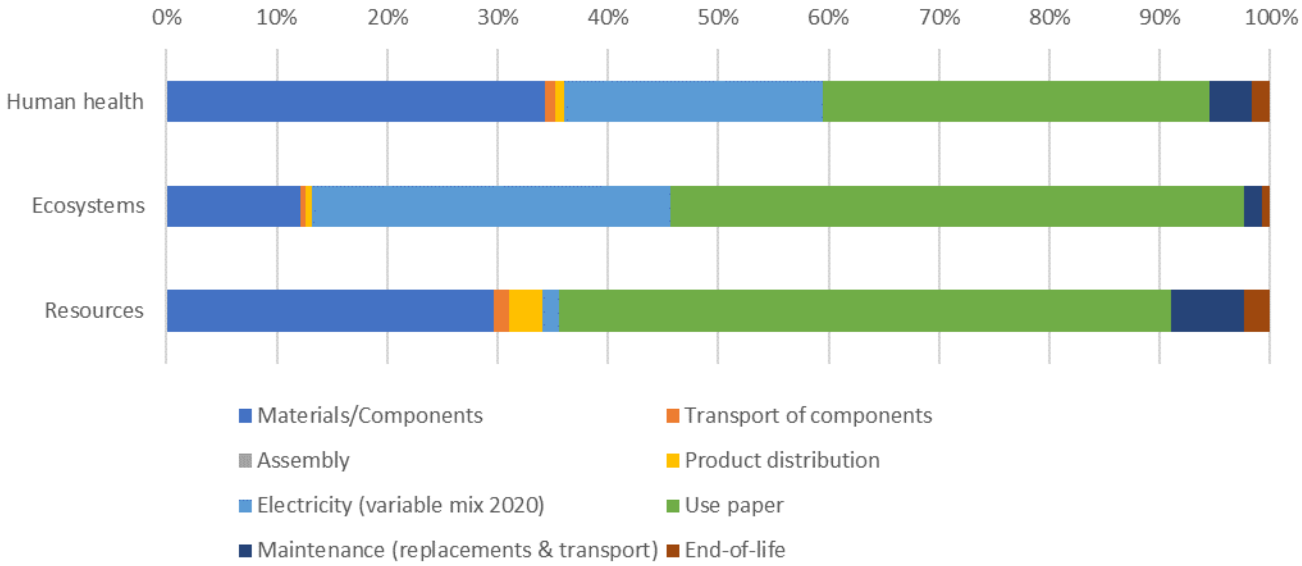

Figure 22. Endpoint impacts for the Reference MLP (cradle-to-grave).

5.4 Reference material circularity indicator

Material flows associated with the laser printer were grouped into the following: 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 148). The Reference laser printer only contains virgin feedstock.

The amount of waste collected for recycling was assumed to be the same as the waste collection rate for large household appliances (see Table 6). It was assumed to be the same for all material categories included in the laser printer taking into account the waste treatment figures in Table 50 and Table 51. The amount of waste going to landfill or energy recovery (W_0) was therefore deducted directly from the waste collection rate.

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. Results for feedstock and waste are collected in Table 58.

MCI calculation for the laser printer (including its replacements) was then conducted, Table 59. 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, was 0.70. The MCI for the laser printer was finally calculated as 0.47.

Table 58. Feedstock and waste for one Reference MLP 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	54.642	30.781	25.564	7.976	2.458
Aluminium	0.923	0.725	0.330	0.307	0.024	0.022

Copper	2.206	1.434	0.995	0.735	0.436	0.086
Gold	1.17E-03	8.81E-04	4.93E-04	3.91E-04	1.72E-04	3.26E-05
Silver	6.07E-03	5.23E-03	3.83E-03	2.02E-03	3.52E-03	9.37E-05
Lead	7.03E-03	3.23E-03	4.22E-03	2.34E-03	3.34E-03	4.22E-04
Platinoid metals	2.17E-05	1.61E-05	1.38E-05	7.23E-06	1.26E-05	6.22E-07
Other metals	1.591	1.384	0.935	0.530	0.788	0.023
Plastic	59.451	50.939	40.991	19.797	39.549	2.837
TOTAL	**140.953**	**109.134**	**74.041**	**46.937**	**48.781**	**5.427**

Table 59. MCI calculation for the Reference MLP.

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	0.70
Material Circularity Indicator of the product MCI_P	**0.47**

5.5 C-SERVEES life cycle inventory

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

5.5.1 C-SERVEES redesign changes

Redesign changes implemented in the LCSA as described in Table 43 are detailed in Table 60. Selected strategy in C-SERVEES PRINTER set is reusing part of the components for remanufacturing new printers. The list of components remanufactured and their percentages of time replaced is detailed in Table 63.

Table 60. C-SERVEES MLP changes implemented in LCSA.

	Reference	CSERVEES
Lifetime, years	5	5
Functional units, printed pages	390000	390000
Recycled content	Recycled plastics	Recycled plastics
Remanufacturing	NO	YES

5.5.2 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 Table 61.

Table 61. Modules of the C-SERVEES MLP.

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 Table 62.

Table 62. LCI datasets of material, components and processes for the C-SERVEES MLP.

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
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

Input	Dataset name	FU
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
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

Input	Dataset name	FU
	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

Remanufactured parts

LEXMARK also provided a list of parts suitable for remanufacturing, including the replacement frequency for each part, expressed as the percentage of times they can be reused to replace virgin parts, Table 63. 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:

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

Table 63. Remanufactured parts in the C-SERVEES MLP.

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
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

Part name	BoM part number	Percentage of time replaced (%)
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

5.5.3 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 5.1.4. The values are shown in Table 64.

Table 64. Estimated amounts of inputs for the use of one C-SERVEES MLP.

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 Table 64) by the impacts calculated from the corresponding LCI datasets for transport modes. The LCI datasets used for each transport mode are listed in Table 65.

Table 65. LCI datasets of transport modes for the C-SERVEES MLP.

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 Table 64) by the impacts calculated from the corresponding LCI datasets, which are shown in Table 66.

Table 66. LCI datasets of electricity, paper, toner cartridges and other replacements for C-SERVEES MLP.

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

5.5.4 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 Table 67 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.).

Table 67. Waste material flows related to the C-SERVEES MLP EoL.

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 Table 68

Table 68. Waste material flows related to EoL of replacements for C-SERVEES MLP (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

Datasets	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
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**

Table 69 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.

Table 69. Total waste material flows related to the C-SERVEES MLP 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 Table 67 and Table 68. 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 was 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 Table 70.

Table 70. Waste material flows related to landfill disposal of one C-SERVEES MLP (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 Table 71.

Table 71. LCI datasets of landfill disposal for one C-SERVEES MLP 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

5.6 C-SERVEES life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

5.6.1 Manufacturing (cradle-to-gate)

Table 72 shows the environmental impacts for the manufacturing of one laser printer, 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.

Table 72. Global warming and endpoint impacts for the manufacturing of one C-SERVEES MLP (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	8.49E-01
21K2300	172.56	5.54E-04	8.28E-07	1.78E+01
Caster	48.05	1.48E-04	2.42E-07	3.53E+00
Developer	12.17	1.01E-04	1.06E-07	1.26E+00
Fuser	9.33	4.49E-05	5.72E-08	7.23E-01
Imaging unit	1.01	1.81E-06	4.10E-09	1.67E-01
ITU (Intermediate transfer module)	10.35	4.30E-05	5.73E-08	9.69E-01
Laser print head	14.97	5.33E-05	7.87E-08	1.45E+00
PCU	15.56	5.45E-05	7.97E-08	1.23E+00
Power cord	1.28	3.23E-05	3.73E-08	1.23E-01
Power supply	88.69	3.85E-04	5.33E-07	6.04E+00
Printer module	358.81	1.61E-03	2.28E-06	2.86E+01
Scanner module	38.77	1.94E-04	2.84E-07	3.82E+00
Toner cartridge	4.98	1.14E-05	2.14E-08	6.62E-01
Waste toner bottle	6.59	1.31E-05	2.75E-08	8.55E-01
Recycled plastic	-44.32	-6.06E-05	-1.01E-07	-6.81E+00
Transport of components	21.53	8.18E-05	1.57E-07	2.93
Total manufacturing	**767.34**	**3.28E-03**	**4.72E-06**	**64.28**

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 Figure 23 and Figure 24, 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.

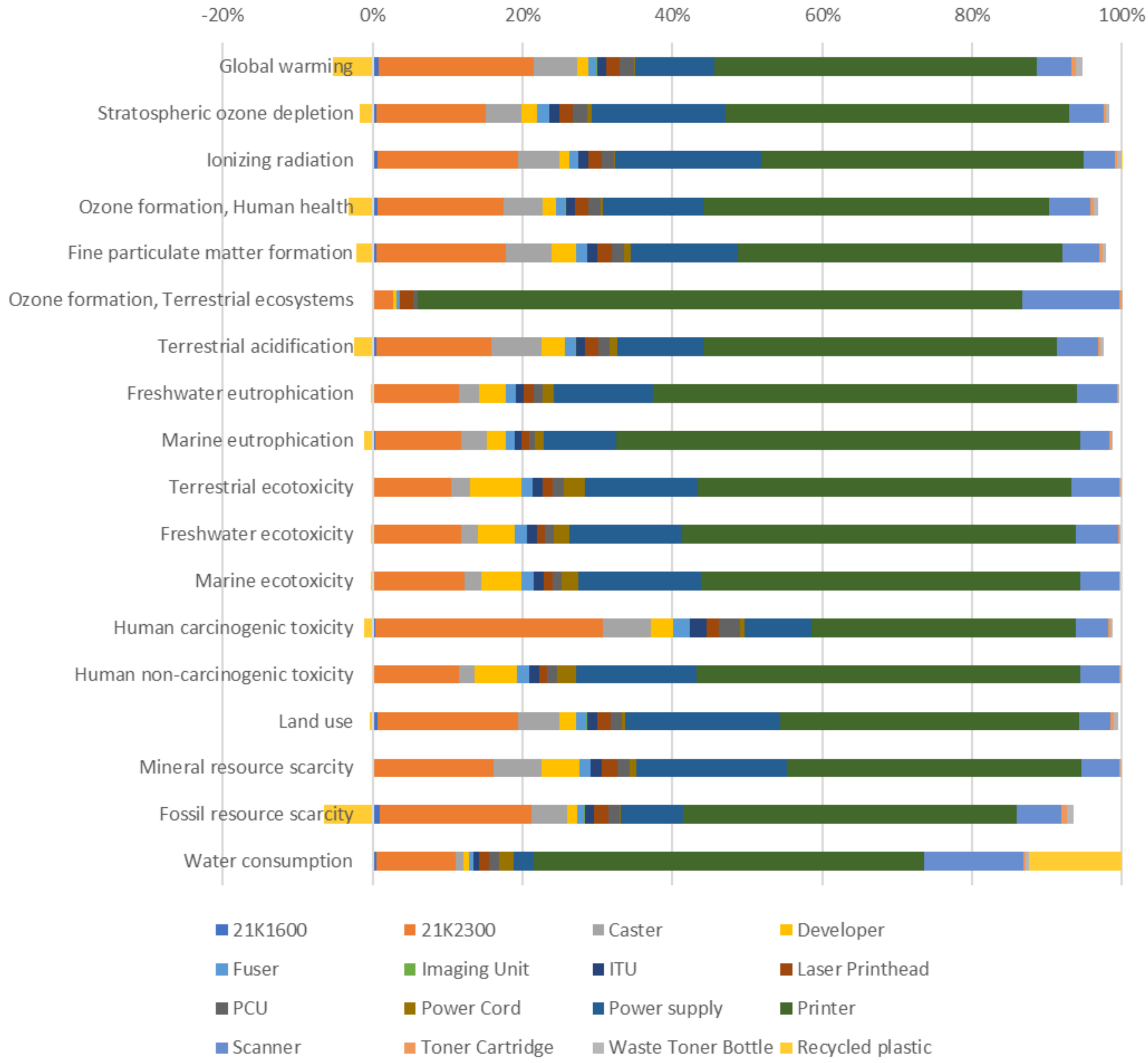

Figure 23. Midpoint impacts for the C-SERVEES MLP manufacturing (cradle-to-gate).

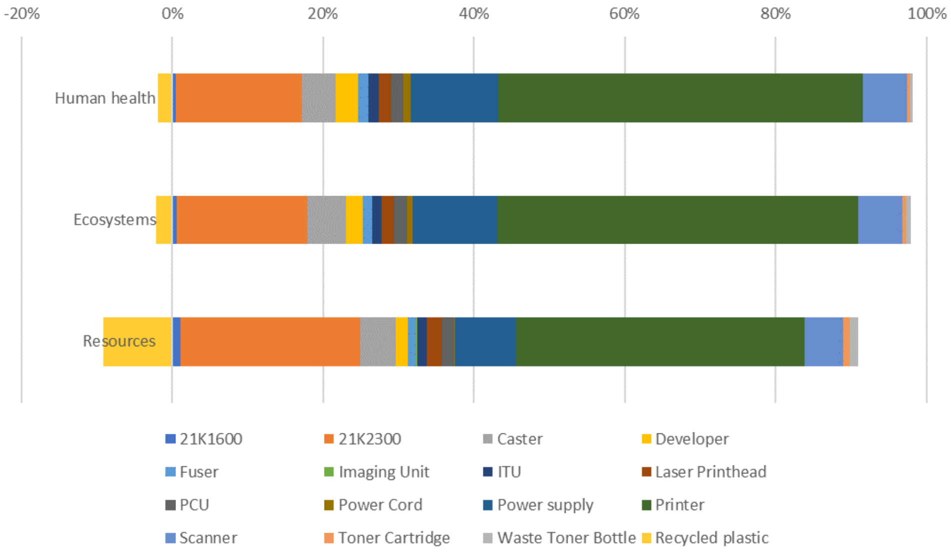

Figure 24. Endpoint impacts for the C-SERVEES MLP manufacturing (cradle-to-gate)

5.6.2 Use

Table 73 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 5 & Figure 6).

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).

Table 73. Global warming and endpoint impacts for the use of one C-SERVEES MLP.

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**

5.6.3 Total (cradle-to-grave)

Table 74 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 Figure 25 and Figure 26, respectively.

Table 74. Global warming and endpoint impacts for the whole life cycle of one C-SERVEES MLP (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	767.34	3.28E-03	4.72E-06	64.28
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)	75.45	1.84E-04	3.81E-07	7.54
TOTAL (variable elect. mix)	**2519.03**	**1.00E-02**	**4.11E-05**	**234.64**
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).

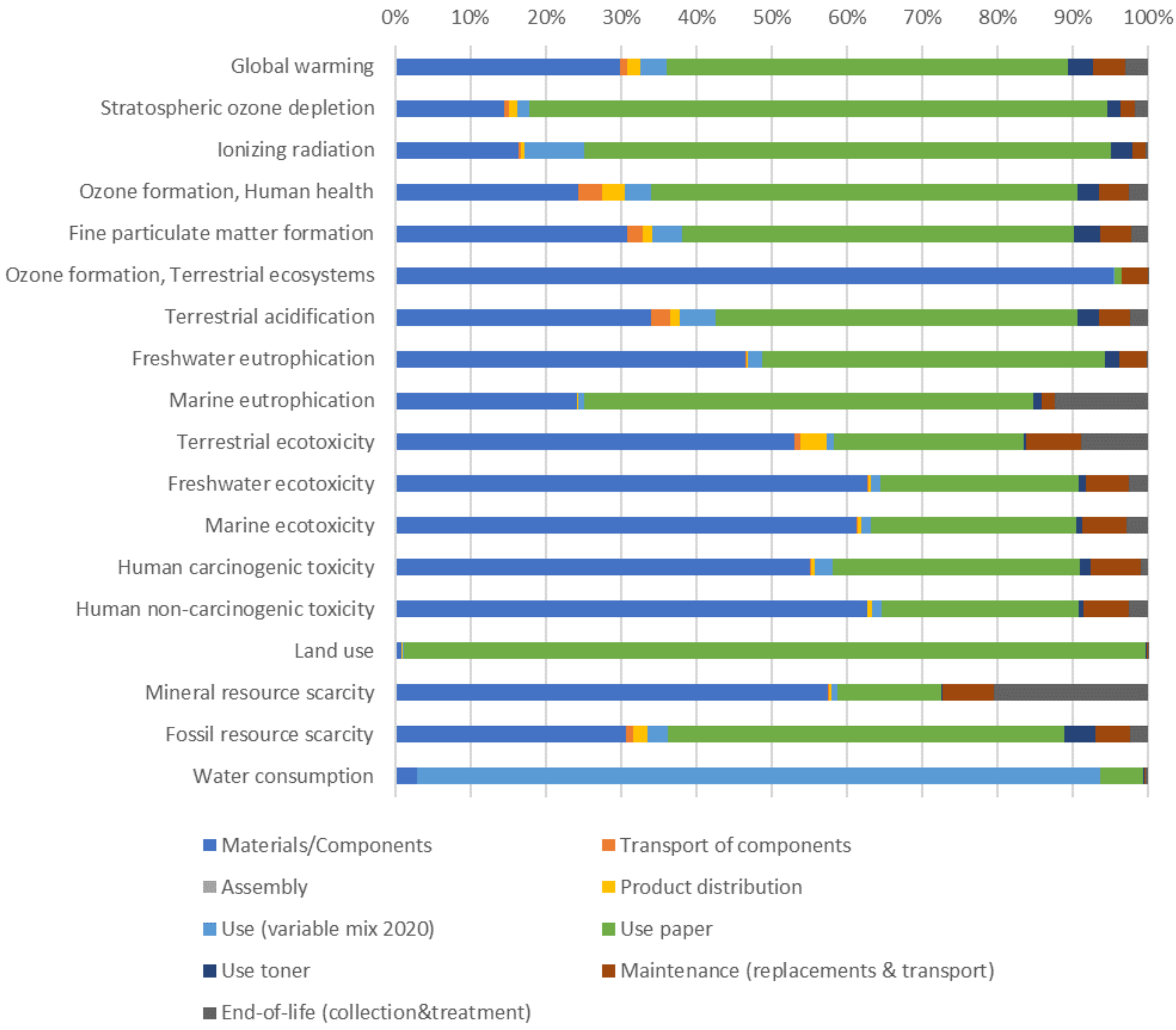

Figure 25. Midpoint impacts for the C-SERVEES MLP (cradle-to-grave).

