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RESEARCH AND ANALYSIS

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Reducing the carbon footprint of ICT products through material efficiency strategies

A life cycle analysis of smartphones

Mauro Cordella[1,2] | Felice Alfieri[1] | Javier Sanfelix[3]

[1] European Commission, Joint Research Centre, Seville, Spain

[2] TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, Spain

[3] European Commission, Directorate General for Research and Innovation, Brussels, Belgium

Correspondence
Mauro Cordella, TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, 48160 Derio, Spain.
Email: mauro.cordella@tecnalia.com

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Abstract

With the support of a life cycle assessment model, this study estimates the carbon footprint (CF) of smartphones and life cycle costs (LCC) for consumers in scenarios where different material efficiency strategies are implemented in Europe. Results show that a major contribution to the CF of smartphones is due to extraction and processing of materials and following manufacturing of parts: 10.7 kg $CO_{2,eq}$/year, when assuming a biennial replacement cycle. Printed wiring board, display assembly, and integrated circuits make 75% of the impacts from materials. The CF is increased by assembly (+2.7 kg $CO_{2,eq}$/year), distribution (+1.9 kg $CO_{2,eq}$/year), and recharging of the device (+1.9 kg $CO_{2,eq}$/year) and decreased by the end of life recycling (–0.8 kg $CO_{2,eq}$/year). However, the CF of smartphones can dramatically increase when the energy consumed in communication services is counted (+26.4 kg $CO_{2,eq}$/year). LCC can vary significantly (235–622 EUR/year). The service contract can in particular be a decisive cost factor (up to 61–85% of the LCC). It was calculated that the 1:1 displacement of new smartphones by used devices could decrease the CF by 52–79% (excluding communication services) and the LCC by 5–16%. An extension of the replacement cycle from 2 to 3 years could decrease the CF by 23–30% and the LCC by 4–10%, depending on whether repair operations are required. Measures for implementing such material efficiency strategies are presented and results can help inform decision-makers about how to reduce impacts associated with smartphones.

KEYWORDS
climate change, industrial ecology, life cycle assessment (LCA), life cycle costs (LCC), material efficiency, smartphone

1 | INTRODUCTION

Although the climate change threat due to anthropogenic emissions of greenhouse gases (GHG) was raised by the scientific community 30 years ago (IPCC, 1992), it has been only partially reflected in effective interventions under the frameworks of the Kyoto Protocol (United Nations, 1997) and the Paris Agreement (United Nations, 2015).

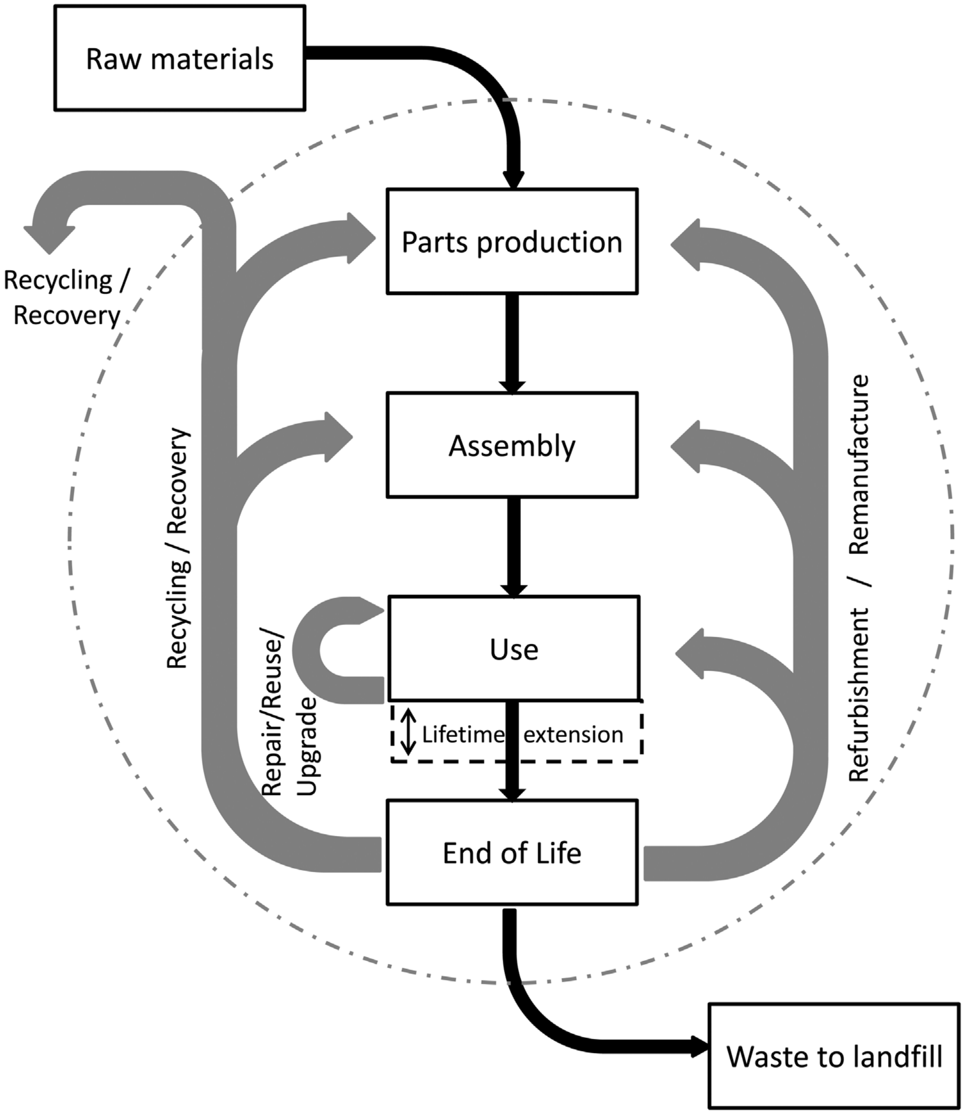

FIGURE 1 Material efficiency aspects in the life cycle of a product (Cordella et al., 2020a)

The European Commission has reinforced its commitment to tackle environmental challenges through the "European Green Deal" (European Commission, 2019a), which includes measures on energy efficiency and circular economy performance of the information and communication technologies (ICT) sector.

The contribution of the ICT sector to the global GHG emissions was about 1.4% in 2007 and could exceed 14% in 2040. In particular, the contribution from smartphones is increasing so rapidly that it could soon become greater than desktops, laptops, and displays. The main reasons for this growth are the high market penetration of smartphones and their short replacement cycles (2 years on average) (Belkhir & Elmeligi, 2018).

In the European Union (EU), ICT products fall within the scope of Ecodesign Directive (European Union, 2009) and Energy Label Regulation (European Union, 2017). These set out a regulatory framework for improving the energy efficiency of energy-related products (European Commission, 2016), with a current shift toward the more systematic consideration of material efficiency aspects (European Commission, 2019b). Material efficiency could be defined as the ratio between the performance of a system and the input of materials required (Cordella et al., 2020a). As shown in Figure 1, material efficiency can be improved along the life cycle of products by strategies that aim to minimize material consumption, waste production, and their environmental impacts (Allwood et al., 2011; Huysman et al., 2015). In practice, this could be achieved by designing products that are more durable and easier to repair, reuse, or recycle (European Commission, 2015).

