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ICT Task Force study: Final Report

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Abstract

Information and Communication Technologies (ICT) play an increasingly important role in society. ICT can be analysed from a dual perspective: as crucial in supporting sustainability strategies, and as responsible for environmental impacts related to energy and material use in their lifecycle.

In order to facilitate policy-making, direct and indirect environmental impacts need to be assessed not just from a device perspective, but the overall system composed by interactions between users, devices and services. Making a reliable estimation of the energy and material savings potential is particularly challenging due to the uncertainty about future market developments, increased connectivity and multifunctionality, and behavioural changes.

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. This JRC Science-for-Policy report is the result of a study, undertaken for the European Commission's Directorate General for Energy, to support this work by providing a comprehensive and dynamic analysis of the ICT sector. Based on material and energy efficiency improvement potentials identified, and considering user behaviour and lifecycle costing aspects, this JRC report provides policy recommendations on the inclusion of ecodesign provisions, but also accounting for the suitability of complementary policy tools.

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Authors

The JRC Team working on this study is composed by Felice Alfieri and Christoforos Spiliotopoulos (JRC).

Executive summary

This report provides an analysis of environmental lifecycle impacts of ICT devices and systems, and provides a set of recommendations to address them.

Firstly, the study provides key definitions for the ICT sector and defines the scope of the study, both in terms of product (ICT device) perspective, and also in terms of the effect levels of ICT impacts. Specifically, it is clarified that the study analysed first order effects (the classic lifecycle impacts of devices), as well as second order effects at systemic level, specifically those of induction and obsolescence (negative effects), and optimisation and substitution (positive effects).

Chapters that follow provide an analysis of impacts using a lifecycle perspective and an analysis of potential improvement strategies (from a technical perspective). The analysis is split between energy-related impacts and material-related impacts, and for each type of impacts, both the ICT device and the ICT system level are addressed.

With regards to energy-related impacts, the assessment of energy consumption associated with the manufacturing of ICT is presented, confirming this lifecycle stage as highly relevant to the overall carbon footprint of ICT systems. Assessing the impact of energy consumption during the use phase of ICT systems boils down to the question of whether technological improvements leading to higher efficiencies are sufficient to compensate for the significant and ever-increasing data demand. Results from the literature range from consumption levels remaining stable in optimistic approaches, to significant increase in some others, should there not be further efficiency gains and overturning of current trends. Finally, the positive effect of systemic optimisation expected by ICT systems are qualitatively assessed in the third section. Those are realised by the efficiencies brought about by the expansion of IoT technologies and their application in a wide range of sectors.

With regards to material-related impacts, the literature review provided suggests significant impacts resulting from material extraction and production of ICT devices. The extraction phase is associated with waste, toxicity impacts and biodiversity loss, amongst other impacts, while ICT manufacturing is also associated with water usage impacts. Material-related impacts are identified in the use phase of ICT (mostly related to the use of accessories, consumables and chargers), as well as in the end-of-life phase which includes potential release of hazardous substances. Regarding systemic material-efficiency related effects, a taxonomy of different types of material obsolescence are defined and described, including the impact of software obsolescence as a particular ICT characteristic. Positive effects of substitution and optimisation are also elaborated. The section related to materials concludes with an identification of strategies for material efficiency, which include reliability, durability, reparability, reusability, remanufacturing, recyclability, recycled content, and others. These strategies are often conflicting, therefore both synergies and trade-offs between them are also described.

This study concludes with a set of policy recommendations using a structure that starts with the device as tangible hardware with direct resource use, and expands to software and telecommunication services that enable further resource use by a range of devices in an ICT system. Specifically, at device level, a range of material efficiency provisions are proposed for consumer electronics using a horizontal approach, which has the potential to address the fast innovation cycles that characterise ICT products. Those are paired with a number of measures that aim at facilitating the development of second-hand product and component use, such as refurbishing, remanufacturing and takeback schemes. Beyond the device boundary, video streaming and the use of application software have been demonstrated to enable energy consumption to a significant degree and could be addressed by means of minimum efficiency requirements (in the case of application software) as well as informational requirements to raise consumer awareness on these impacts. Lastly, wider systemic measures such as the labelling of telecommunication services, consumer information on data use and financial instruments could also contribute to curbing the induction effects of ICT system impacts by allowing consumers to make informed choices in the context of new business models and by fostering competition among providers on the basis of sustainability.

