ICT TASK FORCE STUDY

Task 4-6: Potential for Material Efficiency

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Contents

1 Introduction

In 2016, the Commission announced, in the context of the Ecodesign Working Plan, a separate strand of work on ICT products in order to determine the best policy approach for improving their energy efficiency and wider circular economy aspects. In this context a study called "ICT Impact study" focusing on energy efficiency of 8 main ICT categories of products was carried out by VHK and Viegand Maagøe for the European Commission and published in July 2020. This Joint Research Centre (JRC) study is complementing this work by providing a comprehensive and dynamic analysis of the ICT sector. This study is being developed for the European Commission's Directorate General for Energy.

This project called "ICT Task Force Study" has started in July 2020 and is expected to be completed by the end of 2022. The following tasks have been already completed and the corresponding reports are published at the JRC website[1]:

Task 1 - Creation of project website, initial list of stakeholders, launch of an initial awareness message
Task 2 - Consolidation of the definition and categorisation of the different sectors/products analysed under 'ICT products'
Task 3 - Potential for Energy Savings

This report present the results of the following tasks of this study, mainly focusing on the material efficiency aspects of ICT devices:

Task 4 - Material Efficiency: Collection of data
Task 5 - Analysis of potential for material efficiency
Task 6 - Analysis of trade-offs and synergies

Data collection on material efficiency aspects has been carried out by literature review and includes data on lifetimes, typology of repairs, frequency of failures and bills of materials of ICT products. Assessment of design cycles of the ICT products, and the points of design with highest potential for improvement related to material use, is presented in relation to both first order effects (life cycle impacts of the device) as well as at second order effect level (e.g. obsolescence, induction effects). Strategies against material obsolescence and towards product circularity have been identified based on the points above and taking into account possible trade-offs/synergies between these strategies.

More specifically, this part of the study covers two main aspects:

- A presentation of main impacts related to material use, both in relation to first order effects as well as at second order effect level
- An identification of strategies against material obsolescence and towards product circularity.

At first order effect level (see Figure 1 below), ICT devices demonstrate commonalities with regards to the materials used and manufacturing processes for a number of key components (e.g. batteries, displays, integrated circuits). Therefore they also demonstrate commonalities in terms of the types of environmental impacts caused and the depletion of critical materials. Material use at use phase with the use of ICT accessories, consumables and spare parts, as well as the impacts caused at end of life including improper recycling processes are also non-negligible.

[1] https://susproc.jrc.ec.europa.eu/product-bureau//product-groups/522/documents

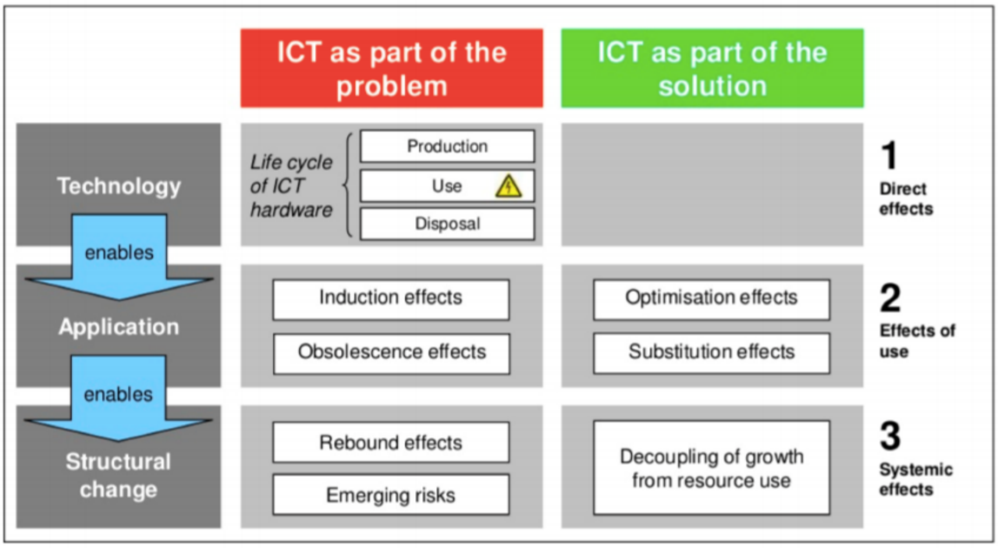


Figure 1: A matrix of ICT environmental effects (Hilty et al., 2015)

In addition to first order effects, second order effects enabling material use are also present in the ICT sector. Contrary to the case of energy use whereby induction and optimisation effects are prominent, in terms of material use the effects are mostly related to obsolescence (more material use) and substitution (less material use). Beyond technical obsolescence, a wide range of obsolescence types observed are presented, including those caused by software unavailability or incompatibility.

The consequences of these effects are reflected in the lifetime of ICT devices. In Chapter 4 of this report explores how the effects are influencing lifetime of components, and therefore devices.

An understanding of first and second order effects and their consequences in determining product lifetime allows for the development of strategies for material efficiency and product lifetime extension. Section 5 of this report presents a number of strategies, ranging from reliability and reparability to recyclability and the use of recycled content in new products. Their use and influence on product lifetime is examined, while examples of their implementation at design level and of their enabling via regulatory measures are provided. Finally, such strategies have the capacity to reinforce each other in a synergetic way towards lifetime extension and material efficiency, while they can often act in a conflicting manner posing trade-offs.

The study will be complemented in the next months by the following additional tasks:

Task 7 - Analysis of user behaviour implications
Task 8 - Grouping of products
Task 9 - Analysis of the Life cycle costing implications
Task 10 - Comprehensive compilation of possible policy instruments for ICTs products
Task 11 - Suitability for different policy instruments
Task 12 - Final Policy Recommendations.

The project foresees stakeholder consultations (during and at the end of the study). Registered stakeholders will be informed about the publication of the upcoming reports and meetings by email.

Based on the findings, JRC will provide policy recommendations for the improvement of the sustainability of ICT products and systems within the context of the ecodesign framework, but also explore the suitability of complementary policy tools beyond ecodesign.

2 Material use in ICT production and consumption

Processes and material flows contributing to the material basis of an ICT device, can be divided in upstream and downstream flows, with material concentration and dilution phases along the life cycle (see Figure 2 figure below (Wager et al. 2014)).

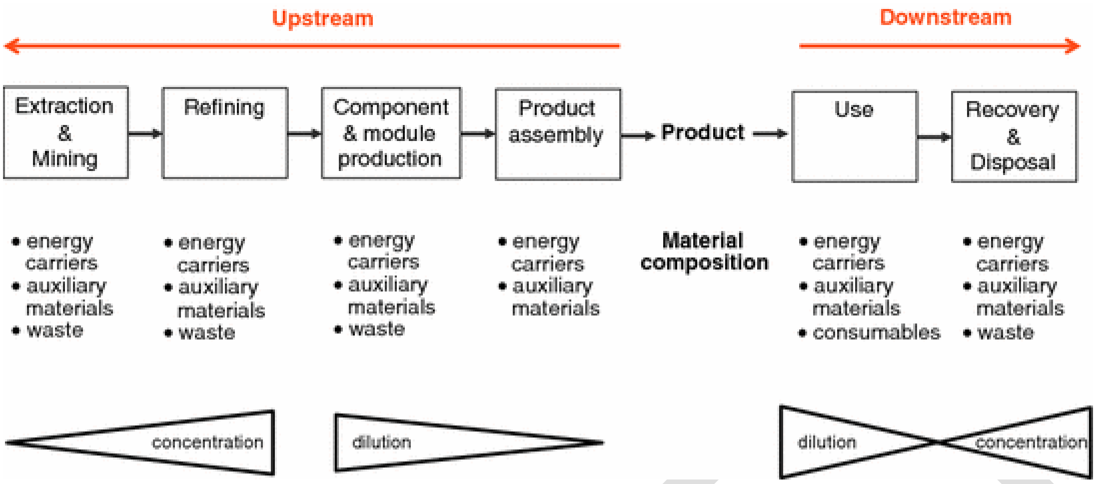


Figure 2: Processes and material flows in ICT life cycle. Source: Wagner et al. 2014

2.1 ICT general bill of materials

Modern ICT systems are based on hardware devices with a complex composition in terms of materials. Even though it is not possible to define a general bill-of materials, Wagner et al. (2014) described an average materials composition of a consumer ICT, based on devices collected in Switzerland in 2010 at the end of their useful life. According to this study, the majority of the mass of such devices consists of:

- the base metals iron (Fe), aluminium (Al), and copper (Cu),
- polymers (mainly ABS, PC, PC/ABS, PE, PS, and SAN)
- glass
- and in minor quantities, other scares metals including, among others, gold (Au), platinum group metals (PGM) silver (Ag), rare earth elements (REE) such as dysprosium and neodymium, indium (In), tantalum (Ta).

According to Wagner et al. (2014) polymers, glass and iron represent the main part of the ICT mass (see Figure 3).

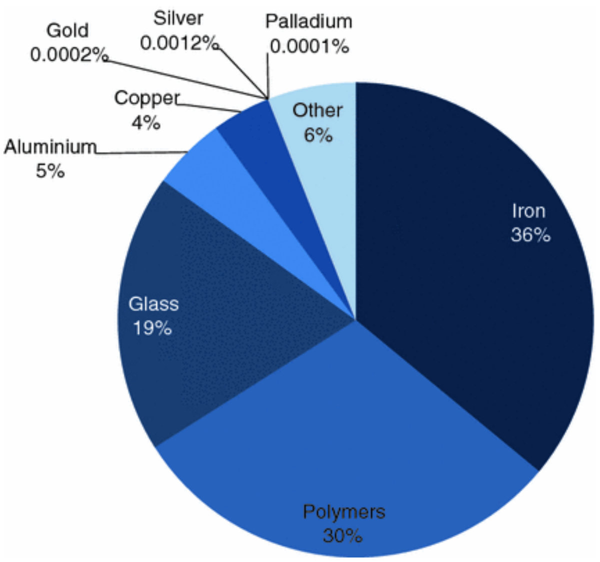


Figure 3: Relative mass distribution of the materials contained in EoL consumer ICT devices in Switzerland (reference year 2010).

More recent estimations from Ericsson shows that ICT confirm the general mass distribution for ICT Entertainment & Media (E&M) devices. Iron, plastic and glass as bulk materials, but in this study also cardboard (for packaging is included). Other scares metals, including copper, silver, gold, PGMs accounting for a minor, but still relevant, fraction of the material consumption.

According to the same study, ICT represent, in terms of mass, only a very small percentage (around 0.5%) of the total mass use of these materials in the economy in one year (Figure 4). However, due to the high use of metals in this sector (e.g. copper and gold) the material carbon emissions (between 0.6% and 1.3%) and were found to be somewhat higher than the weight shares imply, while resource depletion (or abiotic depletion potential, ADP[2]) between 13% and 48%, based on methodological assumptions. (Ericsson, 2018; Malmodin et al. 2018).

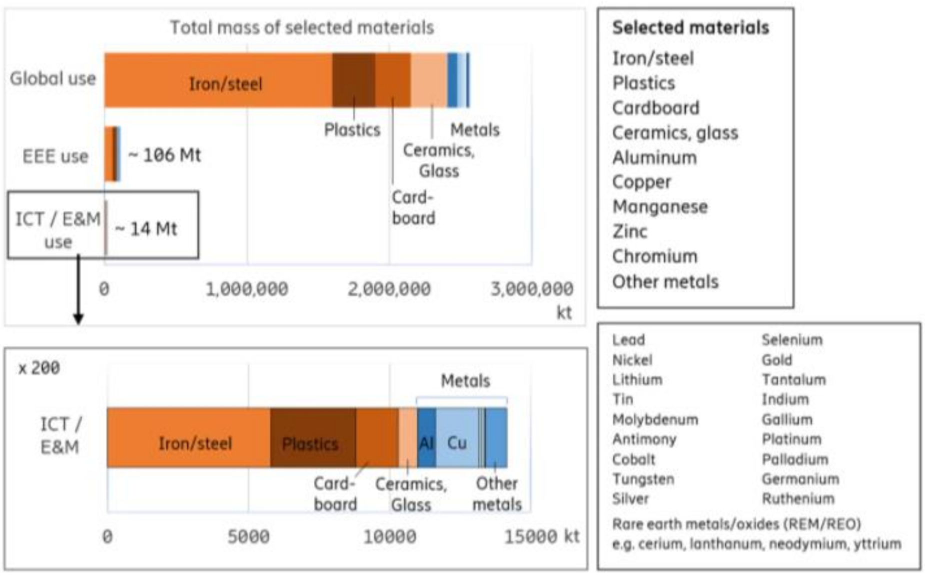


Figure 4: Relative mass distribution of the materials contained in EEE (above) and ICT / E&M devices. Source: Ericsson (2018)

[2] Abiotic depletion refers to the depletion of non-living (abiotic) resources such as fossil fuels, minerals, clay, and peat. Abiotic depletion is measured in kilograms of Antimony (Sb) equivalents.

The bill of materials composing a single ICT device is highly complex: specific materials are concentrated in specific components and associated to specific functions (see Figure 5). As ICT products continue to miniaturize and become more sophisticated, they rely on materials such as metals, alloys and polymers to deliver their different functionalities (ITU and WEEE Forum, 2020). According to Manhart et al. (2016), smartphones host 60 of the 83 stable and non-radioactive elements in the periodic table.

Figure 5: Example of product disassembly for a tablet (Samsung Galaxy Tab 4 SM-T530, 2014), illustrating the main components (Babbitt et al., 2020).

2.2 Impacts from material extraction

Most of the materials used in ICT are metals that are manufactured by a series of engineering operations, starting with exploration to mining, mineral processing, metal extraction and finally manufacturing of final products. Each of these stages is characterised by environmental impacts and waste generation. The cradle-to-cradle cycle or the complete process value chain for metals is illustrated in Figure 6 below.

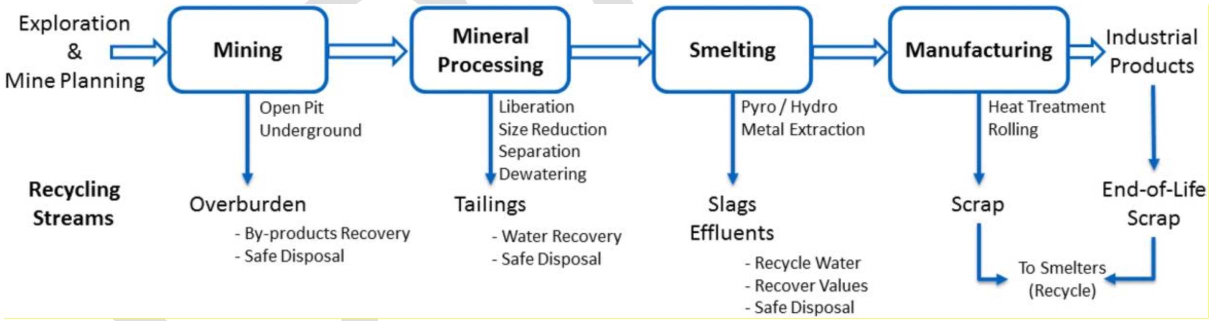


Figure 6: Cradle-to-cradle cycle for metals. Source: Pradip et al., 2019

Most of the materials used in the ICT sector are characterised by complex supply chains (example in Figure 7), where the ore extraction, processing, smelting and final manufacturing can occur in different countries or even continents. Materials as Copper (Cu) and Cobalt (Co), a key element in the cathodes of lithium-ion battery of ICT devices, are mainly extracted in Africa and transported in Asia for processing (Van den Brink et al. 2020).

Mines 2016	Refineries 2016	Intermediate Cobalt Product Trade Flows
Nickel (17) Copper (12) Nickel and/or Copper (10) Cobalt (1)	All items (23)	Cobalt ores and concentrates (tonnes): Cobalt mattes and other intermediate products of cobalt metallurgy, cobalt and articles thereof (tonnes):

Figure 7: Supply chain of Cobalt Source: Van den Brink et al., 2020

In some cases, the supply chain can follow even more complex flows. The NGO CEE Bankwatch Networks (2016) described an anecdotal example of copper and precious metals ore concentrate extracted in EU from a Bulgarian mine and subsequently exported to Namibia for the smelting processes, together with minerals from different sources. This case, shows as part of the environmental (and social) impacts of mining can be externalised in third countries, even when the mining occurs in EU.

Figure 8 : Example of extractive activities involving several countries and continents. Source: CEE Bankwatch Networks, 2020).

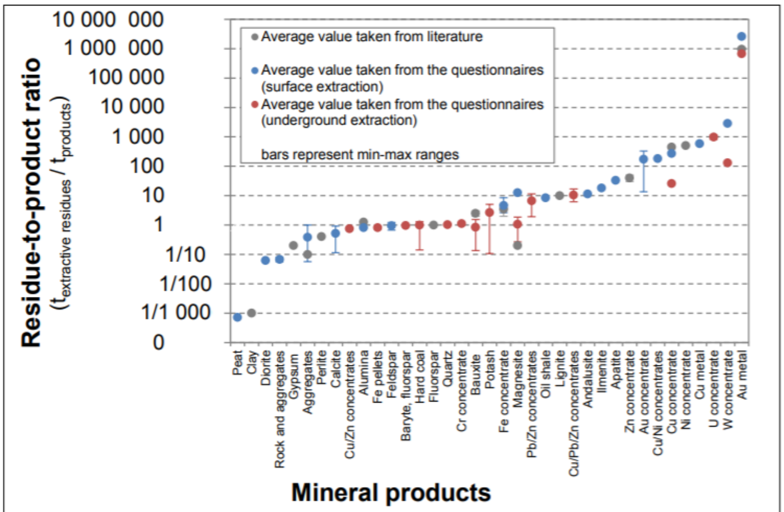
The environmental and socio-economic impacts associated with the extraction, processing and the entire lifecycle of the materials and minerals used in ICT are described in the paragraphs below.

Environmental impacts

According to the Organisation for Economic Co-operation and Development (OECD), the growth in materials use, coupled with the environmental consequences of material extraction, processing and waste, is likely to increase the pressure on the resource bases of the planet's economies and jeopardize gains in well-being (OECD, 2019).

Main environmental impacts of mining activities include:

Production of large quantities of extractive waste and tailings: Gold and silver are among the most wasteful metals, with more than 99 percent of ore extracted ending up as waste. According to the Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries (JRC, 2019), some of the metals used in ICT devices such as gold, copper, tungsten have a very high residue-to-product ratio (Figure 9).



Based on different sources of literature data (BRGM 2001; EC-JRC 2009; IAI 2015; Spitz and Trudinger 2008) and the questionnaires.

Figure 9: Residue-to-product ratio for the extraction of different mineral

Risks from collapse of Extractive Waste Facilities: extractive waste facilities (EWF) in form of dams are built to retain wastes resulting from the treatment of minerals (e.g. slurried extractive waste from mineral processing). These dams can be huge (tens of metres high and heaps even more than 100 m). The collapse of any type of EWF can have short-term and long-term effects. Typical short-term consequences may include: dangerous flow slides; release of hazardous substances; flooding; blanketing/suffocating; crushing and destruction; cut-off of infrastructure; poisoning; casualties. Potential long-term effects may include: metal accumulation in plants and animals, contamination of soil, contamination of groundwater, loss of animal life, adverse effects on human health (JRC, 2019)

In last 10 years two major environmental tragedies involving mining dams occurred in Brazil (Vergilio et al. 2020) The rupture of the Fundão Dam for the iron one mine in the sub-district of Bento Rodrigues, 35 km from the municipality of Mariana in Minas Gerais State on November 5, 2015, resulted in 19 deaths due to the release of more than 40 million m^3 of tailings that were transported to the mouth of the Doce River. The 668 km length of affected water by Fundão tailings is the largest ever recorded. The second incident occurred on January 25, 2019, when a tailings dam ("Dam B1") failed at Córrego do Feijão iron ore mine in the city of Brumadinho, also in Minas Gerais State, releasing approximately 12 million m^3, which directly affected the administrative area of the company and parts of the nearby communities, resulting in 244 deaths and 26 missing people, as some bodies were completely buried in the mud and never found. But these are one-off events.

Reuters[3] reports 11 serious tailings dam failures have occurred in the last decade and such catastrophic events are becoming more frequent, according to researchers at World Mine Tailings Failures (WMTF).

In Europe collapses of dams at operations in Aznalcóllar (Seville) in 1998 in Spain and Baia Mare in Romania (in 2000), as well as the more recent dam failure in Kolontár in Hungary, in 2010, have brought public attention to the management of extractive waste (JRC, 2019).

Sedimentation: sediments from waste rock piles or runoff after heavy rainfall often increases the sediment load of nearby water bodies. In addition, mining may modify stream morphology by disrupting a channel, diverting stream flows, and changing the slope or bank stability of a stream channel.

Acid mine drainage (AMD): this is one of the most serious environmental impacts associated with mining. At metal mines, the target ore (like gold, silver, copper, etc) is often rich in sulfide minerals such us pyrite FeS_2 or pyrrhotite. When the mining process exposes the sulfides to water and air (oxygen), together they react to form sulfuric acid. This acid can dissolve other harmful metals and metalloids (like arsenic) from the surrounding rock. The presence of acid-ingesting bacteria often speeds the process. Waste rock piles, other exposed waste, mine openings, and pit walls are often the source of acidic effluents from a mine site. Acid mine drainage is especially harmful because it can occur indefinitely — long after mining has ended. A relevant case in Europe regards the river Rio Tinto, in Huelva (Spain). Immediately after the cessation of mining activities in 2000 there was a worsening of acid drainage impacts and extreme concentrations of metals were reached (up to 5 g/ L of Fe, 50 mg/L of As, and so on). After that, there was a slight improvement in water quality in terms of pollutant loads. However, the AMD generation in the mining area is expected to continue for many hundreds of years, and the Río Tinto will continue to transport very high amounts of toxic metals to the Huelva estuary (Olias et al. 2020).

Metal deposition and toxicity: Most mining operations use metals, reagents, or other compounds to process valuable minerals. Certain reagents or heavy metals, such as cyanide and mercury, are particularly valued for their conductive properties and thus are frequently used. The release of metals into the environment can also be triggered by acid drainage or through accidental releases from mine tailings impoundments. While small amounts of heavy metals are considered essential for the survival of many organisms, large quantities are toxic. Few terrestrial and aquatic species are known to be naturally tolerant of heavy metals, although some have adapted over time.

Loss of Biodiversity and Habitat: the most obvious impact to biodiversity from mining is the removal of vegetation, which in turn alters the availability of food and shelter for wildlife. At a broader scale, mining may impact biodiversity by changing species composition and structure. For example, acid drainage and high metal concentrations in rivers generally result in an impoverished aquatic environment.

LCA results from Ercan et. al., (2016) show that gold and copper are the main contributors to the toxic impact categories and resource depletion (together with battery metals) but their contribution is highly dependent on the data sources and assumptions on recycling (Figure 10 and Figure 11).

[3] https://www.reuters.com/article/us-vale-sa-disaster-ahome-idUSKCN1Q405J

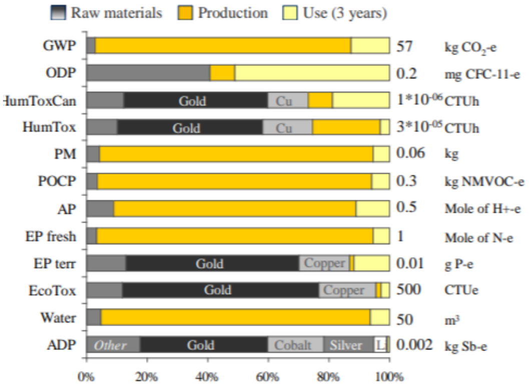


Figure 10: Total life cycle result for all impact categories for smartphone Z5 with accessories using Ecoinvent database and adopting a 50/50 recycling approach with 19% recycling of gold assumed.

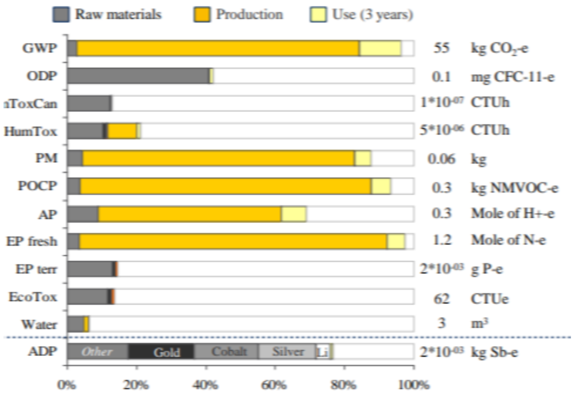


Figure 11: Total life cycle result for all impact categories for smartphone Z5 with accessories using GaBi database for gold and energy production and a 50/50 recycling approach with 83% recycling of gold assumed. Note that the figure shows relative results compared to Figure 10

Environmental problems regarding metallic mineral mining can be site-specific. Mining sites and regions can go through massive Land Use Change in their life cycles; therefore, the in-depth historical LUC estimation is required to understand the footprint of the mining activity (Islam et al. 2020).