The relevance of material efficiency strategies for mitigating climate change impacts depends on the relative impacts associated with each life cycle stage of a product (Iraldo et al., 2017; Sanfelix et al., 2019; Tecchio et al., 2016), which can be quantified through life cycle assessment (LCA) (ISO, 2006a; ISO, 2006b).

The analysis of LCA studies can provide indications about the environmental impacts of smartphones (Cordella & Hidalgo, 2016). For example, Andrae (2016), Ercan et al. (2016), and Clément et al. (2020) analyzed the Bill of Materials (BoM) of specific devices and their life cycle GHG emissions (hereafter referred to as carbon footprint, CF). Manhart et al. (2016) analyzed resource efficiency aspects in the ICT sector, reporting the CF of different devices. CF results are also shared by some manufacturers (e.g., Apple (2019); Huawei (2019)).

In terms of scenarios of use, Ercan et al. (2016) analyzed the effects of different use intensities of smartphones. An assessment of CF mitigation effects of remanufacturing, reuse, and recycling is provided in Andrae (2016), while repair and refurbishment scenarios were assessed by Proske et al. (2016). A comparative assessment of end of life (EoL) repurposing (vs. refurbishment) was carried out by Zink et al. (2014) . Furthermore, Suckling and Lee (2015) provided a comparison of the CF associated with the EoL collection of old phones for reuse, remanufacturing, and recycling.

Economic considerations for EoL scenarios can also be found in the literature (Clift & Wright, 2000; Geyer & Doctori Blass, 2010; Gurita et al., 2018). Furthermore, recent studies go beyond attributional LCA approaches by discussing rebound effects that could happen at macro-scale (Makov & Font Vivanco, 2018; Makov et al., 2018; Zink & Geyer, 2017; Zink et al., 2014).

This study aims to build upon the existing LCA literature for smartphones and expand it by providing a broad and critical analysis of material efficiency strategies and their effect on CF and life cycle costs (LCC) for consumers. Measures are also identified to assist decision-makers in mitigating impacts of smartphones in a cost-effective way.

2 | MATERIALS AND METHODS

2.1 | Life cycle analysis of material efficiency strategies for smartphones

An attributional LCA was carried out for the analysis of material efficiency strategies. The aim was not to compare specific devices but to produce general considerations for the EU. A number of scenarios were assessed that involve different technological and behavioral practices:

I. Baseline scenario (purchase, use and disposal of new smartphones);
II. Extended use scenarios with/without repair operations;
III. Scenarios involving the purchase of remanufactured or second-hand devices (both referred to also as “used devices” in this paper)[1];
IV. Scenarios involving lean design concepts.

Table 1 and the following sections provide an overview of analyzed scenarios and modeling assumptions.

2.1.1 | Reference indicators

The CF, expressed as $CO_{2,eq}$, was calculated based on the 100-year global warming potentials (GWP) of GHG emissions (IPCC, 2013). Although GWP correlates to a number of environmental indicators (Askham et al., 2012; Huijbregts et al., 2006), a broader metric (covering impact categories such as resource scarcity, biodiversity, and toxicity) would allow for a more comprehensive sustainability assessment (Moberg et al., 2014). Additional environmental considerations are addressed qualitatively while discussing results. It is anticipated that the use of broader metric for the assessment of smartphones (Ercan et al., 2016; Moberg et al., 2014; Proske et al., 2016) confirmed the importance played by manufacturing processes and extraction of materials (e.g., cobalt, copper, gold, silver).

The quantitative assessment also included economic considerations about the LCC for consumers (COWI & VHK, 2011), expressed as EUR 2019 and calculated according to Equation (1). The formula was obtained by considering the present value factor equal to 1 (Boyano Larriba et al., 2017).

$$\mathrm{LCC} = \mathrm{PP} + \sum_{1}^{N} \mathrm{OE} + \mathrm{MRC} + \mathrm{ELC}, \tag{1}$$

where:

- LCC: life cycle costs for end users;
- PP: purchase price;
- OE: annual operating expenses for each year of use;
- *N*: reference time in years;
- MRC: maintenance and repair costs (when applicable);
- ELC: end of life costs/benefits.

[1] Definitions used for lifetime extension processes (value-retention processes) vary widely (IRP, 2018). In this work, remanufacturing and refurbishment are used interchangeably to indicate the “modification of an object that is a waste or a product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended.” However, while remanufacturing is typically used for an industrial process to make “as-new” products that carry a legal warranty, refurbishment requires operations that exceed repair but are less structured, industrialized and quality focused than remanufacturing (e.g., data wiping and upgrade, repair for functionality, aesthetic touch-ups). Refurbishment is defined as “comprehensive” when happening within industrial or factory settings (IRP, 2018).

TABLE 1 Scenarios considered for the assessment of material efficiency aspects in the life cycle of smartphones

Scenario	Key assumptions for the CF assessment	Additional consideration for the LCC assessment
Baseline (BL)	*Replacement cycle*: smartphones are replaced with a new device (the same model) every 2 years; new devices are bought and allocated to cover the reference lifetime (i.e., 2.25 units for a period of 4.5 years). *EOL*: the old product is kept unused at home. *Other system aspects*: impact associated to data consumption during the use phase are not considered. For sensitivity analysis, BL+ also consider: - Impact associated to the usage of communication networks during the use-phase; - End-of-Life recycling with pre-treatment for battery recovery.	Costs associated to the mobile contract service are included. For sensitivity analysis, the following scenarios are considered: - BL, where an average product is considered; - BL-HE, where a high-end product is considered; - BL-LE, where a low-end product is considered.
Extended use (EXT)	*Replacement cycle*: compared to BL, replacement cycle increased to 3 (EXT1) and 4 years (EXT2), which results in the need of less devices along the reference lifetime (i.e., 1.5 and 1.125 units, respectively). *Other assumptions: as BL.*	The following scenarios are considered: - EXT1 and EXT2: as BL, with replacement cycle increased to 3 and 4 years, respectively; - EXT1-HE and EXT2-HE: as BL-HE, with replacement cycle increased to 3 and 4 years, respectively.
Battery change (BC)	*Replacement cycle*: compared to EXT1 and EXT2, replacement cycle is the same (i.e., 3 years for BC1 and 4 years for BC2) with the change of the battery. *Other assumptions*: as EXT1 and EXT2.	The following scenarios are considered: - BC1a: as EXT1, with change of the battery made by the user; - BC1b: as EXT1, with change of the battery made by a professional repairer; - BC2: as EXT2, with change of the battery made by the user.
Display change (DC)	*Replacement cycle*: compared to EXT1 and EXT2, replacement cycle is the same (i.e., 3 years for DC1 and 4 years for DC2) with the repair (change) of the display. *Other assumptions*: as EXT1 and EXT2.	The following scenarios are considered: - DC1a: as EXT1, with repair of the display by the user; - DC1b: as EXT1, with repair of the display by a professional repairer; - DC2: as EXT2, with repair of the display by the user.
Battery change + display change (BC-DC)	*Replacement cycle*: compared to EXT1 and EXT2, replacement cycle is the same (i.e., 3 years for BC-DC1 and 4 years for BC-DC2) with battery change and the repair (change) of the display. *Other assumptions*: as EXT1 and EXT2.	Not assessed directly.
Remanufacture (RM)	*Replacement cycle*: remanufactured smartphones bought by users every 2 years, to cover the reference lifetime (i.e., 2.25 units for a period of 4.5 years). *Remanufactured device impacts*: due to battery change, display change, energy for manufacturing and transport. *EOL: the old product is kept unused at home.*	As BL, with purchase price of the product calculated as the cost of battery change and display repair.
Reuse (RU)	*Replacement cycle*: reused smartphones bought by users every 2 years, to cover the reference lifetime (i.e., 2.25 units for a period of 4.5 years). *Reused device impacts*: due to battery change, display change, and transport. *EOL*: the old product is kept unused at home.	As BL, with purchase price of the product calculated as one third of the original price and a margin of 40%.
Lean design (LD)	*Device manufacturing impacts*: reduction of materials used for housing: −10% by weight (LD1), −20% by weight (LD2), −30% by weight (LD3). *Other assumptions*: as BL.	Not assessed directly.