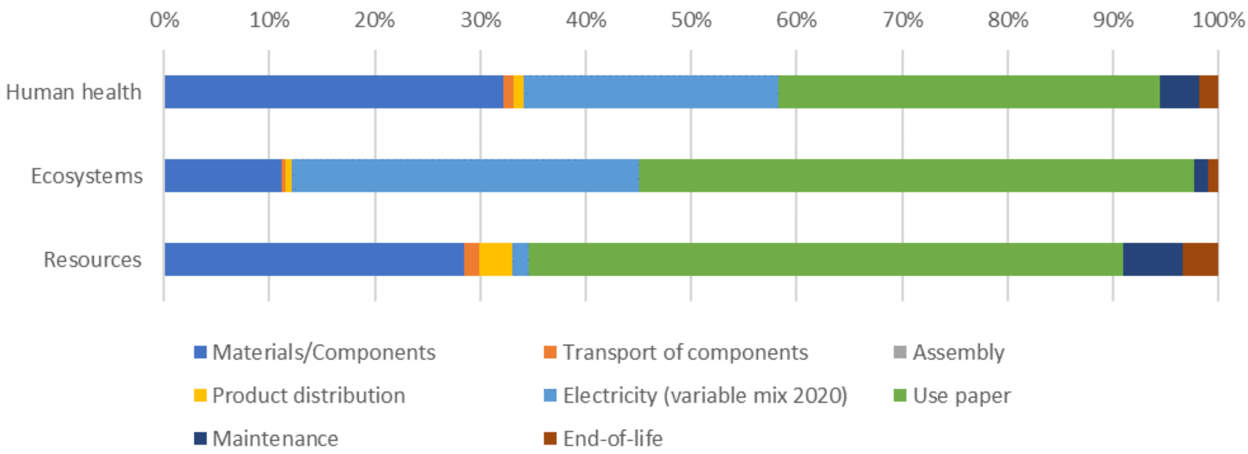

Figure 26. Endpoint impacts for the C-SERVEES MLP (cradle-to-grave).

5.7 C-SERVEES material circularity indicator

Material flows associated with the laser printer were grouped into the following: 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 148). 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 6). 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 Table 67 and Table 68. 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 Table 67 and Table 68). 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 Table 75.

MCI calculation for the laser printer (including its replacements) was then conducted, Table 76. 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, was 0.61. The MCI for the laser printer was finally calculated as 0.54.

Table 75. Feedstock and waste for one C-SERVEES MLP 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**

Table 76. MCI calculation for the C-SERVEES MLP.

Parameter	**Value**
Actual average lifetime of product L (years)	5
Actual average lifetime of industry-average product L_{av} (years)	5

Parameter	Value
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**

5.8 Comparative life cycle assessment

Re-manufacturing laser printers positively affects environmental impacts, Figure 27, an average of 8.0% across all impact categories, if only the printer is considered in the LCA, or 3.3%, if electricity and consumables during the use phase are also considered. The largest impact reduction is in the marine eutrophication category (21% for only printer) due to the reduction of virgin plastic. However, the impact reduction values in the other categories are more homogeneous, 5-10%.

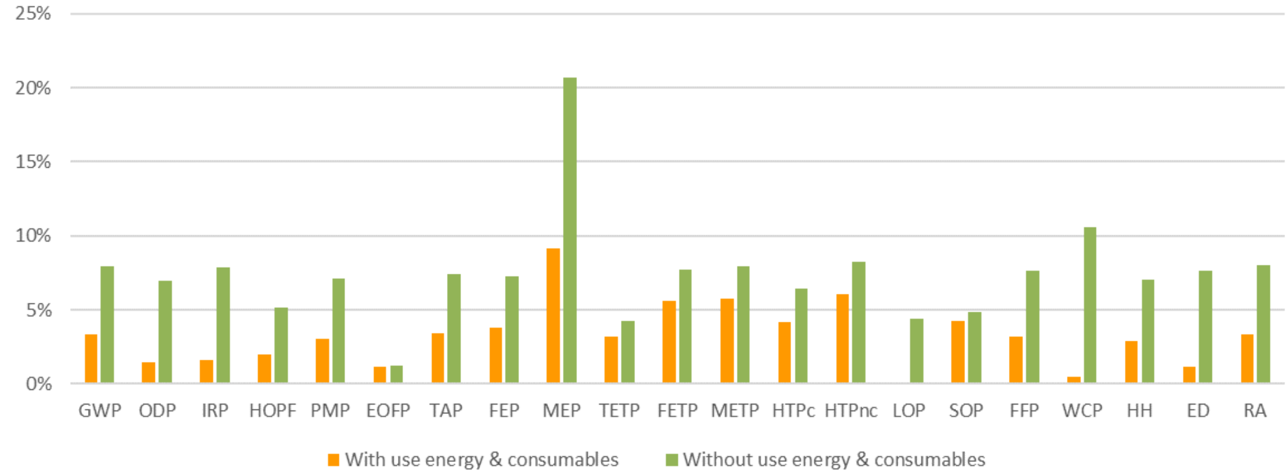

Figure 27. Laser printers relative environmental impact reductions.

Considering global warming impact category, the environmental impact is reduced during manufacturing components by 9.3%, see Table 77 and Figure 28, together with transport of components and maintenance (replacements and transport). To achieve this improvement there is an increase in end-of-life impact (-13.2%) and a loss of recycling benefits (-14%). However, the improvement from remanufacturing is far greater than these losses. Even considering all spare parts and consumables and electricity for use, the carbon footprint improvement is 3.3%. If consumables and electricity are not included during the use phase, the carbon footprint is improved by 8.0% (Figure 27).

Table 77. MLP GWP comparative assessment (including use energy, paper & toner) for 1,000 printed pages.

Units: kg CO_{2eq}		Reference	C-SERVEES	Relative improvement
Manufacturing	Components	2.109	1.912	9.3%
	Transport	0.062	0.055	10.3%
Use	Distribution	0.116	0.116	0.0%
	Electricity	0.227	0.227	0.0%
	Paper	3.456	3.456	0.0%
	Toner	0.22	0.22	0.0%
	Maintenance	0.32	0.28	12.9%
EOL	End-of-life	0.171	0.193	-13.2%
TOTAL		**6.681**	**6.459**	**3.3%**
Recycling	Benefits	-0.387	-0.331	-14.4%

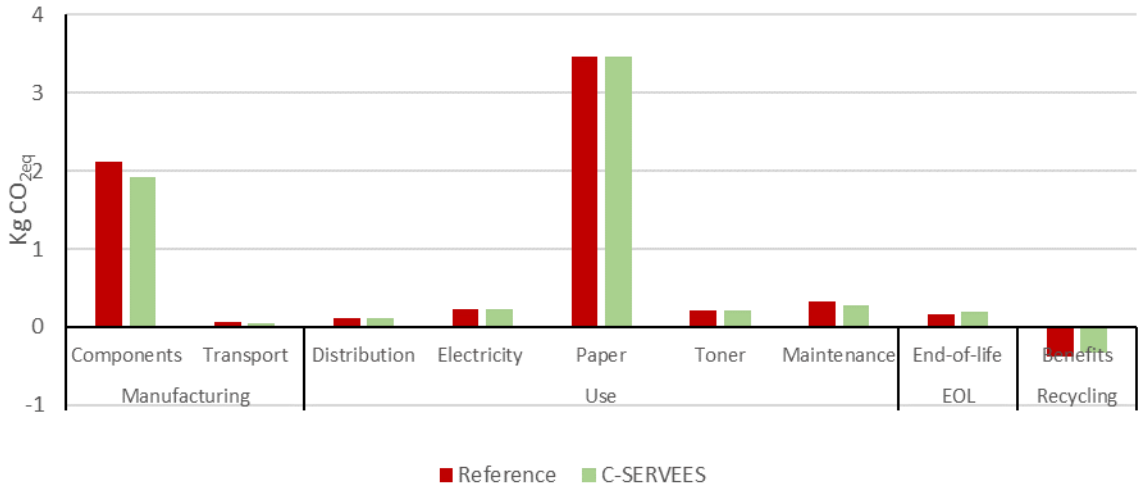

Figure 28. MLP GWP comparative assessment for 1,000 printed pages.

5.9 Comparative material circularity

Circularity enhancement of the C-SERVEES is performed by reusing several parts for remanufacturing new printers and toner cartridges. Remanufacturing reduces virgin feedstock by 16.11 kg for one printer (including replacements), thus material circularity indicator improves by 12.3%, from 0.48 to 0.55, see Figure 29.

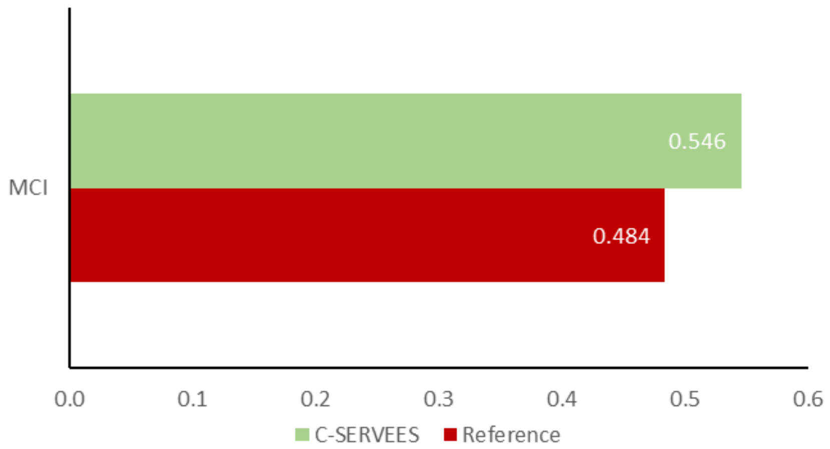

Figure 29. MCI for laser printers (including replacements).

6 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 sensors for fibre monitoring tasks like real-time information on fibre integrity, fast and easy localization of user traffic and remote active 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 active sensors. The ALM product selected as the reference for the life cycle sustainability assessment was the ADVA 16ALM/#1650D/AC, while one sensor configuration for door-opening detection was included in the assessment. More details on the current ALM product selected for the sustainability assessment are shown in Table 78.

The functional unit considered in the present study is one hour of one ALM product monitoring, including the active unit (ADVA 16ALM/#1650D/AC) and 50 passive sensors. This combined system offers continuous monitoring throughout its 8-year lifetime (i.e., 365 days/year and 24 h/day) in the Reference product and 15-year lifetime for the C-SERVEES Product. The assessment was initially performed for one product and at the end converted to the functional unit.

Table 78. 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

The activities conducted in the LCSA were derived from the ALM-CIRCMODE short-term actions validated in WP2. The table below presents the ALM-CIRCMODE canvas sub-components and their validated short-term CE actions, as presented in Table 24 in D2.4, and the selected strategies implemented in WP5 as C-SERVEES product.

Table 79. Validated short-term ALM-CIRCMODE Canvas Key Circular sub-components and their associated Circular Economy Actions relevant for the LCSA.

ALM-CIRCMODE Canvas Sub-Component	ALM-CIRCMODE validated short-term Circular Economy Actions	LCSA implemented
ALM_C1.1 Diversifying circular activities	ALM_A1.1.1 Design for longevity, in particular better maintainability	Lifetime from 8 to 15 years
ALM_C1.2 Embrace eco-design to ensure products circularity across life-cycle stages	ALM_A1.2.2 Devise an eco-design approach in production and Design for Recycling	Recycled passive sensors
ALM-C9.2: Introducing and/or enhancing manufacturing and sales processes to account	ALM_A9.2.1 Reduce costs of manual disassembly for recycling	10% reuse in central unit

ALM-CIRCMODE Canvas Sub-Component	ALM-CIRCMODE validated short-term Circular Economy Actions	LCSA implemented
for costs associated with the end-of life and second life of materials, components and products		

6.1 Scope

6.1.1 Functional unit and system boundaries

The product function for the ALM product is fibre monitoring. The product considered in the study is one ALM product, including the active unit (ADVA 16ALM/#1650D/AC) and 50 passive sensors, which offers continuous monitoring throughout its 8-year lifetime for the Reference Product (i.e., 365 days/year and 24 h/day) and 15-year lifetime for the C-SERVEES Product. The functional unit for the comparative assessment is 1 hour of monitoring network.

Table 80 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.

Table 80. System boundaries considered for the telecom equipment.

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)	

6.1.2 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). 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.

6.1.3 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) 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 Annex A1.1).

6.1.4 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 148).
- 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 6).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[20]

6.2 Reference life cycle inventory

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

6.2.1 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 Table 81. 50 passive sensors were also included in the LCI for door-opening detection, as inventoried in Table 82.

Table 81. Components of one Reference active ALM unit.

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
Total	**-**	**2.363**	**kg**

Table 82. Components of one Reference passive sensor.

Components	Material	Mass (g)
Fiber	Glass fiber	0.025
Fiber coating	Acrylate, Polyacrylamide	0.025
Compression spring	Steel, low-alloyed	0.250
Sensor holder	Aluminum	7.000
Total		**7.300**

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 Table 83.

Table 83. LCI datasets of material, components and processes for the Reference TE 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

Input	Dataset name	FU
Diode, THT glass type (0,596 g average weight)	Diode, glass-, for through-hole mounting {GLO}| market for | Cut-off, U	1 kg
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

6.2.2 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 Table 84.

Table 84. Estimated amounts for distribution of one Reference TE by transport mode.

Transport mode	Amount (tkm)
Road	2.32
Water	1.43

Transport mode	Amount (tkm)
Air	5.07
Total	**8.82**

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 Table 85.

Table 85. Estimated amounts for distribution of the Reference TE by transport mode.

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 Table 86. 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).

Table 86. LCI datasets of electricity for the Reference TE product operation.

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

6.2.3 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the ALM product are classified in Table 87 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.).

Table 87. Waste material flows related to the Reference TE EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
SPA | Aluminium	0.642	0.380	0.380
SPA | Copper within PCB	1.29E-01	0.0763	0.057
SPA | Copper within Wire	2.66E-03	0.0016	0.001
SPA | Copper	0.030007	0.0178	0.014
SPA | Gold within PCB	3.27E-04	1.93E-04	1.508E-04
SPA | Lead within PCB	1.45E-03	0.001	2.459E-04
SPA | PA without BFR, density < 1.3	0.020	0.012	0
SPA | PC without BFR, density < 1.3	0.027	0.016	0
SPA | PCB Other base metals	0.126	0.075	0
SPA | PCB Support	0.194	0.115	0
SPA | Platinoid within PCB	3.64E-06	2.15E-06	2.85E-07
SPA | PVC within wire	0.002	0.001	0
SPA | Silver within PCB	1.08E-03	6.41E-04	8.31E-05
SPA | Steel	1.471	0.871	0.724
LPA| Glass fibres-plastics composites	0.004	0.002	0
LPA| PET without BFR, density < 1.3	0.072	0.043	0
Total WEEE cut-off ALM product	**2.724**	**1.612**	**1.177**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one ALM product) is shown in Table 87. 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 was 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 Table 88.

Table 88. Waste material flows related to landfill disposal of one Reference TE.

Waste type	Mass landfilled (kg)
Plastics	0.130
Aluminium	0.262
Inert material	0.719
Total	**1.112**

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 Table 89.

Table 89. LCI datasets of landfill disposal for the Reference TE 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

6.3 Reference life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

6.3.1 Manufacturing (cradle-to-gate)

Table 90 shows the environmental impacts for the manufacturing of one telecom equipment (i.e., the functional unit used in the study), including the global warming impact and endpoint impacts for every ALM component.

Table 90. Global warming and endpoint impacts for the manufacturing of one Reference TE (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	2,14E-01
Heatsink	2,125	6,54E-06	1,03E-08	9,27E-02
Small mechanical parts	1,095	5,52E-06	8,45E-09	1,33E-01
Printed wiring board (PWB)	23,729	9,42E-05	1,40E-07	1,48E+00
Power supply unit (PSU)	8,179	8,48E-07	1,36E-09	1,28E-02
Power cable	0,159	1,96E-06	1,95E-09	1,22E-02
Integrated circuits (IC)	28,812	2,05E-04	2,04E-07	9,46E-01
Capacitors	2,004	5,21E-05	3,80E-08	2,55E-01
Resistors	0,096	3,73E-06	2,63E-09	1,13E-02
Transistors	0,198	1,03E-06	1,33E-09	1,11E-02
Diodes	0,060	2,77E-07	3,44E-10	3,45E-03
Inductor	0,470	5,68E-06	5,13E-09	4,26E-02
LED	0,375	1,24E-06	1,86E-09	2,06E-02
Lightpipe	0,269	4,63E-07	1,02E-09	2,40E-02
Oscillator	0,012	1,24E-07	1,17E-10	1,02E-03
Connectors	0,493	1,93E-05	1,46E-08	6,24E-02
Coin cell battery	0,016	1,63E-07	1,72E-10	1,37E-03
Optical fibre	1,180	2,59E-06	5,70E-09	6,58E-02
Optical switch module	0,004	1,09E-07	8,12E-11	4,21E-04
Optical jumper	0,004	6,94E-09	1,62E-11	1,03E-03
Optical receiver	0,031	4,70E-07	4,16E-10	3,47E-03
Optical coupler and circulator	0,033	7,71E-08	1,64E-10	2,54E-03
Optical laser diode	0,721	3,78E-05	2,37E-08	1,04E-01
Optical adapter	0.723	1,89E-05	2,03E-08	2,14E-01
Variable optical attenuator	0.660	3,12E-06	4,54E-09	4,59E-02
Transport of components	0,802	2.86E-06	5.61E-09	0.111
Energy for assembly	9.299	6.56E-05	3.47E-07	0.190
50 Passive units	3.971	1.19E-05	1.89E-08	0.179
Total	**88.799**	**5.75E-04**	**8.79E-07**	**4.124**

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 Figure 30 and Figure 31, 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.