Therefore, on behalf of the German Federal Environment Agency, a method ("OekoRess") was developed by Öko-Institut e.V. aiming at the identification of raw material environmental hot spots as well as rankings and prioritizing of raw materials (Manhart et al. 2018). The methodology has been further developed in the OekoRess II method (Dehoust et al., 2020).

This approach takes into account different areas of environmental evaluation with different indicators relevant for each area (see Table 1: Level of evaluation of raw material-related environmental hazard potentials (EHP) and related indicators.. Firstly, within the area of geology, three indicators are applied in relation to the likelihood of radioactive contamination, paragenesis[4] with heavy metals and potential for Acid Mine Drainage (AMD). In this context the raw materials that tend to occur in sulphidic ores pose a higher Environmental Hazard Potential than raw materials occurring in oxidic sedimentary ores

Secondly, some indicators assess the technology level, the mining method and the use of auxiliary substances. Finally, Environmental Hazard Potentials that emanate from the natural environment are assessed (indicators 6-8). This relates to the geographic location of the mine sites and investigates hazard potentials due to floods, landslides, earthquakes and storms. For example, if a majority of mines for a certain raw material are located in areas with frequently occurring floods, the Environmental Hazard Potential for the raw material is more likely to be high, since floods can be a cause of tailing dam failures. Moreover it is determined whether mines are located in areas with a high water stress or low water-availablility (deserts), and if mining sites are located in protected areas.

In addition, the environmental governance (EGov) is assessed based on the weighted EPI according to the production share of the producing countries. If raw materials are mined to a large extent in countries with weak environmental governance, it is more likely that the Environmental Hazard Potentials are not properly managed and the likelihood for the occurrence of environmental impacts is higher.

Lastly, the method includes two indicators addressing the size of global material and energy flows from mining to refining in order to assess the absolute physical dimension of probable impacts. For this inventory

[4]The term "paragenesis" indicates the sequence in which the minerals are formed in an ore deposit.

data for the indicators Cumulative Energy Demand (CED) and Cumulative Raw Material Demand (CRD) are used. The specific values per ton of refined material are multiplied by the world production (2014/15) and depict the size of material flows (SMF) and the size of energy flows (SEF) on a global level. The indicators SMF and SEF could be determined for 52 raw materials.

Table 1: Level of evaluation of raw material-related environmental hazard potentials (EHP) and related indicators.

Areas of evaluation	**Indicators**
Geology	1. Pre-conditions for Acid Mine Drenage AMD 2. Paragenesis with heavy metals 3. Paragenesis with radioactive substances
Technology	4. Mine type 5. Use of auxiliary substances
Natural Environment	6. Accident hazards due to floods, earthquakes, storms, landslides 7. Water Stress Index (WSI) and desert areas 8. Designated protected areas and AZE sites
Environmental Governance	9. Environmental governance in major production countries (EPI)
Global Material and Energy Flow	10. Cumulated raw material demand of global production (CRDglobal) 11. Cumulated energy demand of global production (CED)

Based on this methodology has identified the raw materials with highest environmental hazard potential (aEHP). In total, 21 raw materials are classified with a high aEHP. Most of these materials are also included in the list of Critical Raw Materials (see)

Critical Raw Materials: economy and supply risks

Many of the materials used in the ICT sector are characterised by potential supply concerns / high economic importance. These materials are included in the EU list of Critical Raw Materials (European Commission, 2020a) (e.g. Boron, Cobalt, Gallium, Lithium, Rare Earth Elements ...).

The CRM concept addresses the topic of criticality rather from scarcity than from environmental perspective. However, the extraction and processing of these materials, even the in case of larger availability (e.g. aluminium), has always relevant impacts from the environmental point of view.

The World Bank projects that demand for some metals and minerals will increase rapidly with investment in climate mitigation technologies. The most significant example of this is electric storage batteries, where the rise in demand for relevant metals, aluminium, cobalt, iron, lead, lithium, manganese and nickel would grow by more than 1000 per cent by 2050 under a 2°C scenario compared to a business as usual scenario. The OECD forecasts that, despite improvements in materials intensity and resource efficiency and the growth in the share of services in the economy, global material use will more than double from 79 billion tons in 2011 to 167 billion tons in 2060 (+110%)..

It is a bit unclear how much ICT / digital sector will affect the EU consumption of CRMs,that is expected to be mainly driven by the deployment of strategic sectors as renewables, e-mobility and defence and aerospace sector. ICT / digital technologies play a key role also for the development of these strategic sectors.

Many critical materials have a range of applications in various industrial sectors meaning that there will be increasing competition between all sectors for the same raw materials, processed materials as well as components, especially chips[5].

According to the European Commission study “Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020" critical materials in digital devices include elements like copper, gallium,

[5] https://www.ft.com/content/13094950-fb45-4686-9ef9-8199c674b90d

germanium, gold, indium, PGMs, rare earths and tantalum. China (41%) and African countries (30%) are the dominant suppliers of Critical Raw Materials in digital devices. Moreover EU is largely dependent on other countries (mainly from South-East Asia) for high-tech components and assemblies (European Commission, 2020d).

For these materials it would be important to reduce dependency through circular use of resources, sustainable products and innovation -diversify supply with sustainable and responsible sourcing from third countries, strengthening rules-based open trade in raw materials and removing distortions to international trade (European Commission, 2020b)).

Conflict Minerals and other social Impacts

Even though social impacts from the extraction and processing of materials used in ICT are not in the scope of this study, they are shortly described in this paragraph, as they widely correlate with the environmental impacts (Manhart et al. 2016). These includes occupational health and safety violations that have direct effects on worker's lives; employment conditions including long hours, low wages and temporary contracts: force labour in factories, smelting facilities and mines (ICLEI Europe and Electronics Watch 2020).

According to (Di Noi et al. 2020) the social LCA methodology and indicators appear appropriate to perform an initial social sustainability screening, thus enabling the identification of hotspots in raw material supply chains and the prioritization of areas of action in EU policies.

However, a comprehensive screening and prioritisation of minerals based on their social impacts is not yet available in the literature.

In the last few years, policymakers, NGOs and industry have focused the attention on the social impacts of the materials classified as Conflict Minerals (i.e. 3TG = Tungsten, Tantalum, Tin, and Gold), plus Cobalt. These materials come from areas where they are mined in conditions of armed conflict and in which human rights abuses are common.

Regulation (EU) 2017/821[6] lays down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas. It should be noted that obligations affect importers of these materials and not the import of ICT devices containing these materials.

Cobalt, despite being mainly mined in the Democratic Republic of the Congo, is not listed as a "conflict mineral" due to the fact that the area where cobalt is mined has not been affected by armed and violent conflicts after the end of the Second Congo war in 2002/2003 (Manhart, 2016). Nevertheless, cobalt mining in the DR Congo has manifold adverse social impacts in the region, which are thoroughly described by Amnesty International (2016) and by Mancini et al. (2021).

Other holistic approaches are provided by some OEMs that have developed methodologies in order to prioritise their actions on materials (and related supply chain) with higher environmental / social and economic impact. Examples are the so-called Material Impact Profiles (MIP) from Apple[7], aiming to evaluate potential supply, environmental, and social impacts in a single assessment and the Dragonfly Initiative by Fairphone[8]. Apple has active identified a short list of materials on which to focus initial efforts, including aluminium, cobalt, copper, glass, gold, lithium, paper, plastics, rare earth elements (neodymium, praseodymium, dysprosium), steel, tantalum, tin, tungsten, and zinc. Fairphone identified the following priority minerals: tin, tantalum, tungsten, gold, cobalt, copper, gallium, indium, nickel, and rare earth metals.

Table 2 provides an analysis of the raw materials in present in ICT devices and marking the raw materials with highest criticality in terms of supply risk / economic relevance, environmental relevance and armed conflicts.

Table 2 : materials used in ICT with highest criticality in terms of supply risk, environmental impacts and risk of conflicts.

Material	Raw Materials of High Supply Risk / Relevance (EU List of Critical	Raw Materials of High Environmental Relevance*	Conflict Minerals Regulation (EU) 2017/821

[6] Regulation (EU) 2017/821 of the European Parliament and of the Council of 17 May 2017 laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas

[7] https://www.apple.com/environment/pdf/Apple_Material_Impact_Profiles_April2019.pdf

[8] https://www.fairphone.com/wp-content/uploads/2017/05/MaterialScopingStudy_Feb2017.pdf

	Raw Materials)		
Antimony (Sb)		X	
Borates (B)	X		
Cobalt (Co)	X	X	X**
Copper (Cu)		X	
Chromium (Cr)		X	
Hafnium (Hf)	X		
Gallium (Ga)	X		
Germanium (Ge)	X	X	
Gold (Au)		X	X
Graphite (C)	X		
Indium (in)	X	X	
Lithium (Li)	X		
Magnesium (Mg)	X		
Manganese (Mn)		X	
Nichel (Ni)		X	
Niobium (Nb)	X		
Rare Earth Elements (REE)	X		
Palladium and other Platinum Group Metals (PGM)	X	X	
Silicon metal (Si)	X		
Silver (Ag)		X	
Tantalum (Ta)	X		X
Tin (Sn)			X
Tungsten (W)	X		X

*The Environmental relevance is based on the "OekoRess II" assessment (Dehoust et al., 2020) and includes the materials classified as high he aggregated environmental hazard potential (EHP).
** Cobalt Regulation (EU) 2017/821 does not include cobalt in the EU list of conflict minerals.

2.3. Impacts from manufacturing processes

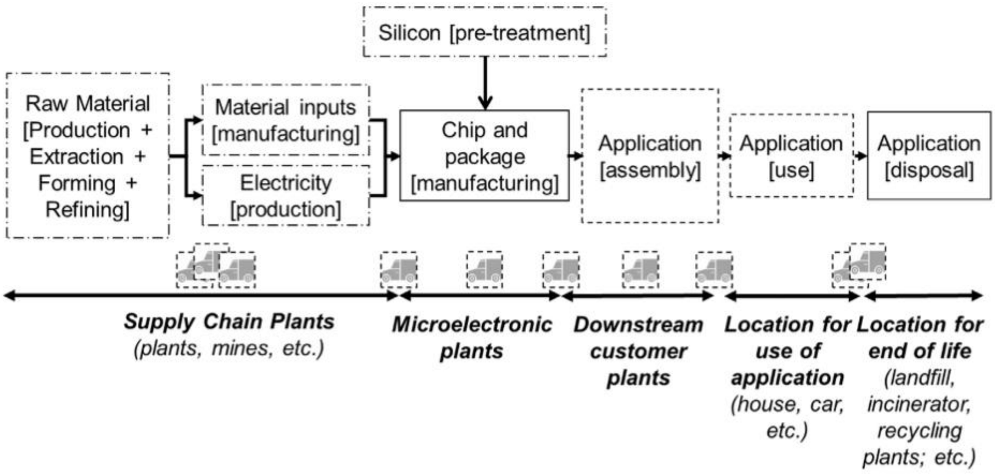
As introduced in the Task 3 Report, relevant environmental impacts for ICT devices are associated to the manufacturing of their semiconductor based components, such as Integrated Circuits (ICs), and other complex components, such as electronic displays and Printed Circuit Boards.

In terms of cradle to grave life cycle, production starts with the extraction and processing of raw materials, including silicon, before entering the microelectronic manufacturing plants. The two stages of manufacturing, wafer production and packaging, are not usually done in the same plants (Figure 12). There are two types of production plants involved in the semiconductor industry:

1) front-end plants, producing wafers (such as a crystalline silicon) containing a large number of semiconductor chips and,
2) back-end plants that package the chips. The package provides protection and electrical connexions when the chip is integrated onto a circuit board. The same chips can be embedded in different electronic equipment.

Following downstream processes aim to the assembly of the chips in the final product before the use and disposal.

Figure 12: Cradle to grave lifecycle of chips. Source: Villards et al. 2015



Villards et al. (2015) identified a set of indicators that are able to capture and point out the main impacts due to semiconductor manufacturing processes:

- Global Warming: it is the most common indicator used to report on environmental changes. In the microelectronic industry it is all the more important that there is a huge amount of electricity consumed during the energy intensive production processes of semiconductor components as highlighted in Task 3 report. Moreover, a considerable quantity of PFCs is consumed during manufacturing process.
- Abiotic depletion: chip manufacturing consumes both energy and mineral resources. Other than coal, rare gases, precious metals and REEs should be mentioned. It is a crucial topic for the whole electronic industry.
- Water eutrophication: the quality of water surrounding microelectronic plants is largely damaged by intensive usage of nitrogen and phosphorous acids, especially in wet cleaning processes.
- Imported volume of raw water: stress on water is mainly due to ultrapure water used for production and general plant functioning. Manufacturers are more and more challenged on water control issues.
- Human eco-toxicity: manufacturing, especially for the semiconductor package, rejects a large range of metals, in different physical forms (particulate and solid). The release of metals in water induces potential effects on toxicity. Other specific liquids (resins, solvents, silicon products, bases and acids) must be controlled regarding potential toxic effects during manufacturing and use in plants. The application of the RoHS directive alone strongly contributes to reduce impacts on human health, especially during end-of-life treatment.
- Photochemical oxidation: several steps of wafer and package processing consume solvents producing VOCs and plant facilities damage the quality of air (boilers, air refrigerators). Photochemical oxidation (also called summer smog) accounts for these pollutions.
- Local electricity consumption: this indicator is the most suitable to account for the total energy consumed by equipment and facilities during manufacturing. It helps to identify hotspots. The section below focus the attention on the potential impacts of manufacturing of ICT on water consumption and pollution

Water in ICT manufacturing

Within the chip manufacturing process, water used both directly (fab manufacturing water) and indirectly (production of electricity). Fab manufacturing water, or 'feedwater', serves three major functions in chip manufacturing: process cooling water, production of ultrapure water to rinse the wafer between processes, and cooling water to maintain cleanroom heating, ventilation and cooling (HVAC) systems. Indirectly water is used also in the production of electricity to power the semiconductor fabs. This is considered is the single largest user of water in semiconductor industry; while fab feedwater (i.e. direct water use) represents another major user Frost and Hua (2019).

Water stress issues caused by the semiconductors production can be amplified by the climate change crisis. Recently, several media reported the fears that the global semiconductor shortage could worsen by water shortage issues in Taiwan[9,10]. In spring 2021 Taiwan has been facing the worst drought in 56 years after experiencing no typhoons in 2020. Even though the semiconductor industry has not been affected yet, competition between different sectors for water as a resource (e.g. farmers/ residential use vs industry) could occur, as farmers and citizens have been suffering water cuts and rationings.

As reported by Frost and Hua (2019), the semiconductor industry has made efforts on reducing water use in their operations and correspondingly, relative water use efficiency has improved over the years. However, the efficiency improvement is not considered sufficient to stop the growth in absolute water use due to year-to-year increases in chip sales (2%–24% from 2016-2018) and associated production capacity, including a 41% increase in capacity for multi-layer flash memory.

According to Frost and Hua (2019), although large reductions in fab water use can be achieved with the appropriate investments in water-saving technologies and these water savings are vital for reducing localized water impacts, , the most efficient way to reduce overall manufacturing water withdrawals (and associated regional watershed impacts) is through reduction in fab electricity use. Reductions in electricity water use can also be achieved by using less water intensive sources of electricity, such as solar PV and wind, which is especially important during seasons of higher water scarcity.

Water reclamation / reuse can be another important strategy to reduce water consumption, but also this strategy comes with several challenges likely to be encountered by fabs include (Den et al., 2018):

- Separating different waste streams: Water recycling and reuse require substantial investment in either complex waste stream segregation with subsequent treatment or sophisticated end-of-pipe solutions. The industry needs to find the best way of separating different wastewater streams to maximize water reuse on site.
- Increase in water reclamation by extracting clean water from waste stream increases chemical concentration in the waste streams, posing environmental compliance difficulty. Dilution with external water to comply with the concentration-based discharge limits is not a sustainable solution. A long-range solution such as reduction in chemical uses and a cost-effective process to concentrate chemical waste remains technically challenging. Increasing water recycling will also likely increase energy and possibly chemical consumption.
- Managing large volume flow rates: Some of the new fabs have been built within existing manufacturing facilities, which increases the total volume of wastewater generated on site. Consequently, new solutions for managing high volumes of wastewater are needed. Increase in energy consumption intensifies cooling load and inevitably evaporates more water during the cooling process. The energy consumption and the extent of in-plant water reclamation need to be analyzed to understand the water-energy nexus of fabs.

Toxicity and occupational poisoning in ICT manufacturing

Occupational health hazard issues in semiconductor industry have been reported by several studies in the scientific literature. They include various types of cancer, negative effects on the reproductive system, and systemic poisoning. Protecting workers in the semiconductor industry against harm from chemical substances is also made difficult by due to widespread use of trade secret ingredients and a lack of hazard information (Yoon et al., 2020; Björnsson, 2020).

Enviromental impacts due to plastic components in ICT devices

ICT products contain a large number of plastic parts and materials. Most of the plastic materials are used for the ICT device housing. This is the case of ICT devices as PCs and displays. In other products, as imaging

[9] https://www.bbc.com/news/world-asia-56798308

[10] https://www.techspot.com/news/88868-taiwan-tsmc-led-semiconductor-industry-has-enough-water.html

equipment, next to plastic housing, there are also many internal plastic parts that play a structural and load bearing role.

Different grades are used depending on the nature and purpose of each part, including aesthetic and mechanical requirements, which both 1) limit the possibility to use material from recycled sources and 2) makes more challenging to recover all the different polymers, for technical or economic reason. Moreover plastic housings from waste electrical and electronic equipment (WEEE housings) contain hazardous substances such as certain brominated flame retardants (BFRs).

The environmental impacts from the manufacturing of plastic components in ICT are relatively less relevant than the impacts occurring for the manufacturing of electronic components (i.e. semiconductors, printed circuit boards and displays) due to their high energy intensive production processes of the latter (Duque Ciceri et al., 2010). However, more relevant environmental impacts are associated to the end of life, especially in the case the use of specific design choices, additives and polymers can make difficult the recycling at the end of life and/or in case have toxicity/bioaccumulation properties of these additivies (as discussed in section 2.3.)

Moreover, the environmental impacts from the manufacturing of plastic components can be reduced by the use of recycled plastic. Industry has been experimenting with the use of recycled plastics in electric and electronic equipment (EEE) since the early 2000s. Where post-consumer recycled material was once considered novel, recycled plastics are now found in a variety of ICT products as companies start to use recycled plastics as part of voluntary agreements/certifications or broader green marketing initiatives[11].

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2.3 Materials in use phase

The environmental impact of ICT systems during their use phase is not limited to the energy consumption for their operation. Indeed, what is described in Task 2 as "induction effect" the use of certain ICT devices can stimulate additional material consumption. Such additional material consumption can be classified in three key sources:

1. The use of accessories
2. The use of consumables
3. The replacement of failed device parts with spare ones

These sources are discussed in the subsections below.

Accessories

ICT devices are often used in groups. Computers and smartphones for example can be connected to a plethora of other small ICT, as in the case of wearables, such as earwear, wristbands, smart glasses, watches and other devices and sensors in the health or sports sectors (Liu et al, 2019; Çiçek, 2015).

The International Data Corporation (IDC) reports that wearables are expected to reach 222.9 million units in 2019, dominated by earwear and watches which will account for more than 70% of all wearables by 2023. More specifically, ear-worn devices are expected to grow from 72 million units in 2019 to 105.3 million in 2023 (Gadgets360, 2019)

Expert interviews conducted by Habibipour et al (2019) on wearable technologies point to the low sensor price as a driver for waste generation, with the example of RFID sensors in many cases not reusable or recyclable.

Liu et al (2019) point to potential risks associated with wearables and smart textiles for human health and ecosystems:

Chemicals and hazardous substances are close to the body. Although the electronic components are encapsulated, long-term safety of the exposure has not yet been proven.

Electromagnetic radiation in wireless networking is close to the body, putting users at risk of exposure.

[11] https://www.digitaleurope.org/wp/wp-content/uploads/2019/01/Best%20practices%20-%20Recycled%20plastics%20paper.pdf

The production of electronic components needs critical raw materials. The widespread application of wearables could lead to more abiotic resource depletion and water depletion. In addition, the added complexity of diverse chemical compositions of substances used to functionalise fabrics could heighten the risks associated with increased production of chemicals along with the energy consumption, substance consumption and pollution. Negative effects on human health and ecosystems may be attributed to substances being released into the environment.

There is currently not enough information on the lifetime of smart textiles. The potential risk could exist that after a short life time the additional functionalized "smart" components are obsolete which increase the amount of e-waste.

- Although a specific legislation for the disposal of electrical equipment exists in the EU[12], the applicability of these textiles with electronic components is vague. The embedded electronic components make the recycling process difficulty. If the smart textiles are disposal by the incineration, there are unknown effects of emission in the air from the additional electronic components.

An illustrative case of the short lifespan of such ICT devices and accessories are true wireless earbuds (wireless earbuds that have no cable connection with either a main device, or between themselves). In the third quarter of 2019 alone, 33 million true wireless earbuds were sold globally, with that number expected to grow to an extent that by 2023, two-thirds of the earbuds market will true wireless earbuds. (Counterpoint, 2019; Futuresource Consulting, 2019).

The absence of cable connection means these devices need to be able to accommodate a number of components, such as a Bluetooth chip and processor, an antenna, a battery, drivers, controls, and microphones, all in the size of an item to be worn by a human ear. In order to save space, product designers resort to solutions which do not facilitate battery removability and replaceability (New York Times Wirecutter, 2021). As a result, the lifetime of already short-living devices cannot be easily extended. Nevertheless, the examples below coming from iFixit's Teardown series (Figure 13) demonstrate that design choices can be decisive in the feasibility to remove and replace a battery, whereby case (1) resulted in damaging the device, while case (2) did not (iFixit, 2019; iFixit, 2020).

Figure 13: Teardown of wireless earbuds

(1) Source: iFixit , 2019 https://www.ifixit.com/Teardown/AirPods+Pro+Teardown/127551
(2) Source: iFixit, 2020 https://www.ifixit.com/Teardown/Samsung+Galaxy+Buds+Live+Teardown/135908

Generally, iFixit report that design choices amongst such products (and therefore their ease of disassembly) were varied, and repair was "somewhat possible" but challenging due to the need to work in tight spaces and with soldering skills (iFixit, 2020a).

Chargers

Another source of material use is associated with powering the devices. ICT devices typically use batteries which can be primary or rechargeable. In the case of rechargeable batteries, material use is related to the use of chargers. A typical material composition of a charger is provided in the Table below for its two main components, the External Power Supply and the cable:

[12] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) Text with EEA relevance (recast)

Table 11: Material composition of a Samsung fast charger

Material	Contained in the EPS (weight in grams)	Contained in the cable (weight in grams)
Plastics	19.74	10.20
Copper	0.47	3.22
Steel	0.75	6.98
Ferrite	6.37	
Aluminium[31]	1.70	
Unspecified[32]	9.06	
Total weight	**38.08**	**20.40**

Source: Adapted from an unpublished disassembly analysis performed by Fraunhofer IZM in the framework of the SustainablySMART project

According to a baseline scenario by the Impact Assessment Study on Common Chargers of Portable Devices (Commission, 2020c), the material consumption of chargers continues to rise until 2022, and then stabilises slightly below 15000 tonnes (Figure 14).