2.1.2 | Functional unit and reference flow

Smartphones are multi-functional devices that provide different types and levels of performance. The assessment of specific devices should refer to a functional unit (FU) that covers both quantitative and qualitative aspects (ETSI, 2019), and only products with similar characteristics should be compared, which is beyond the scope of this study.

The FU considered in this study is the use of smartphones by a European consumer during a reference time of 4.5 years. This was chosen, based on data from Prakash et al. (2015), as a proxy for the potential time during which smartphones can be used. This is comparable with average lifespan data for mobile phones reported by Bakker et al. (2014) (4.5 years in 2005, Dutch data) and Makov et al. (2018) (4.5 and 5.6 years for two brands in 2015–2016, US data), which cover the first use cycle and possible subsequent use cycles of the product before the EoL disposal by the final owner.

The reference flow is the number of smartphone devices purchased, used, and disposed by the consumer during this period. The reference flow is determined by the replacement cycle of smartphones (see Section 2.2.2): for a replacement cycle of *X* years, the reference flow is equal to 4.5 divided by *X*.

2.1.3 | Assessed scenarios and system boundaries

The scenarios assessed in this study are reported in Table 1. For each scenario, the system boundaries cover the cradle-to-grave analysis of a generic, virtual product.

As a baseline (BL), the following stages are considered:

1. Production of parts (extraction, processing and transportation of materials, manufacturing of parts);
2. Smartphone manufacturing (transportation of parts, device assembly);
3. Distribution and purchase (transportation of smartphones to points of sale);
4. Use (energy for battery recharging);
5. EoL replacement (old unused device being kept at home).

Additional scenarios integrate the following aspects: system impacts associated with communication services and EoL recycling (BL+), extended use (EXT), battery change (BC), repair and change of the display (DC), remanufacture (RM), reuse (RU), lean design (LD). Services and material goods necessary to support the business (e.g., research and development, marketing) are excluded from the assessment.

2.2 | Carbon footprint modeling

LCA studies published from 2014 onward were screened to identify relevant sources of data for the analysis (Cordella & Hidalgo, 2016). The CF was calculated based on such information and life cycle inventory (LCI) datasets (cut-off system models) from Ecoinvent 3.5 (Wernet et al., 2016), with proxies used in the presence of data gaps. Assumptions made to handle existing data limitations were discussed with experts in the sector (Cordella et al., 2020b), and results compared with those of other studies (see Table 2). The GHG emission factors used for the assessment are provided in Supporting Information S1.

2.2.1 | Production of parts and manufacturing of the device

An average smartphone was considered to have a display size of 75.53 cm^2 and a weight of about 160 g, including 39 g for the battery and excluding accessories and packaging (Manhart et al., 2016). Additional materials are necessary for packaging (cardboard and plastic materials), documentation, and accessories such as head set, USB cable, charger. The BoM of the virtual product is reported in Supporting Information S1.

Scenarios RM and RU, which involve the purchase of remanufactured or second-hand devices, include a change of battery and display. The weight of materials used for the housing and display of smartphones were proportionally decreased in the LD scenarios, without investigating how this can affect other geometrical design characteristics (e.g., display size).

The assembly of one unit of smartphones was considered to happen in China and require 4.698 kWh (Proske et al., 2016). The same energy consumption value (worst-case assumption) was considered for the remanufacturing of the device in industrial settings. However, when fewer refurbishment operations are needed (e.g., clean-up and software update), the energy intensity of the remanufacturing process could be lower, for example, 0.033 kWh per device (Skerlos et al., 2003). Section 3.1.4 shows a sensitivity analysis on this parameter, which provides an uncertainty range for RM.

Regarding the transport of parts to the assembling factory, it was considered that housing and packaging materials are transported by lorry for 1000 km and 100 km, respectively, while other components (mostly electronics) are transported for 1000 km by flight and 100 km by lorry. Such assumptions aimed to reflect the geographical availability of parts and materials and the ease/difficulty of procuring them.

2.2.2 | Distribution and use

The following means of transport were considered for the distribution of smartphones: 8000 km by flight (distance between Beijing and Brussels) and 600 km by heavy truck (transport distance proxy within Europe).

TABLE 2 Carbon footprints and key parameters from LCA studies on smartphones

Parameter[a)]	BL (this study)	Andrae (2016)	Ercan et al. (2016)	Proske et al. (2016)	Apple (2019)[f)]	Huawei (2019)[g)]
CF, over the reference lifetime (kg $CO_{2,eq}$)[b)]	77.2	39.2	56.7	43.9	45.0–79.0 (average: 61.2)	50.0–84.5 (average: 61.9)
CF contribution due to EOL recycling (kg $CO_{2,eq}$)[c)]	Not considered	0.4	−0.3	−1.0	~0.2	~0.1
Reference lifetime (years)	4.5	2	3	3	3	2
Replacement cycle (years)	2	2	3	3	3	2
Reference flow (smartphone units)	2.25	1	1	1	1	1
Weight of one device (g)[d)]	160	223	152	168	112–208 (average: 159)	142–232 (average: 163)
CF contribution due to the manufacturing of one device (kg $CO_{2,eq}$)[e)]	26.7	38.3	49.8	36.0	24.8–63.2 (average: 45.3)	41.0–70.4 (average: 51.4)
CF, adjusted to BL conditions for this study (kg $CO_{2,eq}$)						
- Over 4.5 years	77.2	87	123	97	66.8–117.3 (average: 90.9)	112.3–189.8 (average: 139.0)
- Normalized to 1 year of use	17.2	19.4	27.3	21.5	14.9–26.1 (average: 20.2)	25.0–42.2 (average: 30.9)
- Normalized to BL	100%	113%	159%	125%	86–152% (average: 117%)	146–246% (average: 180%)

Notes:
a) A full comparison of results is not possible since they depend on modeling assumptions and datasets used in different studies.
b) Communication services excluded.
c) Positive numbers indicate burdens, negative numbers indicate net savings.
d) Accessories and packaging excluded.
e) Including extraction and processing of raw materials, manufacturing of parts and assembling of the device.
f) Based on the analysis of 15 models (additional information reported in the Supporting Information).
g) Based on the analysis of 32 models (additional information reported in the Supporting Information).