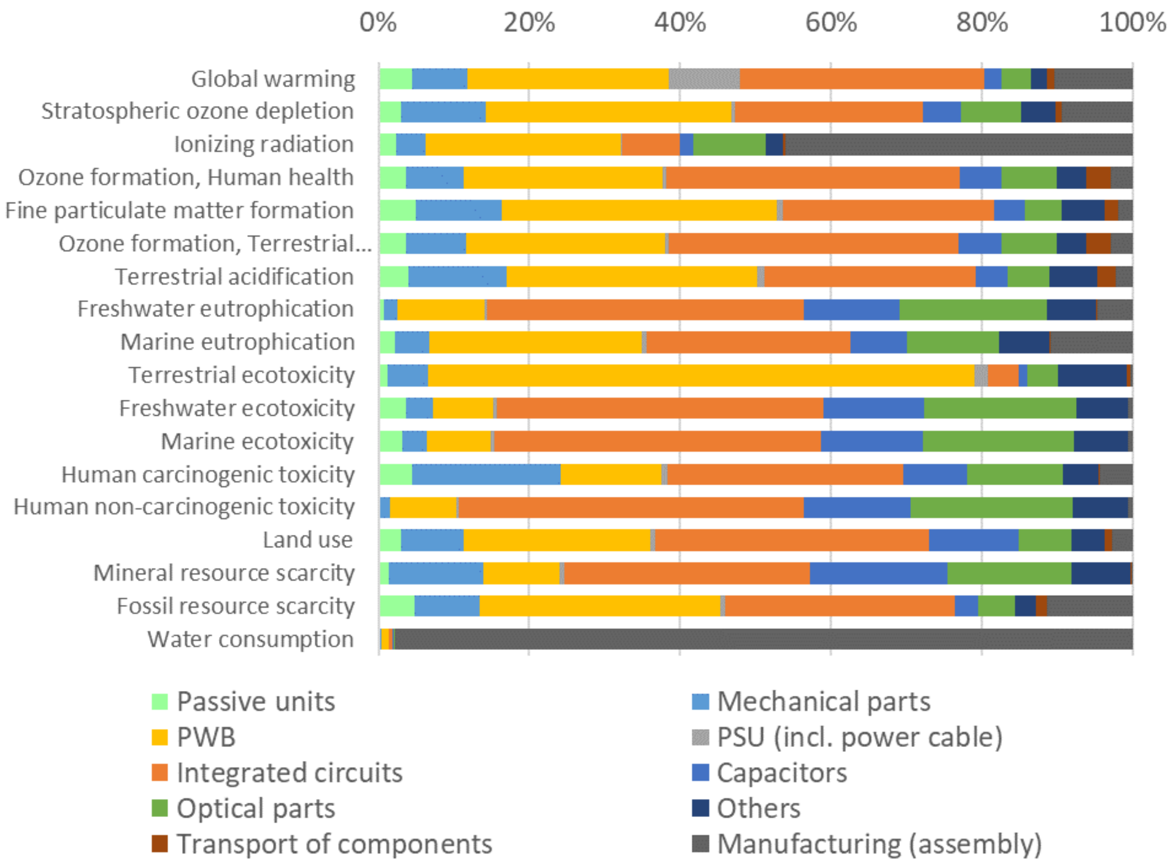

Figure 30. Midpoint impacts for the Reference TE manufacturing (cradle-to-gate).

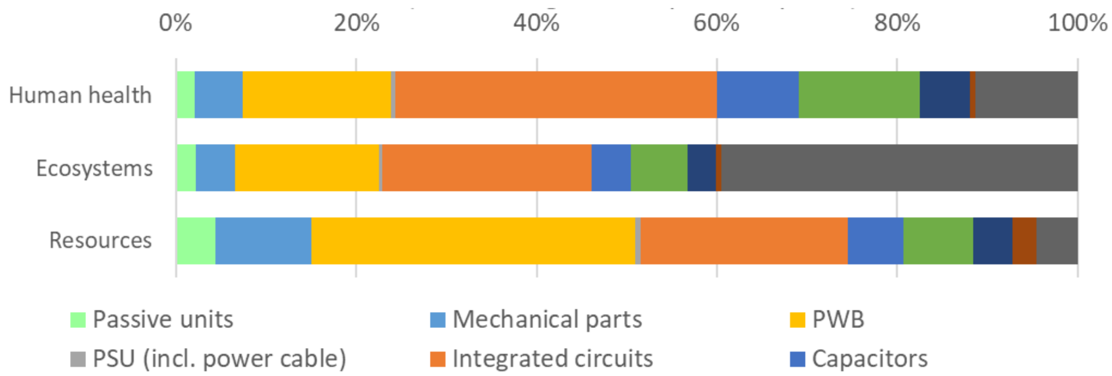

Figure 31. Endpoint impacts for the Reference TE manufacturing (cradle-to-gate).

6.3.2 Use

Table 91 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 5 & Figure 6).

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%.

Table 91. Global warming and endpoint impacts for the use of one Reference TE.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution	5.97	9.51E-06	2.45E-08	0.89
Electricity (variable mix - 2020-2027)	307.83	8.51E-03	4.83E-05	12.81
Electricity (constant mix - 2020)	340.89	8.71E-03	4.92E-05	13.95
Total Use (variable elect. mix - 2020-2032)	313.81	8.52E-03	4.83E-05	13.70
Total Use (constant elect. mix - 2020)	**356.16**	**8.78E-03**	**4.95E-05**	**15.02**

6.3.3 Total (cradle-to-grave)

Table 92 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 TE 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 Figure 32 and Figure 33, respectively.

Table 92. Global warming and endpoint impacts for the whole life cycle of one Reference TE (cradle-to-grave).

Life cycle phase	Global warming (kg CO2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	88.80	5.75E-04	8.79E-07	4.12
Use (variable elect. mix - 2020-2032)	313.81	8.52E-03	4.83E-05	13.70
EoL	1.55	4.98E-06	1.08E-08	0.16
TOTAL (variable elect. mix)	**404.15**	**9.10E-03**	**4.92E-05**	**17.98**
Credits from recycling	-8.01	-3.16E-05	-7.96E-08	-0.74

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 1.18 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).

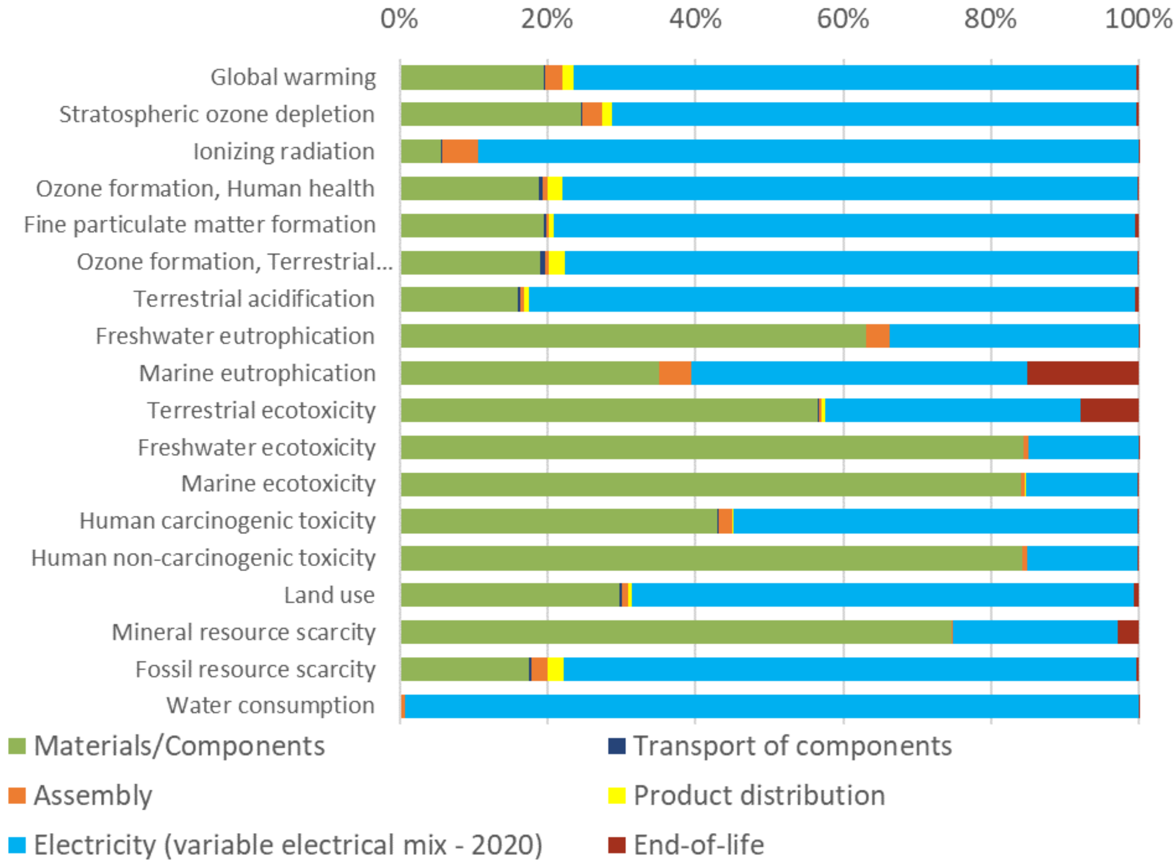

Figure 32. Midpoint impacts for the Reference TE (cradle-to-grave).

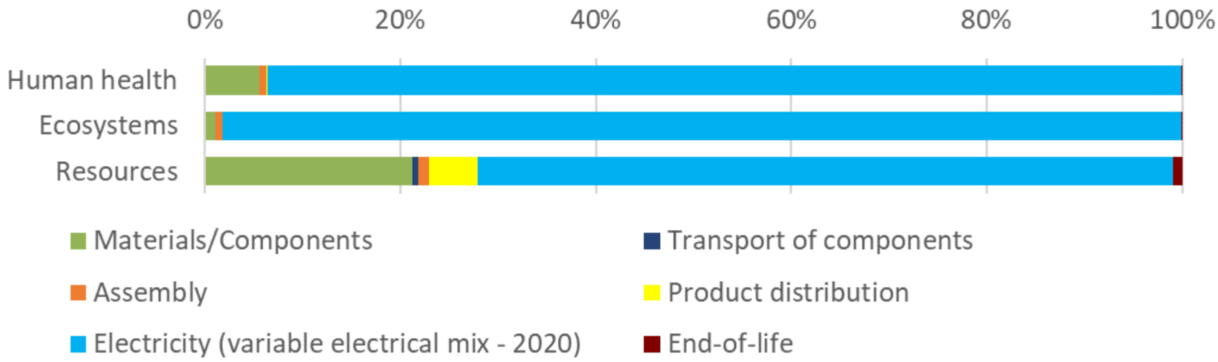

Figure 33. Endpoint impacts for the Reference TE (cradle-to-grave).

6.4 Reference material circularity indicator

Material flows associated with the ALM product were grouped into the following categories (see Table 87): 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 148). 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 6). 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 Table 87). 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 Table 93.

Table 93. Feedstock and waste for one Reference TE 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	1.471	1.047	0.698	0.601	0.147	0.047
Aluminium	0.642	0.505	0.270	0.262	0	0.015
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	7.45E-02	1.82E-03
Plastic	0.319	0.282	0.231	0.130	0.189	0.013
TOTAL	**2.724**	**2.050**	**1.396**	**1.112**	**0.485**	**0.083**

MCI calculation for the ALM product was then conducted (Table 94). 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 (Table 93), was 0.66. The MCI for the ALM product was finally calculated as 0.41.

Table 94. MCI for the Reference TE.

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)	8760
Average number of FUs during the use phase of industry-average product U_{av} (h/year)	8760
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	**0.41**

6.5 C-SERVEES life cycle inventory

This section describes the LCI developed for the C-SERVEES telecom equipment, including inputs/outputs inventoried for each life-cycle phase and the data sources used for their inventory modelling.

6.5.1 C-SERVEES redesign changes

Redesign changes implemented in the LCSA as described in Table 79 are detailed in Table 95. The inclusion of ICT improves maintenance monitoring and allows for a longer service life of 8 to 15 years and also the 10 % reuse of the components for the central ALM unit. Circularity is also improved with the use of secondary aluminium for passive sensors.

Table 95. C-SERVEES TE redesign changes.

	Reference	C-SERVEES
Lifetime, years	8	15
Functional units, hours	70080	131400
Passive units	50	50
Recycled content	No recycled materials	Passive units with secondary aluminium
Remanufacturing	**No**	**10% reuse in central active unit**

6.5.2 Manufacturing

The LCI of the ALM product manufacturing was obtained from primary data provided by ADVA. The ALM unit consists of several components. The different components inventoried and their total amounts are listed Table 96. 50 passive sensors for door-opening detection were also included in the LCI, as inventoried in Table 97

Table 96. Components of one C-SERVEES ALM unit.

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
Total	**-**	**2.369**	**kg**

Table 97. Components of one recycled passive sensor.

Components	Material	Mass (g)
Fiber	Glass fiber	0.025
Fiber coating	Acrylate, Polyacrylamide	0.025
Compression spring	Steel, low-alloyed	0.250
Sensor holder	Secondary aluminum	7.200
Total		**7.500**

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 Table 98.

Table 98. LCI datasets of material, components and processes for C.SERVEES TE manufacturing.

Input	Dataset name	FU
	RAW MATERIALS	
Aluminium alloy	Aluminium alloy, AlMg3 {GLO}| market for | Cut-off, U	1 kg
Aluminium, secondary	Aluminium, wrought alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | 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

Input	Dataset name	FU
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
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

Input	Dataset name	FU
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	6 unit

6.5.3 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 Table 99.

Table 99. Estimated amounts for distribution of one C-SERVEES TE by transport mode.

Transport mode	Amount (tkm)
Road	10.39
Water	6.37
Air	22.66
Total	**39.42**

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 Table 100.

Table 100. Estimated amounts for distribution of one C-SERVEES TE by transport mode.

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 15 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 1314 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 Table 101. 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).

Table 101. LCI datasets of electricity for the C-SERVEES TE operation.

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

6.5.4 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the ALM product are classified in Table 102 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.).

Table 102. Waste material flows related to one C-SERVEES TE EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
SPA | Aluminium	0.682	0.403	0.403
SPA | Copper within PCB	1.42E-01	0.0839	0.063
SPA | Copper within Wire	2.92E-03	0.0017	0.001
SPA | Copper	0.033007	0.0195	0.016
SPA | Gold within PCB	3.59E-04	2.13E-04	1.66E-04
SPA | Lead within PCB	1.59E-03	0.001	2.71E-04
SPA | PA without BFR, density < 1.3	0.022	0.013	0
SPA | PC without BFR, density < 1.3	0.030	0.018	0
SPA | PCB Other base metals	0.138	0.082	0
SPA | PCB Support	0.214	0.126	0
SPA | Platinoid within PCB	4.00E-06	2.37E-06	3.131E-07
SPA | PVC within wire	0.003	0.002	0
SPA | Silver within PCB	1.19E-03	7.05E-04	9.14E-05
SPA | Steel	1.617	0.957	0.796
LPA| Glass fibres-plastics composites	0.004	0.002	0
LPA| PET without BFR, density < 1.3	0.079	0.047	0
Total	**2.970**	**1.758**	**1.280**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one ALM product) is shown in Table 102. 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 was 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 Table 103.

Table 103. Waste material flows related to landfill disposal of one C-SERVEES TE.

Waste type	Mass landfilled (kg)
Plastics	0.143
Aluminium	0.278
Inert material	0.790
Total	**1.212**

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 Table 102.

Table 104. LCI datasets of landfill disposal for the C-SERVEES TE 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

6.6 C-SERVEES life cycle impact assessment

6.6.1 Manufacturing (cradle-to-gate)

Table 105 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.