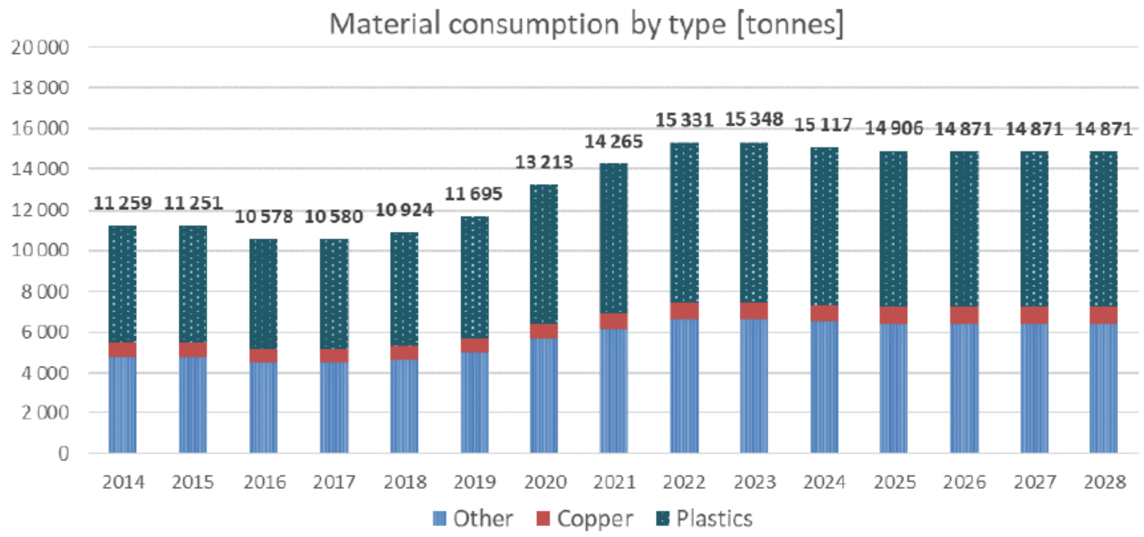

Figure 14: Material consumption of chargers sold each year in the baseline scenario, by material (tonnes), 2014-2018

When these chargers reach their end of life, they are considered WEEE. The figure below shows the e-waste generated by material, and projects an increase in the number of tonnes until 2028, reflecting the increase of weight per charger Figure 15.

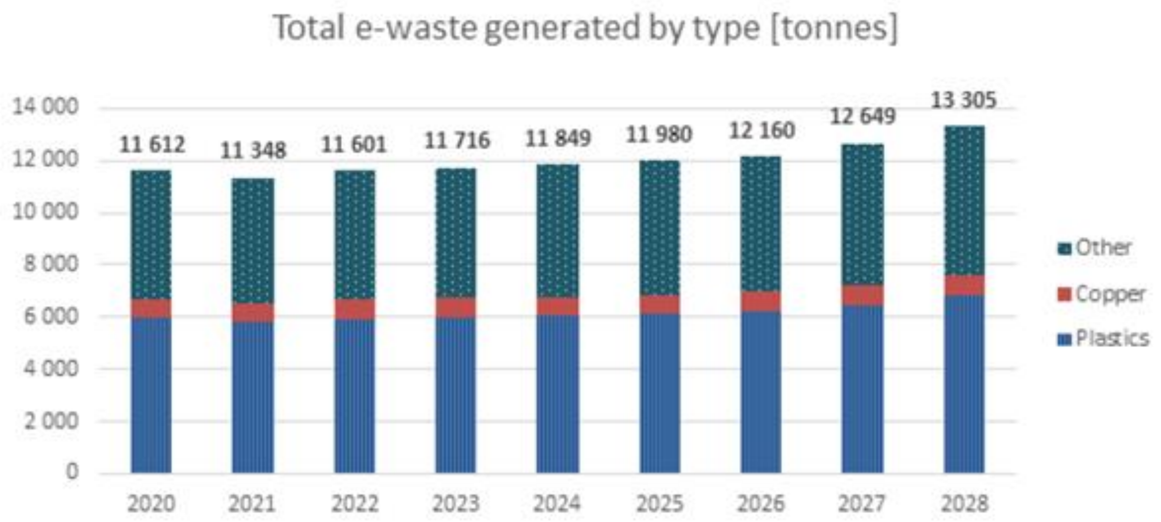

Figure 15: E-waste generation of chargers disposed each year in the baseline scenario, by materials (tonnes), 2020-2028.

Many ICT products, including mobile phones, are expected to increasingly be charged via wireless technologies. According to the same Impact Assessment study, phones enabled to use wireless charging technology have increased six-fold between 2016 and 2018.

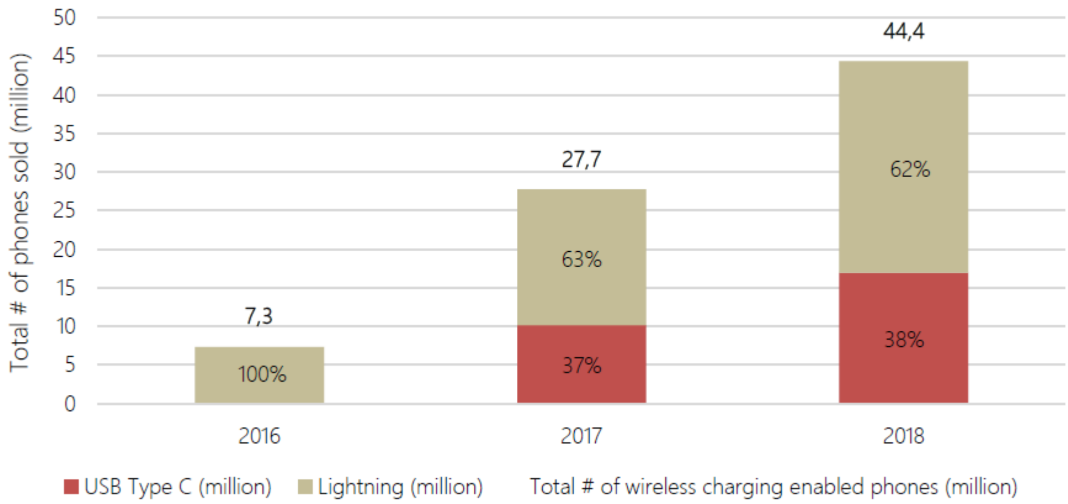

Figure 16: Shipments of wireless charging enabled phones (EU-28 2016-2018)

According to Sánchez et al. (2018), wireless charging has a higher environmental impact than wired charging in almost all impact categories, as a result of manufacturing of electronic components and ICs (Table 3). The only impact category where the impact was found higher for wired charging was water depletion, as in the case of wireless charging a metal back cover would need to be replaced by a plastic one. In a case when the same material for the back cover is used, wired charging demonstrates lower impact in all the categories studied below.

Table 3: Absolute impact values for lifecycle of smartphone, smartphone with same back cover material, and charger. Source: Sánchez et al. 2018

Impact Category	Smartphone (different back cover material)		Smartphone (same back cover material)		Charger	
	Wire	Wireless	Wire	Wireless	Wire	Wireless
Climate	32,4 kg CO_2	32,4 kg CO_2	32,3 kg CO_2	32,4 kg CO_2	6,24 kg CO_2	11,8 kg CO_2

Change	eq.	eq.	eq.	eq.	eq.	eq.
Human Toxicity	65,9 kg 1,4-DB eq.	73,6 kg 1,4-DB eq.	65,8 kg 1,4-DB eq.	75,7 kg 1,4-DB eq.	9,59 kg 1,4-DB eq.	21,8 kg 1,4-DB eq.
Freshwater ecotoxicity	0,103 kg 1,4-DB eq.	0,122 kg 1,4-DB eq.	0,103 kg 1,4-DB eq.	0,131 kg 1,4-DB eq.	0,015 kg 1,4-DB eq.	0,0399 kg 1,4-DB eq.
Fossil depletion	2,8 kg oil eq.	2,81 kg oil eq.	2,78 kg oil eq.	2,79 kg oil eq.	1,72 kg oil eq.	3,48 kg oil eq.
Water depletion	21,7 m^3	17 m^3	16,5 m^3	17,1 m^3	25,4 m^3	40,7 m^3

The induction effect of ICT accessory use is also driven by coupling or bundling, meaning when accessories, such as the charger (external power supply and cable) and headphones are included together with the product in the packaging (Figure 17).

Figure 17: Accessories in a smartphone packaging, Source: Fraunhofer IZM et al, 2020.

Decoupling these accessories from the product package can enable the use of the same accessory for multiple devices, and, in turn, according to European Commission 2020c, result in major positive environmental impacts in terms of material use, e-waste generation and CO_2 emissions. Some smartphone manufacturers, for example, have already started selling their latest smartphone models without a charger included in the package sold (Inquirer, 2020).

When such decoupling is accompanied by standardised connectors on the charger and ports on the device, allowing for a high degree of interoperability across models and devices, the volume of unused or underused chargers can further be reduced.

Consumables

Another area contributing to material use by ICT products is that of consumables in imaging equipment. A technical report developed in the context of the development of the EU Green Public Procurement (GPP) criteria for imaging equipment (Kaps et al 2020) concluded that consumables are responsible for 20-30% of the life cycle Global Warming Potential and Primary Energy Demand of imaging equipment products, in particular printers and multifunctional devices (MFD).

Specifically, the main hotspots of consumables during imaging equipment use identified were:

- The manufacturing of cartridges, in particular of the housing and print head, which can be greatly reduced if cartridges can be refilled; the more refills the less contribution from manufacturing of new cartridges
- The amount of paper the cartridge uses to deliver printouts with a desired quality; the higher the quality the more the reductions of environmental impacts by using less paper.
- The consumer transport for refilled cartridges; the more refills the higher the contribution of transport for the total environmental impacts.

With regard to cartridge waste volumes and reuse rates of cartridges, the study reports that proximately 404 million ink cartridges and containers and 148 million toner cartridges and containers were sold in 2016 in the EU-28, and it is estimated that in total volume per year the 60 -70 % of the cartridges end up in landfills and/or incinerators after single use.

Around 150.000 tonnes of waste material are estimated produced per year from printing consumables (Oldyrevas, 2021) in the European Union. Around 14.000 tonnes is reused in new products. The largest single end of life destination for consumable material is recycling (67.000 tonnes). Around 68.000 tonnes of end of life cartridges is estimated to be incinerated or landfilled during 2021 in EU.

A Voluntary Agreement (VA) is in force since 2015 and focused on reducing the impacts imaging equipment, dealing with aspects such as energy efficiency, design for recycling, polymer composition, spare part availability or paper recyclability, among others. In 2019, a study commissioned by the European Commission recommended to include the printers' consumables in the scope of the VA and to increase the level of ambition on resource efficiency requirements (Huang et al., 2019).

Imaging equipment are among the products groups mentioned as a priority by the CEAP20, which established that "printers and consumables such as cartridges will be covered by the upcoming Ecodesign Working Plan unless the sector reaches an ambitious voluntary agreement within the next six months". In essence, the CEAP20 required industry to update the existing VA and to increase significantly its level of ambition.

A new Voluntary Agreement proposal, published in 2021, was evaluated by the JRC on behalf of DG ENV, to assess compliance of the VA with the requirements for self-regulation, and to ensure that the level of ambition of the commitments is in line with the CEAP. In the evaluation, the JRC identified various aspects that could be considered an improvement from the current VA, such as the inclusion of cartridges within the scope of the document (Bernad Beltran and Alfieri, 2022). However, the JRC also identified some issues of concern regarding compliance with self-regulation criteria and with the level of ambition required by the CEAP. The European Commission has finally considered that the new VA proposal, despite the improvements introduced, has not reached the ambitious objectives in terms of circularity mandated by the new Circular Economy Action Plan and has decided to work on mandatory regulatory measures under the Ecodesign Directive. Based on this decision, the imaging equipment has been included in the list of new measures under the Ecodesign and Energy Labelling Working Plan 2022-2024 (European Commission, 2022).

In order to improve the circularity of the consumables used in the public sector, the "EU GPP criteria for imaging equipment, consumables and print services" (European Commission, 2020e) include provisions to promote their reuse (e.g. by ensuring that the device is not designed to prevent remanufactured toner and/or ink cartridges and containers by constructive, software-based or other measures), remanufacture and more efficient use (e.g. page-yield declaration and minimum page yield) of cartridges and containers, and criteria on the use of more paper-efficient printing techniques (e.g. automatic duplexing requirements, N-up printing, the capability to process recycled paper) (Kaps et al., 2020).

Spare parts

Lastly, another source of additional material use is related to the replacement of failed product parts with spare ones, as part of a repair process. Hard disk drives (HDD) in a server can have a lifetime shorter than the ICT device, the same applies to batteries or external power supplies. Environmental impacts can be expected by the production and transportation of spare parts. However, previous studies have demonstrate that repair of ICT devices as smartphones is beneficial from an environmental point of view as long as it ensure an extension of the product lifetime (Cordella et al. 2020).

Common failures for notebooks (Figure 18) are related to components as screens, keyboards, hard disks drives or solid state drives, batteries, adapters and ports/connectors (Cordella et al. 2019).

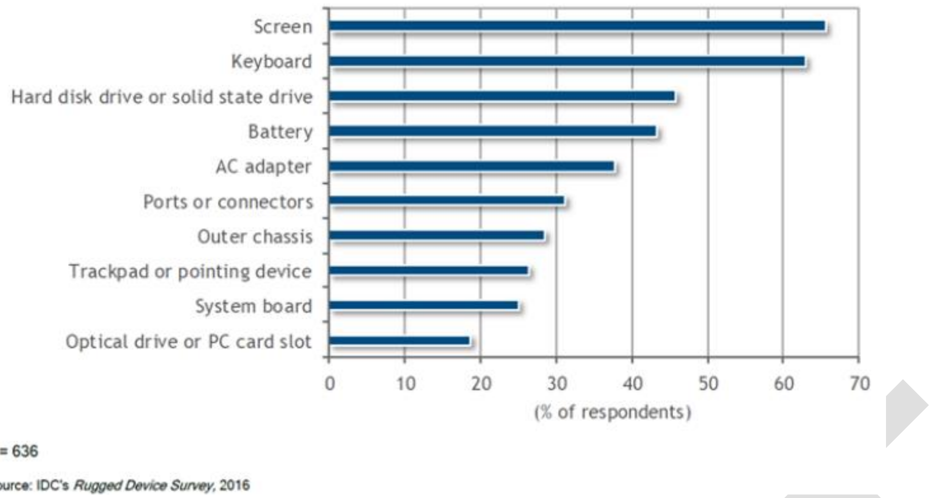

Figure 18: Common parts of notebooks reported to suffer damage.

Similarly for Televisions, a study conducted by WRAP (2011) on three LCD TVs, identified the following most common faults in these products: • Screen faults – due to damage, sometimes caused by impact; • Power circuit board faults; • Main circuit board faults – including hardware and microchip software; • Damage to connections – often between circuit boards; • Damage to television stands.

Finally for smartphones and tablets studies conducted in Germany in 2019 and 2018 (respectively) identify the most common defects as presented in the tables Table 4 and Table 5 (Fraunhofer IZM et al, 2020).

Table 4: Defects in smartphones, Germany 2019 (Source: clickrepair 2019)

Defects	Share
Display	67,4%
Casing	50,0%
Battery	33,9%
Connectors	16,1%
Camera	7,9%

Table 5: Kind of damages of dropped tables, Germany 2018 (Wertgarantie 2018)

Defects	Share
Display	64.1%
Casing	47.1%
Camera	18.1%
Blemish to the appearance	17.5%
Ports	13.6%

The availability of spare parts that demonstrate the highest failure rates is a crucial parameter towards repair and upgrade operations taking place, and often a precondition. These parts are also associated with some environmental impacts, however, legislative clarity in the form of regulatory requirements for spare part availability can stimulate improvements in inventory management. The Ecodesign regulation on electronic displays (EU 2019/2021) already includes requirements for spare part availability of a number of parts, as indicated in Table 6.

Table 6: Requirements on spare parts availability for electronic displays

Product Group	Spare parts availability		
	Which parts?	To whom?	For how long?*
Electronic displays	internal power supply, connectors to connect external equipment (cable, antenna, USB, DVD and Blue-Ray), capacitors, batteries and	professional repairer	min 7 years

(EU)2019/2021	accumulators, DVD/Blue-Ray module and HD/SSD module		
	external power supply and remote control	professional repairers and end-users	min 7 years

Source: adapted from Spiliotopoulos et al. (2021)

In battery powered ICT devices the batteries are often the weakest component, because electrochemical systems are simply not as stable in high temperatures, and they do not have the same longevity as other components in electronics[13]. Batteries are in many portable ICT devices are expected to worn out before the end of the technical life of the other components.

Due to design trends toward non-removable batteries (see the example in Figure 19), the lifetime of small ICT devices tend to be limited by the technical lifetime of its battery.

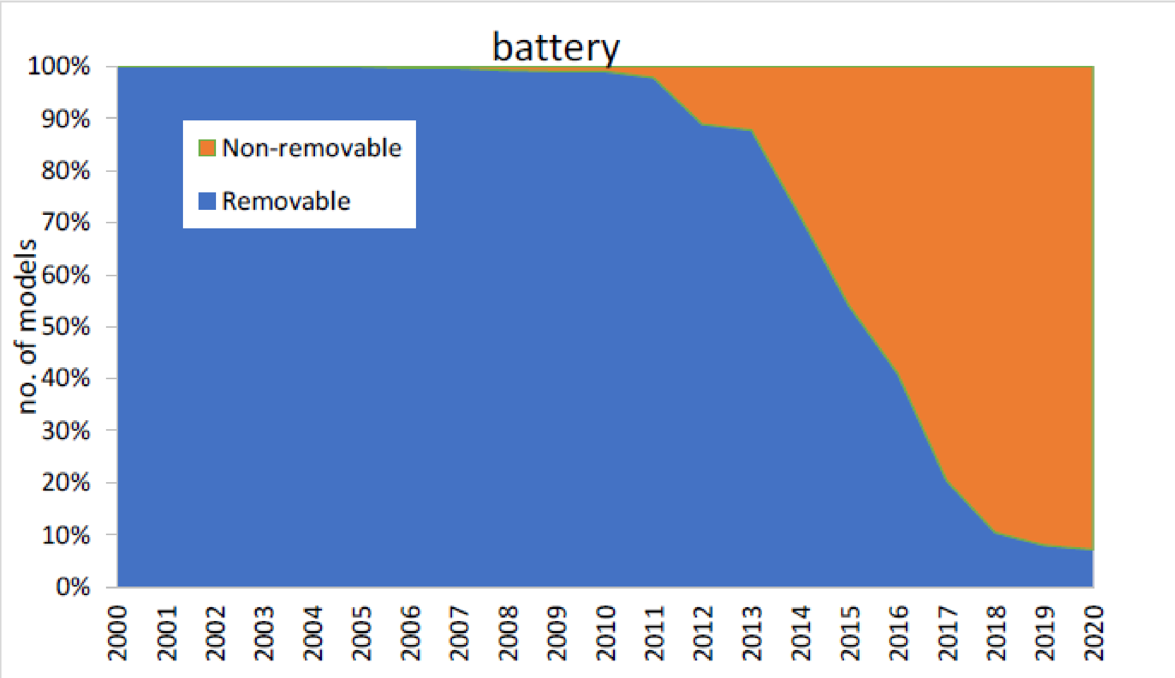

Figure 19: Share of removable and non-removable batteries in mobile phones 3 between 2000 and 2020 (Proske et al. 2020a)

It is not just the quality battery itself that determines how long it lasts, even though its structure and the materials used naturally play a significant role. Factors like how it is used, what the ambient temperature is, or how fast it is charged all have considerable influence on its life expectancy as well (Fraunhofer IZM, 2022)

A relevant parameter used to define the battery life endurance in cycle is the State of Health (SoH) defined as the current full charge capacity (in mAh) expressed as a percentage of the design capacity (rated capacity) (Alfieri et al., 2021).

Regarding applicable thresholds 60% of SoH is used in the IEC EN 61960:3-2017, while other initiatives set criteria based on the 80% SoH, having the advantage of reducing the testing length/cost of testing. Different thresholds are also identified in terms of number of charging/discharging cycles: 300 cycle according IEC EN 61960:3-2017, 500 cycles according to the Ecodesign Proposal for smartphones and slate tablets or 1000 cycles according to other initiatives as EPEAT[14].

The availability of a software determining the battery/accumulator status would facilitate the correct monitoring and implementation of the replacement policy for the mobile ICT devices. Blue Angel criteria for computers[15] require the existence of software determining the battery/accumulator status and allowing the

[13] https://blog.izm.fraunhofer.de/the-weakest-link-aging-lithium-ion-batteries/
[14] https://globalelectronicscouncil.org/
[15] https://produktinfo.blauer-engel.de/uploads/criteriafile/en/DE-UZ%20078-201701-en-Criteria-V4.pdf

reading of the battery's/accumulator's "state of health", "state of charge“, as well as the number of full charge cycles already performed by the battery/accumulator and to display these data for the user.

The wearing out of batteries can also be limited by the use of specific protection software. The preparatory study on the revision of the EU Ecodesign Regulation for computers (Vito and Viegand Magoe, 2018) proposed criteria with regard to a ‘Battery optimisation built-in functionality’. According to this proposal manufacturers shall provide pre-installed software to enable a limit on the battery state of charge (SoC) when the computer is used systematically in grid operation. This functionality would prevent the battery to be loaded at full charge under these conditions and the manufacturer should inform the user of the existence and the benefits of using such a functionality.

This approach is already integrated in some ecolabelled devices as notebook computers. TCO Certified[16] and Blue Angel[17] requires the availability Battery/Accumulator Protection Software shall be able to limit the battery's/accumulator's charge to a value smaller to the maximum amount of usable electricity (e.g. 80% of full charge capacity) to extend the battery's life.

A further evolution of these protection software the availability of pre-installed battery management system that includes intelligent charging software able to identify the user’s regular charging habits/pattern, stop the charging process before it reaches 100% (e.g. at 80%), and fully charge the device only when needed by the user.

Barriers to the reuse of ICT products

ICT devices and infrastructure are more and more subject to cybersecurity and privacy threats, as an increasing number of services require high levels of data protection and the need of a reliable ICT infrastructure. At the same time, the computing power and storage capacity requested from the market are growing at a very fast pace. These trends in the production and use of ICT devices can affect not only the energy efficiency during operation, but also material efficiency (i.e. the use of materials per unit of services), management of waste ICT and, overall, the environmental life cycle impacts of the whole sector.

According to Coughlan and Fitzpatrick, (2020), the way in which the ICT market will evolve in the upcoming years will be certainly influenced by issues related to cybersecurity, privacy and environmental impacts. The issue of data protection is high on consumer’s minds when it comes to disposing of EEE and give an opportunity for a second life.   ICT devices from personal computers to smartphones suffer from a phenomenon known as the “closet effect” where users store their devices at home long after they have ceased to use them. The lack of cloud storage for older devices may hinder the divestment of these devices but the proliferation of cloud services for more modern devices may have allayed consumers data protection issues.

Looking at the B2B sector, the recent publication of the General Data Protection Regulation (GDPR)[18] in Europe has highlighted the responsibilities that organisations have when they are in business of storing consumer and business data. The IT Asset Disposal (ITAD) sector provides data destruction and sanitisation services to companies who require complete security in the destruction of their data. The presence of company data on a device can have many ramifications for the user and the organisation. The services of the ITAD sector tend to only operate in the B2B sphere due to data protection issues, the cost of destroying company data and hard drives is offset by the value of the remaining equipment which can be reconditioned and sold on. Reconditioned equipment tends to be high value servers, rackmount equipment, laptops, desktops, tablets and smartphones.

More specifically for the imaging equipment sector it is important to highlight the existence of the so-called ‘killer chips’ (Huang et al. 2019). These are electronic components which provide useful functionalities for the user, e.g. ink detector levels, or page counters, that make re-use difficult if they do not include provision for resetting the chip during reuse.

[16] https://tcocertified.com/files/certification/tco-certified-generation-9-for-notebooks-edition-2.pdf
[17] https://www.blauer-engel.de/en/certification/basic-award-criteria
[18] https://eur-lex.europa.eu/eli/reg/2016/679/oj

2.4 Impacts of End-of-life phase

When ICT devices are discarded and are no longer intended for use or reuse, they become waste. Specifically, in the EU context, those fall within the category of WEEE, Waste from 'electrical and electronic equipment' whereby EEE is *equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1000 volts for alternating current and 1 500 volts for direct current* (WEEE Directive[19]). Besides IT and consumer equipment, other categories that are already considered WEEE include household appliances, lighting equipment and toys. Nevertheless, with the development of IoT technologies, electronic components similar to those used in ICT are increasingly found in a wide variety of products. Since August 15, 2018, the so-called open scope has been in place. This means, in practice, that new products, such as clothes and furniture with electric functionality, can fall under the directive.