The use of smartphones directly implies electricity consumption for the battery recharging cycles. The duration and frequency of recharging cycles can vary depending on technical characteristics of devices as well as user behavior (Falaki et al., 2010). An electricity consumption of 4.9 kWh/year was calculated by Proske et al. (2016) considering a battery capacity of 2420 mAh, 3.8 V of voltage, 69% of recharge efficiency, and 365 charge cycle per year. According to Andrae (2016), energy consumption is 1.538 times the battery capacity and can be 2–6 kWh/year, which is similar to the 3–6 kWh/year estimated by Manhart et al. (2016). Ercan et al. (2016) instead quantified that the annual electricity demand of a smartphones can range from 2.58 kWh (1 recharge every 3 days) to 7.74 kWh (1 recharge per day). Based on the available information it was assumed that the average electricity consumption directly associated with the use of smartphones is 4 kWh/year.

Furthermore, it was considered as BL that smartphones are used for 2 years (Belkhir & Elmeligi, 2018; Prakash et al., 2015), before being replaced with new devices. This does not mean that the device performance is necessarily compromised after 2 years. The decision to replace a smartphone is often based on perceived functional obsolescence when compared to new models on the market (Makov & Fitzpatrick, 2019; Watson et al., 2017).

The replacement cycle was extended in other scenarios, resulting in the need for fewer device units over the reference time of 4.5 years (see Section 2.1.2), as indicated in Table 1. In some scenarios, this was associated with a repair operation. Replacements of battery and/or display are analyzed since these parts are frequently impacted by loss of performance, failures, and breakages (OCU, 2018, 2019). Cordella et al. (2020b) estimated that the likelihood of replacing the display or the battery during the lifespan of a smartphone could be up to 24% and 50%, respectively. These proxies were used to build an average EU scenario (see Section 3.3).

2.2.3 | End of life

Based on the literature (Ellen MacArthur Foundation, 2012; Ercan, 2013; Manhart et al., 2016), it was estimated that about 49% of devices are kept unused at home once they reach their EoL; 36% find a second use (either as donation or through second-hand markets); 15% are collected and recycled/remanufactured. As BL, it was assumed that devices are kept unused at home.

With respect to recycling, impacts can vary depending on characteristics of product recycling process (Geyer & Doctori Blass, 2010), as well as on assumptions made and data used. For example, Proske et al. (2016) estimated that the recycling of battery, copper, and other precious materials from a smartphone of 168 g yields a net saving of 1140 g $CO_{2,eq}$ (calculated as "burdens from impacts" minus "credits from avoided impacts"). Andrae (2016) instead reported that the recycling of a smartphone of about 220 g result in the emission of 400 g of $CO_{2,eq}$. A net saving of about 2150 g of $CO_{2,eq}$ would result by taking the full recovery of precious metals into account (calculated based on Manhart et al. (2016) and Andrae (2016)). Although technologically feasible, a full recovery of precious metals (e.g., magnesium, tungsten, rare earth elements, tantalum) may not be economically viable (Manhart et al., 2016).

The typical recycling process for smartphones consists of mechanical and manual operations for the separation of materials, including plastics, and the recovery of batteries, copper, precious metals (gold, silver, platinum), aluminum, and steel (Manhart et al., 2016).

To provide an indication of the potential benefits associated with the recycling of smartphones (Cordella et al., 2020b), the estimate from Proske et al. (2016) was rescaled to 160 g (device weight considered in this study), and credits were assigned to the recovery of materials and energy from the housing (display excluded). It was assumed that:

- Recycled materials can fully displace primary materials, which is not necessarily the case in real markets (Palazzo et al., 2019), as also discussed in Section 3.1.3.
- Aluminum and steel can be completely recycled at the EoL, and their recycling avoids the production of new materials, while emitting 1.01 and 0.85 g of $CO_{2,eq}$ per gram of aluminum and steel recycled, respectively.
- Plastics are incinerated, which avoids 0.094 Wh of electricity and produces 1.04 g of $CO_{2,eq}$ per gram of plastic incinerated.

As a net result, it was estimated that the recycling of a smartphone could lead to the saving of 1640 g of $CO_{2,eq}$.

2.2.4 | Communication services

Beside battery recharging, energy is also needed for the operation of communication services such as mobile networks, fixed access networks (e.g., wi-fi), and core networks (e.g., data center and transmission infrastructures). Ercan et al. (2016) estimated that the energy used for operating mobile, wireless, and core networks correspond to 28.7 kWh/year for a light user, 33.3 kWh/year for a representative user, and 49 kWh/year for a heavy user. According to Andrae (2016), the electricity consumption for operating networks and data center infrastructures is 1.16 kWh/GB. Considering an average consumption of 4 GB per month (Transform Together, 2018), the annual consumption of electricity would be 55.7 kWh. This figure, which is close to the heavy user estimation by Ercan et al. (2016), was considered in this study, also to reflect the trend toward increased data consumption (Transform Together, 2018).

2.3 | Life cycle cost modeling

2.3.1 | Purchase price for new products and operating costs

A business model in which users are owners of smartphone devices was considered, which is a common scenario in the EU. It was estimated that the average purchase price for a new smartphone in the EU is 320 EUR. This changes to less than 130 EUR and more than 480 EUR for low- and high-end products, respectively (Cordella et al., 2020b).

The LCC effects of lean design concepts or changes in material composition of devices were not assessed. However, almost 70% of the purchase price of smartphones is independent of parts and materials (Benton et al., 2015).

Operating costs include electricity consumption to recharge the battery and mobile service contract. They were considered equal to 0.2113 EUR/kWh (Eurostat, 2019), and 31.80 EUR/month (DG Connect, 2018) for a service contract including 5 GB of data, 100 calls, and 140 SMS. The service contract cost decreases to 14.11 EUR for 100 MB, 30 calls, and 100 SMS (as EU average in 2017).

Product–service systems (PSS) appears a less common scenario for smartphones (Poppelaars et al., 2018) and were not directly assessed. The main advantage of PSS business models is the enhanced possibility for service providers of collecting and reprocessing used devices. From a consumer perspective, the LCC considerations provided in Section 3.2 can address the discussion of PSS business models. When the acquisition of a smartphone is associated to a contract subscription with a telecommunication service provider, the product purchase cost is integrated in the subscription costs and the consumer has the full ownership of the smartphone. Furthermore, smartphone contracts and replacement cycles have similar lengths (Prakash et al., 2015), typically up to 2 years in the EU. Subscription contracts can vary when users do not own the device: for example, a 1-year subscription can cost from 15 EUR/month for low-end devices up to 100 EUR/month for high-end devices (Grover, 2021).

2.3.2 | Cost of more durable devices

The replacement cycle could be extended when more reliable and resistant devices are used (see Section 3.4). This is generally the case for high-end devices and specific market segments (e.g., rugged smartphones), and to a lesser extent for medium-price devices (Cordella et al., 2021). The purchase prices of average and high-end devices were considered in the assessment of extended use scenarios (EXT), where no repair operation is needed because of enhanced design characteristics.

2.3.3 | Repair costs

Battery or display replacement was considered in the repair scenarios (BC/DC). It was assumed that the replacement costs are 20 EUR for the battery and 87 EUR for the display, when done by the user. When the replacement involves professional repairers, costs increase to 69 EUR for the battery and 201 EUR for the display (Cordella et al., 2020b). Design concepts integrating reparability aspects could stimulate a reduction in the repair costs. However, the influence of such aspects on LCC was not directly assessed.