1 Introduction

Information and Communication Technologies (ICT) play an increasingly important role in society and the daily lives of European citizens. This has been clearly demonstrated by the critical importance of ICT devices and infrastructure during the Covid-19 pandemic, which allowed people to work and study from home, keep in touch with family and friends and stay informed. Indeed, according to the IEA, global internet traffic surged by almost 40% between February and mid-April 2020, driven by growth in video streaming, video conferencing, online gaming, and social networking and following a general growth in demand for digital services over the past decade[1].

At the same time, this increased demand does not come without costs. In the pursuit to address the environmental challenges that society is facing, the ICT sector can be analysed from a dual perspective: from one side as crucial in supporting and enabling sustainability strategies, and from the other side as responsible for relevant impacts related to energy and material use in its lifecycle.

In order to provide a basis for policy-making to improve the sustainability of ICT, the direct and indirect environmental impacts from ICT need to be evaluated from a perspective of an overall system, considering the interactions between end-users, devices, telecommunication network and data storage and processing by edge computing/data centres.

Making a reliable estimate of the energy and material savings potential in ICT is a particularly challenging task due to aspects like the uncertainty about future market developments, the increased connectivity and multi-functionality of products, the advent of smart appliances and the behavioural changes in our society.

In 2016, the Commission announced, in the context of the Ecodesign Working Plan, a Task Force on ICT products, composed by experts from different Directorates, aiming to explore how ICT products could best be addressed under the Ecodesign Directive and the Energy Labelling Regulation.

In this context, the Joint Research Centre has supported the activities of the ICT Task Force by providing a comprehensive and dynamic analysis of the ICT sector. In particular, this work is being developed for the European Commission's Directorate General for Energy.

The output of the different tasks of the ICT Task Force study are presented in the following chapters: **Chapter 2 to Chapter 7** provides a consolidation of the definition and categorisation of the different sectors/products analysed under 'ICT products', an overview of the environmental impacts of the ICT sector and define the scope of the study, both in terms of product groups and order of effects covered and describes the main research question of the study.

Chapter 8 to Chapter 11 includes an analysis of the Potential for Energy Savings. In particular chapter 9 provides an overview of the energy demand and carbon emission impacts from the life cycle of the device perspective, chapter 10 focuses on the induction effects, in particular the energy consumption of telecommunication network and data centres linked to the use of the ICT end-use. Finally Chapter 11 provides a qualitative assessment of the optimisation effects linked to the use of Internet of Things (IoT) technologies.

Chapter 12 to Chapter 15 focuses on material efficiency aspects. More specifically, this part of the study provides a summary of the main impacts related to material efficiency, both in relation to first order effects (chapter 12) as well as at second order effect level (chapter 13), an analysis of the lifetime of ICT products on the market (chapter 14) and the identification of design strategies against material obsolescence and towards product circularity, including the analysis of potential trade-offs (chapter 15).

Chapter 16 to Chapter 18 are related to policy recommendations. Based on the material and energy efficiency analysis above, products are grouped based on similarities (chapter 16). The current policy landscape is described (chapter 17) and a list of policy recommendations on the inclusion of Ecodesign requirements and on complementary policy tools to improve the sustainability of ICT products/systems is presented (chapter 18).

Finally, the results of a complementary user behaviour study carried out in the context of this project are provided as a separate report (IPSOS, 2022).