In 2019, 53.6 Mt of e-waste was generated globally, which translates into average of 7.3 kg per capita, and signifying an increase by 9.2 Mt since 2014. E-waste generation is projected to grow to 74.7 Mt by 2030 – almost doubling in only 16 years (Forti et al., 2020). The same source calculated WEEE generation in Europe at 12.0 Mt, or 16.2 kg per capita, meaning that Europe generates most WEEE per capita than any other region in the world.

With regards to collection, in 2019, the formal documented collection and recycling was 9.3 Mt, thus 17.4% compared to e-waste generated. It grew with 1.8 Mt since 2014, an annual growth of almost 0.4 Mt. However, the total e-waste generation increased by 9.2 Mt, with an annual growth of almost 2 Mt. Thus the recycling activities are not keeping pace with the global growth of e-waste. (Forti et al., 2020)

The EU WEEE Directive proceeds to set minimum collection rates to be achieved annually by EU members states. Eurostat[20] estimates that in 2017, 3.7 million tonnes of WEEE was collected in EU-27, including 1.9m large household, 0.38m small household, 0.54m IT and telecom, 0.55m consumer eq & PV and 0.32m other waste. Figure 20 demonstrates the percentages by type of WEEE. These statistics constitutes Europe as the region with the highest collection and recycling rate globally with 42.5% (Figure 21).

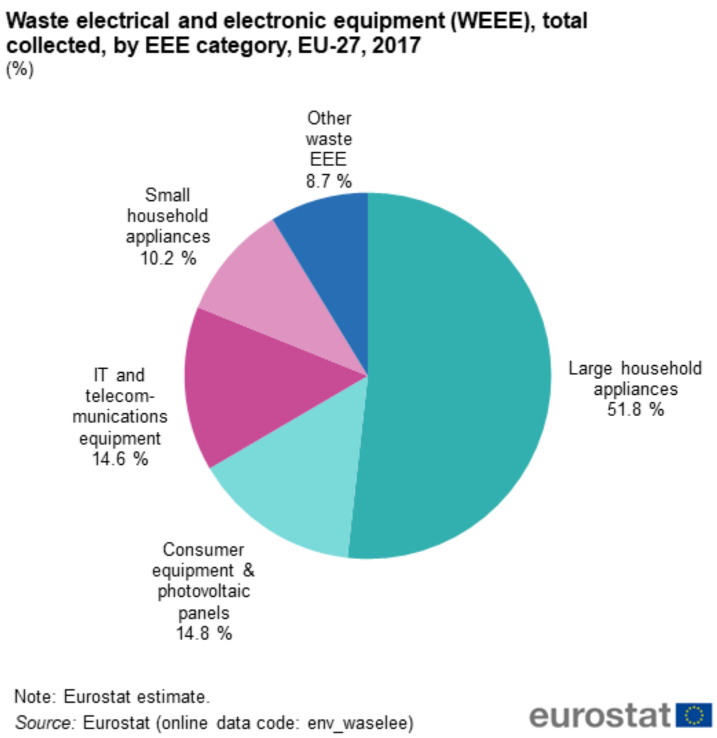

Figure 20: Collected Waste Electrical and Electronic Equipment (WEEE) by EEE Category (%), EU27, 2017. Source: Eurostat

19

20 https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment

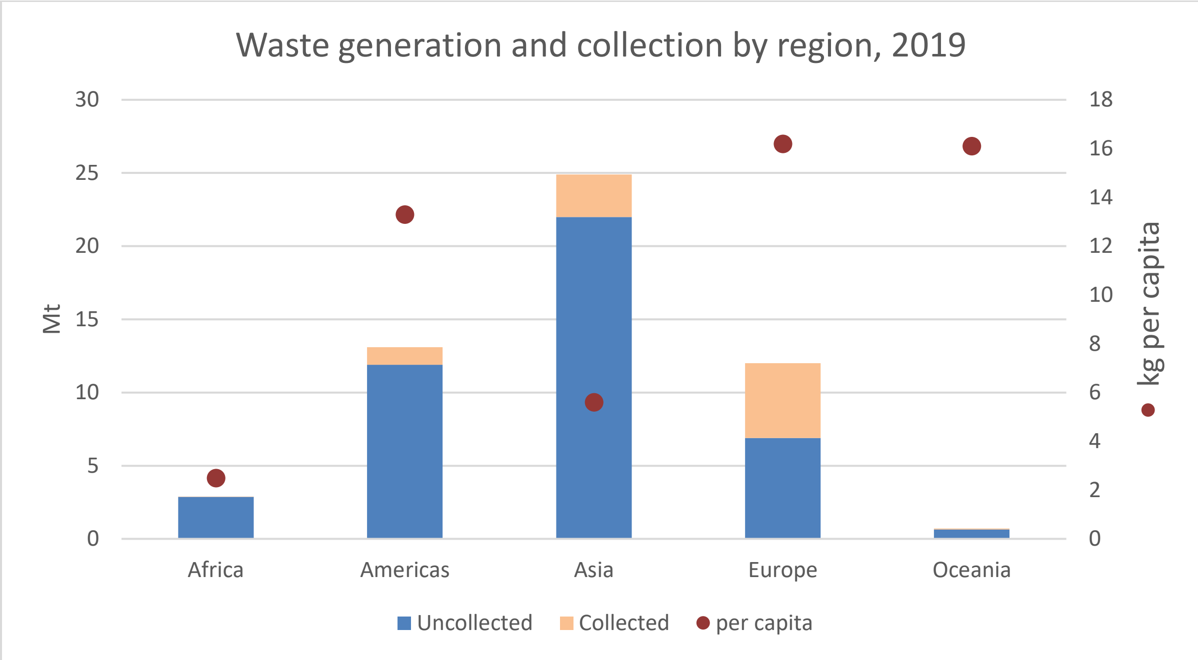

Figure 21: Waste generation and collection by region (2019). Source: own with data from the Global E-Waste Monitor 2020 (Forti et al., 2020)

The collection rates in Europe can be attributed to established e-waste management infrastructure to collect e-waste in shops and municipalities by private operators, as well as to further recover the recyclable components of the collected e-waste and dispose residuals in a compliant and environmentally sound manner. Still, collection varies across the EU Member States, from 2.4 kg per inhabitant in Romania to 14.1 kg per inhabitant in Sweden in 2017. As from 2019, the collection targets are increased to 65 % of the average weight of EEE placed on the market in the three preceding years in the Member State concerned, or alternatively 85 % of WEEE generated on the territory of that Member State (WEEE Directive, Article 7).

Nevertheless, 82.6% (44.3 Mt) of e-waste generated in 2019 globally is not handled by formal channels, which leads to higher environmental impact varies. That impact is disproportionally distributed amongst regions, as high income countries have more developed waste recycling infrastructure. Furthermore, around 8% of the e-waste is discarded in waste bins and subsequently landfilled or incinerated. This is mostly comprised of small equipment and small IT (Forti et al., 2020).

Environmental impact of recycling processes

When products are discarded, and are not reused or refurbished, a series of steps followed from collection to transportation to a treatment site Figure 22 .

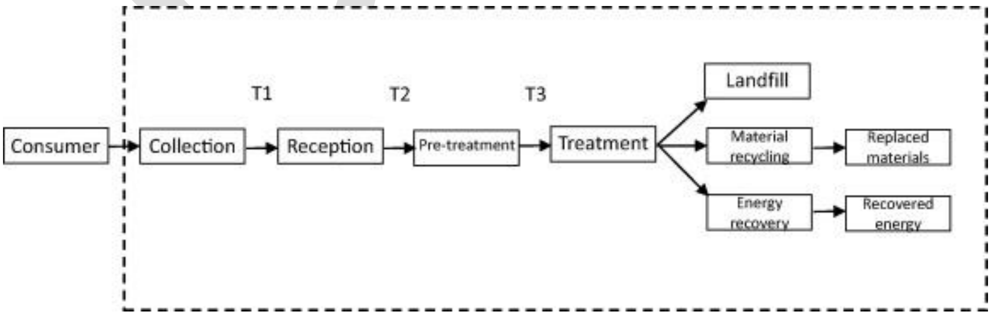

Figure 22: End-of-life processes. Source: Baxter et al 2016

A major environmental impact is at the treatment stage, although if the overall recycling process is not well designed and implemented, when for example fossil-fuel-powered individual cars are used to drop-off WEEE at collection sites or when the energy required for the treatment is used inefficiently, these stages could also have a contribution to environmental impacts (Jaunich et al, 2020).

WEEE contains many elements that result in direct environmental impacts if disposed of improperly – they contribute to global warming, and some are toxic/hazardous (Baxter et al 2016).

Apart from valuable materials, such as copper, aluminium, gold and silver, WEEE contain hazardous components, such as capacitors, toner cartridges or plastics containing flame retardants. Some of those, such as antimony, silicon metal and rare earths, are included in the list of 30 materials considered Critical Raw Materials in the EU (European Commission, 2020a).

Collecting and recycling WEEE contributes to material efficiency through avoidance of virgin material extraction. It also brings about economic benefits as a result of recovering valuable materials, such as gold and silver. In other cases, the recovery of materials does not take place, due to, amongst other reasons, that recycling processes are not deemed economically feasible with current technologies. The EU-funded project CEWASTE[21], identified the economic feasibility of a number of key CRMs typically found in ICT products, presented in the table below (CEWASTE, 2021).

Table 7: feasibility of the recycling for a number of key components and CRMs typically found in ICT products.

Source Component	KCE	CRMs	Current Economic Feasibility
Fluorescent powders	CRT monitors and TVs	Y, Tb, Eu, Gd, La, Ce	No
Nd-magnets	Laptops (HDD)	Nd, Pr, Dy, Gd, Tb	No
	Desktop computers, prof. IT (HDD)		
PCBs	Desktop computers, prof. IT	Au, Ag, Bi, Pd, Sb	Yes
	Laptops		
	Mobile phones		
	Tablets		
	External/internal CDDs, ODDs		
Screen	Mobile phones	In	Yes
Li-ion batteries	Laptops	Co	Yes
	Mobile phones		
	Tablets		
NiMH battery	NiMH batteries in WEEE	Co (Ce, La, Nd, Pr)	Yes (Co), No (REE)
Lead acid batteries	Lead acid batteries	Sb	Yes

Source: Adapted from CEWASTE (2021).

In some cases, the recycling of some CRMs are conflicting with the recycling of other materials. For example, PCBs may contain very small quantity of tantalum the recycling of which would require a process different than that for the treatment of precious material such as gold. For economic reasons the recovery of the former is thus abandoned (Deubzer et al, 2020).

[21] https://cewaste.eu/

As a result, those materials are not recovered and fed back to the production stage sufficiently to meet demand. Figure 23 below describes the low contribution of recycling to meet the EU demand of CRM (SCRREEN, 2019).

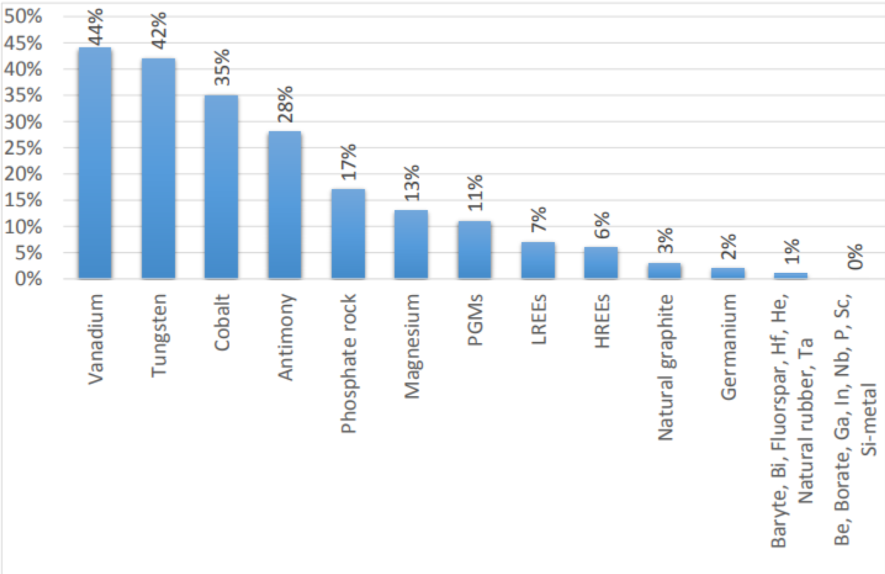

Figure 23: Contribution of recycling to meet EU demand of CRMs: End-Of-Life Recycling Input Rate (EOL-RIR). Source: SCRREEN (2019) (JRC elaboration based on the 2017 CRM study and on the MSA study 2015).

From a WEEE recycler's point of view, recycling of WEEE is becoming more and more challenging as innovations in devices lead to a highly complex and more heterogeneous waste stream (Unger et al 2017). In fact, the heterogeneous and complex structure of WM-PCBs is the main obstacle to recovery metals from it.

Moreover, recycling processes, regardless of the material content and the economic cost of recycling, do not come without an environmental impact, depending on the process used.. A typical PCB recycling process consists of the stages of disassembly, treatment and refining (Cucchiella et al, 2016). During disassembly, hazardous components such as batteries are separated from other valuable ones, such as memories and microprocessors, which are sent to different treatment processes. During treatment, PCBs pieces are shredded and grinded, then separated between metal and non-metal ones before being refined to obtain almost pure secondary resources. Rene et al 2021 present three types of recovery of base and precious metals from e-waste:

— hydrometallurgical (extraction of metals from solid resources by using chemicals),

— pyrometallurgical (wherein non-ferrous and precious metals are leached from WEEE), and

— biometallurgical (biological), with the use of microorganisms for the recovery of metals in a simple, eco-friendly, and cost-effective manner

The advantages and limitations of these different processes are described in Table 8.

Table 8: advantages and limitations of different strategies for the recycling of PCBs

	Advantages	Limitations
Pyrometallurgy	• the PCB can be used without any pretreatment, • very fast processing time • produces cu rich allow that can be separated and processed further.	• energy intensive, • high investment cost • corrosion resistant reactor/furnace design is required • low efficiency in the conversion/recovery of metals • downstream hydrometallurgical and electrometallurgical techniques required to

		reach higher yields.
Hydrometallurgy	• easy to apply, manage, high selectivity, fast reaction kinetics, and good extraction efficiency for different metals • single/multi-stage leaching can be done in two stand-alone reactors/ vessels, at a low cost • low gas emission, less operational temperature • no slag generation and high recovery rates.	• protection of workers/safety is required due to the use of toxic chemicals (lixiviates) • produces large quantities of leachate • special corrosion-resistant equipments are required • high cost for the selective recovery of the desired metal, • requires multiple chemicals to recovery different metals
Bio-hydrometallurgy	• considered as an upgraded, modern and green technology, • both precious and base metals can be recovered from e-waste, • low operational temperature, energy requirement, low investment/operating cost • selective leaching of metals can be achieved by using different microorganisms.	• difficulty in maintaining the purity of the inoculated microorganism, and reproducing the results in lab-scale and pilot-scale bioreactors • microorganisms require nutrients and carbon source to support its growth • toxicity of specific metal components present in e-waste can affect the activity of the microorganism • long processing time compared to other technologies for e-waste refining
Pyrolysis	• the e-waste can be used in its "as available" form, irrespective of the discarded electronic or electrical appliance • very short processing time • reduces e-waste volume • produces gases, oil and even metal containing char that can be processed further.	• energy intensive, high investment cost • requires further treatment of the toxic gases produced • low metal recovery rates and less purity of the final product, • requires post-treatment to increase the recoverability of the metals from e-waste

Apart from heavy metals, electronic waste comprises also of other materials such as halogenated compounds, plastics, ceramics and resins (Rene et al 2021). Furthermore, improper e-waste processing techniques result in the emission of several organic pollutants including polyaromatic hydrocarbons (PAHs), polyvinyl chloride (PVC), polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs), brominated flame retardants (BFRs) including polybrominated diphenyl ethers (PBDEs) and polychlorinated dibenzo-p-dioxin furans (PCDD/Fs). Despite the banning of many of these substances from being present in new products, the issue of legacy materials is still being addressed.

In plastics, chemical recycling aims at separating polymers from other contaminants in waste, either via purification of the whole polymer chains from contaminants, or by breaking down the polymer to its monomers and them re-polymerising it (Eunomia and ChemTrust, 2020). However, these processes are associated with environmental impacts, most importantly energy demand.

Plastics can contain additives that can be emitted into the environment with indiscriminate plastics disposal and can cause a series of risks to flora and fauna, including via their entry into the food chain (Wagner and Schlummer, 2020). Such additives include **Brominated flame retardants** (BFRs) used in plastic products for their fire-resistant properties. Many BRFs are today restricted. Another type of additives in plastics include **plasticisers** which offer flexibility to the material, but at the same time enable their release into the environment. Finally, metal-based **stabilisers** protect plastic materials from thermal degradation but studies indicate that they can cause severe health issues such as bone softening, kidney failure and learning difficulties in children exposed to lead (Rodríguez and Mandalunis, 2018; Wani et al., 2015), as well as soil contamination.

European legislation imposes restrictions to such substances, such as the RoHS Directive and the REACH Regulation 1907/2006/EC which demands physicochemical, toxicological and ecotoxicological data for each chemical with an annual production or trading quantity exceeding 1 tonne. (Wagner and Schlummer, 2020)

Environmental and Health impacts of illegal e-waste trade

The previous section describes established recycling processes. However, as described and despite the fact that 71% of the world population live in countries with e-waste-related legislation, the majority of e-waste is not documented as properly collected and treated (Forti et al., 2020). In middle- and low-income countries, the e-waste management infrastructure is not yet fully developed or, in some cases, is entirely absent. Hence, e-waste is managed mostly by the informal sector, and improper treatment has higher environmental and health impacts. If the materials in e-waste are not recycled, they cannot substitute primary raw materials and reduce greenhouse gas emissions from extraction and refinement of primary raw materials. According to a study for the European Commission (BIO intelligence Service 2013), roughly 15% of used electrical and electronic equipment (UEEE) is exported from the EU, mainly for reuse.

20–25% e-waste generated in the world are recycled in a formal way to developing countries such as those in Asia and Africa. merely 25% of e-waste is handled in formal and regular recycling centres with proper protection for their workers. People living in those sites get exposed to the hazardous compounds by two ways: direct exposures during recycling work, and indirect exposures through environmental pathways (Li and Achal, 2020).

When plastics containing hazardous Brominated Flame Retardants (BFR) are incinerated improperly, they release dioxins and furans, posing risks to both environment and health. The EU ROHS Directive[22] has restricted the use of PBDEs and PBBs in all new electrical and electronic equipment (maximum concentration values tolerated by weight in homogeneous materials is 0.1%), while they were listed in the Persistent Organic Pollutants Annex of the Stockholm Convention for elimination (UNEP and Stockholm Convention, 2019). Some of these contaminants have been banned in Europe, as risk assessment studies have shown that they are persistent, bioaccumulative, and toxic, and can be responsible for kidney damage, several skin disorders, and nervous and immune systems and effects to the nervous and immune systems.

All European countries adhere to the Basel Convention[23] which gives the right to prohibit the import of hazardous waste and states that countries shall not permit its export. However, e-waste still ends up being exported illegally, with the pretext that it is being exported for reuse and through mingling e-waste with legal materials to gain false classification (Forti et al., 2020; Palmeira et al 2018). At the same time, the extraction of valuable materials mentioned in the previous section is creating demand from importers of e-waste, as the difficult to establish the origin of those materials may allow re-legalisation (Palmeira et al 2018). Moreover, the use of informal recycling methods, not only adds to the environmental impact of formal recycling processes, but constitutes such methods attractive from a cost perspective, with the use of non-skilled manual labour, and a disregard of environmental or health hazards. Such methods include heating circuit boards by blowtorch method, stripping of metals in open-pit acid baths to recover gold and other metals and open-air burning of components (cables, PCBs, plastic metal assemblies) in order to recover wanted materials (Forti et al., 2020; Vaccari et al., 2019)

When toxic material disperses via open burning, it can be found in air, water and sediments near recycling sites, causing damages not only to the workers but residents in the surrounding areas via inhalation, dermal exposure, or the soil-crop-food pathway due to the wind patterns (Vaccari et al., 2019; Li and Achal, 2020).

Forti et al. (2020) cites a number of studies demonstrating health impacts, which include adverse birth outcomes (Zhang Y et al. 2018), altered neurodevelopment (Huo X et al. 2019b), adverse learning outcomes (Soetrisno et al. 2020), DNA damage (Alabi OA et al. 2012.), adverse cardiovascular effects (Cong X et al. 2018), adverse respiratory effects (Amoabeng Nti AA et al. 2020), adverse effects on the immune system (Huo X et al. 2019b), skin diseases (Decharat S et al. 2019; Seith et al. 2019), hearing loss (Xu L et al. 2020), and cancer (Davis JM et al. 2019).

In conclusion, it is worth highlighting recycling does not come without costs and environmental impacts. Even when those are lower compared to virgin material use, they are minimized when repair and reuse processes are preferred. Considering that in reality most of WEEE is not treated us such and via legal and transparent channels, environmental impacts associated with the end-of-life of ICT are not only higher, but expand wider to health impacts.

[22] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment Text with EEA relevance (recast)

[23] http://www.basel.int/

3 Second Order effects

ICT is also characterised by rapid technological development, for instance in terms of computational power and memory capacity. A downside of rapid technological development is the risk of premature obsolescence and underutilised lifetimes. Short technology cycles, new functionalities and features (e.g. for smartphones) often trigger product replacement (functional and psychological obsolescence) more than technical failures do (Proske et al., 2016) (Zhilyaeva et al. 2021).

ICT short technological cycles can shorten the useful life of others products due to incompatibility. Devices that are no longer supported by software updates and are not able to communicate in a fast developing ICT context are rendered obsolete. A recent study from the German Environmental Agency summarise the following reasons for a possibly shorter life or useful lifetime of “networked devices” (Umweltbundesamt, 2022):

- Higher risk of failure and poorer repairability with additional integrated components with a high level of complexity, especially if rather inexpensive components are used,
- Rapid obsolescence of communication interfaces,
- Software-related obsolescence due to expiring support for the smartphone apps required for operation,
- Lack of security updates,
- Turning off cloud services that are required to use the devices,
- Psychological obsolescence due to a high innovation dynamic.

3.1 Lifetime and obsolescence in the ICT sector: taxonomy

The concepts of lifetime and obsolescence are strictly connected. A product becomes **obsolete** when it is no longer wanted and/or the **useful lifetime** ends (EEA, 2020).

The **lifetime** (also called **lifespan**) of a product is a parameter, typically expressed as number of years (or using different units of measure as the number of cycles or the hours of operation), which can serve to orient designers, researchers, policy makers and consumers in their decisions (Stamminger et al., 2020).

A **useful** or **actual lifetime** refers to the time from the moment a product is sold to when it is discarded or replaced (EEA, 2020). The **service life** and represents the time interval between acquisition and the exit from active use. ICT products have relatively short lifetime, after active use they are sometimes stored for up the equivalent of the length of active use, and a large proportion of products that are not actively used are still in good working condition (Zhilyaev, 2021).

The useful lifetime can differ from the **designed lifetime** that refers to the maximum lifetime that a manufacturer intends its product to remain functional, which is mainly determined by the product design and after-sale service.

At the same time, the **desired lifetime**, can be defined as the time that consumers want products to last.

Multiple studies have discussed different types of obsolescence affecting the lifetime of products and probably the most important distinction in the literature is between “**absolute obsolescence**” and “**relative obsolescence**” (Cooper, 2016) where:

- **Absolute obsolescence:** refers to the physical wear down of the product, when a product is broken and cannot be repaired. Absolute obsolescence refers to the failure of a product to function and is mainly influenced by the product nature determined by design. In this case, the actual lifetime equals the designed lifetime. It may be further categorized as follows.
- **Relative obsolescence:** depends on the users’ evaluation of a product in comparison to new products, when a product is physically still functioning but considered obsolete by the user. Relative obsolescence refers to the disuse of a functional product. In this case, the actual lifetime is less than the designed lifetime. This is a joint result of the product’s nature and consumer’s decision. This decision can be highly influenced by marketing, sometimes also referred to as marketing induced obsolescence. It includes further different types of obsolescence, including the following

According to the literature **absolute obsolescence** may be further categorized as follows.

- **Technical (also called material, or mechanical) obsolescence:** when the product no longer functions due to lack of performance of material or components.
- **Incompatibility obsolescence (also called functional obsolescence):** when the product no longer works properly due to lack of interoperability of software and/or hardware.