2.3.4 | Purchase price for used devices

The value of electronic devices drops over time (Culligan & Menzies, 2013). Makov et al. (2018) calculated residual values of smartphone models from two brands. Average residual values were about 50–60% of the original price after 1 year, and 40–30% after 2 years.

In this study, the purchase price of second-hand device (RU scenario) was set equal to 149 EUR, considering that the product value drops to one third of the original value, and that a 40% margin is applied. The purchase price of remanufactured products (RM scenario) was estimated as the sum of costs for the replacement of battery and display by professionals: 270 EUR, corresponding to a market value loss of 16% (for an "as-new" device but "old" model). However, the purchase price of remanufactured and new products could be the same in case remanufacturing results in "as-new" devices with upgraded performance.

2.3.5 | End of life costs and benefits

Economic benefits from the re-sale of old devices were not considered in the assessed scenarios but their possible effects are discussed in Section 3.2.

Fees associated with WEEE services at the EoL were integrated in the product purchase price (Boyano Larriba et al., 2017).

The EoL recycling can also generate profit depending on factors such as collection rates, mass flow and design of devices, recycling technique efficiency, as well as content and market value fluctuations of materials (Geyer & Doctori Blass, 2010; Renner & Wellmer, 2020). The profitability could improve through separate processing of smartphones (Gurita et al., 2018), although mobile phones may not be an important source of income for recyclers (Clift and Wright, 2000; Geyer & Doctori Blass, 2010). In any case, the relatively small profits from the recovery of materials are not expected to affect the price of smartphones (Benton et al., 2015).

3 | RESULTS AND DISCUSSION

3.1 | Carbon footprint

3.1.1 | Baseline scenario (system aspects excluded)

In the scenario BL, smartphones are replaced every 2 years in a reference time of 4.5 years, which results in manufacturing and using 2.25 device units. Old devices are kept unused at home and the usage of communication services is not considered. The storage of old devices at home is a worst-case scenario leading over time to the piling-up of a stock of unused devices. In reality, some devices are sold or recycled at the end of the first useful life (see Sections 3.1.3 and 3.3).

A CF of 77.2 kg $CO_{2,eq}$ over 4.5 years (equivalent to 17.2 kg $CO_{2,eq}$/year) was quantified. Figure 2 shows the breakdown of the CF by life cycle stage: the main contribution comes from the BoM (62%), followed by device assembly (16%), distribution (11%), and use (11%).

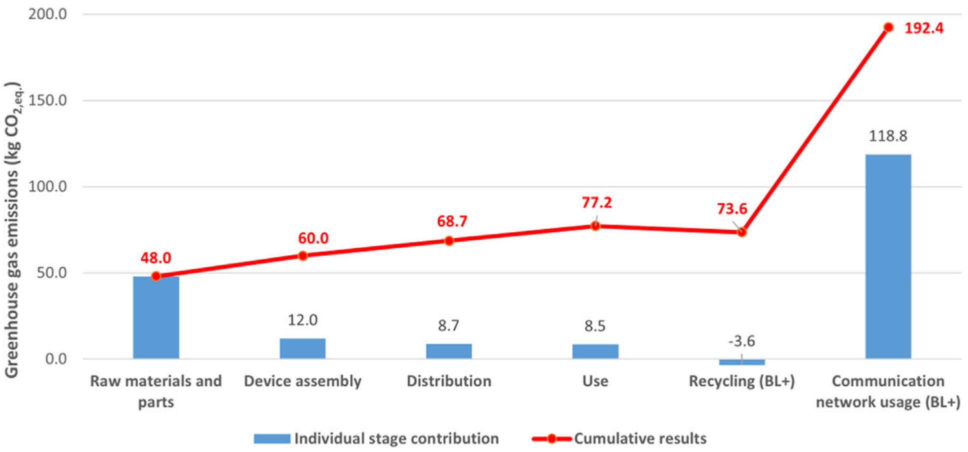

FIGURE 2 Carbon footprint results for the baseline scenario(s) (reference: 4.5 years, 2.25 smartphone units)

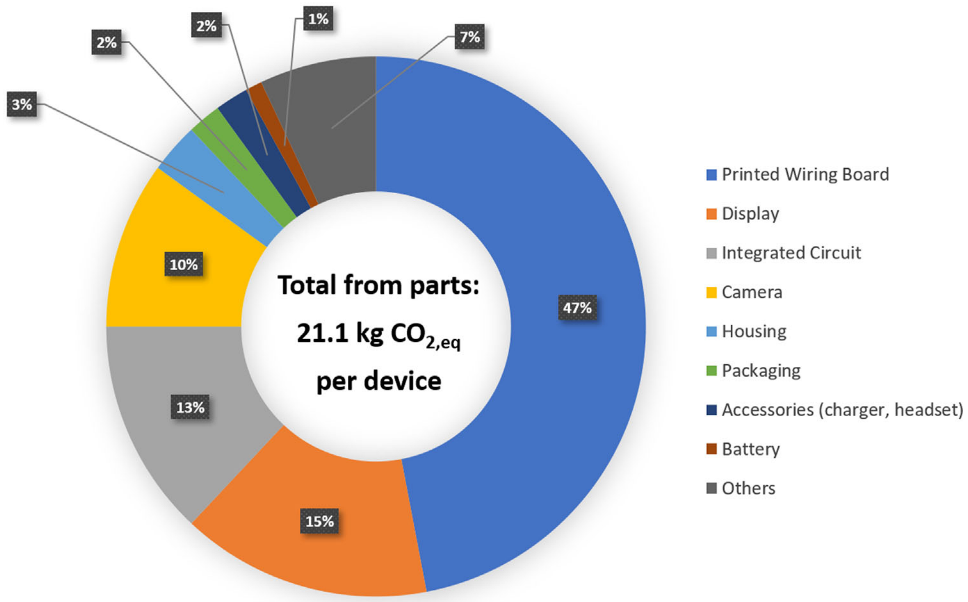

FIGURE 3 Carbon footprint associated to the Bill of Materials of one smartphone unit and contribution of different parts

To understand the plausibility of the CF result for BL, this was compared with other studies, as reported in Table 2. Results are also in line with the literature in highlighting the important contribution of materials and manufacturing processes to the CF of smartphones (78% for BL). Figure 3 shows the breakdown of the CF associated to materials for different parts of smartphones. The significant contribution of integrated circuit (IC), printed wiring board (PWB), display, and camera is notable. The importance of IC, PWB, and display is confirmed by other studies (Andrae, 2016; Clément et al., 2020; Ercan et al., 2016; Manhart et al., 2016; Proske et al., 2016). The importance of the camera unit was also highlighted by Proske et al., 2016. A smaller contribution is instead quantified for the battery. This is comparable with the results from Andrae (2016), although lower than indicated in Ercan et al. (2016) and Proske et al. (2016).

Absolute results can vary depending on design characteristics, user behavior, system aspects, as well as modeling approach, assumptions, and data used in different studies (Manhart et al., 2016; Clément et al., 2020). In particular, GHG emissions for IC are lower than in Andrae (2016), Ercan et al. (2016), and Proske et al. (2016). Given the lack of primary data, it was necessary to consider proxies for the BoM. The deviation observed for IC and PWB depends on weights and LCI datasets considered for these parts (see Supporting Information S1). However, the deviation is lessened when IC and PWB are considered together and results converge in the identification of priority parts, at least qualitatively.