Table 105. Global warming and endpoint impact for the manufacturing of one C-SERVEES TE (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	2.14E-01
Heatsink	2.125	6.54E-06	1.03E-08	9.27E-02
Small mechanical parts	1.095	5.52E-06	8.45E-09	1.33E-01
Printed wiring board (PWB)	23.729	9.42E-05	1.40E-07	1.48E+00
Power supply unit (PSU)	8.179	8.48E-07	1.36E-09	1.28E-02
Power cable	0.159	1.96E-06	1.95E-09	1.22E-02
Integrated circuits (IC)	28.812	2.05E-04	2.04E-07	9.46E-01
Capacitors	2.004	5.21E-05	3.80E-08	2.55E-01
Resistors	0.096	3.73E-06	2.63E-09	1.13E-02
Transistors	0.198	1.03E-06	1.33E-09	1.11E-02
Diodes	0.060	2.77E-07	3.44E-10	3.45E-03
Inductor	0.470	5.68E-06	5.13E-09	4.26E-02
LED	0.375	1.24E-06	1.86E-09	2.06E-02
Lightpipe	0.269	4.63E-07	1.02E-09	2.40E-02
Oscillator	0.012	1.24E-07	1.17E-10	1.02E-03
Connectors	0.493	1.93E-05	1.46E-08	6.24E-02
Coin cell battery	0.016	1.63E-07	1.72E-10	1.37E-03
Optical fibre	1.180	2.59E-06	5.70E-09	6.58E-02
Optical switch module	0.004	1.09E-07	8.12E-11	4.21E-04
Optical jumper	0.004	6.94E-09	1.62E-11	1.03E-03
Optical receiver	0.031	4.70E-07	4.16E-10	3.47E-03
Optical coupler and circulator	0.033	7.71E-08	1.64E-10	2.54E-03
Optical laser diode	0.721	3.78E-05	2.37E-08	1.04E-01
Optical adapter	0.723	1.89E-05	2.03E-08	2.14E-01
Variable optical attenuator	0.660	3.12E-06	4.54E-09	4.59E-02
Transport of components	0.873	3.33E-05	2.09E-08	9.62E-02

Energy for assembly	9.299	6.56E-05	3.47E-07	0.190
50 passive sensors	1.738	6.00E-06	1.28E-08	9.34E-02
Total	**93.430**	**5.70E-04**	**8.73E-07**	**4.047**

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 Figure 34 and Figure 35, 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.

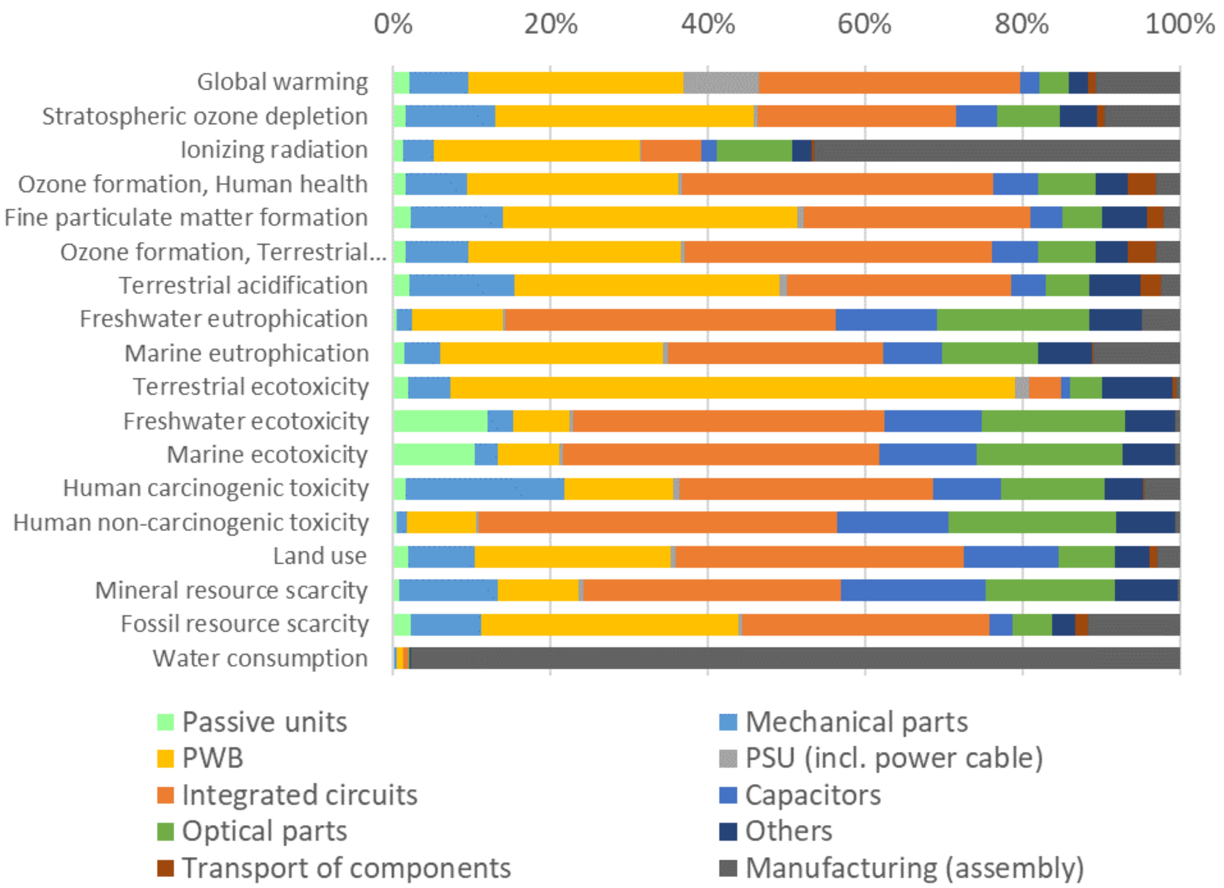

Figure 34. Midpoint impacts for the C-SERVEES TE manufacturing (cradle-to-gate).

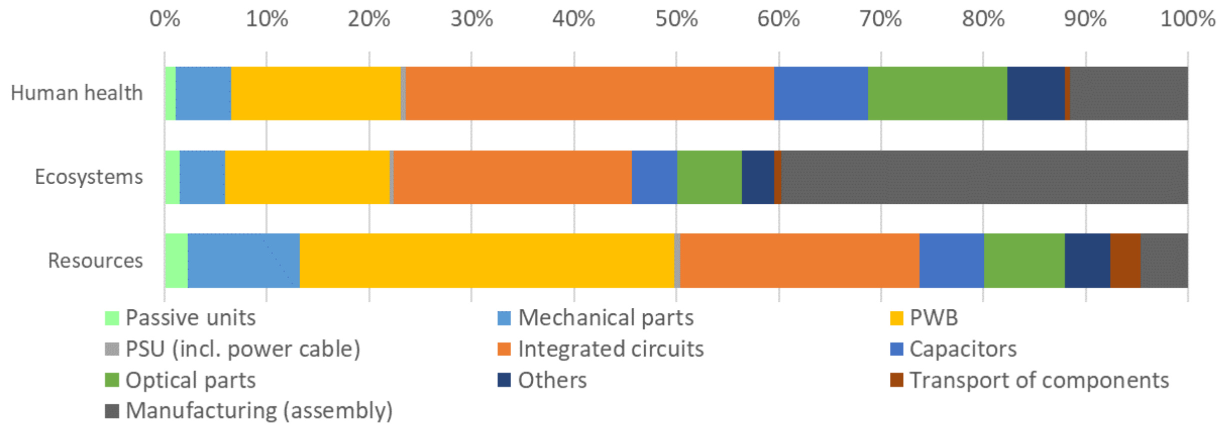

Figure 35. Endpoint impacts for the C-SERVEES TE manufacturing (cradle-to-gate).

6.6.2 Use

Table 106 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 5 & Figure 6).

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%.

Table 106. Global warming and endpoint impacts for the use of one C-SERVEES TE.

Life cycle process	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution	26.69	4.25E-05	1.09E-07	3.97
Electricity (variable mix - 2020-2027)	515.21	1.56E-02	8.90E-05	21. 90
Electricity (constant mix - 2020)	639.17	1.63E-02	9.22E-05	26.15
Total Use (variable elect. mix - 2020-2032)	541.91	1.56E-02	8.92E-05	25.86
Total Use (constant elect. mix - 2020)	665.86	1.64E-02	9.23E-05	30.11

6.6.3 Total (cradle-to-grave)

Table 107 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. Figure 36 and Figure 37, respectively.

Table 107. 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)	93.43	5.70E-04	8.73E-07	4.05
Use (variable elect. mix - 2020-2032)	541.91	1.56E-02	8.92E-05	25.86
EoL	1.69	5.45E-06	1.18E-08	0.17
TOTAL (variable elect. mix)	**637.03**	**1.62E-02**	**9.00E-05**	**30.08**
Credits from recycling	-8.69	-3.45E-05	-8.70E-08	-0.81

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 1.28 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).

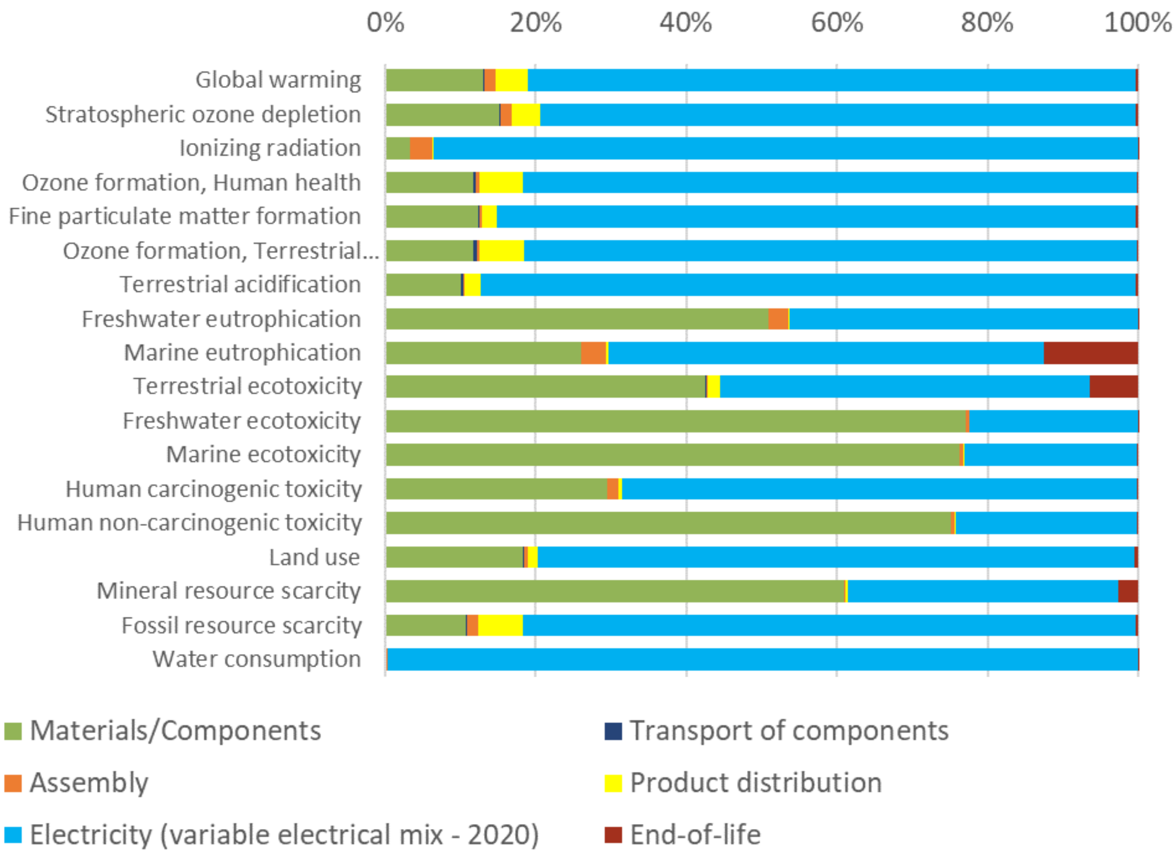

Figure 36. Midpoint impacts for the C-SERVEES TE (cradle-to-grave).

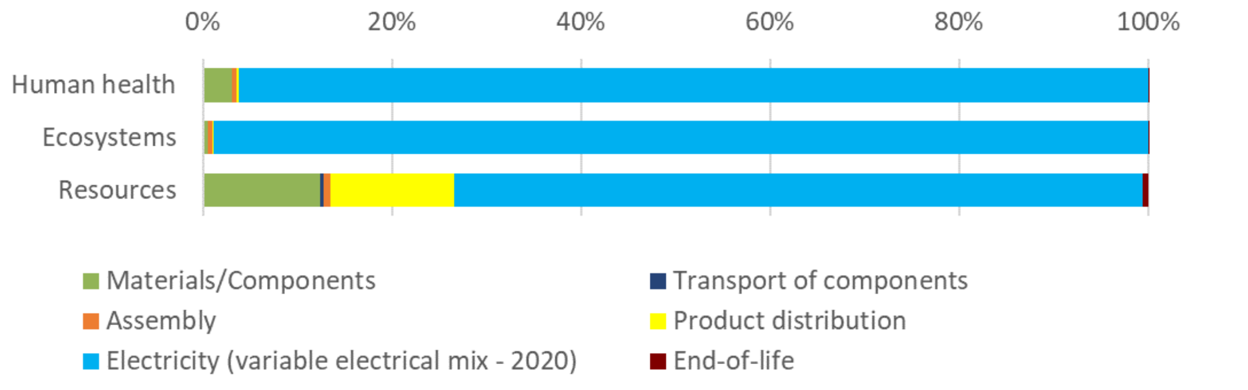

Figure 37. Endpoint impacts for the C-SERVEES TE (cradle-to-grave).

6.7 C-SERVEES material circularity indicator

Material flows associated with the ALM product were grouped into the following categories (see Table 102): 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 148). 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 6). 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 Table 102). 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 Table 108.

Table 108. Feedstock and waste for one C-SERVEES TE 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	1,617	1,151	0,767	0,660	0,162	0,052
Aluminium	0,682	0,253	0,302	0,278	0	0,048
Copper	0,178	0,116	0,116	0,073	0,080	0,007
Gold	3,59E-04	2,69E-04	1,75E-04	1,47E-04	4,67E-05	9,98E-06
Silver	1,19E-03	1,03E-03	8,02E-04	4,86E-04	6,14E-04	1,84E-05
Lead	1,59E-03	7,31E-04	1,03E-03	6,49E-04	6,70E-04	9,54E-05
Platinoid metals	4,00E-06	2,99E-06	2,72E-06	1,63E-06	2,06E-06	1,12E-07
Other metals	0,138	0,120	0,098	0,057	8,20E-02	2,00E-03
Plastic	0,351	0,310	0,254	0,143	0,208	0,014
TOTAL	**2,970**	**1,952**	**1,540**	**1,212**	**0,533**	**0,122**

MCI calculation for the ALM product was then conducted (Table 109). 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 0.48. The linear flow index, considering feedstock and waste results (Table 108), was 0.61. The MCI for the ALM product was finally calculated as 0.71.

Table 109. MCI calculation for the C-SERVEES TE.

Parameter	Value
Actual average lifetime of product L (years)	15
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	1.88
Utility factor F(X)	0.48
Linear Flow Index LFI	0.61
Material Circularity Indicator of the product MCI_P	**0.71**

6.8 Comparative life cycle assessment

Environmental impacts are significantly improved thanks to the introduction of ICT that have improved the maintenance of the TE increasing the lifetime from 8 to 15 years and making feasible the 10% reuse of the central ALM unit together with the use of recycled material for sensors, see Figure 38. The environmental improvement is an average of 40% across all impact categories, if only the printer is considered in the LCA, or 20%, if electricity during the use phase is also considered.

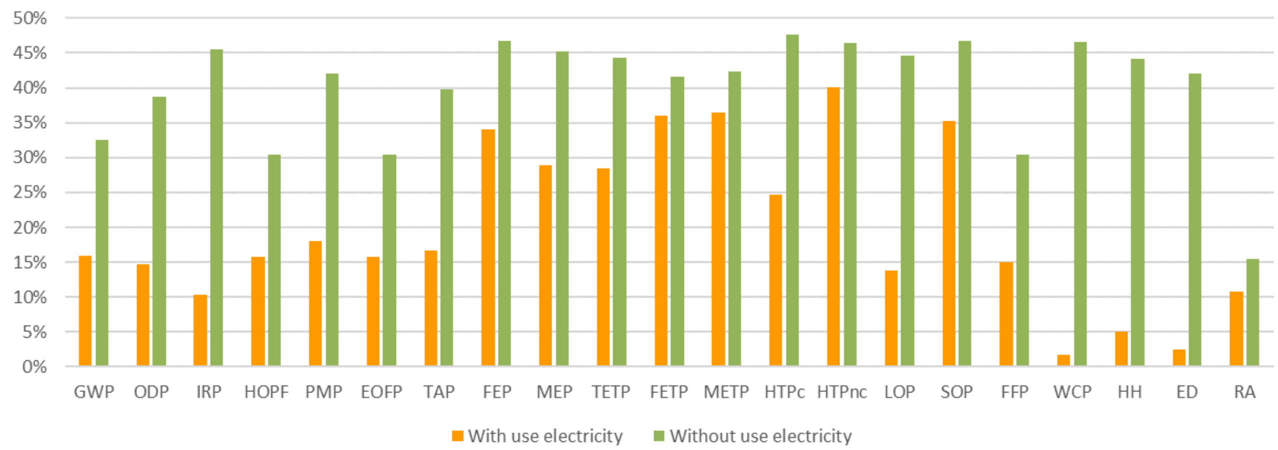

Figure 38. TE relative environmental impact reductions.

Considering the global warming impact category, the environmental impact is greatly reduced during the manufacturing of passive sensors by 77% and, overall, the manufacturing phase is reduced by 44%, see Table 110 and Figure 39. To achieve this improvement there is an increase in distribution impact (-138%) and a loss of recycling benefits (-42%). However, the improvement from circularity enhancements is far greater than these losses. Even considering the use electricity, the carbon footprint improvement is 16%. If electricity is not included during the use phase, the carbon footprint is improved by 33% (Figure 38).

Table 110. TE GWP comparative assessment (including use electricity) for 1 hour monitoring network.