Relative obsolescence may be further categorized as follows.

- **Psychological obsolescence**, or style, cosmetic or aesthetic obsolescence: when a product is replaced because the desire for a new item is strong although the old one is still functional.
- **Economic obsolescence:** when the old product is replaced as the cost of repair or upgrading is high compared to replacement (Prakash et al., 2020).
- **Technological obsolescence:** when the old item is replaced as a new product offering better quality, functionality or effectiveness is available.

Another relevant distinction to be made is between **planned** and **premature obsolescence:**

Premature obsolescence describes the phenomenon of 'the disposal of a product at a point in its 'life' that arrives too soon'. (Prompt Project, 2020). According to EEA (2020), **premature obsolescence** implies a comparison between the actual and designed lifetimes, and is thus an evaluation. It can occur when a product's useful lifetime does not live up to:

i) what is possible – the designed lifetime; or

ii) What is desirable – the product lifetime as reasonably expected by consumers, or the optimal lifetime from a sustainability perspective, taking state-of-the-art technology into account.

If the premature obsolescence is intentional, when a product is designed to have a shorter life, consumers are stimulated to repeat purchases, it is referred to as **planned or programmed obsolescence**.

The concept of **ecological obsolescence** is also found in the literature and refers to a case when a new product has a less harmful impact on the environment than the existing one (Wilson et al, 2017). An example could be provided by the replacement of an existing device with a new one which is much more energy efficient due to significant technological development during the lifetime of the existing device.

The categories of obsolescence identified in the previous chapter can be used to describe and classify common reasons for obsolescence of ICT devices.

Table 9: Obsolescence issues and corresponding examples in the ICT sector

Obsolescence Issue	Example in the ICT Sector
Technical Obsolescence (1st order effect)	Individual components or materials wear out and render the product unusable. Common components in ICT exposed to wear include, among others, batteries, external power supplies and ports. Battery degradation is mainly due to charging / discharging cycles, even though different mechanism can also contribute as, for example, long term storage of the battery unused. USB ports, quite common in many ICT devices, are also, exposed to tear due to the insertion / extraction cycles. According to the standard EN IEC 62680-1-3:2018, the durability rating shall be 10,000 cycles minimum for the USB Type-C connector family, according to the testing conditions provided in the standard. No physical damage to any part of the connector and cable assembly shall occur.
Functional Obsolescence / Incompatibility (2nd order effect)	In the case of functional obsolescence the device itself still works but because of technical developments it is no longer up to current standards – for example, because hardware or software interface requirements have changed. A major example of functional obsolescence is when working ICT devices became outdated at a stroke due to the end of support for the operating system. Digital services and applications could not be not fully compatible / available for older

	hardware, making ICT devices obsolete. These issues can involve firmware, Operating System level and third party applications level. At Operating System level, this means no more updates, no more features, and no more security patches. At application level, it means end of support for products and the application not working anymore on the device (e.g., streaming service providers could end support for some older operating systems, making some smart televisions obsolete before the technical obsolescence. Moreover, operating system / software upgrade can trigger hardware requirements (e.g. RAM, CPU) that can be also a reason for obsolescence.
Psychological obsolescence (2nd order effect)	Consumers replace fully functioning products or devices because they are no longer fashionable or the latest model has desirable new features. This happens particularly frequently with entertainment electronics (games consoles, TVs, smartphones and tablets). There is evidence that product obsolescence in high-income economies may largely be driven by psychologic and behavioural factors. Research in Germany showed that more than 60 per cent of fully functional flat screen televisions TVs were replaced in 2012 because the owners wanted newer, better devices. Key factors in replacing a television were found to be the desire for a larger screen and better picture quality in combination with falling prices of devices (Prakash et al., 2016). Makov et al. (2019) documented through a large-scale second-hand market analysis that “intangible utility”, namely consumer perception of brand equity, explained most differences in economic life spans between products from top smartphone producers. According to Zhilyaev et al (2021) policies should incentivize the development of products designed for consumer attachment and trust, sustained by extended producer support cycles.
Economic Obsolescence (2nd order effect)	The concept of economic obsolescence is related not only to the technical possibilities of carrying out repairs, but also to the availability of repair service and especially incurring repair costs. Appreciation of costs between product replacements and repairs is in most cases the key factor for decisions pertaining to repairs and crucial for changing useful service life of products. Business models and market practices as “razor and blades” (e.g. for printers and consumables; consoles and games) can also incentivise obsolescence, for two main reasons: 1) this business model is profitable if the consumable does not last too long and it is often replaced; 2) Once a failure occur the consumer would prefer the replacement to the repair due to the low initial price compared to the repair price. In the ICT sector a quite interesting example is the one of a company offering trade-up program, which lets customers get a discount on a newer device, but requiring customers to permanently brick a functional product[24]. More in general market practices as special deals for purchasers who have purchased the previous generation and replace / trade-in the older generation of the same device with the new generation can contribute to shorten the lifetime of devices.
Technological Obsolescence (2nd or 3rd order effect)	According to Zhilyaeva et al (2021) that technology transitions (e.g. from feature phones to smartphones) might have been resulted in a decreasing service life of phones. However, when the technological shift is complete, service life could rebound. Another typical example is the transition from TVs to smart TVs

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Ecological Obsolescence	The concept of ecological obsolescence is also found in the literature and refers to a case when a new product has a less harmful impact on the environment than the existing one (Wilson et al, 2017). An example could be provided by the replacement of an existing device with a new one which is much more energy efficient due to significant technological development during the lifetime of the existing device. The likelihood of such obsolescence taking place very much depends on the economic aspects of the resource saved. For instance, high energy prices may enable ecological obsolescence if motivated by energy efficiency. It is important to highlight and evaluate the potential presence of a trade-off between the benefits of a new product with improved product characteristics from an environmental perspective and the negative impacts of replacing a functional product (see section on trade-offs).

3.2 Functional obsolescence: Software obsolescence

Software is another key element affecting the durability of ICT products. Three main categories of software are identified according to the Preparatory study for the Ecodesign and Energy Labelling Working Plan 2020-2024 (Viegand Maagøe et al., 2021):

- Firmware
- System Software (Operating System)
- Application Software

Firmware is a specific class of electronic software that provides the low-level control for a device's specific hardware, often stored on electrically programmable memory devices. Typical examples of devices containing firmware are embedded systems, consumer appliances (e.g. white goods, headsets, speakers, televisions, audio equipment, routers etc.), computers, computer peripherals, and others. Almost all electronic devices beyond the simplest contain some firmware. Examples of firmware in consumer products are for example: timing and control systems for washing machines; or controlling sound and video attributes, as well as the channel list, in modern televisions.

System software is a software for managing computer hardware behaviour, as to provide basic functionalities that are required by users, or for other software to run properly, if at all. System software includes the following: Operating systems, which are essential collections of software that manage resources and provide common services for other software that runs "on top" of them; device drivers, which operate or control a particular type of device that is attached to a computer; and utilities, which are computer programs designed to assist users in the maintenance and care of their computers.

On the other hand, application software is software that uses a computer system to perform special functions or provide entertainment functions for end-users beyond the basic operation of the computer itself. There are many different types of application software, such as word processors, databases, image or video editing.

Firmware and software not updated can be a reason for functional obsolescence (i.e. necessary replacement even without the hardware being defect) if:

1) software or firmware updates to run the appliance properly or at all, or to ensure IT security and privacy are not provided anymore, or
2) the update of firmware or software for example demands faster processors or larger memory capacity than provided with the existing appliance,
3) important external services provided by software are switched off or changed, the hardware can no longer be used for the expected use.

Poppe et al. (2021) describe a method to measure and assess the risk factors affecting the obsolescence of a software, by the so called Legal-Executable-Usable-Function (LEUF) Circle (Figure 24).

Figure 24: LEUF-Circle and its circular dependencies (Source: Poppe et al. 2021)

The LEUF-Circle is based on four premises of the use of software-based products according to their intended purposes and specifications: (1) The user must have at least the right to use the software which must be usable in conformity with the law (data protection, copyright), (2) The software must be/remain technically executable with the existing hardware, (3) An appropriate usability of the software must be given, (4) The software must fulfil its intended functions sufficiently. The table below summarise the obsolescence risk factors identified by Poppe et al. (2021).

Software obsolescence is induced by the software itself (direct) or by changing requirements on the functional and non-functional properties of the software (indirect). Example of direct and indirect software obsolescence are described Table 10.

Table 10: Software induced obsolescence (direct) and software related obsolescence (indirect)

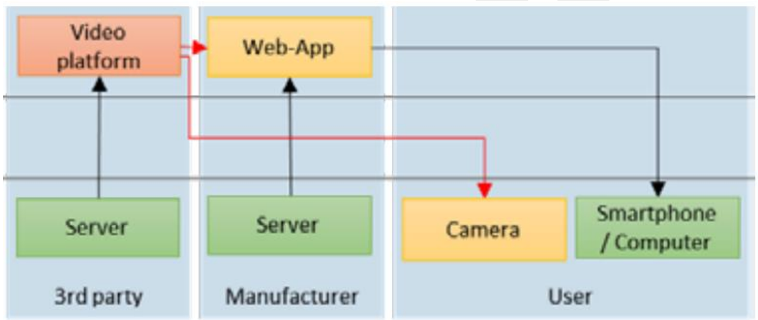
Casual Chain	Example
Direct (software induced obsolescence)	- Functional software failure - Built in software-controlled shutdown or counting devices - Software inefficiencies can lead to higher performance load (software bloat) and hardware degradation
Indirect (software related obsolescence)	- Functional software deficits due to changing system environments • Lack of upward and downward compatibility with other software and data formats • Incompatibility with new hardware - Expiry of software licences or cloud platforms - Loss or limited user friendliness (usability)

3.2.1 Software-induced and software-related obsolescence

A review of the literature have been carried out in order to identify case studies for software induced and software related obsolescence of ICT.

Only in few cases end of life is due to direct software-induced effects (such as the software "kill switches" or “software bloats"). Case studies of software-induced reported in the literature are described in Table 11.

Table 11. Case studies of software-induced obsolescence issues in ICT devices.

Sonos (The Verge, 2020)	In 2020 Sonos stopped providing software updates for its oldest products, and they'll no longer receive any new features. The decision impacts "legacy" devices that are currently part of the company's trade-up program, including all Sonos Zone Players, the Connect and Connect:Amp, the first-generation Play:5, the CR200 controller, and the Bridge. It's important to note that with the Connect and Connect:Amp, this only applies to devices manufactured between 2011 and 2015. Sonos ran into criticism over its "recycle mode," a software kill-switch that renders these legacy products inoperable whenever customers opt to participate in the trade-up program for a 30 percent discount on a current Sonos product[25]. After the criticism received Sonos removed Recycle Mode from its app[26]
Belkin Net-Cam shutdown (Wagner et al. 2020)	The Belkin case was caused by the shutdown of a security video service platform (iSecurity cloud), were end-consumer hardware (Wemo Netcam security cameras) rely on. It is assumed that this platform was run by a 3rd party, as the manufacturer statements are passively formulating ("the platform we use is shutting down") and action (cloud shutdown) has taken place on short notice with 1 month warning time. As consequence the cameras are not executable and therefore obsolete as usage of third party software is not possible. Customer were offered a refund under special conditions, assumingly to reduce dissatisfaction[27]. 

In most of the cases the software is responsible of indirect effects that are less obvious and do not always cause the direct and total obsolescence of the product system. The degradation process of the product quality can take place gradually over time and consumer can experience issues related to upward compatibility, interconnectivity or performance and quality degradation.

The indirect software obsolescence issues are the 'known unknowns' that are by nature difficult to measure and generalize. However, given the many factors and interdependencies, Poppe et al., (2021) considers that indirect effects cause a majority of software obsolescence.

Requirements on the functional and non-functional (e.g .security) properties of the software change over time. According to Umweltbundesamt (2020), the discontinuation of support for older operating systems has led to scenarios where security-relevant updates for operating system and software were no longer available, impeding protection against Trojan and viruses.

Among the software related-issues there is incompatibility in terms of hardware requirements. New functionalities of ICT devices (e.g. smart TVs) place significantly higher requirements on software. If the software used does not have a modular structure and the devices lack a scalable memory, older devices are

[25] https://www.theverge.com/2020/1/21/21075043/sonos-software-updates-ending-play-5-connect-zone-players

[26] https://www.theverge.com/2020/3/5/21166777/sonos-ending-recycle-mode-trade-up-program-sustainability

[27] https://www.iottechtrends.com/belkin-shut-down-wemo-netcam-feeds/

quickly pushed to their limits due to the new content and functions. Installing an up-to-date operating system on older ICT device (e.g. notebooks, smartphone) may no longer be possible due to their performance restrictions. If the minimum requirements of the operating system are not met, the operating system will be unable to run on the hardware in question. Even though this issue does not represent a direct failure of the device, it could increase the perceived obsolescence and induce the replacing despite not having yet reached its technical end of life.

Lack of compatibility (e.g. change in the data transmission standards) can be another source of software related obsolescence.

In some cases software updates can limit the usability, functionality and interoperability of the device, indirectly contributing to its obsolescence. Some practices in the ICT sector make use of software and software update to limit the use of third-party aftermarket spare parts and/ or consumables. This is a practice used also in the imaging equipment sector. Several OEMs have been introducing significant limitations to the use of non-original ink/toner cartridges in many inkjet and laser printers sold to consumers. Based on firmware and firmware updates printers can deny printing when they recognize non-original cartridges (Bernad and Alfieri, 2022).

The practices described above are not direct reasons for obsolescence but can indirectly contribute to the obsolescence of the device, due to issue of incompatibility, mistrust or performance degradation. Table 12 below describes some case studies of software related issues for ICT devices on the market.

Table 12. Case studies of software-related obsolescence issues in ICT devices.

Lightify System (Wagner et al. 2020)	The wireless LIGHTIFY Pro system by OSRAM enables wireless configuration and control of key functions of lighting installations using mobile devices. On March 2020 Osram announced that is shutting down the server for the Lightify system. Osram has decided to shut down server support for smart lamps from the Lightify lighting system within 18 months. Osram will therefore be shutting down the cloud server for controlling the Lightify gateway on August 31, 2021. Osram Lightify lights are compatible with number with other Smart Home platforms and can be used with different controllers[28] Lightify customers were informed in March 2020 in a newsletter notified separately directly in the app. Customers had one and a half years to switch to an alternative smart-home platform where they can continue to use their smart lamps and luminaires under the ZigBee standard. Only local functions will be possible from August 31, 2021.
Microsoft: Windows 11 hardware requirements	Windows 11 will require Intel 8th Gen Coffee Lake or Zen 2 CPUs and up, TPM 2.0 (Trusted Platform Module) support, 4GB of RAM, and 64GB of storage. Microsoft doesn't typically enforce such specific processor requirements with Windows — with both Windows 8 and Windows 10 only requiring a 1GHz processor, 1GB of RAM (2GB for 64-bit), and 16GB of storage (20GB for 64-bit). Millions of PCs that were sold during the launch of Windows 10 will be left behind. For many users cannot upgrade to the latest OS, because the computer does not meet the hardware requirements. (Source: The Verge[29])
PSP, PS3, PS Vita: loss of functionalities – Purchase of games	In 2021, Sony announced its plans to shut down the online stores for the PlayStation Portable, the PlayStation 3 (PS3), and the PlayStation Vita in summer of the same year. After receiving opposition from owners of PS3 and PS Vita, the company backtracked a bit and put its plans for the PS3's and Vita's demise on hold. The PlayStation Portable PSP wasn't so lucky, and the 16-year-old handheld console said goodbye to its store last July. The stores for the PS3 and PS Vita will continue operating for the foreseeable future, at least until Sony makes another unpopular announcement. However, according to several

[28] https://pixelfriedhof.com/en/which-alternative-controllers-can-control-osram-lightify-lights/

[29] https://www.theverge.com/2021/6/29/22555371/microsoft-windows-11-cpu-support-hardware-requirements-tpm-response

	websites and web-magazines, Sony, for these consoles, it's making it harder to shop games as will no longer accept credit or debit cards and PayPal as payment options by PS3. Instead, you'll have to use a PlayStation Store gift card or load up the wallet tied to your account on the PlayStation Store on the web, your phone, or on a PS4 or PS5. Read More: https://www.slashgear.com/ps3-and-ps-vita-stores-will-no-longer-accept-credit-cards-and-paypal-06694117?utm_campaign=clip https://www.tomsguide.com/opinion/buy-ps3-games-online#xenforo-comments-497403 https://www.theverge.com/2021/10/6/22713526/sony-ps3-vita-buy-games-credit-debit-card-paypal
Peloton's touchscreen monitor for fitness bikes (The Verge, 2019)	In 2019, Peloton ended software support for the first generation of its fitness bikes with touchscreen monitor. The screen is removable from the bike, so customers at home can install an updated version by swapping the monitor which will still work with the rest of the bike regardless of when it was purchased. https://www.theverge.com/2019/7/30/20746919/peloton-first-generation-bike-monitor-screen-stop-updates

Parts pairing

According to Right to Repair[30], parts pairing is an increasingly common practice used by manufacturers of smartphones and other electronic products to control who can perform certain types of repairs (in particular replacement of hardware components)[31]. It is made possible by serialisation of some spare parts, which is paired by manufacturers to an individual unit of a device using software.

If any of these parts need replacing during a repair, they might not be accepted, or lose some of their functionality unless remotely paired to the device again via software by the manufacturer.

According to Right to Repair, by mainstreaming these practices, manufacturers could require that only new genuine spare parts sold by them could be used to complete a repair. This would effectively mean controlling the cost of type of repairs that can be performed. It would also mean that independent repairers, consumers and community repair initiatives could be prevented from attempting repairs using genuine parts recovered from another phone or any aftermarket spare part, irrespective of their quality.

Software pairing solutions have been introduced for key components of smartphones as the battery, display and camera which makes replacement for non-registered service providers impossible.

According to the evidence collected by the Right to Repair campaign , once a device subject to part pairing is repaired or refurbished by an independent professionals, customers can receive warning messages like the ones in **Error! Reference source not found.** to inform them that the new part "isn't genuine" and even sometimes that it's not working.

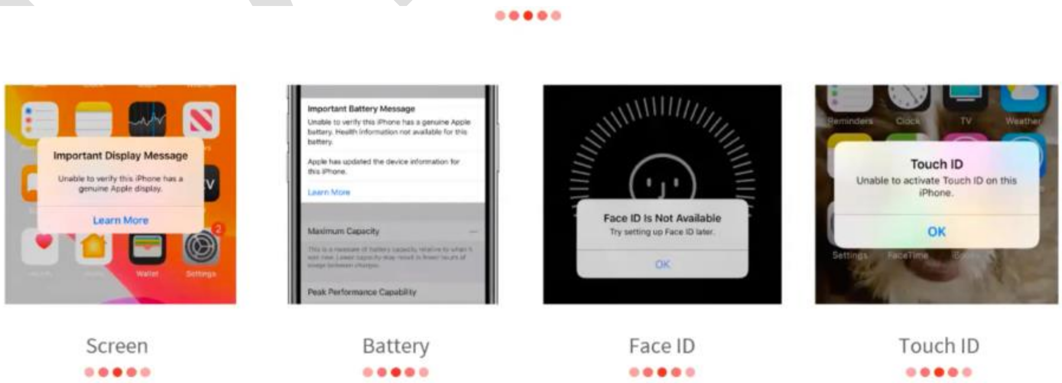


Figure 25: warning messages after replacing a part with a not paired one.

[30] https://repair.eu/about/
[31] https://repair.eu/news/part-pairing-a-major-threat-to-independent-repair/

The use of these warning messages is confirmed by OEMs like Apple and it is justified with the aim of providing warning about compatibility or performance issues that circumstances as the use of a non-genuine component might cause (**Error! Reference source not found.**). At the same time, these practices can generate stress and mistrust for independent repairs and refurbishments carried outside the official OEM network. Backmarket[32], a leading platform of refurbished products and a member of the European Right to Repair campaign, has noticed an increase in aftermarket services tickets since the rise of products affected by part pairing and a share of customers returning the tickets as reported during the webinar “How software could make independent repair impossible”[33].

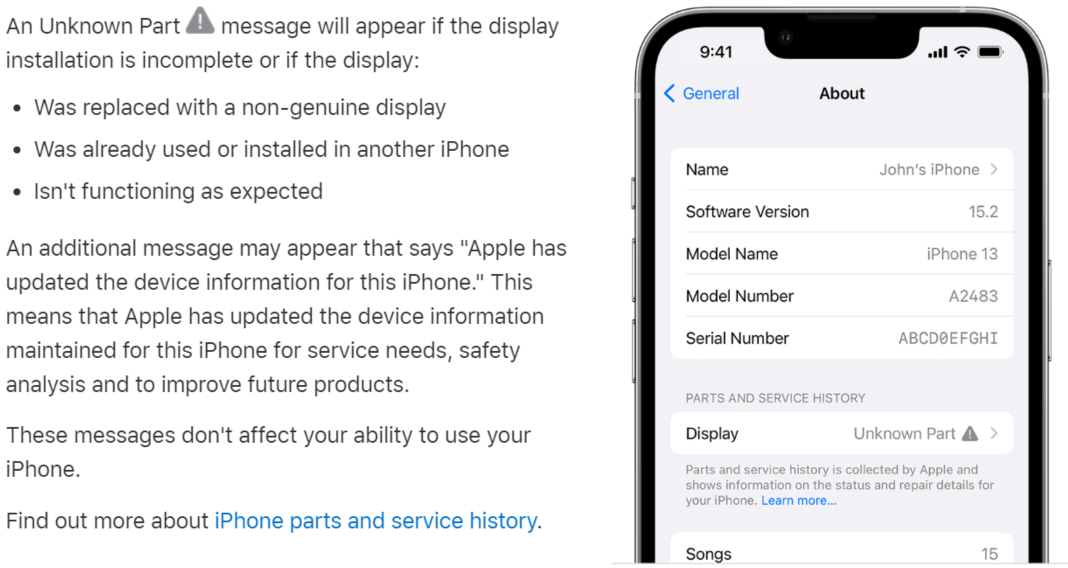


Figure 26: Unknown Part Message from Apple. Source: https://support.apple.com/en-au/HT210321

According to The Repair Academy[34] there is a serious risk in consumers losing trust in repair businesses because of the error messages and the functionality losses and this would not only affect the repair industry and lead to loss of jobs, but would also result in an increase in the amount of electronic waste discarded every year and new products being purchased.

3.3 Induction effects

The increased traffic and number of connected devices presented in Task 3 cause an induction effect at the level of network infrastructure. This is further amplified by the rollout of new telecommunication networks, currently the 5G protocol, which, even though leads to increased efficiency, is still associated with material use for the upgrade of the network system and accommodation of traffic needs. Investment in infrastructure is expected in various network domains, as demonstrated in Figure 27 (McKinsey and Company, 2018).

[32] https://www.backmarket.com/
[33] Webinar recording available at https://youtu.be/CvCThm0tHCA
[34] https://therepairacademy.com/

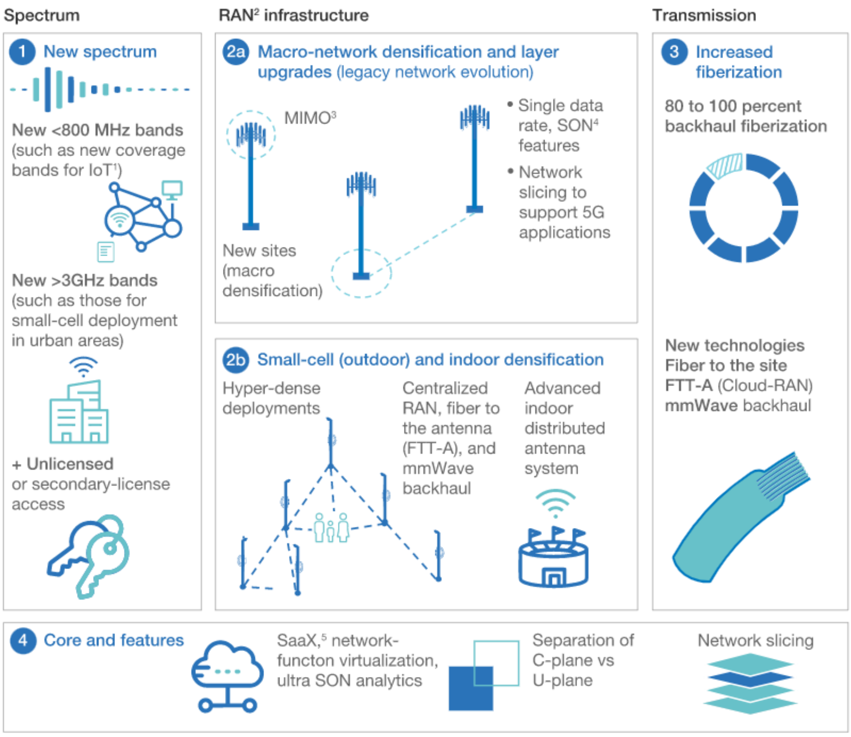


Figure 27: Growth in the ICT infrastructure related to the 5G rollout. Source: McKinsey and Company, 2018

Source: https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/the-road-to-5g-the-inevitable-growth-of-infrastructure-cost

The introduction of IoT devices for data collection and storage in a wider range of products, from household appliances to wearable gadgets means a different product categories entering the WEEE stream, affecting not only the amount but also the end-of-life management. (ITU and WEEE Forum, 2020). Increased mobile network use and fast-paced technological innovation constitute main drivers of WEEE growth as highlighted in the figure below.