[1] International Energy Agency (2020), Data Centres and Data Transmission Networks, https://www.iea.org/reports/data-centres-and-data-transmission-networks

2 What is ICT? Definition and scope

Information and Communication Technology is defined by ISO (ISO, 2008) as "technology for gathering, storing, retrieving, processing, analysing and transmitting information".

A definition of ICT products is provided by OECD (OECD, 2011): "ICT products must primarily be intended to fulfil or enable the function of information processing and communication by electronic means, including transmission and display".

In VHK and Viegand Maagøe (2020), "ICT products" are understood to be products from both the information technology and the communication technology sectors.

The main characteristic these product groups share is that they (increasingly) allow communication between devices through the internet (including home networks using other protocols but are ultimately connected to the internet). ICT products can enable the communication at end-use level, by providing telecommunication network infrastructure or by providing data storage and processing in data centres / cloud. These represent the main elements and relationships of an information and communications technology (ICT) system (see Figure 1).

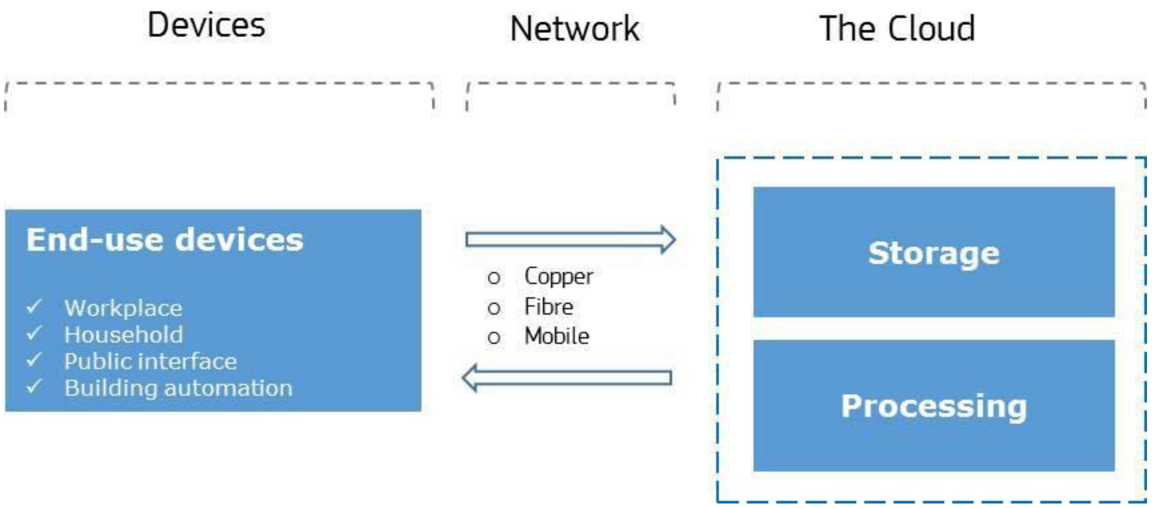


Figure 1: Use of ICT End-user devices and relationships with telecommunication network and cloud

3 Environmental impacts of the ICT sector: a preliminary overview

The number of devices connected to the Internet, including the machines, sensors, and cameras that make up the Internet of Things (IoT), continues to grow. The International Data Corporation (IDC) estimates that in 2025 there will be 41.6 billion connected devices in the world. This means an enormous amount of data produced and stored in data centres, transmitted by the telecommunication network infrastructure but also used and stored at the endpoint ICT devices (such as PCs, smartphones, and IoT devices).

This growth in terms of devices and data processing and transmission could result in increasing pressure and impacts on the environment. Relevant environmental aspects and impacts recognised to be associated to the ICT sector are summarised in Table 1 below.