Units: kg CO_{2eq}		Reference	C-SERVEES	Relative improvement
Manufacturing	ALM unit	1.07E-03	6.20E-04	41.8%
	Passive units	5.67E-05	1.32E-05	76.7%
	Transport	1.14E-05	6.64E-06	42.0%
	Assembly	1.33E-04	7.08E-05	46.7%
Use	Distribution	8.52E-05	2.03E-04	-138.3%
	Electricity	4.39E-03	3.92E-03	10.7%
EOL	End-of-life	2.21E-05	1.28E-05	41.8%
TOTAL		**5.77E-03**	**4.85E-03**	**15.9%**
Recycling	Benefits	-1.14E-04	-6.62E-05	-42.2%

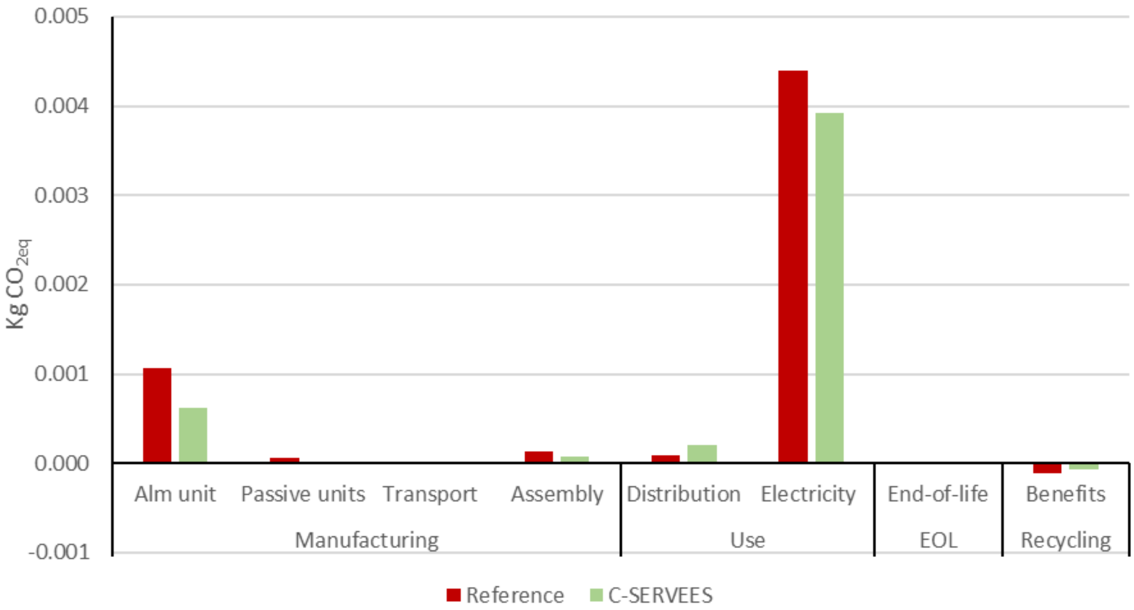

Figure 39. TE GWP comparative assessment (including use electricity) for 1 hour monitoring network.

6.9 Comparative material circularity

Circularity enhancement of the C-SERVEES is performed by increasing the lifetime from 8 to 15 years and making feasible the 10% reuse of the central ALM unit together with the use of recycled material for sensors, thus material circularity indicator improves by 73%, from 0.41 to 0.71, Figure 40.

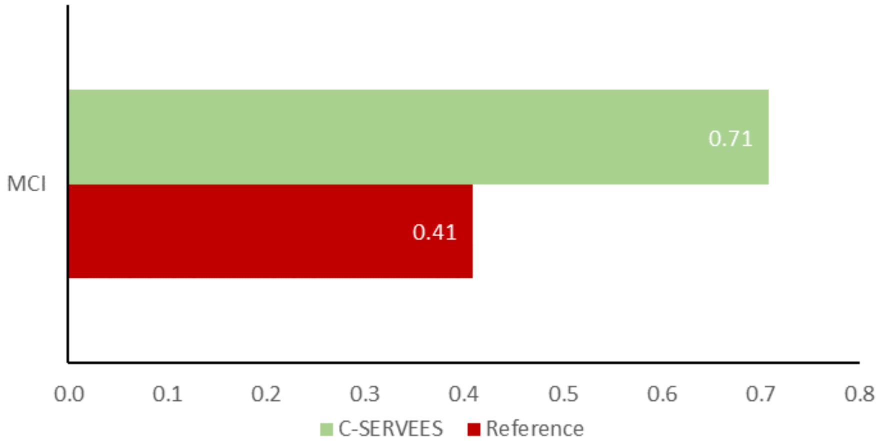

Figure 40. MCI for TE.

7 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. More details on the current TV set selected for demonstration are shown in Table 111.

The functional unit considered in the present study is one watched hour of the 43" TV set GRUNDIG G43C 891 5A. The performance of this TV set is 10,784 hours of viewing during its 8-year lifetime (assuming an average use of 337 days/year and 4 h/day). The assessment was initially performed for one and at the end converted to the functional unit.

Table 111. 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

The activities conducted in the LCSA were derived from the TV-CIRCMODE short-term actions validated in WP2. The table below presents the TV-CIRCMODE canvas sub-components and their validated short-term CE actions, as presented in Table 24 in D2.5, and the selected strategies implemented in WP5 as C-SERVEES product.

Table 112. Validated short-term TV-CIRCMODE Canvas Key Circular sub-components and their associated Circular Economy Actions relevant for the LCSA.

TV-CIRCMODE Canvas Sub Component	TV-CIRCMODE validated short-term Circular Economy Actions	LCSA implemented
TV_C1.1 Diversify circular activities	TV_A1.1.1 Increase recycled plastic content in TV components	rPC-ABS (30%) back cover
	TV_A1.1.2 Decrease packaging waste	100% recycled cardboard
TV_C2.3 Introduce and/or expand the use of ICT to foster circular economy	TV_A2.3.1 Use QR codes to provide information about materials and company's circularity to all the value chain	Remanufacturing
TV_C5.3 Change traditional relationships with customers, for instance: can a customer become a supplier?	TV_A5.3.1 Initiate a take back collection system in Europe with a partner	
	A1.1.5, A1.4.1, A2.1.1, A2.2.1, A5.3.1	

7.1 Scope

7.1.1 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).[4]

Table 113 shows the system boundaries considered for the TV, identifying the life cycle phases, processes and other elementary flows included and excluded in the study.

Table 113. 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	
End of life	Transport EoL treatments Landfilling of waste fraction not recycled	
Benefits and burdens beyond system boundaries	Recycling benefits (included as credits)	

7.1.2 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). 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.

7.1.3 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) 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.

7.1.4 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 148).
- 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).
- Waste collection rate was assumed to be the European average for consumer equipment (Table 6).
- The EoL inventories were assumed to be as the ones modelled in the WEEE LCI project.[20]

7.2 Reference life cycle inventory

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

7.2.1 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 Table 114.

Table 114. Modules of the Reference TV set.

Modules in TV set	Total amount (kg)
Packaging	3.09
Cabinet	5.53
Display Assembly	2.18
Remote Control	0.10
Stand	0.38
Total	**11.27**

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 Table 115.

Table 115. LCI datasets of material, components and processes for the Reference 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

Input	Dataset name	FU
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
	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 Table 116.

Table 116. Estimated amounts for transport of materials/components for one Reference TV set.

Transport mode	Amount (tkm)
Road	1.66
Water	22.51
Railway	0.28
Total	**24.45**

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 Table 117.

Table 117. LCI datasets of transport modes for the Reference 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

7.2.2 Use

Distribution

The TV set is distributed to a wide list of countries as shown in Table 118.

Table 118. Reference TV set distribution by countries.

Country	Market share
Turkey	66.21%
Germany	15.82%
United Arab Emirates	9.85%
Serbia	3.52%
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 Table 119. 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 Table 117.

Table 119. Estimated amounts for distribution of one Reference TV set by transport mode.

Transport mode	Amount (tkm)
Road	11.3
Water	5.0
Railway	3.1
Total	**19.4**

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 Table 120.

Table 120. LCI datasets of electricity and batteries for Reference 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

7.2.3 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the TV are classified in Table 121 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.).

Table 121. Waste material flows related to the Reference TV set EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	Mass recycled (kg)
FS| ABS-PC without BFR, density < 1.3	2.040	1.717	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	0.070	0.059	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
Paper	1.421	1.421	1.279
Plastic packaging	0.756	0	0.000
Total	**11.207**	**9.023**	**3.480**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one TV set) is shown in Table 121. 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 was 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 Table 122.

Table 122. Waste material flows related to landfill disposal of on Reference TV set.

Waste type	Mass landfilled (kg)
Plastics	1.446
Inert material	0.738
Total	**2.184**

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 Table 123.

Table 123. LCI datasets of landfill disposal for the Reference 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

7.3 Reference life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

7.3.1 Manufacturing (cradle-to-gate)

Table 124 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.

Table 124. Global warming and endpoint impacts for the manufacturing of one Reference TV set (cradle-to-gate).

Modules in TV set	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Packaging	6.64	1.23E-05	3.14E-08	0.83
Cabinet	105.36	7.82E-04	8.12E-07	8.17
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	0.49	1.63E-06	3.25E-09	0.07
Total manufacturing	**226.00**	**1.30E-03**	**1.51E-06**	**16.88**

In addition, the contribution of each module to the total impact of TV manufacturing for every midpoint and endpoint category assessed is described in Figure 41 and Figure 42, 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.

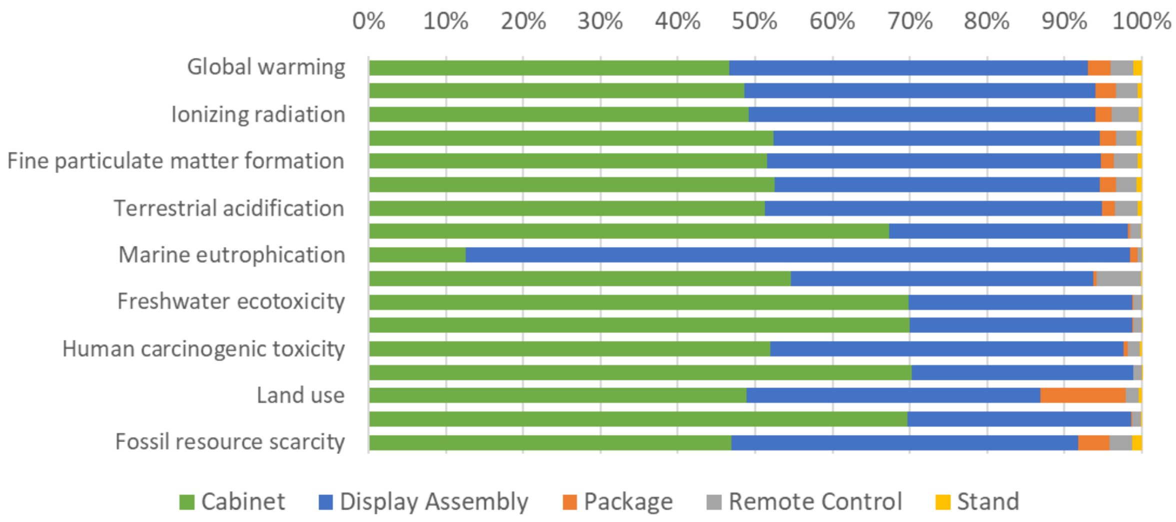

Figure 41. Midpoint impacts for the Reference TV set manufacturing (cradle-to-gate) by modules.

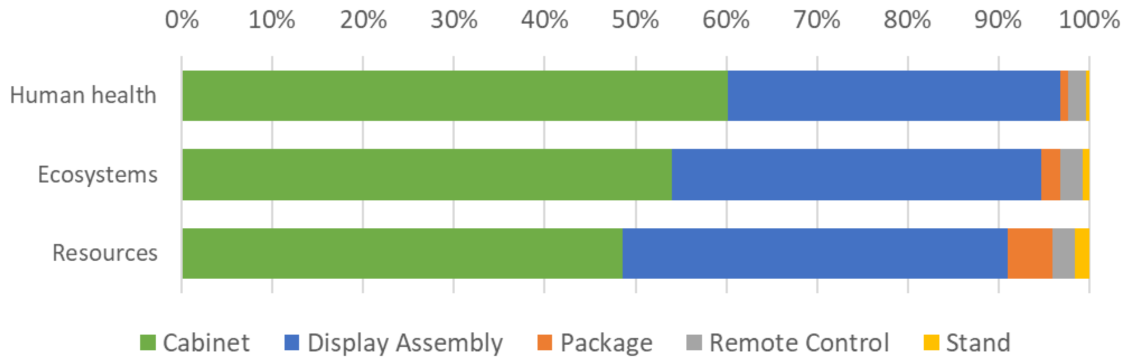

Figure 42. Endpoint impacts for the Reference TV set manufacturing (cradle-to-gate) by modules.

7.3.2 Use

Table 125 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 5 & Figure 6).

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%.

Table 125. Global warming and endpoint impacts for the use of one Reference TV set.

Life cycle process	Global warming ($kg\ CO_2\ eq$)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution (road)	0.22	4.43E-07	1.07E-09	3.31E-02
Product distribution (water)	0.26	1.15E-06	2.11E-09	3.30E-02
Product distribution (railway)	0.01	3.62E-08	7.66E-11	1.21E-03
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 - 2020-2027)	237.48	6.55E-03	3.72E-05	9.94
Total Use (constant elect. mix - 2020)	262.91	6.70E-03	3.78E-05	10.81

7.3.3 Total (cradle-to-grave)

Table 126 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 Figure 43 and Figure 44, respectively.

Table 126. Global warming and endpoint impacts for the whole life cycle of one Reference 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)	226.00	1.30E-03	1.51E-06	16.88
Use (variable elect. mix - 2020-2027)	237.48	6.55E-03	3.72E-05	9.94
EoL (waste treatment)	7.82	1.87E-05	4.04E-08	0.52
TOTAL (variable elect. mix)	**472.49**	**7.87E-03**	**3.87E-05**	**27.51**
Credits from recycling	-17.98	-7.82E-05	-1.94E-07	-1.78

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 3.48 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).

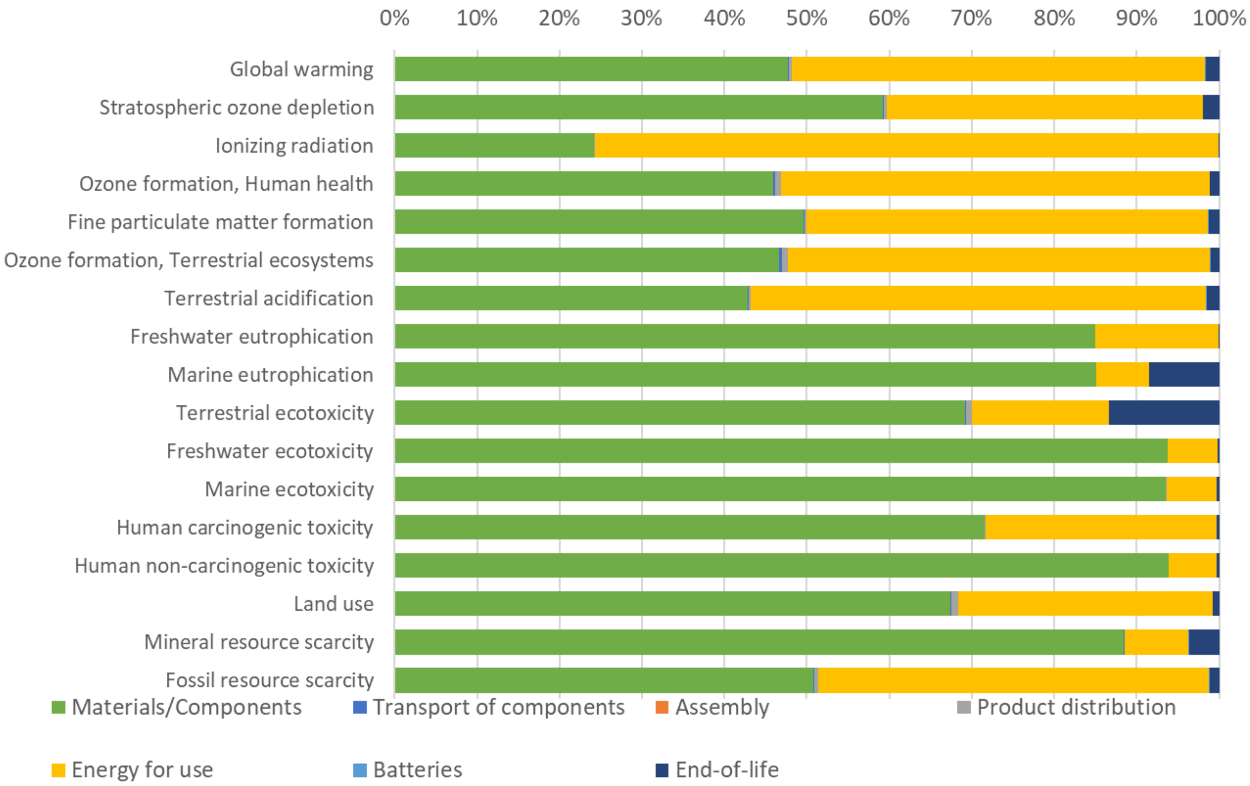

Figure 43. Midpoint impacts for the Reference TV set (cradle-to-grave).