As calculated in Proske et al. (2016), materials and assembly of the device are dominant contributors to the life cycle impacts of smartphones also for other impact categories (i.e., abiotic depletion potential, human toxicity, and ecotoxicity). Environmental impacts are due to manufacturing processes and the extraction and sourcing of materials (Moberg et al., 2014): the acquisition of gold and other metals (e.g., palladium) can contribute to about 10% of the CF (Andrae, 2016), while cobalt, copper, gold, and silver are important for resource scarcity, eutrophication, and human toxicity (Ercan et al., 2016).

3.1.2 | Inclusion of system aspects in the baseline scenario

Figure 2 shows the effects of including EoL recycling and usage of communication services in the scenario BL+.

Recycling reduced the CF by 5% compared to BL, thanks to recovery of materials and energy. State-of-the-art practices were considered in the modeling. The application of more advanced recycling technologies could allow a more efficient recovery of materials, with $CO_{2,eq}$ saving that could be ~30% higher. On the contrary, the EoL could even result in environmental burdens if materials are not recovered (see Section 2.2.3).

It should also be observed that the approach followed in this work is to assume the 1:1 displacement of primary material by recycled material. The displacement of primary materials in EoL modeling has been object of extensive discussion. Recent studies integrating consequential LCA considerations (Palazzo et al., 2019, 2020; Zink & Geyer, 2017) indicate that recycled materials do not necessarily replace primary materials of the same type. Therefore, actual benefits associated with the recycling of smartphones could be lower than calculated in this study.

Benefits of recycling would be better depicted through indicators relating to the scarcity of materials: according to Proske et al. (2016), recycling of smartphones can reduce impacts associated with materials and manufacturing stage by 3% for GWP, 6% for ecotoxicity, 9% for abiotic depletion of fossil fuels, 10% for human toxicity, and 59% for abiotic depletion of elements. Furthermore, recycling is important because smartphones includes CRM (e.g., cobalt, rare earths) and minerals from conflict-affected and high-risk areas (e.g., gold) (Manhart et al., 2016).

The inclusion of communication services (i.e., mobile networks, fixed access networks, data centers, and transmission infrastructure) resulted in the increase of the CF from 77.3 to 192.4 kg $CO_{2,eq}$ (2.5 times BL). This is due to the GHG emissions associated with the energy used for operating networks and data centers: 55.7 kWh/year, compared to 4 kWh/year for battery recharging and 4.7 kWh consumed for the manufacturing of a device. The impact of communication services is particularly relevant in case of internet content consumption with high bit rate (e.g., for video streaming) (Schien et al., 2013), which requires a large transmission of data. The CF would increase considerably (1.8 times BL) also when data consumption is halved.

The energy intensity of communication services is expected to decrease in the future since mobile-access network energy efficiency has improved by 10-30% annually in recent years (IEA, 2020). However, the energy efficiency increase associated with newer network technologies may not continue with 5G (Pihkola et al., 2018), and the simultaneous growth of data traffic could offset expected efficiency improvements (Ericsson, 2020; Lange et al., 2020; Montevecchi et al., 2020). In fact, data traffic volumes over mobile networks are increasing, and at a more dramatic rate than fixed-line traffic, mainly due to the increased consumption of video-streaming services (Cisco, 2015; Ericsson, 2020; Morley et al, 2018).

The significant and “hidden” contribution of networks and data centers (Andrae, 2016; Ercan et al., 2016; Suckling & Lee, 2015) calls for a system approach in the analysis and mitigation of the impacts associated to ICT products and related communication networks (Schien et al., 2013; Coroama & Hilty, 2014).

3.1.3 | Comparison between scenarios implementing material efficiency strategies

Table 3 and Figure 4 provides CF results for BL and material efficiency scenarios described in Table 1.

The CF can significantly decrease by extending the average replacement cycle of devices from 2 to 3 years (EXT1: −30%) or 4 years (EXT2: −44%). The CF reduction was associated with fewer device units (and thus parts and materials) being allocated to the reference time of 4.5 years (2.25, 1.5, and 1.125 units in case of replacement cycles of 2, 3, and 4 years, respectively).

In case of battery or display change in the first 2 years of use, the CF increased by 1% (BC) and 9% (DC) compared to BL, respectively. When the change of battery comes with an extension of the replacement cycle to 3 years (BC1) or 4 years (BC2), the CF decreased by 29% and 44%, respectively. The change of battery would not cause significant increase in the GHG emissions. In case of display change and replacement cycle of 3 years (DC1) or 4 years (DC2), the CF decreased by 23% and 40%, respectively. The CF decreased because the impacts associated with the manufacture of additional parts are compensated by the benefits of using smartphone devices longer.

The CF decreased to about half of BL when considering the purchase of remanufactured devices (RM), and the same energy consumption for producing new and remanufactured devices (4.7 kWh per device). The CF decrease could be more significant if less energy were needed for the reprocessing of devices. For example, the CF could decrease by 70% (compared to BL) considering 0.033 kWh for the refurbishment of a device (Skerlos et al., 2003). The CF could decrease even more (by about 80%) when refurbishment is not needed for the acquisition of second-hand devices (RU).

Environmental savings are possible under the assumption that the purchase of used devices, inclusive of both remanufactured and second-hand smartphones, perfectly replace the sale of new smartphone units. Actual benefits depend on “what” and “how much” is displaced (Zink et al., 2014).

TABLE 3 Carbon footprint results for different scenarios implementing material efficiency strategies

Scenario	Greenhouse gas emissions (kg $CO_{2,eq}$)		
	4.5 years	1 year	Relative (%)
BL: baseline (2-year replacement cycle)	77.3	17.2	100
BL+: as BL + system aspects	192.4	42.8	249
EXT1: as BL with replacement cycle increased to 3 years	54.4	12.1	70
EXT2: as BL with replacement cycle increased to 4 years	42.9	9.5	56
BC: as BL with battery change	77.9	17.3	101
BC1: as EXT 1 with battery change	54.8	12.2	71
BC2: as EXT 2 with battery change	43.2	9.6	56
DC: as BL with display change	84.5	18.8	109
DC1: as EXT1 with display change	59.2	13.2	77
DC2: as EXT2 with display change	46.5	10.3	60
BC-DC: as BL with battery and display change	85.1	18.9	110
BC-DC1: as EXT1 with battery and display change	59.6	13.2	77
BC-DC2: as EXT2 with battery and display change	46.8	10.4	61
RM: Purchase of remanufactured device	37.0	8.2	48
RU: Reuse (purchase of second-hand device)	16.3	3.6	21
LD1: as BL with 10% lighter housing and display	75.5	16.8	98
LD2: as BL with 20% lighter housing and display	73.7	16.4	95
LD3: as BL with 30% lighter housing and display	71.9	16.0	93

Note: Absolute values calculated over 4.5 years, normalized to 1 year, and expressed in relative terms with reference to the BL.