Table 1 Key Environmental Aspects and Impacts of ICT systems

Key Environmental Aspects and Impacts
• Use of finite resources, including critical raw materials to produce ICT devices • Energy consumption and resulting Greenhouse Gas emissions from production and use of ICT devices • Air, soil and water pollution, bioaccumulation and effects on organisms due to raw material extraction and processing, and hazardous substances used in ICT products. • Generation of potentially hazardous electronic waste upon its final disposal

3.1. Materials

ICT is based on a multitude of hardware devices with specific, complex material compositions. The average material composition of a consumer ICT device at the end of its useful life (reference year 2010) has the following characteristics: most of the mass of such a device consists of the base metals iron (Fe), aluminium (Al), and copper (Cu), polymers (mainly ABS, PC, PC/ABS, PE, PS, and SAN) and glass. Besides the three base metals, consumer ICT devices also contain a large number of scarce metals, including, among others, gold (Au), indium (In), platinum group metals (PGM) such as palladium (Pd) and platinum (Pt), rare earth elements (REE) such as dysprosium and neodymium, silver (Ag), and tantalum (Ta). In the last few decades, an increasing number of elements represented in the periodic table has found its way into both infrastructure (e.g., servers, routers, switches, base stations, and optical fiber cables) and consumer ICT devices. However, the material composition of ICT devices tells only part of the story about the material basis of ICT. Both "upstream" processes (mining, refining, and production of the raw materials; production and assembly of the components; and the product itself) and "downstream" processes (product use, materials recovery, and final disposal) associated with an ICT device generate a multitude of material flows which are not obvious to its user.

The increased demand for data usage will have a big impact on technologies for data storage, including the additional demand of materials for memories production[2]. Many CRMs are particularly essential for ICT in general, and more in particular for data storage.

Based on Ku (2018), the expected 2025 global datasphere could require up to 80 kilotonnes of neodymium, about 120 times the current yearly EU demand of this material. Using instead emerging technologies such as ferroelectric RAM would require up to 40 kilotonnes of platinum, which is about 600 times the current yearly demand of the EU (European Commission, Joint Research Centre, 2020).

Trade of some minerals used in IT products, such as tantalum and gold, can be used to fuel violence, human rights abuses or other crimes (European Commission, 2017). Unsafe mining methods also lead to severe health problems for workers and environmental degradation in the communities where they live (TCO Development, 2020).

[2] European Commission, (2020). Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020

3.2. **Manufacturing**

According to Cabernard et al. (2019), between 1995 and 2015, climate change impacts of ICT manufacturing have doubled and the material footprint has quadrupled. In 2015, ICT manufacturing contributed ~ 2% of global climate change impacts, half of which is caused by the production of material resources used for ICT manufacturing.

According to Malmodin and Lundén (2018), the embodied carbon footprint plays a relevant role in the carbon footprint of ICT devices, and it represents the main contribution for small personal ICT devices as notebooks, tablets and smartphones. This is also in line with several peer reviewed studies in the literature.

Environmental impacts from ICT production are to a large extent linked to printed circuit boards (PCB). In particular, production of integrated circuits (IC) mounted on PCBs is consistently reported as environmentally burdensome (André et al., 2019).

3.3. **Use Phase**

According to VHK and Viegand Maagøe (2020), the ICT products consume almost 260 TWh or ~10% of the EU27 electricity consumption. This is less than electricity consumption for light sources, more than electricity for water heaters and comparable to the annual electricity consumption of Spain or Turkey. In terms of net final energy consumption, i.e. following the accounting principles of the Eurostat energy balance sheets, ICT consumes 2% of the EU27 total. Electricity use for ICT is declining after peaking in the year 2012 at 289 TWh/yr, the ICT electricity use decreased on average by 1.7% annually and is expected to reach 240 TWh/yr by 2022. Despite the exponential increase in data traffic and ICT product performances over the period, the energy efficiency of ICT-related products increased even more.

At global level, demand for data centre and network services are expected to grow strongly in the next years, driven in particular by rapidly growing demand from streaming video and gaming. According to the International Energy Agency (2020), between 2019 and 2022, traffic from internet video is projected to more than double to 2.9 ZB[3], while online gaming is projected to quadruple to 180 EB.6 Together, these streaming services are projected to account for 87% of consumer internet traffic in 2022. Additionally, emerging digital technologies such as machine learning, blockchain, 5G, and virtual reality are also poised to raise demand for data services.