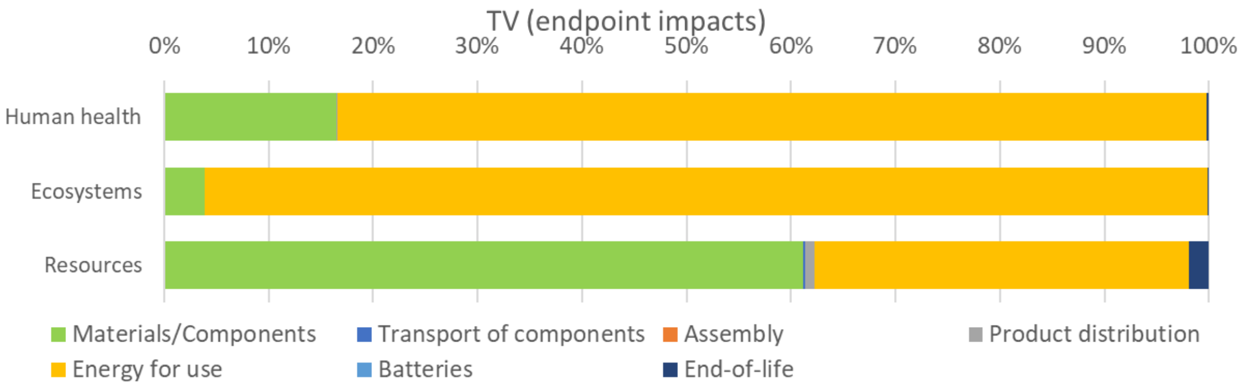

Figure 44. Endpoint impacts for the Reference TV set (cradle-to-grave).

7.4 Reference material circularity indicator

Material flows associated with the TV were grouped into the following categories (Table 121): 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 148). 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 6). 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 (Table 121). 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 Table 127.

Table 127. Feedstock and waste for one Reference 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	2.95	2.10	0.74	0.47	0.46	0.09
Copper	0.28	0.18	0.08	0.04	0.06	0.01
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	0.39	2.87E-05	2.07E-05	6.08E-06	2.81E-05	1.08E-06
Other metals	0.44	0.38	0.26	0.07	0.37	6.35E-03
Glass-LCD	0.99	0.93	0.58	0.16	0.83	6.60E-03
Plastic	4.36	3.85	2.61	0.69	3.67	0.17
Paper	1.42	0.71	0.11	0.00	0.14	0.07
TOTAL	**11.2**	**8.82**	**5.16**	**2.18**	**5.54**	**0.40**

MCI calculation for the TV set was then conducted (Table 128). The average lifetime and intensity of use for the target TV set investigated herein were assumed to be the same as 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 (Table 123) was 0.7. The MCI for the TV set was finally calculated as 0.37.

Table 128. MCI calculation for the Reference 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	0.70
Material Circularity Indicator of the product MCI_P	**0.37**

7.5 C-SERVEES life cycle inventory

7.5.1 C-SERVEES redesign changes

Redesign changes implemented in the LCSA as described in Table 112 re detailed in Table 129. Recycled PC-ABS is used for the TV back cover and 100% recycled cardboard is used for the TV box. Most significantly, in C-SERVEES TV set, several components are reused for remanufacturing new TVs.

Table 129. C-SERVEES TV set changes implemented in LCSA.

	Reference	C-SERVEES
Lifetime	8 years	8 years

	Reference	C-SERVEES	
Functional units	10784	10784	
Recycled content	No recycled materials	30% recycled PC-ABS - Halogen Free	
		100 % recycled Cardboard	
Remanufacturing	No remanufacturing	**Components**	Replaced rate
		Power cable	50%
		Back Cover	50%
		Plastic Stand Bracket	50%
		Wall Mount Bracket	50%
		Cable	50%
		T-con Board	50%
		Main Board	50%
		PSU Power Supply Unit	50%
		Loudspeaker	50%
		Wi-fi/Bluetooth Board	50%
		Front Plastic Cover	50%
		Display	50%
		Display Plastic Frame	50%
		Reflective plastic film	50%
		Led bar	50%
		Remote control	50%

7.5.2 Manufacturing

The LCI of the TV CSERVEES manufacturing is the same as in the initial case. The different modules inventoried and their total amounts are listed in Table 130.

Table 130. Modules of one C-SERVEES TV set.

Modules in TV set	Total amount (kg)
Packaging	3.09
Cabinet	5.53
Display Assembly	2.18
Remote Control	0.10
Stand	0.38
Total	**11.27**

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 Table 131.

Table 131. LCI datasets of material, components and processes for the C-SERVEES 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

Input	Dataset name	FU
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
	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

ARÇELIK provided a list of parts suitable for remanufacturing, including the replacement frequency for each part, expressed as the percentage of times they can be reused to replace virgin parts, Table 129. Refurbished parts reduce the mass of primary materials/components in the TV set by 18% (from 11.27 kg to 9.19 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 TVs (WCR = 84.2%), as follows:

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

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 non-recycled 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 Table 132.

Table 132. Transport of non-recycled materials/components for one C-SERVEES TV set.

Transport mode	Amount (tkm)
Road	1.30
Water	16.04
Railway	0.19
Total	**17.53**

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 Table 133.

Table 133. LCI datasets of transport modes for the C-SERVEES 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

7.5.3 Use

Distribution

The TV set is distributed to a wide list of countries as shown in Table 134.

Table 134. C-SERVEES TV set distribution by countries.

Country	Market share
Turkey	66.21%
Germany	15.82%
United Arab Emirates	9.85%
Serbia	3.52%
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 Table 135. 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 Table 133

Table 135. Estimated amounts for distribution of one C-SERVEES TV set by transport mode.

Transport mode	Amount (tkm)
Road	11.3
Water	5.0
Railway	3.1
Total	**19.4**

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 Table 136.

Table 136. LCI datasets of electricity and batteries for C-SERVEES 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

7.5.4 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 5 & Table 6).

Waste treatment

Material flows associated with the EoL treatment of the TV are classified in Table 137 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 reuse and 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.).

Table 137. Waste material flows related to one C-SERVEES TV set EoL.

Datasets	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
FS| ABS-PC without BFR. density < 1.3	2.040	1.717	0.841	0.877	0.000
FS| ABS without BFR. density < 1.3	0.023	0.019	0.010	0.010	0.000
FS| Copper within PCB	0.208	0.176	0.088	0.088	6.60E-02
FS| Copper within Wire	0.072	0.061	0.030	0.030	2.34E-02
FS| Gold within PCB	4.91E-04	4.13E-04	0.000	0.000	1.61E-04
FS| LCD panel	0.989	0.833	0.416	0.416	0.00
FS| Lead within PCB	0.002	0.002	0.001	0.001	2.19E-04
FS| PCB Other base metals	0.440	0.370	0.185	0.185	0.000
FS| PCB Support	0.340	0.286	0.143	0.143	0.000

Datasets	Mass put on market (kg)	WEEE collected (kg)	WEEE to reuse (kg)	WEEE to recycle (kg)	Mass recycled (kg)
FS| PE	0.043	0.037	0.000	0.037	0.000
FS| PET without BFR. density < 1.3	0.453	0.381	0.041	0.340	0.000
FS| Platinoid within PCB	3.85E-05	3.24E-05	0.000	0.000	2.14E-06
FS| PMMA	0.088	0.074	0.002	0.072	0.00
FS| PS without BFR. density < 1.3	0.614	0.517	0.000	0.517	0.000
FS| PVC within wire	0.070	0.059	0.029	0.029	0.000
FS| Silver within PCB	8.97E-03	7.55E-03	0.004	0.004	4.89E-04
FS| Steel	2.945	2.480	0.015	2.464	2.01E+00
LPA| Glass fibres-plastics composites	0.603	0.508	0.254	0.254	0.00
LPA| PA without BFR. density < 1.3	0.059	0.049	0.017	0.032	0.00
LPA| PUR foam	0.031	0.026	0.007	0.018	0.00
Paper	1.421	1.421	0.000	1.421	1.2789
Plastics packaging	7.56E-01	0	0.000	0.000	0.00
Total	**11.207**	**9.023**	**2.084**	**6.938**	**3.377**

Recycling

The mass of each material flow that is recycled in relation to the functional unit (one TV set) is shown in Table 137. 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 was 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 Table 138.

Table 138. Waste material flows related to landfill disposal of on C-SERVEES TV set.

Waste type	Mass landfilled (kg)
Plastics	0.690
Inert material	0.738
Paper	0.756
Total	**2.184**

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 Table 139.

Table 139. LCI datasets of landfill disposal for the C-SERVEES 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

7.6 C-SERVEES life cycle impact assessment

Life cycle impact assessment was conducted using the impact assessment method ReCiPe v1.03 (as explained in Section 3.2). 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).

7.6.1 Manufacturing (cradle-to-gate)

Table 140 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.

Table 140. Global warming and endpoint impacts for the manufacturing of one C-SERVEES TV set (cradle-to-gate).

Modules in TV set	Global warming (kg CO_2 eq)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Packaging	6.64	1.23E-05	3.14E-08	0.83
Cabinet	61.42	4.54E-04	4.73E-07	4.78
Display Assembly	67.49	3.02E-04	3.90E-07	4.78
Remote Control	3.84	1.45E-05	2.14E-08	0.24
Stand	1.61	3.35E-06	8.33E-09	0.16
Transport of materials/components	0.36	1.19E-06	2.39E-09	0.050
Total manufacturing	**141.36**	**7.87E-04**	**9.26E-07**	**10.83**

In addition, the contribution of each module to the total impact of TV manufacturing for every midpoint and endpoint category assessed is described in Figure 45 and Figure 46, 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.

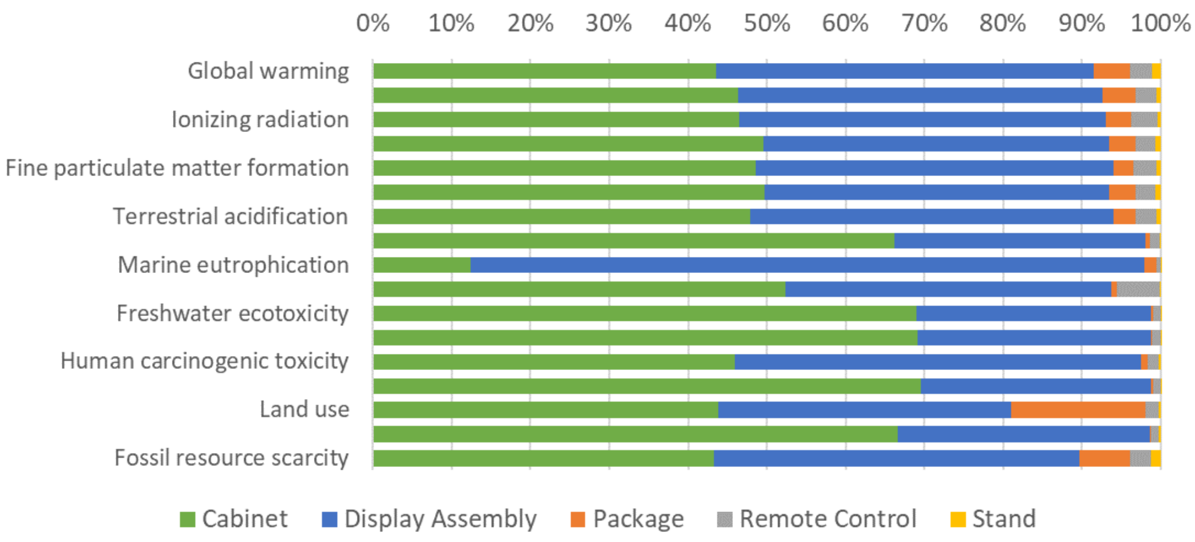

Figure 45. Midpoint impacts for the C-SERVEES TV set manufacturing (cradle-to-gate) by modules.

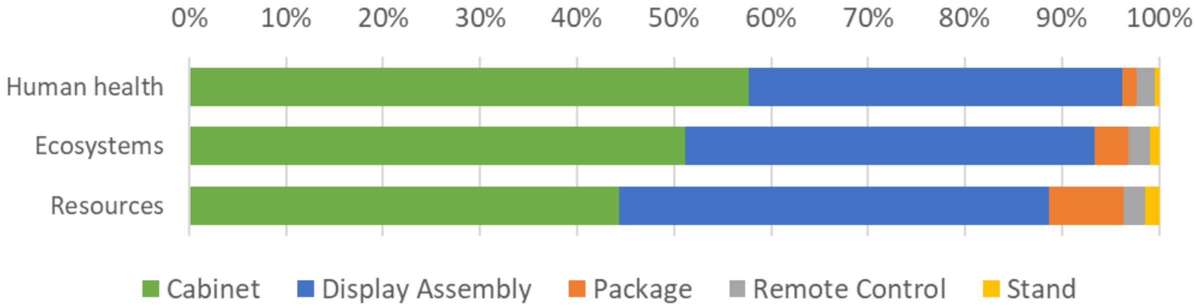

Figure 46. Endpoint impacts for C-SERVEES TV set manufacturing (cradle-to-gate) by modules.

7.6.2 Use

Table 141 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 5 & Figure 6).

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 and with the original product) except for terrestrial ecotoxicity (increased by 0.40%), land use (increased by 0.28%) and mineral resource scarcity (increased by 0.65%). 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 0.37% for human non-carcinogenic toxicity up to 7.40% for terrestrial acidification. Global warming is reduced by 6.42%, while endpoint impacts are reduced as follows: human health damage by 2.02%. ecosystem diversity damage by 1.65% and resource availability by 4.10%.

Table 141. Global warming and endpoint impacts for the use of one C-SERVEES TV set.

Life cycle process	Global warming (kg $CO_{2\ eq}$)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Product distribution	1.68	3.68E-06	8.63E-09	0. 25
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 - 2020-2027)	238.67	6.55E-03	3.72E-05	10.11
Total Use (constant elect. mix - 2020)	264.102	6.70E-03	3.78E-05	10.99

7.6.3 Total (cradle-to-grave)

Table 142 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 Figure 47 and Figure 48, respectively.

Table 142. Global warming and endpoint impacts for the whole life cycle of one C-SERVEES TV set (cradle-to-grave).

Life cycle phase	Global warming (kg $CO_{2\,eq}$)	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Manufacturing (cradle-to-gate)	141.36	7.87E-04	9.26E-07	10.83
Use (variable elect. mix - 2020-2027)	238.67	6.55E-03	3.72E-05	10.11
EoL (waste treatment)	7.26	1.65E-05	3.62E-08	0.64
TOTAL (variable elect. mix)	**387.29**	**7.36E-03**	**3.81E-05**	**21.59**
Credits from recycling	-12.00	-4.69E-05	-1.11E-07	-1.12

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 3.38 kg of materials recycled (including gold, aluminium, steel, copper, silver and others).

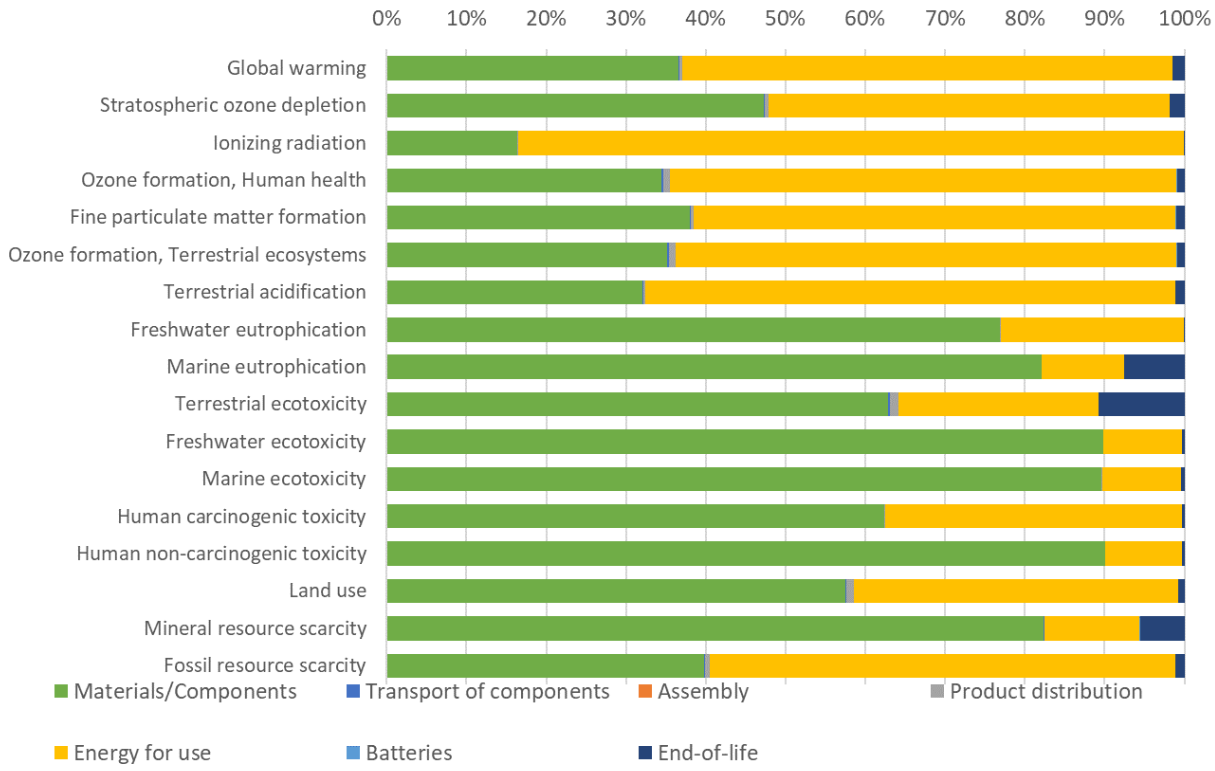

Figure 47. Midpoint impacts for the C-SERVEES TV set (cradle-to-grave) by life cycle phases.