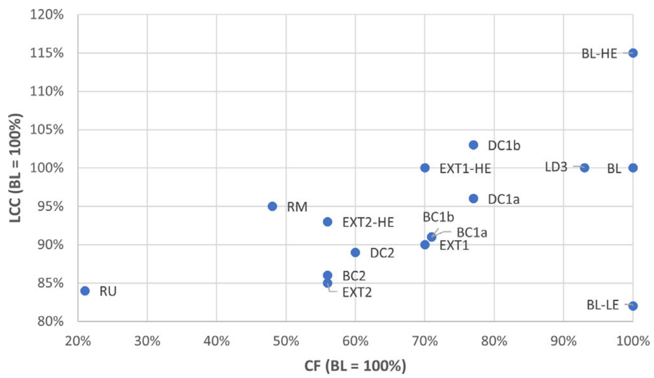

FIGURE 4 CF and LCC results for selected scenarios implementing material efficiency strategies (underlying data used to create this figure are provided in Supporting Information S2). *Legend*: BC1a (battery change by user, smartphone replacement cycle: +1 year), BC1b (battery change by professional repairer, smartphone replacement cycle: +1 year), BC2 (battery change by user, smartphone replacement cycle: +2 years), BL (baseline), BL-HE (baseline, high-end device), BL-LE (baseline, low-end device), DC1a (display change by user, smartphone replacement cycle: +1 year), DC1b (display change by professional repairer, smartphone replacement cycle: +1 year), DC2 (display change by user, smartphone replacement cycle: +2 years), EXT1 (extended use, smartphone replacement cycle: +1 year), EXT1-HE (extended use, high-end device, smartphone replacement cycle: +1 year), EXT2 (extended use, smartphone replacement cycle: +2 years), EXT2-HE (extended use, high-end device, smartphone replacement cycle: +2 years), LD3 (lean design, housing: −30% by weight), RM (remanufacture), RU (reuse). *Note:* System aspects excluded from the assessment of the CF; higher service contract costs considered for the assessment of LCC

In the past, used smartphones were often sent to developing countries, where consumers owned no smartphone (Zink & Geyer, 2017). Zink et al. (2014) estimated that the displacement of new smartphones by used devices could be equal to 0–5%. At a macro-scale, this would increase the overall consumption of the sector (Makov & Font Vivanco, 2018; Zink and Geyer (2017). However, the market of used smartphones has recently become more important also in developed countries (Watson et al., 2017). Worldwide shipments of used smartphones are expected to increase from 175.8 million units in 2018 to 332.9 million units in 2023 (IDC, 2019), against a total shipment of smartphones that is stagnant at around

TABLE 4 Life cycle costs for different scenarios implementing material efficiency strategies

	Life cycle costs (EUR 2019)					
	Higher service costs			Lower service costs		
Scenario	4.5 years	1 year	Relative (%)	4.5 years	1 year	Relative (%)
BL: baseline (2-year replacement cycle, average device)	2441	542	100	1486	330	100
BL-HE: as BL, with high-end device	2801	622	115	1846	410	124
BL-LE: as BL, with low-end device	2014	448	82	1058	235	71
EXT1: as BL with replacement cycle increased to 3 years	2201	489	90	1246	277	84
EXT1-HE: as BL-HE with replacement cycle increased to 3 years	2441	542	100	1486	330	100
EXT2: as BL with replacement cycle increased to 4 years	2081	462	85	1126	250	76
EXT2-HE: as BL-HE with replacement cycle increased to 4 years	2261	502	93	1306	290	88
BC1a: as EXT1 with battery change made by the user	2231	496	91	1276	284	86
BC1b: as EXT1 with battery change made by a professional repairer	2305	512	94	1349	300	91
BC2: as EXT2 with battery change made by the user	2104	468	86	1148	255	77
DC1a: as EXT1 with display change by the user	2332	518	96	1376	306	93
DC1b: as EXT1 with display change by a professional repairer	2503	556	103	1547	344	104
DC2: as EXT2 with display change by the user	2179	484	89	1224	272	82
RM: purchase of remanufactured device	2329	518	95	1373	305	92
RU: reuse (purchase of second-hand device)	2057	457	84	1102	245	74

Note: Absolute values calculated over 4.5 years, normalized to 1 year, and expressed in relative terms with reference to the BL.

1.4 billion units (Statista, 2019). This can be partly explained by the fact that used smartphones can offer similar features of new devices at lower price (IDC, 2019), at least until 5G networks and 5G-compatible smartphones achieve broad market penetration.

Furthermore, some authors (Makov & Font Vivanco, 2018; Makov et al., 2018; Zink & Geyer, 2017) pointed out that benefits from the sale of used devices could be partially offset by other rebound effects associated with the re-spending of economic savings. Makov and Font Vivanco (2018) estimated that at least one third of the emission savings resulting from smartphone reuse could be lost because of rebound effects.

Material design change was assessed in terms of lean design, where quantities of materials for housing and display are decreased by 10% (LD1), 20% (LD2), and 30% (LD3). It was estimated that the CF can decrease by 2–7%. The display size was maintained unvaried. Lean design could help counterbalance the increase of impacts associated with larger display sizes by reducing the amount of materials used. However, the actual variation of impacts also depends on inherent characteristics of used materials and their supply chains. For example, a substantial CF reduction can result from the use of renewable energy along the value chain and the recovery of metal scraps (Clément et al., 2020). Materials can also have an impact on the generation of manufacturing scraps, the recycling process, and the market of recycled materials (Cordella et al., 2020b).

3.2 | Life cycle costs

Different LCC scenarios are shown in Table 4 and Figure 4. When higher service contract costs were considered, a LCC of 2441 EUR over 4.5 years (542 EUR/year) was calculated for BL. LCC are 3.4 times the purchase price of single device units, with the larger contribution due to the use phase (70.5%), mainly because of the service contract. LCC were 15% higher (+81 EUR/year) in case of high-end product (purchase price: +50%) and 17% lower (−92 EUR/year) for the low-end product (purchase price: −40%), under the assumption that devices are replaced every 2 years.

For longer replacement cycles of 3 or 4 years (EXT1, EXT2), LCC decreased by 10% (−54 EUR/year) and 15% (−81 EUR/year), respectively. If the increased lifetime of the product is associated with high-end products (EXT1-HE, EXT2-HE), economic savings for consumers could be more moderate or even offset by the higher purchase price.

In case longer replacement cycles come with the battery change (BC1a, BC1b, BC2) there could be still LCC savings for consumers, although the intervention of professional repairers can lower them (BC1b). In case the longer replacement cycles come with the repair and change of the display

(DC1a, DC1b, DC2), there could be less or no LCC savings for consumers, due to higher repair costs. Facilitating the replacement of the displays by users can help reduce LCC (DC1a, DC2). However, the service contract appeared a more significant factor.

Finally, a decrease of LCC by 5% (−25 EUR/year) and 16% (−85 EUR/year) was calculated for the purchase of remanufactured (RM) or reused devices (RU) and higher service costs.

If lower service contract costs are considered (e.g., 14.11 EUR/month instead of 31.80 EUR/month), fluctuations over BL would be more significant in all the scenarios due to the increased importance of the product-related costs.

No recovery of residual value through re-sale of old devices was considered so far. As discussed in Sections 3.1.1 and 3.3, a number of devices are sold or recycled when approaching their EoL, which could allow recovering their residual value. Economic benefits from the re-sale of old devices could be considerable for consumers, for example, up to 288 EUR over 4.5 years (64 EUR/year) for BL.