The Figure 28 below highlights main drivers enabling WEEE growth.

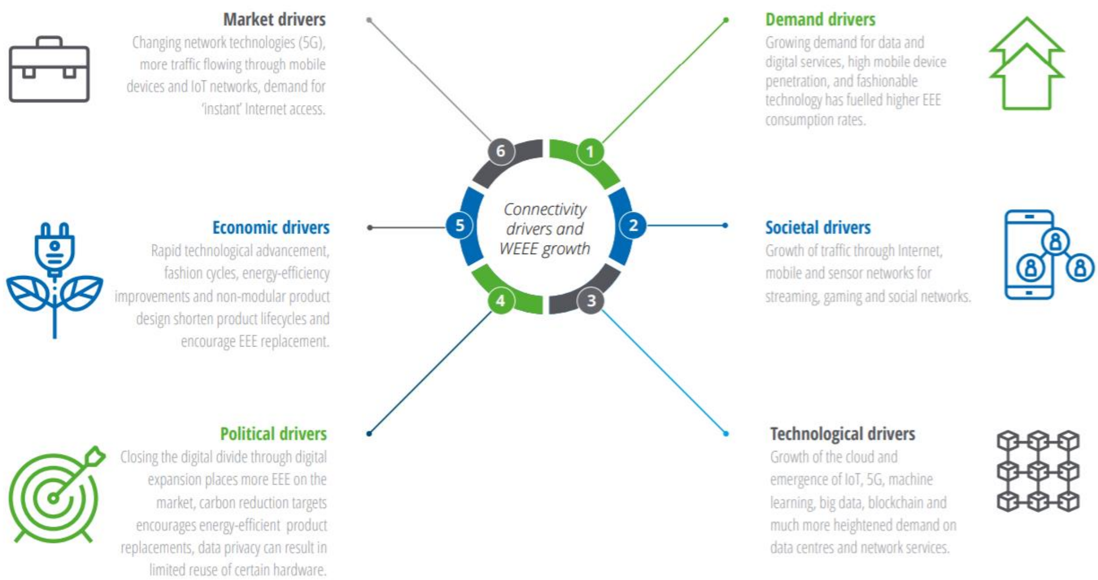


Figure 28: Main drivers enabling WEEE growth. Source: ITU and WEEE Forum, 2020.

These devices then form parts of ICT systems that extend to network infrastructure and data centres, which themselves require a wide range of materials from precious metals to plastics (Figure 29).

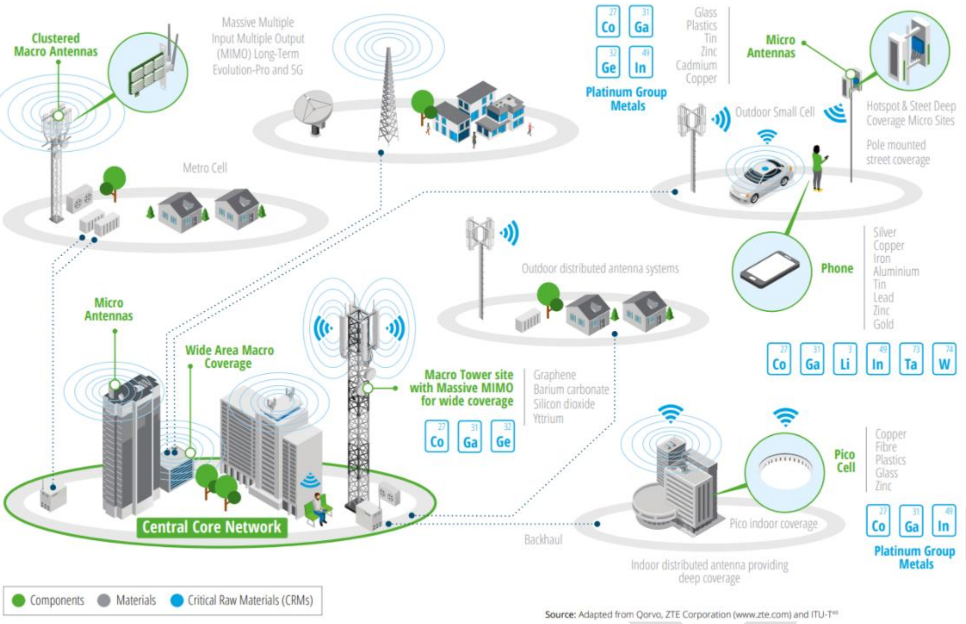
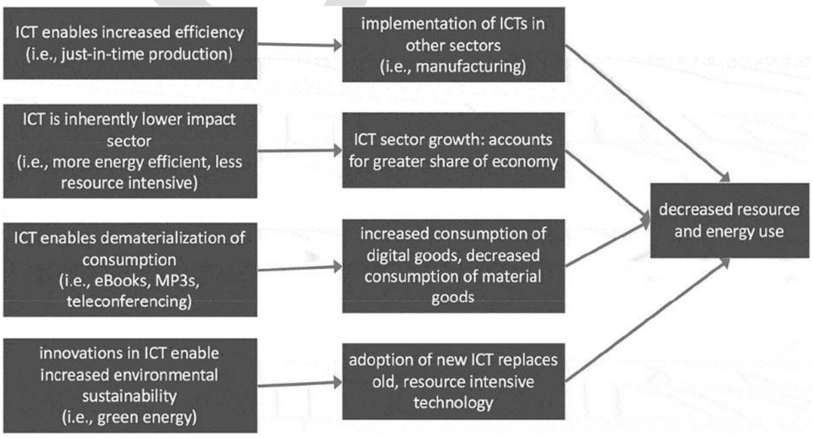


Figure 29: Overview of 5G network infrastructure and associated critical materials. Source: ITU and WEEE Forum, 2020.

On one hand, devices from home modes to network antennas will need to be replaced as a result of the diffusion of new protocols like 5G, while new data centre architectures (as described in Task 3) also lead to product retirement and substitution, which in term generate WEEE. On the other hand, each of these upgrades have the potential to offer higher material efficiency. For example, in data centres, fibre installations are more material efficient, having lower demand for fewer line cards and fewer racks, reducing waste (ITU and WEEE Forum, 2020). Therefore, as it is the case with energy consumption levels described in the previous Task 3, WEEE generation levels will similarly depend on whether technological and design innovation leading to a more efficient use of materials will compensate for the device demand growth and the fast pace of technological obsolescence. To that end, product design with circularity in mind, such as enabling reuse, repair, upgrade and recycling are crucial in avoiding WEEE growth.

3.4 Substitution effects

Dematerialization refers to a reduction in the material resources, including energy sources such as fossil fuels, required for a given level of economic production (Rieger, 2020). Figure 30 present the ICT-related drivers and enablers leading to either an increase or decrease of resource use.



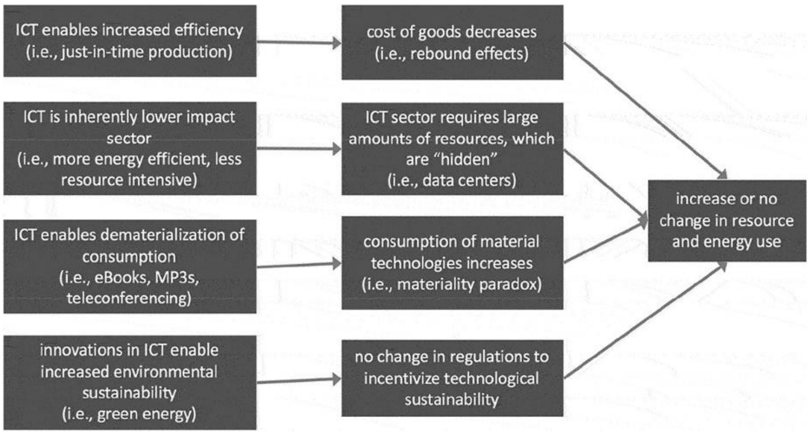


Figure 30: ICT sector as driver of reduction (or increase) in material and energy consumption

On one hand, ICT has the potential to facilitate resource use reduction through increased efficiency and dematerialized of consumer goods, and industries. On the other hand, both pressure from the growth of device demand and connected devices, as well as reduced costs as a result of increased ICT efficiency could lead to sustained resource use and to rebound effects. Similarly to the debate on energy use, the future trend of material use in ICT depends on whether resource efficiency would compensate for the increased number of devices.

Investigating the trend in demand of raw materials between 2013 and 2034 for various products including ICT technologies, Marscheider-Weidemann et al. (2016) project an increase in the production levels by 2035, also due to the growing demand of ICT. These materials include dysprosium/terbium, rhenium, tantalum, cobalt, germanium, scandium, and neodymium. Table 13 considers the raw material demand for the emerging technologies; any demand beyond these technologies is not taken into account (Marscheider-Weidemann et al., 2016).

Table 13: Global demand for metals in 2013 and 2035 compared to the global production volume of the respective metal in 2013. Source: (Marscheider-Weidemann et al., 2016).

Metal	$Demand_{20xx}$ / $Production_{2013}$		Emerging technologies
	2013	2035	
Lithium	0.0	3.9	Lithium-ion batteries, lightweight airframes
HREE (Dy/Tb)	0.9	3.1	Magnets, e-cars, wind power
Rhenium	1.0	2.5	Super alloys
LREE (Nd/Pr)	0.8	1.7	Magnets, e-cars, wind power
Tantalum	0.4	1.6	Micro-capacitors, medical technology
Scandium	0.2	1.4	SOFC fuel cells
Cobalt	0.0	0.9	Lithium-ion batteries, XTL.
Germanium	0.4	0.8	Fibre optic, IR technology
Platinum	0.0	0.6	Fuel cells, catalysts
Tin	0.6	0.5	Transparent electrodes, lead-free solders
Palladium	0.1	0.5	Catalysts, seawater desalination
Indium	0.3	0.5	Displays, thin layer photovoltaics
Gallium	0.3	0.4	Thin layer photovoltaics, IC, WLED
Silver	0.2	0.3	RFID
Copper	0.0	0.3	Electric motors, RFID
Titanium	0.0	0.2	Seawater desalination, implants

Malmodin et al. (2018) similarly estimate that the ICT and E&M (entertainment & media) sectors represent only about 0,5% of the global annual usage of selected materials, but for several materials (indium, gallium and germanium), they represents as much as 80-90% of global usage.

Even though out of scope of this study, it is worthy of noting potential third order effects. Digitilisation has the potential to improve the quantity and quality of information available to consumers with regards to the the environmental impact of production and ways of consuming more sustainably. However, it is unclear whether digitalization would actually lead to social values change and more sustainable consumer behaviour (Santarius et al, 2020).

4 Lifetime of ICT devices on the market

The determination of the lifetime characteristics of ICT devices is a complex task. Existing data regarding the lifetime of electronic equipment (EE) are based on diverging definitions of lifetime as well as different temporal and regional scopes (Thiébaud et al. 2017a).

At the time of replacement, EE is often not disposed of immediately, but stored for some time. This leads to, for example, very few mobile phones are collected for disposal despite high sales numbers. Comparisons of assumed product lifetimes with the product age at recycling facilities have shown that products are often older than expected (Thiébaud et al. 2017a). The use phase of ICT devices can include one or more reuses and storage periods (also called hibernations) as described by Thiébaud et al. (2017b). The modelling of the material flow is described in Figure 31 below.

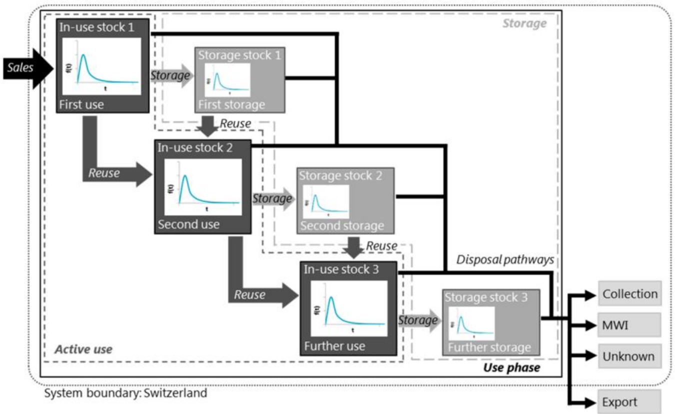


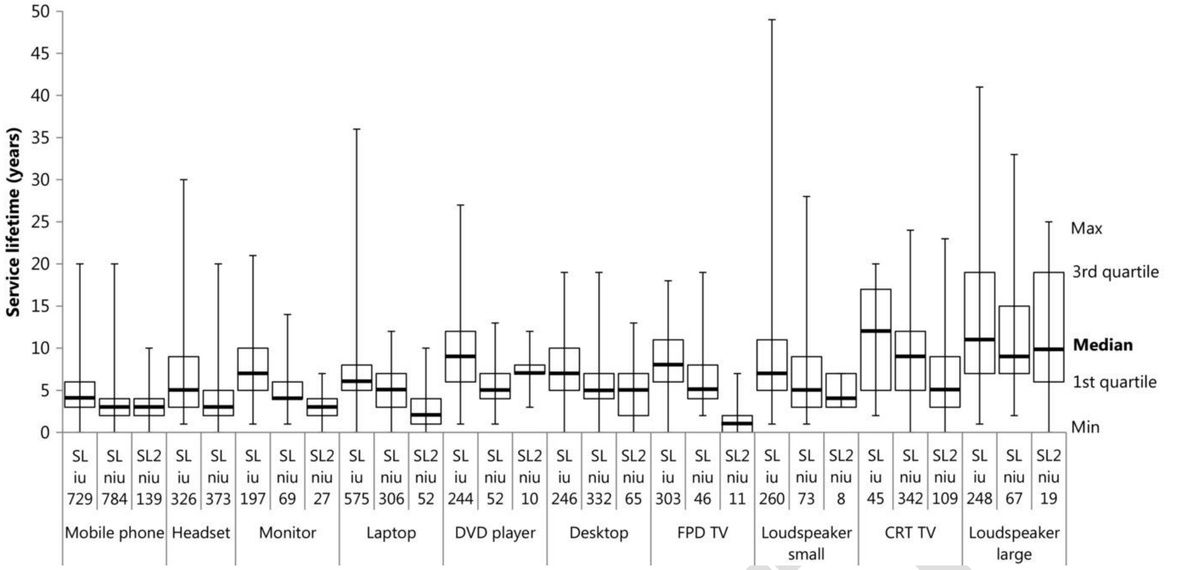
Figure 31: "Cascade model" of the use phase of ICT devices, including several active uses and storage periods. Cascade model of the process "use phase", divided into "active use", and "storage". Source: Thiébaud et al. (2017b)

A results of a survey conducted in the UK show that only a third (33.70%) of previously owned mobile phones were returned back into the system, with the duration of hibernation even exceeding the duration of use on average (Wilson et al, 2017). The main reason for hibernation by 75% of respondents is the willingness to keep the device as spare, followed by a lack of knowledge on what to do with an old device, a perception that the device is not worth anything, and finally that valuable information is stored in the device (the last reason, thus, constituting a barrier for reusability) (Wilson et al, 2017).

The determination of in-use stocks and lifetime characteristics is dependent on methods combining various top-down and bottom-up approaches. Top-down data includes time series of domestic consumption (usually available statistics, production and trade data), while bottom-up approaches such as surveys are used to determine stock age profiles and probability distribution curves for lifetimes (likelihood of products coming out of use over time).

Thiébaud et al. (2017a), present the results of a survey on the service lifetime, storage time, and disposal pathways of EE that we conducted between 2014 and 2016 in Switzerland. The goal of the survey is to obtain detailed "bottom-up" information of the service lifetime and storage time (hibernating time) of EE in Switzerland.

Figure 32 shows the box plots of the service lifetime of devices still in use compared to the box plots of the service lifetime and the second service lifetime of devices no longer in use. The service lifetime for devices still in use includes an estimate of the time the user intends to continue to use the device. Service lifetime for products in use is generally longer than the lifetime of the products not in use. However, literature mentioned in the same study shows that people tend to overestimate future service lifetimes of their devices.



SL iu = service lifetime of devices in use; SL niu = service lifetime of devices no longer in in use, that is, already stored or disposed of; SL2 niu = second service lifetime of devices no longer in use. The number in the third line indicates the sample size. FPD TV = flat panel display television; CRT TV = cathode ray tube television; DVD = digital video disc.

Figure 32: Comparison of the box plots of the service lifetime for ten different electronic device types.

The median service lifetime of devices still in use, including the estimated years the user intends to continue to use it, varies between 4 years for mobile phones and 12 years for CRT TVs. The median service lifetime of devices no longer in use varies between 3 years for mobile phones and headsets and 9 years for Cathod Ray Tube TVs and large loudspeakers. The corresponding average service lifetimes are 3.3, 3.8, 9.2, and 10.8 years, respectively. The median second service lifetime is equal to or shorter than the median (first) service lifetime, depending of the type of device and with the exception of digital video disc (DVD) players and large loudspeakers. The first and third quartiles as well as the minimum and maximum values illustrate the often large variance of the data.

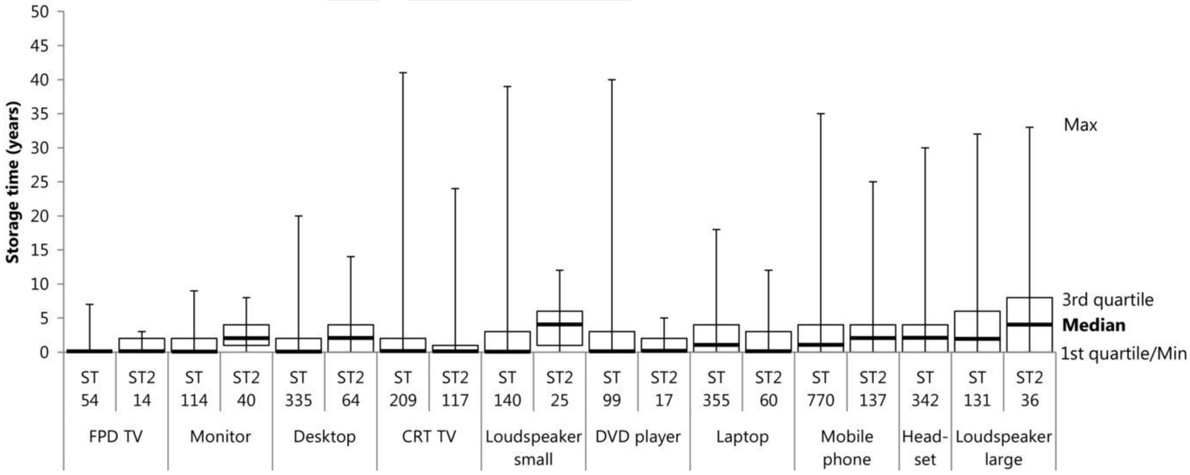


Figure 33: Comparison of the box plots of the storage time for ten different electronic device types.

In terms of storage (hibernation) ICT devices as laptops and mobile phones were found to have a median storage time of 1 year, headsets and large loudspeakers of 2 years. The average storage time ranges from 0.8 years for flat panel display TVs to 3.6 years for large loudspeakers.

However, only a few studies have so far comprehensively quantified different lifetime phases of ICT products Storage, termed hibernation or dead storage, partly explains missing ICT e-waste, and in general is a phenomenon that impedes business models based on reuse, repair/refurbish, and/or remanufacture, as well as delaying the general availability of resources for recycling.

A results of a survey conducted in the UK show that only a third (33.70%) of previously owned mobile phones were returned back into the system, with the duration of hibernation even exceeding the duration of use on average (Wilson et al, 2017). The main reason for hibernation by 75% of respondents is the willingness to keep the device as spare, followed by a lack of knowledge on what to do with an old device, a perception that the device is not worth anything, and finally that valuable information is stored in the device (the last reason, thus, constituting a barrier for reusability) (Wilson et al, 2017).

Zhilyaeva el al. (2021) examined in-use stocks, dead-storage stocks, and waste volumes of four ICT products in Denmark and determined lifetime characteristics during active use and storage. According to this study ICT products have relatively short lifetimes, after active use they are sometimes stored for up the equivalent of the length of active use, and a large proportion of products that are not actively used are still in good working condition.

A temporal analysis of the length of service life for mobile phones revealed significant changes in the period the technology transitioned from feature phones (pre-2008) to smartphones. This technology transition implied a significant reduction in service life, affecting the outgoing technology, but results also suggest that service life rebounds after the transition is completed. Further, this work provides insight into the drivers that determined product obsolescence, including an analysis of differences in lifetime characteristics between product brands. Results reinforce the notion that absolute obsolescence (e.g. physical durability) is not the main driver for consumers stopping to use products. Observed differences between product brands, may partially be explained by differences in intangible product properties, such as consumer perception of brands and other psychological factors underlying consumer-brand relations.

Zhilyaeva el al. (2021) recommended that policy approaches addressing circular economy for ICT products go beyond physical and technical aspects and also address underlying consumer and business drivers inducing current high paced obsolescence levels. In particular, policies should incentivize the development of products designed for consumer attachment and trust, sustained by extended producer support cycles. The issues of expanding dead storage stock might be addressed through the development of a more effective and convenient collection and return system and incentivizing the return of used products (for example through trade-in schemes). Lastly, targeted awareness campaigns could play an important role for extending the lifetime of ICT products as well as reducing the dead storage time and dead storage stocks

Wieser and Troger (2018) combined quantitative evidence from a large-scale questionnaire survey (n = 988) with 25 qualitative household interviews to identify consumers' motivations underpinning their considerations regarding replacement timing, replace versus repair, and new versus second-hand phones. The findings from this study suggest that mobile phone replacements are not only based on a desire for the new, but primarily on the perceived obsoleteness of the current phone. The study identified three forms of perceived obsolescence, being either related to a phone's 1) basic functionality, 2) up-to-dateness, or 3) ability to keep up with social practices. The forms of perceived obsolescence described by Wieser and Troger (2018) seem to correspond with the description of relative obsolescence in the chapter above. Furthermore, Wieser and Troger (2018) showed that the perceived speed of obsolescence is key to considerations of phone repair and reuse. Overall, the results call into question the prevalent picture of novelty-oriented mobile phone consumers, exposing the paradoxical nature of consumer strategies to resist the fast pace of obsolescence.

The results of recent survey on the reason to replace a device seems to confirm the relevance of the software obsolescence IPSOS (2022). The absence of software support and the decries in device performance (possibly also due to software issues) are indicated as the main reasons for device replacements for products as laptops, tablets and smartphones and relevant reasons also for smart TVs and game consoles.

5 Strategies for material efficiency of ICT

Reliability and durability

Material efficiency of ICT products can be improved first of all making sure that product are designed to be reliable and durable. Reliability, according to the standard EN45552:2020[35], is defined as the probability that a product functions as required, under given conditions. According to the EN45552:2020, reliability and durability convey similar concepts but have distinct and separate meanings. At the simplest level, reliability and durability are both concerned with the ability to function as required under certain conditions until a limiting state is reached. Both reliability and durability expect that maintenance will be undertaken as applicable to the product (by the user/a professional service provider), to retain the product in a condition where it is able to function as required. However durability includes also the possibility of extending the use-phase by one or multiple repairs, potentially involving different parts, to return the product to a functional state.

For electronics and ICT in commercial applications common reliability testing can ensure that products do not fails when exposed to specific events and stresses including electric stresses, thermal stresses, vibration, shocks due to accidental drops, exposure to dust and liquids.