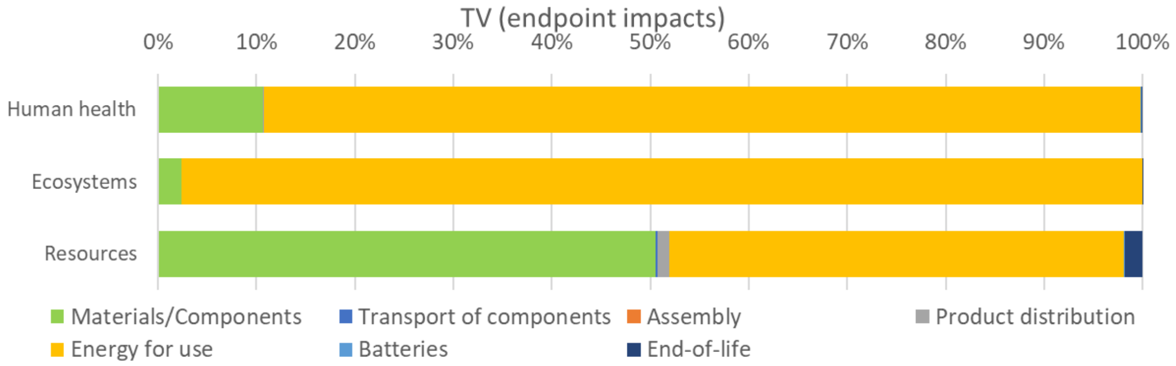

Figure 48. Endpoint impacts for the C-SERVEES TV set (cradle-to-grave) by life cycle phases.

7.7 CSERVEES material circularity indicator

Material flows associated with the TV were grouped into the following categories: steel, copper, gold, silver, lead, platinoid metals, other metals, plastics, glass and paper. 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 148). 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 6). 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 Table 138). 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 Table 143.

Table 143. Feedstock and waste for one C-SERVEES 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	2.95	2.085	0.741	0.466	4.56E-01	0.094
Copper	0.28	0.106	0.062	0.044	2.88E-02	0.006
Gold	4.91E-04	0.000	1.04E-04	7.76E-05	4.54E-05	7.89E-06
Silver	8.97E-03	0.004	3.10E-03	1.42E-03	3.28E-03	8.02E-05
Lead	1.81E-03	4.83E-04	5.90E-04	2.86E-04	5.43E-04	6.29E-05
Platinoid metals	3.85E-05	1.65E-05	1.34E-05	6.08E-06	1.41E-05	6.39E-07
Other metals	0.44	0.221	0.164	0.070	1.85E-01	3.68E-03
Glass-LCD	0.99	0.539	0.367	0.156	4.16E-01	0.004
Plastic WEE	4.36	1.702	2.074	0.690	2.33E+00	0.439
Paper	1.42	0.706	0.111	0.000	1.42E-01	0.079
Plastic packaging	0.76	0.667	0.771	0.756	0.00E+00	0.030
TOTAL	**11.21**	**6.032**	**4.293**	**2.184**	**3.561**	**0.656**

MCI calculation for the TV set was then conducted in Table 144. The average lifetime and intensity of use for the target TV set investigated herein were assumed to be the same as 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 (Table 143) was 0.49. The MCI for the TV set was finally calculated as 0.56.

Table 144. MCI calculation for the C-SERVEES 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	0.49
Material Circularity Indicator of the product MCI_P	**0.56**

7.8 Comparative life cycle assessment

Re-manufacturing TV sets positively affects environmental impacts, Figure 49, an average of 38% across all impact categories, if only the TV set is considered in the LCA, or 23%, if electricity during the use phase is also considered.

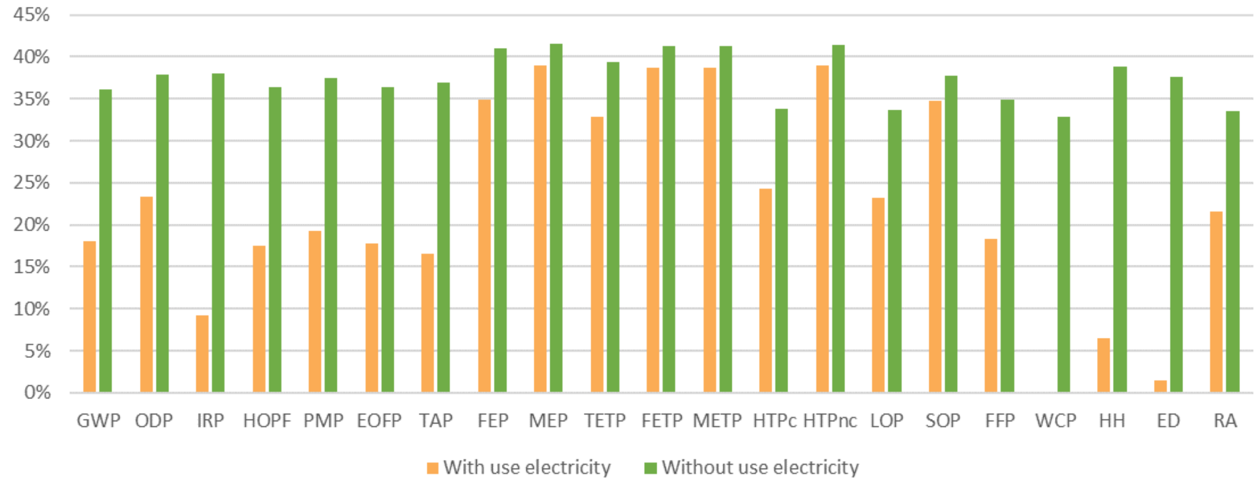

Figure 49. TV sets relative impact reductions.

Considering global warming impact category, the environmental impact is reduced during manufacturing components by 37.5%, see Table 145 and Figure 50. To achieve this improvement there is a loss of recycling benefits (-33.2%). However, the improvement from remanufacturing is far greater than this loss. Even considering electricity for use, the carbon footprint improvement is 18%. If electricity is not included during the use phase, the carbon footprint is improved by 36% (*Figure 49*).

Table 145. GWP comparative assessment (including use electricity) for 1 hour of TV watching.

Units: kg CO_{2eq}		Reference	C-SERVEES	Relative improvement
Manufacturing	Components	2.09E-02	1.31E-02	37.5%
	Transport	4.50E-05	3.35E-05	25.6%
Use	Distribution	1.56E-04	1.56E-04	0.0%
	Electricity	2.20E-02	2.20E-02	0.0%
EOL	End-of-life	1.31E-05	6.73E-04	7.2%

TOTAL		**4.31E-02**	**3.59E-02**	**18.0%**
Recycling	Benefits	-1.67E-03	-1.11E-03	-33.2%

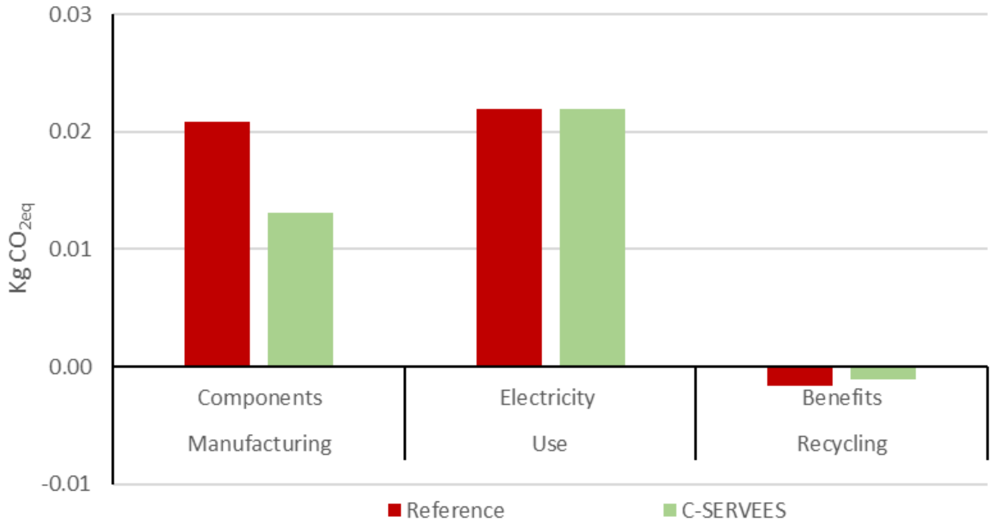

Figure 50. GWP comparative assessment (including use electricity) for 1 hour of TV watching.

7.9 Comparative material circularity

Circularity enhancement of the C-SERVEES is performed by reusing several parts for remanufacturing new TV sets. Remanufacturing and recycled materials reduces virgin feedstock by 2.79 kg for one TV set, thus material circularity indicator improves by 52%, from 0.37 to 0.56, see Figure 51.

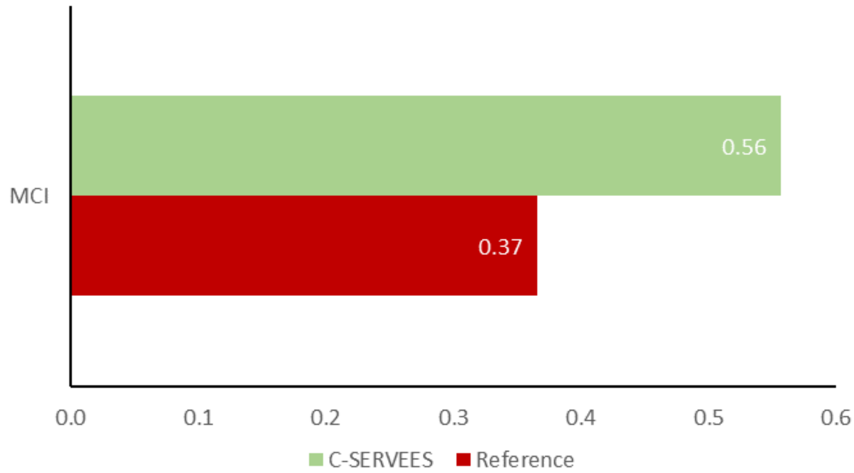

Figure 51. MCI for TV sets.

8 Sensitivity analysis

LCA sensitivity analysis on lifetime and use intensity was performed to determine the conditions under which faster or slower changeover of products may be beneficial under a circular scenario. Partners were asked to report on the minimum and maximum potential number of units during the lifetime respect the standard or reference value, see Table 146.

Table 146. Variation of the number of units respect the standard or reference value during the lifetime of the four products.

PRODUCT	Functional unit	Standard	Minimum	Maximum
Washing machine	1 washing cycle	2,750	1,500	3,000
Laser printer	1,000 printed pages	390	195	390
Telecom equipment	1 monitored hour	70,080	70,080	140,160
TV set	1 watched hour	10,784	7,189	14,379

The potential maximum is twice the minimum number of units for the four products, although with differences with respect to the reference value for the functional unit, i.e. for the laser printer the reference value coincides with the maximum potential, meantime for the telecom equipment the standard value coincides with the minimum potential.

LCA was performed considering the minimum and maximum units during the lifetime. For each product, these environmental issues were identified:

- Issues that are independent of the number of units during the lifetime: manufacturing, product distribution and EoL (of the manufactured product).
- Issues that are lineally dependent with the number of units: consumables as electricity, water, paper, etc.
- Issues that follow a step function with the number of units: maintenance in the laser printer

The modified number of units during the lifetime is consequence of a modification of the intensity of use of the laser printer, the washing machine and the TV set. For these three products, the number of years of lifetime remains unchanged. However, for the telecom equipment, the intensity of use is unchanged (24 hours a day) and the number of years increases. It should be considered that electricity has a variable impact depending on the year and it is assumed that the impact of each kWh will decrease in the future. Environmental impacts for each impact category were relativized respect the impact value for the standard number of units. Results for the global warming potential and for the endpoint impact categories (human health, ecosystems and resources) are plotted in tornado charts, see Figure 52.

A value of 1 in this figure means that the value of the environmental impact with the modified number of units is the same as the impact with the standard number. Higher differences respect one, means higher sensitivity. Green colours in Figure 52 (left sides) are for impacts with the maximum potential numbers of units and the environmental impacts are equal or lower than the reference. Orange colours (right side) are for the impacts with the minimum potential number of units and the environmental impacts are equal or higher.

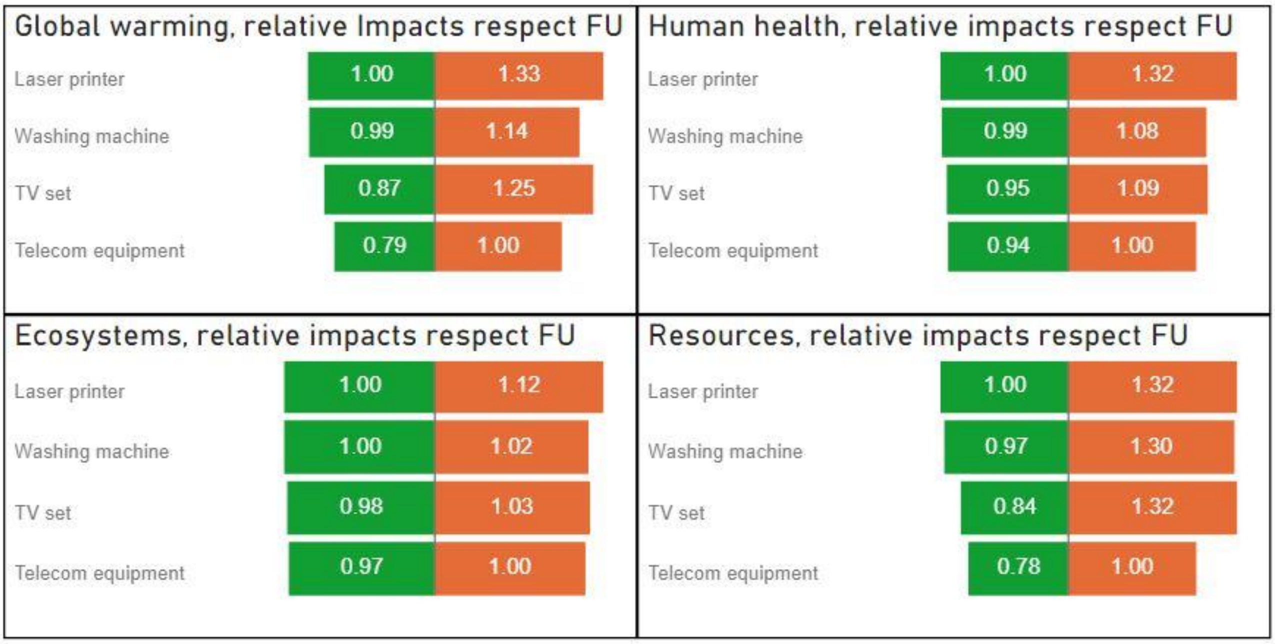

Figure 52. Tornado charts of the relative environmental impacts for the modification of the number of units during the lifetime.

Laser printer is the product with the highest sensitivity in all four charts of the Figure 52. Telecom equipment is the product with the lowest sensitivity. The environmental impacts of consumables and maintenance of the laser printer are less significant than the impacts of the manufacturing, mainly due to electronics. In contrast, the electricity consumption for monitoring is relatively more significant than manufacturing impacts.

Global warming potential and the endpoint impact categories of human health and resources follow a quite similar pattern. However, the intensity of the relative impacts in the ecosystems category is very low, close to 1 (except for the laser printer with the minimum potential number of printed pages).

The four product have different functional units, so the Figure 52 shows the sensitivity intensity for each of them. To compare between the products, a sensitivity dependence analysis is shown in Figure 53. SD is the relative variation of the environmental impact with respect to the relative change in the number of units over the lifetime.

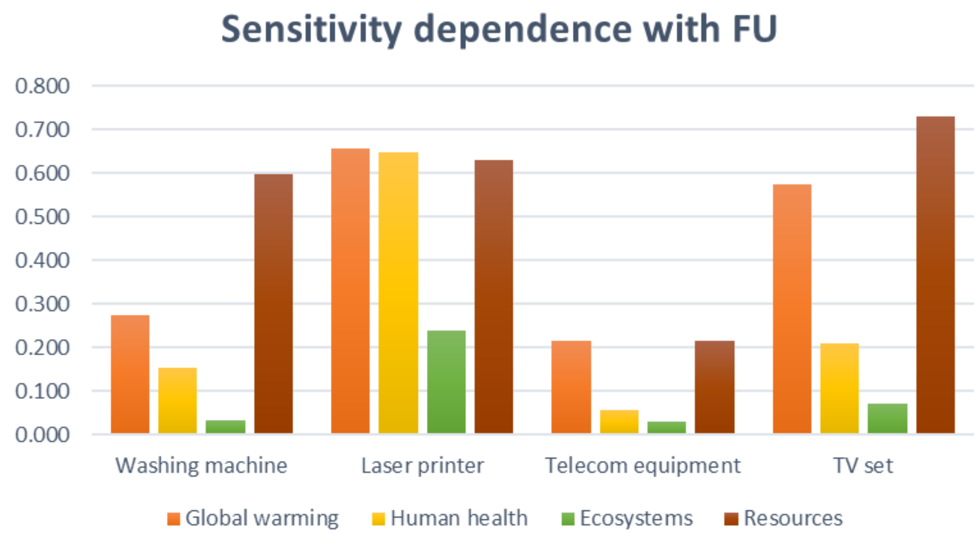

Figure 53. Sensitivity dependence with the change in the number of units during the lifetime.

All values of the SD are less than one. This means that the relative environmental impacts variation is less than the relative variation of the number of units. Values closer to 0 mean lowest dependence. Telecom equipment is clearly the product with the lowest sensitivity dependence. The highest SDs for the global warming potential, human health and ecosystems categories are for the laser printer; only the TV set has a higher SD than the printer for the resources category.

Telecom equipment is the only target product that applies a strategy of increasing the lifetime to enhance circularity in the C-SERVEES project. As shown in Figure 52 and Figure 53, the lowest sensitivity with lifetime increase is precisely the telecom equipment. This means that the other three target products could still further improve their environmental impacts by increasing their lifetime in the future.