In terms of energy consumption, the strong growth in demand for data centre services has been, until now, almost entirely offset by efficiency improvements for servers, storage devices, network switches and data centre infrastructure, as well as a shift to much greater shares of cloud and hyperscale data centres. However, the efficiency trends of current technologies could slow (or even stall) in upcoming years and the overall energy and emission impacts of 5G are still uncertain (IEA, 2020).

Belkhir, L. and Elmeligi A., (2018) estimate that contribution of ICT to the total carbon footprint has grown from a 1% in 2007 to more than double in 2020, reaching a 3% of the total worldwide GHGe with the contribution of the ICT infrastructure (data centre and telecommunication networks) making up the lion share of the overall industry impact, growing from 61% in 2010 to 79% in 2020. The same researchers estimate that by 2040, carbon emissions from the production and use of electronics, including devices like PCs, laptops, monitors, smartphones and tablets and related ICT infrastructure (data centres and telecommunication networks) could reach 14% of the global GHG emissions.

Consumer's ICT devices (such as smartphones, tablets, notebooks) are also characterised by relatively short lifetimes and 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 (Zhilyaeva et al. 2021).

The implementation of material efficiency strategies (durability reparability, upgradability, reusability) to extend the length of the product use can reduce the overall impacts associated to the use of ICT.

[3] This estimation does not take in to consideration the systemic effects of the COVID-19 crisis.

3.4. **End of Life**

Recycling rates for ICT devices are globally low. Even in the EU, which leads the world in e-waste recycling, just 35% of e-waste is officially reported as properly collected and recycled[4]. Globally, the average is 20% and the remaining 80% is undocumented, with much ending up buried under the ground for centuries as landfill (PACE 2019).

[4] https://ec.europa.eu/eurostat/databrowser/view/t2020_rt130/default/line?lang=en

4 Current policies and initiatives

Up to the 2019 the policy measures adopted by the Commission in the field of ICT focused mainly on the Energy Efficiency of end user ICT devices.

In 2019, a number of measures under the Ecodesign Directive were adopted which introduced also requirements related to material efficiency. Amongst other products, ICT sector products were also included, such as servers and data storage products, and electronic displays (including televisions). The requirements introduced included:

- for servers:
  - ensuring that joining, fastening or sealing techniques do not prevent the disassembly for repair or reuse purposes for a number of components;
  - the availability of a functionality for secure data deletion;
  - the availability of firmware (and the latest available security update) for a period of eight years free of charge or at a fair, transparent and non-discriminatory cost.
  - instructions on the disassembly operations

- for electronic displays:
  - ensuring that joining, fastening or sealing techniques do not prevent the disassembly for repair or reuse purposes for a number of components;
  - the availability of dismantling information needed to access product components referred.
  - The marking of plastic components heavier than 50g and flame retardants
  - A cadmium-inside or cadmium-free logo
  - A restriction of use of halogenated flame retardants in the enclosure and stand of electronic displays
  - The availability of spare parts to professional repairers for a number of years
  - Ensuring that spare parts can be replaced with the use of commonly available tools and without permanent damage to the appliance;
  - Access to repair and maintenance information
  - the availability of firmware (and the latest available security update) for a period of eight years free of charge or at a fair, transparent and non-discriminatory cost.

More advanced material efficiency criteria have been introduced at voluntary level (EU Ecolabel / Green Public Criteria) and for several categories of ICT devices: EU GPP for Computers and Displays, EU GPP Criteria for Data Centres; EU GPP Criteria for Imaging Equipment EU Ecolabel Criteria for Electronic Displays, among others.

Furthermore, in its 2020 Circular Economy Action Plan[5], the European Commission further recognised the sector of Electronics and ICT as a contributor to increasing waste streams in the EU. A number of measures are thus proposed, such as ecodesign measures related to mobile phones, tablets and laptops under the Ecodesign Directive, as part of the 'Circular Electronics Initiative'.