The preparatory study for mobile phones, smartphone and tablets[36] identifies a number of areas for potential regulatory intervention by reliability requirements, related to resistance to accidental drops, scratch resistance, protection from dust and water, battery longevity.

It is important to note that the reliability and durability measures can cover failure events where the functional state immediately drops, or progressively degrades (e.g. in the case of batteries) to a limiting state (discrete or continuous case, respectively) as described in Figure X below.

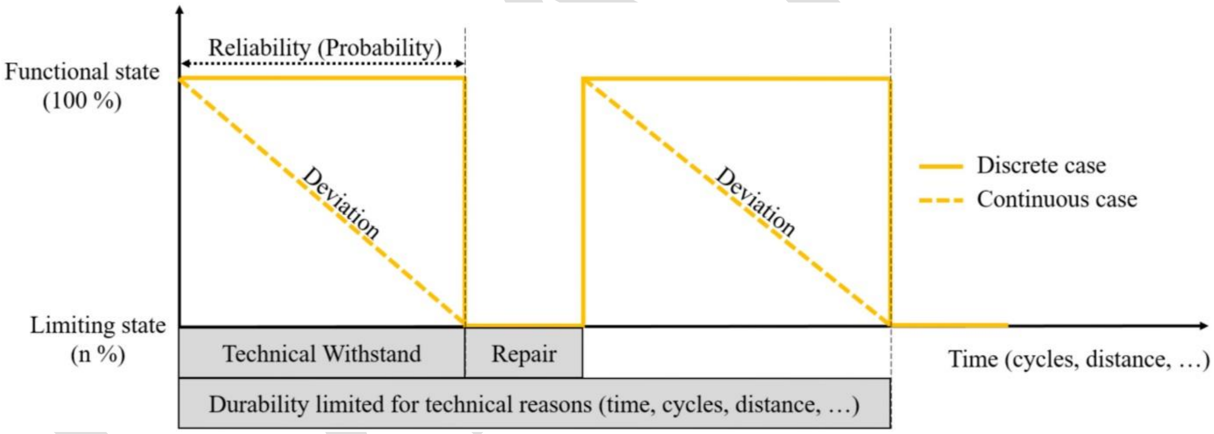


Figure 34: Relationship between reliability, repair and durability (adapted from EN 45552:2020). Source: Cordella et al. 2021)

Moreover some reliability aspects can be not linked to primary functions but still relevant as contribute to reducing replacement of devices for aesthetic reasons (e.g. scratch resistance). Scratches make devices not desirable anymore and as such also limit their reuse.

The table below includes examples of reliability provisions in existing product policy tools such as ecodesign regulations, green public procurement criteria and type-1 ecolabels.

Table 14: Example of reliability provisions of ICT devices

Product group	Reliability aspect	Rationale
Smartphones and tablets (proposals	Scratch Resistance - Screen of the device passes the hardness	Measures to increase the withstand of the glass used to cover the display do not only prevent

[35] EN45552:2020. General method for the assessment of the durability of energy-related products

[36] https://www.ecosmartphones.info/

for reliability requirements).	level 4 on the Mohs hardness scale.	breaks in case of accidents, but also scratches of the display, which might lead to hard to read displays and may also weaken the glass in case of accidents.
	Resistance to accidental drops	Measures to increase the withstand of the device to accident
	Ingress Protection	Measures to increase the withstand of the device to the ingress of liquids and dust.
	Battery endurance in cycles	Measures to ensure that the batteries used in the devices achieve at least X cycles at Y percent remaining charge capacity.
	Instruction for battery maintenance	Measure to increase consumer awareness of impacts on battery lifetime related to exposing the device to elevated temperatures, state of charge, fast charging and other known adverse effects on battery lifetime;
EU green public procurement criteria for computers, monitors, tablets and smartphones SWD(2021) 57 final	Information on battery state of health	Pre-installed software to determine and monitor the status of the battery/accumulator and allow for the reading of the battery or accumulator's 'state of health' and 'state of charge', as well as the number of 'full charge cycles' already performed from the battery/accumulator and to display these data for the user. See the explanatory note below for the definitions. The software must also provide tips for users to maximise battery lifespan
EU green public procurement criteria for computers, monitors, tablets and smartphones SWD(2021) 57 final	Battery Protection Software	Pre-installed battery protection software that can lower the maximum battery charge level to at least 80%.
EU green public procurement criteria for computers, monitors, tablets and smartphones SWD(2021) 57 final	Intelligent Charging	Intelligent charging software able to identify the user's regular charging habits/pattern, stop the charging process before it reaches 100% (e.g. at 80%), and fully charge the device only when needed by the user.
Servers and data storage products Commission Regulation (EU) 2019/424	Information on Operating Condition Classes (temperature and humidity)	The operating conditions classes provide information on the allowable environmental ranges where manufacturers test their equipment in order to verify that it will function within those boundaries.
Electronic displays Commission	Firmware shall be made available for a minimum period	Measure to avoid the functional obsolescence,

Regulation (EU) 2019/2021 and Commission Delegated Regulation (EU) 2019/2013	of eight years after the placing on the market of the last unit of a certain product model	safety and incompatibility issues of the device. The provision cover security and functionality updates for the operating system.
	Info. on minimum guaranteed availability of software and firmware updates, and of product support more generally	The lifetime of software is crucial to the lifetime of electronic appliances; whereas given that software is becoming obsolete more and more rapidly, electronic appliances need to be adaptable in order to stay competitive on the market

Software availability and performance

As described in the previous chapter, software is a product component that can determine the functional (premature) obsolescence of ICT devices. Strategies to avoid this issue need to address both the availability and the performance of software.

Existing software related requirements under the Directive 2009/125/EC focus on extending the availability of the latest available version of the firmware/software and the availability of security updates (see Table 15). The Commission Regulation (EU) 2019/2021 for Electronic Displays and the Commission Regulation (EU) 2019/424 for Servers and Data Storage products make reference to security updates. However, these measures, still do not addresses any specific software quality aspects, such as the executability, usability and functionality of the products with the software. (Poppe et al. 2021). The ecodesign regulation for smartphones and slate tablets could refer more specifically to functional aspects (functional updates to the operating system) (Fraunhofer IZM et al, 2020a). Example of software related ecodesign requirements are reported in Table 15.

On this area, the "Directive (EU) 2019/771[37] provides some liability provisions: if the digital content or digital service is supplied by a single act of supply, the seller should be liable to provide the updates necessary to keep the goods with digital elements in conformity for a period of time that the consumer can reasonably expect, even if the goods were in conformity at the time of delivery. In particular, the period of time during which the consumer can reasonably expect to receive updates should be assessed based on the type and purpose of the goods and the digital elements, and taking into account the circumstances and nature of the sales contract. A consumer would normally expect to receive updates for at least as long as the period during which the seller is liable for a lack of conformity, while in some cases the consumer's reasonable expectation could extend beyond that period, as might be the case particularly with regard to security updates. In other cases, for instance as regards goods with digital elements the purpose of which is limited in time, the seller's obligation to provide updates would normally be limited to that time. The Directive (EU) 2019/771 provides liability provisions for the lack of digital services, but do not obliges to a design with long lasting software / digital services. Moreover the use of terms as "reasonably expect" leave the door open to different interpretation and does not seem to provide opportunity for improvement from the current business-as-usual.

The Commission proposal Empowering Green Transition initiative[38] aims to establish an obligation to inform consumers before concluding the contract on the existence of software updates and the period for which the producer commits to provide them, when this information is provided by the producer.

Other complementary strategies could include measures aiming to:

- a longer compatibility of software updates with hardware

[37] Directive (EU) 2019/771 of the European Parliament and of the Council of 20 May 2019 on certain aspects concerning contracts for the sale of goods, amending Regulation (EU) 2017/2394 and Directive 2009/22/EC, and repealing Directive 1999/44/EC.

[38] European Commission (2022a). COM(2022) 143 final: Proposal for a Directive of the European Parliament and of the Council amending Directives 2005/29/EC and 2011/83/EU as regards empowering consumers for the green transition through better protection against unfair practices and better information

- avoid software-based solutions preventing the use of remanufactured / second hand spare parts (including pairing)

Strategies for the material efficiency of the software can also directly address the software as a product. The Type-I Ecolabel “Blue Angel” has introduced criteria addressing software as a product. The scope of these Basic Award Criteria covers software products that belong to the group of “application software” with a user interface. The Blue Angel environmental label for “Resource and Energy-Efficient Software Products” (DEUZ-215)[39] may be awarded to products that use hardware resources in a particularly efficient manner and consume a low amount of energy during their use. Criteria cover aspects like:

- information on minimum system requirements
- information on hardware utilisation and electrical power consumption in idle and active mode
- potential hardware operating life (e.g. software updates must not result in the need for an hardware update)
- backward compatibility
- user autonomy (Data formats; transparency, continuity of the software product)
- Uninstallability
- Offline capability
- Modularity
- Freedom from advertising
- Documentation of the software product (including information on reducing the use of resources).

Lowering the performance requirements, longer operating lives for the hardware are possible. In addition, by ensuring higher level of transparency can give users greater freedom in their use of the software and reduction of the associated impacts. According to Blue Angel, the next revision of the Basic Award Criteria will expand the scope to include, above all, server-client software products.

Additional approaches are suggested by Rüdenauer and Gröger (2022) in the context of a study commissioned by the Federal Agency of Germany (Umweltbundesamt). They include the disclosure of interfaces or program code and the possible decoupling of device functionality to external data services (e.g. cloud services). According to this proposal:

1) cloud service should be obliged to provide longer-term support for the devices in data centers, so that the operation of the device can be maintained (e.g. for a period of of at least 5 years after the last specimen was placed on the market model).
2) When turning off the external cloud service, the user must either through the built-in functionality or through appropriate software updates be "freed" from the coupling to the external service and the device from it can use independently.

Moreover other suggested strategies include the availability of core functionalities (if the core functionality of a device does not consist of receiving or sending data via the network) even without an activated network function and the labelling on the product that it relies on an internet connection or external cloud services. Rüdenauer and Gröger (2022).

Table 15: Example of software related provisions on ICT devices

Product group	Software Aspect	Rationale

[39] https://produktinfo.blauer-engel.de/uploads/criteriafile/en/DE-UZ%20215-202001-en-Criteria-2020-02-13.pdf

<table>
<tr><td>Electronic Displays (Commission Regulation (EU) 2019/2021)</td><td rowspan="2">Firmware and safety updates shall be made available for a minimum period of eight years after the placing on the market of the last unit of a certain product model</td><td rowspan="3">Measure to avoid the functional obsolescence, safety and incompatibility issues of the device.

The provision cover security and functionality updates for the operating system.

The lifetime of software is crucial to the lifetime of electronic appliances; whereas given that software is becoming obsolete more and more rapidly, electronic appliances need to be adaptable in order to stay competitive on the market</td></tr>
<tr><td>Commission Regulation (EU) 2019/424 of 15 March 2019 laying down ecodesign requirements for servers and data storage products</td></tr>
<tr><td>Smartphones and tablets (proposal for software related requirements)</td><td>Minimum requirements for the availability of software functionality / security updates

Software updates to be available after maximum X months from the release of an update of the underlying operating system.</td></tr>
</table>

Modularity

Modularity is the degree to which a system’s components are designed with relatively independent functional units that can be combined (Steichen et. al., 2017). A modular structure consists of self-contained, functional units (modules) with standardised interfaces and interactions. “Self-contained” is understood to mean that the function is realised within the module itself. Replacing one module with another allows users to maintain or repair the same product (i.e. a manufactured or renewed product) with relative ease or create a new, higher quality variant of the product (i.e. increase its functionality).

Characteristics of modular design include:

Distinguishable – independent modules that can be easily separated from the rest of the equipment (e.g. a removable battery on a laptop computer)

Defined purpose – each module has a defined function (e.g. a camera on a smartphone)

Interchangeable – modules can be substituted for those with different functions that change the way the whole system operates •

Designed for disassembly – the ability to easily deconstruct the product to the level of the underlying modules without compromising its integrity.

Not all of these characteristics must be present for a given product to be considered modular; however, demonstration of more than one can certainly improve the degree of modularity and could have an improved impact on circularity. The characteristics of a modular design give a finished product certain attributes that differentiate it from non-modular comparisons.

Using the examples provided (or other examples where modularity had a transformative effect on the way users engage with a product or product category), the potential benefits of modular products primarily include:

- Upgradability – the capacity to improve a product by altering the functionality of one or more modules
- Maintenance – the ability to isolate errors in individual modules and correct them, while maintaining functionality of the product as a whole
- Reparability – the ability to isolate faults in individual modules so that they can be repaired or replaced
- Recyclability – the ability to easily disassemble and separate the components of a product so the materials within them can be recycled.

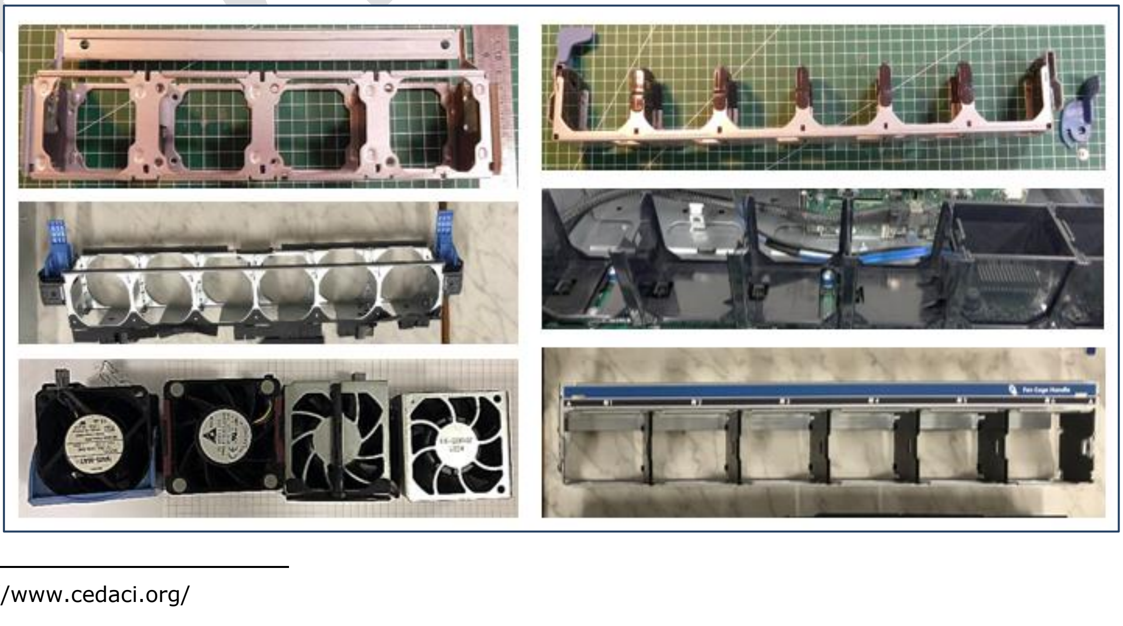
However, as explained by Schischke et al. 2019, modularity requires some design changes. The most evident design change is the need for connectors to provide mechanical and electrical contact between individual modules. Depending on the nature and use scenario of a connector reliability, robustness, wear resistance, and non-reactive surfaces, modularity leads to a group of "modularity materials," which are essential for such circular design approaches, but at the same time are among those materials with a large environmental footprint or limited recyclability. A life cycle assessment of a modular smartphone shows a roughly 10% higher environmental life cycle impact compared with a conventional design. This needs to be compensated by reaping the circular economy benefits of a modular design, i.e., higher likeliness of getting a broken device repaired, extending the lifetime through hardware upgrades and refurbishment.

Modularity of ICT hardware: the example of servers

An analysis of modularity of hardware has been conducted in the framework of Data of CEDaCI[40] (Circular Economy for the Data Centre Industry), a 5-year Interreg-funded project that runs across 7 countries in North-Western Europe and is piloted by London South Bank University. The disassembly and analysis of 16 different servers across different generations and brands showed that modern servers are designed with a small degree of modularity aimed at general repair - the results show there is no standardisation in the overall design, and it differs considerably between brand models and even generations, meaning the majority of parts cannot be interchanged.

CEDaCI researchers found that component constraint points are often moved, or chassis are completely re-designed which stops parts from being re-used between different servers (CEDaCI, 2021). In different generations, locks are placed at a different location and hinges are changed in such a way that lids cannot be interchanged and re-used. The same issue was found with the fans. Fans are standard electronic parts on their own but get encapsulated in difficult to remove plastic casing that only fits a particular brand or even generation (Fig, A)

Different server chassis (the metal structure that is used to house or physically assemble servers) are used across different generations and brands. The lack of standardisation between different brand models and even generations, means the majority of parts cannot be interchanged. Design of the chassis can affect the reusability of components like fans (Figure 35)



[40] https://www.cedaci.org/

Figure 35: Examples of design of the server's chassis and effects on reusability of fans. Source: Cedaci Interreg project

Standardising and simplifying chassis design can avoid excessive material use and over-engineering, and allowing second-hand parts from different brands to be reused (e.g. fans). In terms of design, CeDaCi recommends to standardise, simplify and make the chassis and sub-assemblies reusable by creating common component constraint points, removing any unnecessary fastenings.

Example of modular design can be found also in the smartphone industry. In the case of Fairphone 3, users can upgrade specific modules (e.g. the camera) instead of replacing the entire device.[41]

Figure 36: modular components of the Fairphone 3 smartphone.

It is important to consider modularity not without ensuring the desired environmental outcomes. An approach for a trade-off would be to implement modularity strategies for components that have high functional relevance for the product, but are associated with low failure likelihood ("two-level modu-larity") (Revellio et al, 2020).

Interoperability

ISO/IEC 2382-01[42] defines interoperability as follows: "The capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units.

Common Chargers and External Power Supplies

In 2021, under the Common Charger Initiative, the European Commission has proposed to increase the interoperability of several ICT devices including smartphones, tablets, cameras, headphones, portable speakers and handheld videogame consoles by amending the Directive 2014/53/EU[43]. The Commission proposal include:

- Harmonised charging port for electronic devices: USB-C will be the common port. This will allow consumers to charge their devices with the same USB-C charger, regardless of the device brand.
- Harmonised fast charging technology will help prevent that different producers unjustifiably limit the charging speed and will help to ensure that charging speed is the same when using any compatible charger for a device.
- Unbundling the sale of a charger from the sale of the electronic device: consumers will be able to purchase a new electronic device without a new charger. This will limit the number of unwanted

[41] https://www.fairphone.com/en/impact/long-lasting-design/#:~:text=Modular%20Smartphones&text=Fairphones%20are%20designed%20out%20of,unconventional%20can%20deliver%20major%20benefits.

[42] ISO/IEC 2382-1:1993 - Information technology — Vocabulary — Part 1: Fundamental terms

[43] COM(2021)547 - Proposal for a Directive amending Directive 2014/53/EU on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment

chargers purchased or left unused. Reducing production and disposal of new chargers is estimated to reduce the amount of electronic waste by almost a thousand tonnes' yearly.

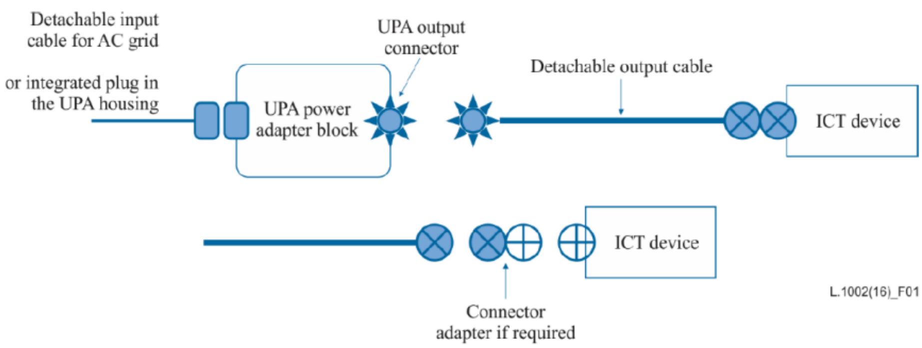
- Improved information for consumers: producers will need to provide relevant information about charging performance, including information on the power required by the device and if it supports fast charging.

Linked to Common Charger Initiative, the EU Ecodesign and according to the Energy Labelling Working Plan 2022-2024, the Commission is working at the revision of the Ecodesign Requirements for External power supplies are power adaptors used to convert electricity from household power mains into lower voltages. This initiative aims to review the EU rules on these devices that have been in force since 2020. Objectives include promoting circularity and interoperability, facilitating the USB power delivery protocol and improving information requirements to help consumers identify external power supplies/chargers that are suitable for their device.

From a technical point of view, beyond the harmonisation of the charging port of the ICT devices, there are opportunities to improve the modularity and interoperability of the External Power Supplies of ICT devices. In 2016 ITU published the Recommendation ITU-T L.1002. External universal power adapter solutions for portable information and communication technology devices. The recommendation ITU-T L.1002 (10/16) sets out technical specification for common EPS, designed for use with portable ICT devices, also referred to in the recommendation as Universal Power Adaptors (UPAs). The basic EPS configuration suggested by ITU-T L.1002 consists of an EPS with a detachable (AC) input cable[44] and a detachable (DC) output cable[45] to the ICT device (see Figure 37). The input cable can, as alternative, be integrated in the housing of the adaptor.

A detachable DC cable is required as the DC cable is generally the weakest point of the portable power supply and the main point of failure. Adapters which have captive cables, in case of failure of the latter, require all the rest of the equipment and in particular its active part to be discarded, creating unnecessary e-waste and costs for users that could be a barrier for repair. Furthermore, the detachable cable enables more reuse and an increased lifetime of the power supply unit. The recommendation ITU-T L.1002 also suggests implementing the USB type-C connector for the interface of EPS, in order to support broad reusability and interoperability. This suggestion is in line with the Common Charger Initiative outputs.

Figure 37: Basic Universal Power Adaptor (UPA) configurations and connection options (Source: ITU-T 2016)



According to Sustainably-smart (2019), cables are the least impactful part of the system. The considerable difference in terms of environmental impacts between the AC adapter and the cable suggests that it is much more important to keep in use the adapter and not necessarily the cable. However, also keeping the cable in use and avoiding the production of a new cable yields environmental benefits according to this screening study. The life cycle impacts of complex electronics products are dominated by the manufacturing phase and proper end-of-life treatment results only in minor credits, if at all. Thus, the environmental argument for

[44] Detachable alternating current (AC) cable: A detachable cable used to connect the power adapter to the AC mains for powering through two connectors, one on the universal power adapter side and the other on the AC mains side.

[45] Detachable direct current (DC) cable: A detachable DC cable connects the power adapter to the ICT device for powering through two connectors, one on the universal power adapter side and the other on the ICT device side.

harmonizing chargers is rather with avoiding production of not necessarily needed chargers and the effect of avoided e-waste is only the “tip of the iceberg”.

The trend of modularity in chargers (the AC adapter and the cable being separated pieces connected via a USB Type A or C plug) seems to be beneficial since the failure of one element does not necessarily lead to the replacement of both. The environmental impacts of chargers is much more related to the AC adapter than to the power and data cable. It is therefore of much higher importance to standardize the interface on the secondary side of the adapter than to standardize also the interface between the power / data cable and the end device. This approach requires logically a detachable cable.

Interoperability of Smart Devices

Under the ecodesign & energy labelling framework, some preparatory work for addressing energy-smart appliances has been completed. The preparatory study on smart appliances[46] established the scope for further work (i.e. selected product categories with the highest potential for demand response), validated the economic benefits that can be achieved by a large scale deployment of energy-smart appliances, and proposed some generic technical requirements for those. As a general approach, the study proposed a non-mandatory measure (i.e. to help differentiate on the market the energy-smart appliances and ensure their full interoperability, but not to ban ‘non-smart’ products from the market). However, the study’s conclusion is that more work is needed in order to come up with a regulatory proposal.

The main issue identified is regulating in a way that would ensure full interoperability among different products from various manufacturers. This would require compliance with a multitude of standards, some of them not yet (fully) developed. In addition, any such regulation would heavily rely on these standards (references to which might need to be included in the regulatory text), while the standards themselves are in a very rapid evolution (much faster than the regulatory cycles).

Thus, while regulation seems inappropriate, rapid technological developments could also lead to the consolidation of different product ecosystems, which will use proprietary solutions and will inherently be incompatible (i.e. not interoperable) with each other. Therefore, as explained in the Communication from the Commission Ecodesign and Energy Labelling Working Plan 2022-2024 (European Commission, 2022), the Commission intends to foster coherent development on the market and adherence of industry to open standards through a voluntary approach and the development of a Code of Conduct[47].