9 Conclusions

This Deliverable 5.2 validates the environmental feasibility of the target products and related eco-services of the new business circular models developed in the C-SERVEES project that aims to boost a resource-efficient circular economy in the electrical and electronic sector 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 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.

Two different types of scenarios are assessed and compared for each target product to validate the sustainability of the new circular business models:

- 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.

This Deliverable 5.2 shows the life cycle costs of each target product under the conventional scenario, called Reference product, and under the C-SERVEES scenario, called C-SERVEES product, and their comparison. The impacts of the C-SERVEES scenario are also compared to those for the conventional scenario to calculate the environmental benefits that can be achieved with the solutions developed in the project.

The main conclusion of this Deliverable 5.2 is that the four target products, under the new circular economy models relying on the systemic eco-innovative services demonstrated in the project, and excluding electricity and consumables during the use phase**, have reduced global warming by 20%, human health and ecosystems quality by 22%, resources scarcity by 14% and improved circularity by 35%.**

Conclusions for each target product are as follow:

Washing machine: Environmental and circularity enhancement of the washing machine is performed with recycled materials for the inner door, the detergent box and the tub, as well as mass reduction of the tub and some less reductions in the inner cover and the detergent box. These improvements reduce the environmental impact in almost all impact categories to a maximum of 0.3% and increase the material circularity indicator 1.7%, from 0.249 to 0.253.

Laser printers: Circularity and environmental enhancement of the laser printer is performed with remanufacturing. The environmental impact is reduced during manufacturing components, together with transport of components and maintenance (replacements and transport). To achieve this improvement there is an increase in end-of-life impact and a loss of recycling benefits. However, the improvement from remanufacturing is far greater than these losses. Even considering all spare parts and consumables, the carbon footprint improvement is 3.3%. If consumables and energy during the use phase are not included, the carbon footprint, and also the average of all impact categories, improves by 8.0%. Material circularity indicator improves by 12.3%, from 0.48 to 0.55.

Telecom equipment: Environmental impacts are significantly improved thanks to the introduction of ICT that have improved the maintenance of the TE increasing the lifetime from 8 to 15 years and making feasible the 10% reuse of the central ALM unit together with the use of recycled material for sensors. The environmental improvement is an average of 40% across all impact categories, if only the printer is considered in the LCA, or 20%, if electricity during the use phase is also considered. Material circularity indicator improves by 73%, from 0.41 to 0.71.

TV set: Re-manufacturing TV sets positively affects environmental impacts. An average of 38% across all impact categories, if only the TV set is considered in the LCA, or 23%, if electricity during the use phase is also considered. Remanufacturing and recycled materials reduces virgin feedstock by 2.79 kg for one TV set, thus material circularity indicator improves by 52%, from 0.37 to 0.56.

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Activating Circular Services in the Electric and Electronic Sector

GA NUMBER: 776714

Deliverable 5.2. Results of environmental analyses.

Annex 1 – Methodological issues

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	D5.2
Deliverable title	Environmental analysis of C-SERVEES products and services: Life cycle assessment
Submission due date	M51
Actual submission date	
Work Package	WP5
WP Leader	AIMPLAS
Dissemination Level	Public
Version	01
Deliverable Lead Beneficiary	AIMPLAS

A1.1. Environmental modelling of electronic components

Printed wiring boards

Printed wiring boards (PWB) are among the EEE components with the highest environmental impact and greatest uncertainty. Recent studies[14] 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[15] 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[16] 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 54 was applied.

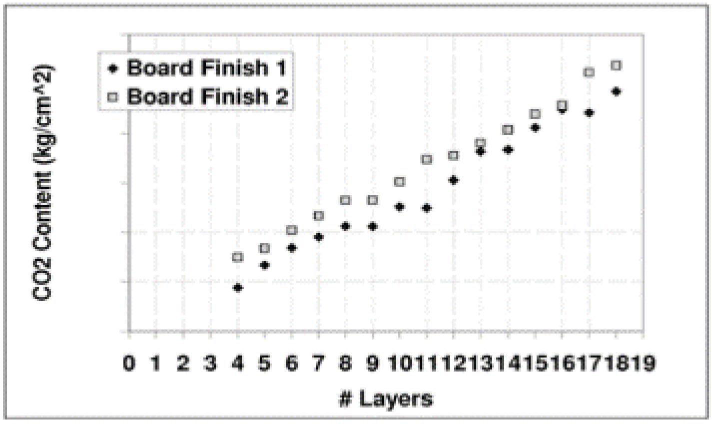

Figure 54. Global Warming Potential (GWP) for manufacturing of PWB depending on the number of layers.[16]

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[17] (Figure 55). The amount of energy required by this process is defined by the die section processed and the node technology[18] (Figure 56). 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.

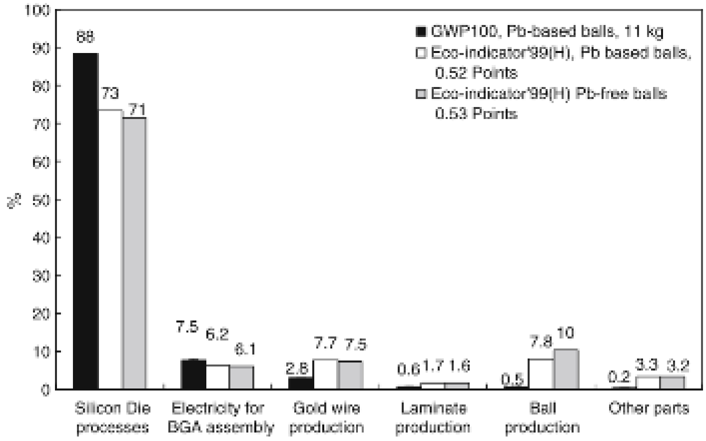

Figure 55. Environmental importance of sub-parts of a IC (Metal BGA-560 microchip).[17]

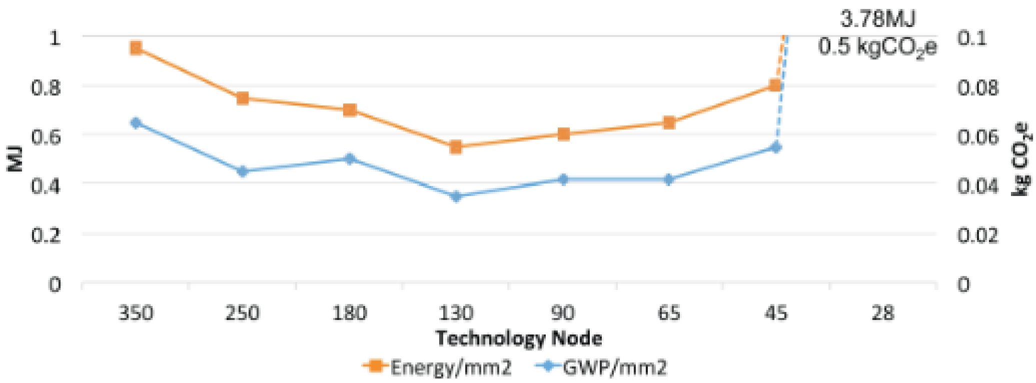

Figure 56. Energy demand and Global Warming Potential (GWP) for manufacturing of IC (CMOS).[18]

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.

$$EI_{IC} = EI_{Si\ die\ process} + EI_{Si} + EI_{rest\ package} \quad (1)$$

Table 147 shows electricity consumption for silicon die process for each technology node, which was obtained from Boyd[19] for logic IC and Schmidt et al.[20] 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.[18]

Table 147. Electricity consumption for silicon die processing per area unit.

IC device	Technology node	Electricity (MJ/Si mm^2)
Logic[19]	350	0.160
	130	0.084
	90	0.087
	65	0.091
	45	0.106
DRAM[20]	-	0.035

The die area is obtained from the IC area using empirical relation for each housing type as used in GaBi database.[15] 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.[21] 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.[15] 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.[22] 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.

A1.2. Environmental modelling of 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 57).

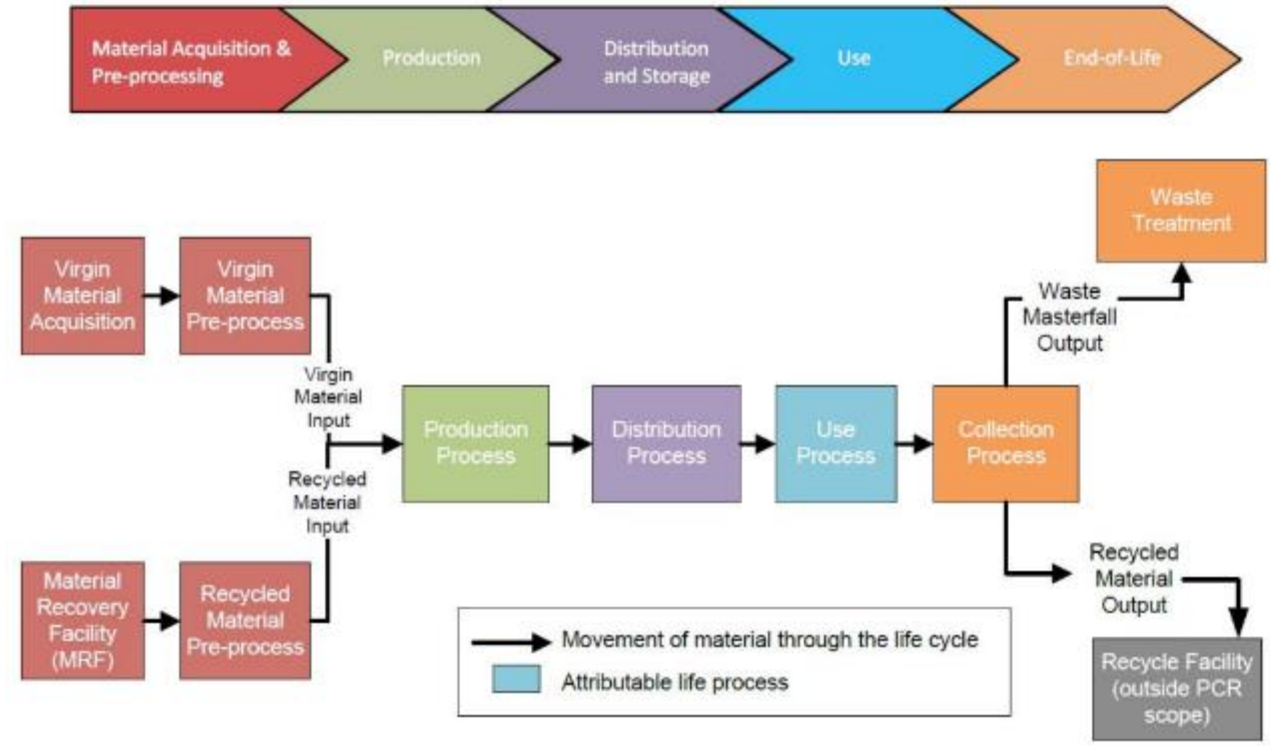

Figure 57. Example of the cut-off method.

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 must 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.[10]

However, in the present study, impacts due to waste collection, transport, intermediate and final treatment operations were considered as indicated in Figure 57. 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):

$$Credits = Impacts_{cut-off} - Impacts_{with\ benefits} \quad (2)$$

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.[10] 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).

A1.3. Modelling Material Circularity Index

The MCI is essentially constructed from a combination of three product characteristics: the mass V of sed 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).

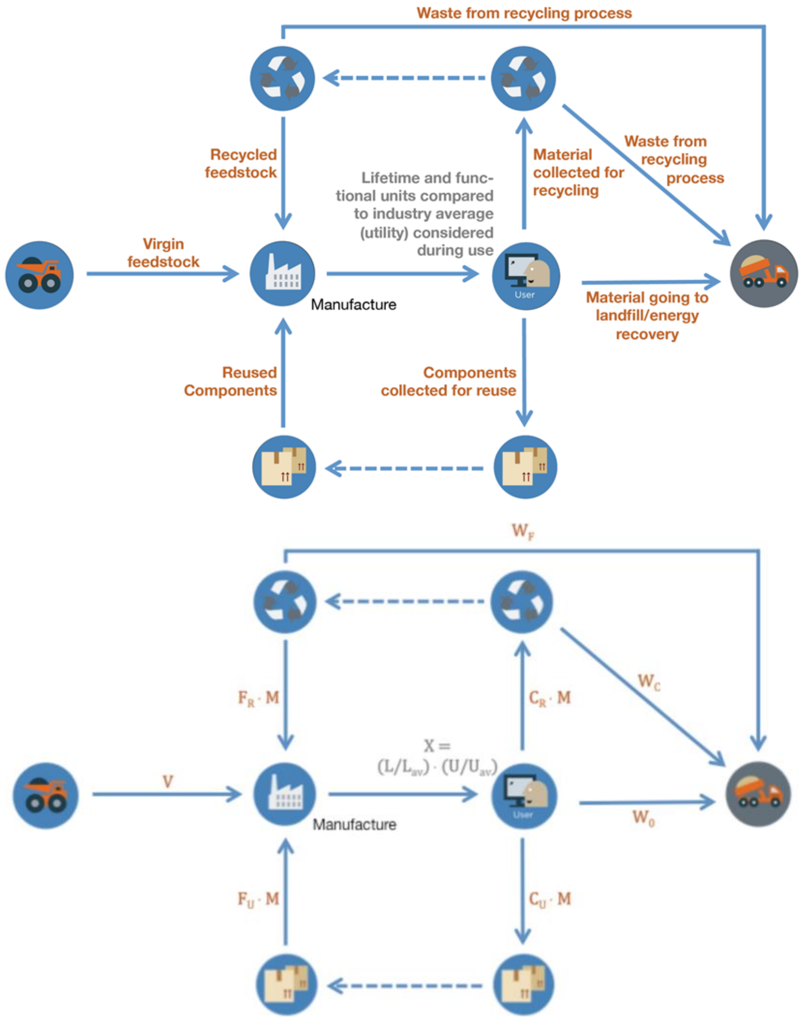

Figure 58. Diagrammatic representation of material flows used in MCI methodology.

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:

$$W = W_0 + \frac{W_F + W_C}{2} \quad (4)$$

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 58).

These amounts of unrecoverable waste are calculated as follows:

$$W_0 = M \cdot (1 - C_R - C_U) \quad (5)$$

$$W_C = M \cdot (1 - E_C) \cdot C_R \quad (6)$$

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

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:

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

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:

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

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:

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

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.[23] 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 59).

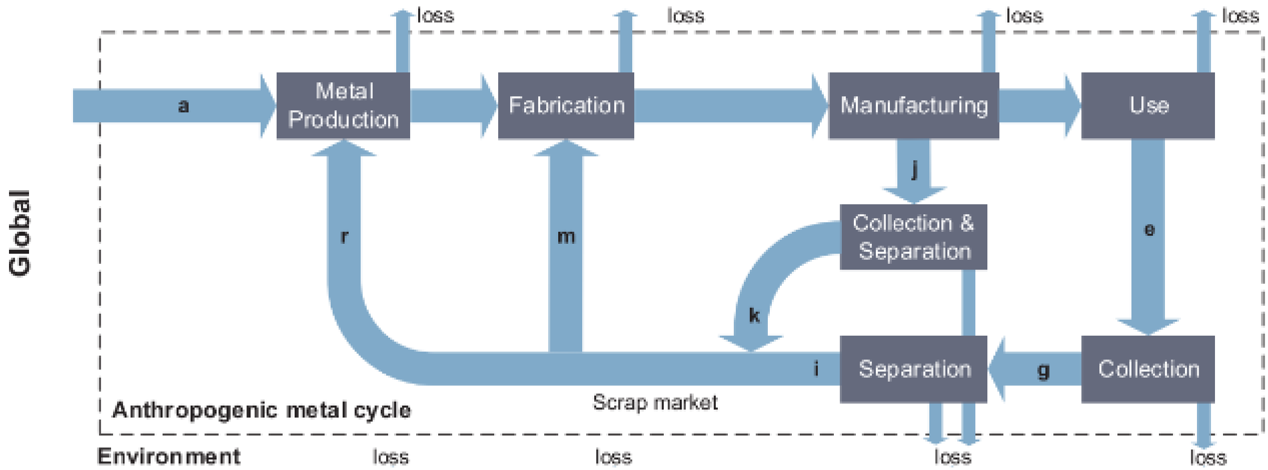

Figure 59. Material flows used in the definition of metal recycling rates.[24]

Table 148 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 148. 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[25] (electric arc furnace)	RIR	27.9	10.4	63.7	40.9	67.8	32.6	24.5	67.8
Aluminum[26] (secondary)	RIR	21.4	16.5	19.5	26.9	67.1	18.4	100	
Copper	RIR	35[27]	44[28]		52[29]				
Flat glass	RC				6[30]-11[31]				
Paper[32]	RIR	50.3	72.6		54.0	38			
Tin	RIR	13[33]							
Tin in alloys	RIR	31[33]							
Gold	RC	25.0[34]							
Silver	RC	13.9[35]							
Palladium	RC	25.3[36]							
Platinum	RC	25.8[36]							
Plastics	RC	11.8[37]							
Lead	RIR	54.0[38]							

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 6, 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.[13] 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 149 shows the values used in the present study for industry average lifetime and functional units for the target products.

Table 149. 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)	Product functional unit delivered to users
Washing machine	12.5[6]	220 cycles/year[6]	1 wash cycle done
Multifunctional laser printer	5[39]	50 ppm[40]	1000 printed pages
ALM	8	365 days/year, 24 h/day	1 monitored hour
TV set	8[4]- 6[41]	4h/day; turned off 4 weeks/year[4]	1 television watched hour