In particular the following actions are planned in the time period 2020-2022:

- New and or revised ecodesign measures for electronics and ICT computers including mobile phones, tablets and computers in order to ensure that devices are designed for energy efficiency and durability, reparability, upgradability, maintenance, reuse and recycling.
- focus on electronics and ICT as a priority sector for implementing the 'right to repair', including a right to update obsolete software;
- regulatory measures on chargers for mobile phones and similar devices, including the introduction of a common charger, improving the durability of charging cables, and incentives to decouple the purchase of chargers from the purchase of new devices;

[5] COM(2020)98 A new Circular Economy Action Plan For a cleaner and more competitive Europe

- improving the collection and treatment of waste electrical and electronic equipment including by exploring options for an EU-wide take back scheme to return or sell back old mobile phones, tablets and chargers;
- review of EU rules on restrictions of hazardous substances in electrical and electronic equipment and provide guidance to improve coherence with relevant legislation, including REACH and Ecodesign.

The CEAP plan also foresees initiatives enhancing the sustainability of the batteries. A new legislative proposal will build on the evaluation of the Batteries Directive and the work of the Batteries Alliance. Possible aspects that would be addressed are rules on recycled content, sustainability and transparency requirements, the carbon footprint of battery manufacturing, the ethical sourcing of raw materials and security of supply, and facilitating reuse, repurposing and recycling.

5 Scope of the study (1): order of effects

This project's aim is to determine the best policy approaches for improving the environmental performance of ICT. Based on the scientific evidence JRC will produce recommendations on the inclusion of Ecodesign Criteria, but also on complementary policy tools to improve the sustainability of ICT products and systems.

The overall scope of the project includes the direct life cycle impacts of ICT devices (production – use – disposal) but also aspires to go beyond that. ICT systems can themselves have an impact on the environment, so also have the potential to themselves become more sustainable over their whole life cycle, mainly by an reduction of the energy and material flows they invoke (Sustainability in ICT). At the same time, ICT has the potential to trigger wider effects, either by creating, enabling, and encouraging sustainable patterns of production and consumption (Sustainability by ICT), or by stimulating ever increasing consumption.

Hilty et al., 2015 developed a 'framework for ICT Impacts on Sustainability' (Figure 2), consisting of three orders of effects and a categorisation based on whether the environmental impact is positive (part of the solution) or negative (part of the problem).