All in all, results indicate that the analyzed material efficiency strategies can be economically appealing for consumers. However, as discussed in Section 3.1.3, it cannot be excluded that LCC saving can lead to re-spending rebound effects (Zink & Geyer, 2017).

3.3 | Average EU scenario

Results reported above aim to analyze different scenarios of use and disposal for smartphones. Repair frequencies and EoL disposal routes (see Section 2.2) were used to build an average EU scenario. Over a period of 4.5 years, this resulted in an average CF of 52 kg of $CO_{2,eq}$ (11.5 kg of $CO_{2,eq}$/year) and an average LCC of 2294 EUR (510 EUR/year) per user, which are 33% and 6% lower than in the BL, respectively. This supports the importance of extending the replacement cycle of devices and promoting remanufacturing, reuse, repair, and recycling activities, with even more evident benefits that could be observed with other metrics.

3.4 | Technical measures to improve the material efficiency of smartphones

Results support the importance of material efficiency strategies for smartphones. In particular, considerable CF and LCC decreases were associated with strategies oriented to extend the lifetime of device or its parts (see Figure 4).

This can be promoted through designs aimed at improving the reliability of the device, especially for electronics and parts as batteries and displays that could cause a premature replacement, as well as its resistance to accidental drops and its protection from water and dust (Cordella et al., 2021).

A lifetime extension can be pursued also through repair, remanufacture, and re-sale of devices. Apart from ensuring the availability of quality-compliant parts, these strategies can be enhanced through design-for-disassembly and modular design concepts (which would also enable hardware and aesthetic upgrades), as well as the integration of functions for data transfer and deletion, password reset, and factory-setting restoration (Cordella et al., 2020b; Peiró et al., 2017).

Durability considerations go beyond the hardware and cover also software and firmware (OCU, 2017). Measures that could avoid the premature functional obsolescence of smartphones (e.g., not working applications, unavailability of security updates) include the installation of sufficient capacity (memory) in the device, as well as the availability of update support (e.g., operating system [OS] and/or security updates) and compatible open source OS. Furthermore, the battery management software plays a key role in preserving the battery (Cordella et al., 2021).

Complementary measures should aim at facilitating the recycling of smartphones (Kasulaitis et al., 2018), in particular by enhancing the collection of devices and the separation of parts and materials (Geyer & Doctori Blass, 2010).

It should also be observed that potential trade-offs associated with specific design concepts should be evaluated carefully. For example, products designed to be more resistant may see their repairability limited, and vice versa (Cordella et a., 2021), while leaner design concepts may reduce the flow of recyclable materials and hinder EoL recycling (Geyer & Doctori Blass, 2010). Profitability of recycling is particularly affected by the price volatility of materials, with recycling itself partly contributing to decrease the price of primary materials (Clift & Wright, 2000). This scenario may change in future since the transition to a "green economy" may have a substantial impact on the market of materials and provide incentives for recycling (Renner & Wellmer, 2020).

Other EoL alternatives (reuse and remanufacture) may be more profitable than smartphone recycling (Geyer & Doctori Blass, 2010). However, as discussed in Section 3.1.3, environmental benefits achievable with the purchase of remanufactured and second-hand devices may be counterbalanced by possible rebound and market expansion effects.

Furthermore, consumers may find it difficult to understand the benefits associated with specific design options and that their replacement choices can be driven by perceived (psychological) obsolescence and the desire of having new devices (Makov & Fitzpatrick, 2019; Watson et al., 2017). To be effective, the technical measures described above should be accompanied by the sharing of information about correct use, maintenance and disposal of smartphones and associated benefits (e.g., why and how preserving the battery life, applying protective accessories, collecting unused smartphones at the EoL).

4 | CONCLUSIONS

This study analyzed how different material efficiency scenarios can affect the CF of smartphones, and their LCC from the perspective of consumers. Technical measures to implement material efficiency strategies for this device were then discussed. The following conclusions are drawn.

4.1 | Material efficiency scenarios and system aspects

The analysis of a sample of smartphone devices suggested an apparent increase in display size and memory configuration for newer models, which can partly contribute to increase the CF of smartphones. However, other circumstances that can more significantly contribute to the overall increase of GHG emissions from smartphones are their growing market penetration and short replacement cycles.

Extending the replacement cycle of smartphones (beyond 2 years) avoids the need of new devices, parts, and materials. This appeared as a win–win solution to reduce CF and LCC, as depicted in Figure 4. Appreciable savings could be possible also in case of battery/display replacement. An extension of the replacement cycle could be supported through design concepts that enhance hardware reliability, repairability, and upgradability, as well through the availability of appropriate software and firmware solutions.

Remanufactured and second-hand devices could potentially yield greater benefits. However, results are dependent on the 1:1 displacement assumption made in the assessment, based on which devices, parts, and materials can be perfectly replaced by secondary ones, while rebound effects could occur in real markets.

Since a large portion of smartphones is not properly collected at the EoL, enhancing their collection is vital for product and material value retention. Measures to facilitate the recycling of smartphones are complementary to those promoting an extension of the lifetime of the device and its parts. Additional benefits could come with the adoption of leaner designs, although this strategy was not assessed thoroughly.

However, it should be highlighted that the analysis of material efficiency aspects is complicated by the presence of possible trade-offs, and that the effective implementation of material efficiency strategies rely on behavioral aspects and comprehensive information of users.

Furthermore, although the focus of this work was on material efficiency aspects, it was interesting to observe how major contributions to CF and LCC are beyond the physical device boundaries.

The CF of smartphones is determined to a large extent by the usage of communication services. This calls for the importance of addressing their energy efficiency and informing users about the "hidden" impacts associated with the use of smartphones.

From a LCC perspective, the main cost for consumers is instead associated to service contracts. Apart from their economic relevance, service contracts can also play an environmentally strategic role for smartphones since they can affect the amount of data that users exchange and how frequently devices are replaced.

4.2 | Application of results and future research perspectives

This study can be used by decision-makers as a base of information to reduce the impacts associated with the production and consumption of smartphones. For example, it could: (i) guide purchase decisions of consumers and public procurers; (ii) support product design and business development activities of manufacturers and service providers; (iii) feed discussion on product testing and/or regulation, as currently happening at the EU level (Ecosmartphone, 2020).

This study focused on virtual scenarios for the EU and a limited number of quantitative indicators. Future research could build on this study by considering further scenarios (e.g., focusing on network systems and PSS business models) based on real case studies, and the adoption of broader sustainability assessment metrics (Peña et al., 2021), also to understand the magnitude of possible trade-offs and rebound effects that could reduce circular economy benefits at a macro-scale (Makov et al., 2018; Zink & Geyer, 2017).

However, gathering information for smartphones was a challenging process. This was handled through a transparent description of available information and assumptions made, as well as the critical analysis of the results, also through the consultation of ICT experts. Further effort and collaboration between manufacturers, researchers, and policy makers is necessary to develop and make available relevant data for smartphones (and other electronics), such as BoM and LCI datasets, failure and repair frequencies, user statistics.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Mauro Cordella https://orcid.org/0000-0001-9121-1134
Felice Alfieri https://orcid.org/0000-0003-1147-719X
Javier Sanfelix https://orcid.org/0000-0002-4465-2276

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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