Reparability and upgradability

According to the standard EN45554:2020[48] the following definitions apply for the concepts of repair and upgrade:

- Repair: process of returning a faulty product to a condition where it can fulfil its intended use;
- Upgrade: process of enhancing the functionality, performance, capacity or aesthetics of a product;

Strategies to improve reparability of devices can address different aspects, including the easy of disassembly of the product and service related aspects. According to EN45554:2020, aspects influencing the reparability an energy related product include product related criteria as disassembly depth, fasteners, tools, working environment, skill levels and support related criteria as the availability of diagnostic tools and interfaces, availability of spare parts, information and return options. Some of these strategies have been addressed in existing ecodesign regulation for ICT devices and a more comprehensive approach is proposed for the Ecodesing and Energy Labelling of smartphone and tablets Table 16. Less attention has been paid until now to design for upgrading strategies.

Table 16: Examples of reparability / upgradability requirements applied (or proposed) for ICT devices in the EU Ecodesing and Energy Labelling framework.

Product group	Reparability / upgradability aspects	Rationale

[46] https://eco-smartappliances.eu/en
[47] https://ses.jrc.ec.europa.eu/development-of-policy-proposals-for-energy-smart-appliances
[48] EN45554:2020 General methods for the assessment of the ability to repair, reuse and upgrade energy-related products

Servers and data storage products Commission Regulation (EU) 2019/424	Easy of disassembly of key components:	Measure to avoid premature obsolescence of ICT devices by making easier: - Returning a faulty product to the functional state - enhancing the functionality, performance, capacity or aesthetics of a product
Electronic displays Commission Regulation (EU) 2019/2021	Availability of spare parts; Access to repair and maintenance information; maximum delivery time of spare parts	
Smartphone and Slate Tablets (proposals)	Availability of spare parts: Access to repair and maintenance information Maximum delivery time of spare parts information on maximum expected price of spare parts disassembly requirements including types of tools, fasteners, working environment and skill level Combination of the previous factors + additional factors in a overall score to score the reparability	

Reusability

According to the standard EN45554:2020 reuse is the process by which a product or its parts, having reached the end of their first use, are used for the same purpose for which they were conceived. Secure erasure of data is a precondition for ICT device reuse.

The ability of products to be reused is dependent on the ability to be repaired and/or upgraded. However there are some additional design aspects that are specifically for relevant for the reuse. The inability to reset a password and restore factory settings can pose a major barrier to reuse of ICT devices.

The EN45554:2020 also make reference to secure data deletion and password and factory resets as elements relevant for the reusability of energy related products

From the technical point of view secure data erasure can be reached through two main strategies:

- overwriting the data that aims to completely destroy all electronic data residing on a hard disk drive or other digital media, or
- in case data are encrypted, permanently remove the encryption key.

Ecodesign requirement on the availability of a built-in function for the secure erasure of data have been introduced for servers and storage devices under the Commission Regulation (EU) 2019/424. This measure tackles directly the market failure that relates to the issue of sensitive and personal information in reused equipment. This requirement is aimed at facilitating the deployment of reuse practises and at empowering the customer and the Data Controller in taking the most appropriate decision regarding media sanitization, following a risk based approach. Literature shows that built-in functions for data sanitization offered in many storage devices (ATA and SCSCI standard) are capable of providing a fairly strong assurance in the process, suitable for many typical scenarios of risk (Polverini et al. 2018).

During the development of a design measure for servers and data storage, the main impediment in the practical application of this approach, was found to be the need of compatible software to trigger the process. This is the reason why in the requirement of built-in function for secure erasure of data, the approach hereby presented is aimed at empowering the customer by mandating the existence of a ready-to-use function in the product that could drive the process.

The requirement on a **functionality for secure data deletion** can be implemented by means of technical solutions such as, but not limited to, a functionality implemented in firmware, typically in the Basic Input/Output System (BIOS), in software included in a self-contained bootable environment provided in a bootable compact disc, digital versatile disc or universal serial bus memory storage device included with the product, or in software installable in the supported operating systems provided with the product.

Secure data deletion in ICT devices can be achieved by a 'secure deletion of the encryption key', that means the effective erasure of the encryption[49] key[50] used to encrypt and decrypt data, by overwriting the key completely in such a way that access to the original key, or parts of it, becomes infeasible.

It is expected that the reuse of enterprise servers and data storage products will increase if such secure data erasure function, capable of securely erasing all data with a selectable degree of assurance, is ready and can easily be used by customers for each equipment (Polverini et al. 2018).

This secure data deletion function will also allow a boost for resource efficiency of enterprise servers and data storage. In particular, embedded options for secure data deletion will stimulate the decision towards erasure instead of destruction, so a progressive change in the aptitude of users and EoL operators is expected for a wider acceptance of product reuse. Secure data deletion from a data storage of an ICT device can be also achieved by overwriting the data completely in such a way that access to the original data, or parts of them, becomes infeasible.

ICT devices as smartphones and tablets use pre-installed data encryption technologies. Functionalities that allow for erasure or removal of the encryption keys have been proposed for the ecodesign requirements of these group of devices.

A requirement on a functionality for secure erasure of the encryption key is already implemented for servers and data storage devices (see Table 17) and could be implemented by means of technical solutions such as functionalities implemented in firmware, typically in the bootloader, in software included in a self-contained bootable environment, or in software installable in the supported operating systems provided with the product.

Table 17: Examples of reusability requirements applied (or proposed) for ICT devices in the EU Ecodesing and Energy Labelling framework.

Product group	Reusability aspect	Rationale
Servers and data storage products Commission Regulation (EU) 2019/424	Functionality for secure data deletion shall be made available for the deletion of data contained in all data storage devices of the product.	'A secure data deletion can give the confidence to consumers in order to allow reuse of the device and avoid the issue of devices hibernation.
Smartphone and slate tablets	The devices include a software function, that resets the device to its factory settings and erases	

[49] 'encryption" means a (reversible) transformation of data by a cryptographic algorithm to produce ciphertext, i.e. to hide the information content of the data;

[50] 'key' means a sequence of symbols that controls the operation of a cryptographic transformation (e.g., encipherment, decipherment)

(proposal)	securely by default address book, text messages and call history; Information that data encryption is enabled by default shall be displayed in the course of configuring a new device, including an explanation that this eases data erasure through factory reset;	

Refurbishing and Remanufacturing

The ICT sector is characterised by an active market for refurbished and remanufactured devices: examples are platfroms as Backmarket with more than 1500 sellers and five millions of clients worldwide, providing a marketplace for refurbished computers, smartphones, smartwatches, cameras, game consoles, headphones, and hear-buds and other ICT consumer devices[51].

Refurbishment has often also a social inclusion mission. RECOSI[52] (Regional and European Co-Operative for Social Industry) is a social franchise focusing on the reuse and refurbishment of ICT equipment (PCs, laptops, monitors and tablets) and WEEE (waste electrical and electronic equipment). Its mission is to encourage employment of marginalised people, to support the environment through reuse and to close the digital divide. RREUSE[53] is an international non-profit network representing social enterprises active in the circular economy since 2001.

Refurbishing and remanufacturing is also a growing practice in the B2B sector. An example is the organisation Aliter Networks provide remanufactured servers and storage devices, and network equipment[54], and having as its goal to double the lifetime of 1 million IT products by 2025.

The current Ecodesign regulations do not directly address the ability of ErP to be refurbished or remanufactured. However, the standard EN45553:2020[55] defines aspects and design strategies facilitating the remanufacturing of ICT devices, based on the feasibility of performing the following general remanufacturing process steps:

1) Inspection;

2) Disassembly;

3) Cleaning;

4) Reprocessing;

5) Assembly

6) Testing;

7) Storage.

The design strategies that are, according to the standard EN45553:2020, relevant for the remanufacturing, are summarised in Table 18

Table 18: Design strategies relevant for remanufacturing according to the EN45553:2020.

Design strategies	Rationale
Improve the ability to be identified of products/parts	The ability to be identified describes the ability to determine the condition of the ErP and its parts and the functionality of the ErP and its parts. It also describes the ability to determine which parts need reprocessing e.g. repair, reworked, replaced or upgraded and which parts might need special care. Furthermore, it covers the ability to determine the original legal requirements applying to the ErP

[51] https://www.backmarket.com/

[52] https://circulareconomy.europa.eu/platform/en/good-practices/recosi-refurbishing-ict-products-re-use
[53] https://rreuse.org/about-us/
[54] https://www.aliternetworks.com/
[55] EN45553:2020 General method for the assessment of the ability to remanufacture energy-related products

	by giving information on the applicable legislation at the time the product was placed on the market. Typical criteria that influence the ease of identification of the ErP and its parts are: • Access for diagnostics (e.g. embedded or external diagnostic tools to verify condition); • Information on how to determine its functionality; • Information on the status of the functionality (e.g. if the different functions of the ErP are still operational); • Information on wear-sensitive parts (e.g. if certain parts do not withstand specific cleaning methods); • Indication of the applicable legislation at the time the original ErP was placed on the market; • Indication of parts containing hazardous substances (e.g. to safeguard health and safety of operators performing remanufacturing); and • Indication of the need for special care / handling during the testing in view of e.g. safety of the testing expert, of others, or of the equipment itself.
Ability to locate access points and fasteners	” The ability to locate access points and fasteners describes the ability to localize key elements for disassembling and assembling the ErP. It is applicable to the ErP and its parts and is an element of the assessment of the ability to be remanufactured. Typical criteria that influence the ease of locating access points and fasteners are: • Indication of where access points are located (e.g. by markings or making clear where and how to connect the diagnostic equipment to the product); • Indication of where fasteners are located; and • Provision of diagrams/drawings with the location of access points and fasteners
Accessibility of parts	The accessibility of parts describes the ability of an ErP to give operators physical access to its parts. The evaluation is specific to the situation when a physical action by the operator is required, e.g. during disassembly. It is linked to the ErP and its parts and is an element of the assessment of the ability to be remanufactured. In order to facilitate remanufacturing, it can be important that areas which need to be cleaned are accessible. A typical criterion that influences cleaning is: Any surface that requires cleaning should be capable of being cleaned by an appropriate method (e.g. this can be facilitated by preventing uneven surface boundaries which could attract dirt). For disassembly it is important to have access to the parts that need to be disassembled. Typical criteria that influence accessibility to support disassembly are: • Access to parts during disassembly; • Modularity of the parts of the ErP; and • Access to fasteners, e.g. joints, gripping points and breaking points.

	For reprocessing it is important to have access to parts that need to be repaired, reworked, replaced or upgraded.. For testing it is important to have access to the location where the functionality can be checked.
Ability to be disassembled/assembled"	The ability to be disassembled/assembled describes the ability of an ErP to be separated into its parts and the ability of its parts to be assembled. Typical criteria that influence the ability of an ErP to be disassembled and assembled are: • Ability to handle parts (e.g. they are not too small, bulky, heavy, soft, sticky or sharp, they do not have a tendency to tangle); • Number of operators needed for disassembly and assembly; • Number and type of tools needed for disassembly and assembly; and • Number of (different) fasteners Typical criteria that influence the ability of parts of an ErP to be assembled are: • Asymmetry/symmetry of parts (e.g. to ensure correct assembly), • Ability to insert constituents (e.g. good visibility during assembly and low resistance during insertion), and • Ability of parts to be secured directly upon insertion without any extra operations after the insertion (e.g. screwing, tightening or gluing).
Wear and damage resistance during the remanufacturing process steps"	The ability to be wear and damage resistant during the remanufacturing process steps describes the ability of the ErP and/or its parts to withstand all treatment necessary during the remanufacturing steps without being damaged. It is linked to the ErP and its parts and is an element of the assessment of the ability to be remanufactured. Typical criteria that influence wear and damage resistance so as to avoid premature deterioration due to the remanufacturing process include using: • materials and fasteners to be sufficiently strong to enable the product to be remanufactured one or more times; • materials and markings being able to withstand cleaning agents (either chemical or mechanical)

Recyclability

The current Ecodesign regulations mainly focused on recyclability, intended as removability of components by commonly available tools, especially regarding components in Annex VII to WEEE Directive or Article 11 of Directive 2006/66/EC on batteries. However, other aspects that are relevant for recyclability have not been addressed, as the use of materials that are "recyclable".

Berwald et al. (2021) presents the results of a a multi-stakeholder collaboration established across the entire WEEE value chain within the H2020 project PolyCE[56], involving companies as Fraunhofer IZM (Research Instiitute) Philips (Original Equipment Manufacturer), Imagination Factory (product designers) ,Erion (Extended Producer Responsibility System), ecosystem (Extended Producer Responsibility System), MGG Polymers (WEEE recycler), SWEEEP Kuusakoski (WEEE recycler), Enva (recycler), and Sun recycling (recycler). The PolyCE project produced design recommendations for recyclability.

According to PolyCE one of the current barriers to processing and recycling plastics coming from electrical/electronic products is the sheer number of different polymers. One feasible solution to reduce the

[56] https://www.polyce-project.eu/results/

huge variety would be manufacturers agreeing on the types of plastics and different polymers they use in their products; this would scale up more pure material stream volumes and make it financially more viable to invest in new recycling technologies. The PolyCE (Post-consumer high-tech recycled polymers for a Circular Economy) project's recommendation is to use polymers with known high recyclability rates, such as ABS, HIPS, PS, and PP, in parts such as housings, frames, etc. which are significant also in terms of weight (PolyCE, 2021).

Among the design barriers to recyclability identified by the PolyCE there are the use of polymer blends, hermosets and composites, coatings, additives. A review of the applicable design strategies to improve the recyclability of Electric and Electronic products is provide in Table 19.

Table 19: Design strategies and rationale to make easier the recycling of WEEE. Source: PolyCE (2022)

Guideline and design strategies	Rationale
Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible.	Common plastics can be easily recycled with existing technologies and processes and should be considered as a first choice. If other materials are required, the reasons should be motivated and supported. Other plastics currently occur in too small volumes for economically viable recycling. If other than the common plastics are used, alternatives outside the density range of 0.85–1.25 g/cm3 should be considered to facilitate separation.
Avoid polymer blends.	Mono-material streams should be favoured. Blends like - POM/ABS (polyoxymethylene/acrylonitrile butadiene styrene) - PA/ABS (polyamide/acrylonitrile butadiene styrene) - PC/PBT (polycarbonate/polybutylene terephthalate) - PPE/PS (polyphenyl ether/polystyrene) - PET/PBT (polyethylene terephthalate/polybutylene terephthalate) pollute material streams (except for PC/ABS, since it can be properly recycled with existing technologies).
Avoid glass fibre-filled plastics.	Glass fibres pollute material streams, reduce mechanical properties (e.g., impact strength), and cause wear. For a high modulus, mineral filled plastics such as PP-talc should be considered, since they can be recycled. Carbon fibres are also considered a better alternative.
Minimise the use of thermoplastic elastomers.	Most of the elastomers can be filtered out during the separation steps. Those elastomers that are not filtered out are likely to end up in the PS stream. When elastomers are necessary (e.g., for functionality), minimise their use and choose, if possible, Styrol-Ethylen-Butylen-Styrol (SEBS) based thermoplastic elastomers (TPE). If a SEBS-based TPE ends up in the PS stream, it may act as an impact modifier, causing the least harm.

Avoid the use of thermoset rubbers	Thermoset rubbers cannot be recycled and should be reduced, if possible.
Minimise additives in plastic materials.	Additives reduce the purity of the plastic streams. For this reason, the real necessity for additives should be evaluated cautiously.
Avoid thermosets and composites.	Thermosets and composites cannot currently be recycled with existing technologies. When they are necessary (e.g., for functional reasons), materials outside the density range of commonly recycled plastics (0.85–1.25 g/cm3) should be preferred.
Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	The mentioned techniques connect plastics with metals, a combination that cannot be separated in the recycling process.
Avoid the use of coatings on plastics.	All forms of coatings pollute the material stream or make the recycling process more challenging. Coatings change the density of the plastic, which can cause the plastic to end up in the wrong material stream. Printing numbers or lines for level-indication are not considered problematic and are usually better than using a sticker for the same purpose. Other options are screen-printing, in mould texturing or laser engraving. When a coating is still needed, a density difference
Minimise the use of thermoplastic elastomers.	Thermoplastic elastomers are currently not recycled and have to be separated. Particles that are not separated pollute the waste stream.
Avoid the use of foam.	Foam can lead to issues during the recycling process. When foam is necessary (e.g., for functionality), thermoplastic foam should be preferred to foam from elastomers or thermosets
Minimise the use of magnets.	Magnets end up in the ferrous material stream, leading to a pollution of the stream. For this purpose, the use of magnets should be reduced to a minimum when the functionality is required and no alternatives are currently available (e.g., neodymium magnets in mobile phones).

Recycled Content

Industry best practices have shown that it is feasible to use recycled plastics in a number of ICT products when innovative solutions are explored for particular products or components (Digital Europe. 2016)..

However, according to DigitalEurope (2016), while the merits and opportunities of using recycled plastic are numerous, there are just as many barriers and challenges, which should not be ignored:

- Using recycled plastics in EEE products create additional challenges in complying with EU chemical substance regulations such as RoHS and REACH since recycled plastic content introduces a risk of unknown contaminants.
- The market for recycled plastics in terms of quality, quantity, dependability and price is uncertain, and the roll-out potential seems to be difficult to assess for producers. Furthermore, a switch in an existing product to recycled content requires expensive re-testing to ensure compliance with safety regulations and quality/durability requirements.
- Recycled plastics are likely to come from several different suppliers, which are smaller in size than typical suppliers of virgin plastics. Hence, they are less able to meet fluctuations in demand volume as they cannot control the rate of source materials arising without holding expensive feedstock or finished material buffer volumes.
- Consumer acceptance needs to be tackled. Cosmetic blemishes from recycled content may not affect technical performance of a product, but can still influence aesthetic factors. So it is difficult to expect the wide use of recycled plastics for the products whose design and look can play a critical role in consumer purchase decisions

Synergies and Trade-offs

There is a wealth of circularity aspects and strategies related to ICT, which act in a synergic manner towards lower environmental impacts, but also present trade-offs, both amongst each other (e.g. reliability with reparability) and in relation to other aspects related to sustainability (e.g. circularity vs energy efficiency).

One determining factor for the direction of the relationship are design-related and service-related parameters which simultaneously influence the ability to repair, reuse, upgrade products (including ICT devices) or components. Table 20 below presents such parameters, as those were selected in the context of the development of the Reparability Scoring system for Smartphones and Tables, and indicates which circularity strategies they influence.

Table 20: Parameter-based influence of the ability to repair, reuse, upgrade products (including ICT devices) or components.

Parameters		Relevance for process					
		Product or Component Level				Component Level	
		Reliability	Reparability	Reusability	Upgradability	Removability	Replaceability
Disassembly depth		Yes	Yes		Yes	Yes	Yes
Fasteners/ Connectors	Type	Yes	Yes		Yes	Yes	Yes
	Number	Yes	Yes		Yes	Yes	Yes
	Visibility	Yes	Yes		Yes	Yes	Yes
Tools	Type	Yes	Yes		Yes	Yes	Yes
Spare part availability	Target Group		Yes				
	Duration		Yes				
	Interface		Yes				

Software update availability		Yes	Yes	Yes	Yes		
Repair/Disassembly Info	Comprehe nsive		Yes		Yes	Yes	Yes
	Target Group		Yes		Yes	Yes	Yes

Table 21 describes the direction of this established relationship and the potential that one circularity strategy positively correlates to another (synergy), or negatively correlates (trade-off).

Table 21: Synergies and trade-offs between circularity strategies

	Reliability	Reparability	Upgradability	Reusability	Ability to be remanufactured	Recyclability	Recycled Content
Reliability		Trade-offs Design measure to make product more reliable could come at expenses of reparability (e.g. use of glues for strong Ingress Protection) (Cordella et al. 2021) Synergies Products that are more reliable (or perceived to be more reliable) have more possibilities to be repaired (Makov and Fitzpatrick, 2021).	Synergies Products that are more reliable are expected to have a longer lifetime and consumer are more willing to upgrade them.	Synergies Products that are more reliable are expected to have a longer lifetime and have more opportunities to be have a second user and a longer useful lifetime.	Synergies Reliable components/assemblies can provide the basis for a remanufactured product	Trade-offs Design measure to make product more reliable could come at expenses of recyclability (use of glues for strong Ingress Protection)	Synergies High quality material (e.g. plastics) can offer both reliability, but also good quality material for a future product.
Reparability	Trade-offs Products that are more reparable are sometimes perceived to be less reliable. Some easy to repair design can have trade off with		Synergies Easy disassembly facilitates both	Synergies Easy disassembly facilitates both	Synergies Easy disassembly facilitates both	Synergies Easy disassembly facilitates both	

	reliability						
Upgradability	Trade-offs Products that are more reparable are sometimes perceived to be less reliable. Some easy to upgrade design can have trade off with reliability	Easy disassembly facilitates both		Easy disassembly facilitates both	Easy disassembly facilitates both	Easy disassembly facilitates both	
Reusability		Easy disassembly facilitates both Reset and data transfer/erasure facilitates both.	Easy disassembly facilitates both		Easy disassembly facilitates both	Easy disassembly facilitates both	
Ability to be remanufactured		Easy disassembly facilitates both	Easy disassembly facilitates both	Easy disassembly facilitates both		Easy disassembly facilitates both	
Recyclability		Easy disassembly facilitates both	Easy disassembly facilitates both	Easy disassembly facilitates both	Easy disassembly facilitates both		
Recycled Content	Recycled content may affect quality of product. Certain materials may lose their reliability/quality the more times they are recycled.					Legacy chemicals/pollutant s may deem recyclability less desirable or feasible (Dalhammar et al., 2021)	

Synergies and trade-offs are encountered not only amongst circularity strategies, but also between circularity strategies and other product environmental aspects. Examples are provided by the following:

- recycled content vs chemicals legislation: there might be hesitation to use recycled materials in new products, fearing potential non-compliance with chemicals legislation, such as the RoHS Directive, or the REACH Regulation;
- remanufactured products vs chemicals legislation (as above) or sustainable sourcing;
- material efficiency vs energy efficiency:

As indicated in previous Tasks, for most ICT hardware, especially end-use devices and battery-powered devices, environmental hotspots are observed mostly at manufacturing stage rather than the energy consumption at the use phase. Therefore, the trade-off between material efficiency and energy efficiency is for most products not a consideration. Rather, the trade-off is more present in product types for which energy efficiency improvement potential is high and fast. Once energy efficiency gains are achieved, environmental impacts reductions are rather achieved via lifetime extension. This may not be the case for every single ICT product however. Overall, product design decisions to optimise sustainability are dependent on the product type, characteristics and knowledge on component failure[57].

Modularity and use of resources

Modularity of ICT devices can be associated to extra housing and module connections. In the case of smartphone those are made through flex cables and press-fit connectors. According to Proske et al. (2022) the GWP modularity overhead for the Fairphone 3 is 0.744 kg CO2e, which represents 2.3 % of all production impacts. For the abiotic depletion potential (ADP) elements the share is bigger at around 17.2 %, due to the gold plating of the connector contacts. The benefits from modular design is high dependent on the related use phase extension associated to the easier repair and upgrade.

According to Steichen et al. (2017), the modular design's drawback is the additional material required during the manufacturing phase. However, the environmental impact of this additional material can be offset through the lifecycle within an acceptable period of time, if the repair/refurbishment rate increases by at least 5 to 10% above non-modular design. The logistic model (i.e. refurbishment centre location and transport modes) and the design modifications (i.e. additional material required to design a modular product) are two key parameters to achieve at the offset.

Lifetime extension and energy efficiency.

Durability of products is generally seen to be a desirable goal. However, the extension of the lifetime of energy-using products is not necessarily the optimal strategy, as the efficiency of products can decreases with wear, and their substitution by more energy-efficient products can be more environmentally beneficial in the long run.

For most of the ICT devices in the scope main part of the environmental impacts are associated to the extraction of raw materials and manufacturing, making durability a favourable option from the environmental point of view, also in the long run. However, for some ICT devices energy consumption in the use phase could still represent the highest share of the life cycle environmental impacts (e.g. the device is high energy demanding and operated continuously). In this case the energy lifetime extension vs energy efficiency trade-off should be carefully considered and in case the efficiency of new devices placed on the market is expected to improve very rapidly an optimal lifetime from the environmental point of view should be determined.

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6 Conclusions

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