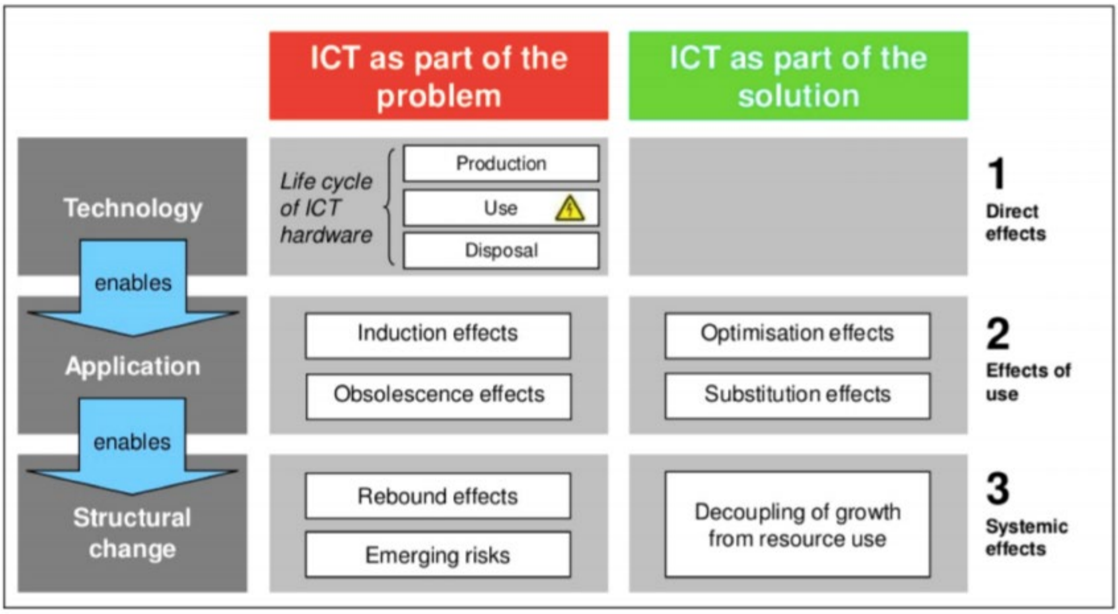


Figure 2: A matrix of ICT environmental effects (Hilty et al., 2015)

First Order Effects

First Order (Level 1) effects refer to the direct effects of the production, use and disposal of ICT, and are effects that can be assessed with a Life-Cycle Assessment (LCA) approach at device level (attributional LCA) (Pohl et al., 2018). In particular, this includes the demand for materials and energy throughout the whole life cycle of ICT products. These effects are placed entirely on the negative side as they represent the environmental cost of the hardware providing ICT services. These effects are typically addressed by European Product Policy tools such as the Ecodesign Directive, the Energy Labelling, the EU Ecolabel and Green Public Procurement.

Second Order Effects

Second Order (Level 2) refers to the enabling effects of ICT systems, or the effects of applying ICT. These are indirect environmental effects of ICT due to its power to change processes, resulting in a modification (decrease or increase) of their environmental impacts. From a sustainability point of view, these effects may be positive or negative:

Negative effects:

— Induction effect: ICT stimulates the consumption of another resource. For example, the increased connectivity and performance of ICT devices can affect the use of telecommunication infrastructure and the related energy demand for data storage, processing and transmission.

— Obsolescence effect: ICT can shorten the useful life of another resource due to incompatibility, a device that is no longer supported by software updates is rendered obsolete. 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).

Positive effects:

— Substitution effect: The use of ICT replaces the use of another resource (e.g. an e-book reader can replace printed books, which is positive if it avoids the printing of a sufficiently large number of books).

— Optimization effect: The use of ICT reduces the use of another resource (e.g. less energy is used for heating in a smart home that recognises where occupants are located, which windows are open, what weather is forecast, etc.).

Third Order Effects

Hilty et al., 2015 also describes Third Order (Level 3) effects. The Third Order refers to the systemic effects, i.e. the long-term reaction of the dynamic socio-economic system to the availability of ICT services, including behavioural change (lifestyles) and economic structural change. On the negative side, rebound effects prevent the reduction of total material resource use despite decoupling (see by converting efficiency improvements into additional consumption). On the positive side, ICT has the potential to support sustainable patterns of production and consumption.

The impacts of such effects, especially high order ones, are not easily captured and quantified. The deployment of ICT systems is complex and variable, while there are still data gaps on how humans interact with systems. As a result, findings so far are associated with uncertainty, meaning that although there is an understanding that ICT has large energy saving potential, the realization of that potential is by no means assured. For example, a set of case studies conducted in the EU find ICT-related rebound effects from e-commerce and telework ranging from 14% to 73% (Jørgensen et al 2006). Third order sustainability effects are not included in the scope of this study.

6 Scope of this study (2): product groups

In their "ICT Impact Study", VHK and Viegand Maagøe (2020) consider the product (sub)groups listed in Table 2 below. As this wealth of products are interconnected within an ICT system, the present study aims to analyse the environmental aspects of ICT from an end-use perspective. The rationale for the selection of this scope is threefold:

- end-user devices are responsible for relevant first order effects (life cycle impacts) as described above;
- to investigate the ever-increasing environmental impacts of relevant secondary effects which are associated to the end use of ICT devices (e.g. the increasing data demand driven by video streaming or on line gaming);
- to focus on end-use allows for exploring legislative options that are more likely to be compatible with an EU product policy framework.

The present study will focus on the end-use devices with highest potential for improvement among the products listed in Table 2. The focus on end-use devices does not imply that products related to other parts of an ICT system as in Figure 1 (e.g. data storage or transmission devices) will be ignored. Those products will be considered as far as the environmental impact of their use phase is associated with the usage patterns of end-devices.

In that sense, this study is extending beyond the limitations of typical ecodesign preparatory studies. Many ICT-related products are covered by the implementation of European sustainable product policies such as: Ecolabel, Green Public Procurement, ErP (Ecodesign of Energy related Products) and Energy Label and by voluntary agreements (VA). Product policy processes are ongoing for relevant products are computers and smartphones. and more ICT products are expected be part of the ecodesign & energy labelling working plan 2020-2024.

Table 2: List of product Groups in the scope

Product Group	Sub categories	Existing EU legislation
Data Centre Devices	Servers	ErP (EU) 2019/424 EU GPP Criteria SWD(2020)55 final
	Storage	ErP (EU) 2019/424 EU GPP Criteria SWD(2020)55 final
	Networking (switches/routers)	
	UPS	
	Cooling Equipment	
Telecommunication Network	Broadband communication equipment	
	Network in Offices (1GB/10+ GB LAN, WLAN)	
	Mobile networks (mobile radio, aggregate/core, satellite TV, TETRA, 2G, 3G, 4G, 5G	
	Cable (fixed, landline) networks (i.e. PSTN/KSDN, TV-cable, ADSL, VDSL,	

		FTTLA, FTTH/B, FTTH)	
End user devices	Electronic displays	Televisions	ErP (EU) 2019/2021; Energy Labelling (EU) 2019/2013
		Monitors	
	Audio/video devices	video players/recorders	
		video projectors / beamers	
		video game consoles	VA COM/2015/0178 (under revision)
		interactive whiteboards	
		videoconference systems	
		MP3 players	
		stand-alone home audio	
		network connected home audio	
		complex set-top boxes	VA COM/2012/0684 (retired)
		digital TV services	
	Personal ICT Equipment	Desktop PCs,	ErP (EU) 617/2013 EU GPP Criteria SWD(2016) 346 final (under revision)
		Workstations	
		Notebooks/Laptops	
		Tablets/Slates	
		Home/Office fixed phones	
		Smartphones	ErP (under development)
	Imaging Equipment	Monochrome laser MFD (Multi-Functional Printer)	VA COM/2013/023 (under revision) GPP (SWD(2020) 148 final)
		Colour laser MFD	
		Monochrome laser printer	
		Colour laser printer	
		Colour inkjet MFD	
		Colour inkjet printer	
		Professional printer and MFD	

		Scanner	
		Copier	
		Facsimile (fax) machine	
		3D Printers	
	Home / Office Network Equipment	Home gateway / IoT access devices	
		Home routers/gateways, integrated access devices	
		Base stations	
		Home network equipment	
		Office network equipment (servers, routers, switches)	
		Home NAS	
	ICT in public Space	ATMs	
		Cash Registers and POS Terminals	
		Ticket Machines	
		Public WLAN hotspots	
		Toll-related ICT	
		Security cameras	
	Building Automation and Control		ErP (under development)
	Industrial Sensors		
	Uninterruptible Power Supply (UPS)		
	Audio Equipment	Loudspeakers	
		Radios	
		Players/recorders	
		Amplifiers	
		Receivers	
		Tuners	
		Microsets	

		Wireless speakers	
		Smart speakers	
		Soundbars	
		Network audio players	

In summary, the scope of this study can be presented in Table 3 below.

Table 3: Summary of study scope

		ORDER OF EFFECTS		
		FIRST ORDER	SECOND ORDER	THIRD ORDER
PRODUCT/ DEVICE TYPES	CLOUD	production	Induction	
		use	Obsolescence	Rebound effects
		end of life	Substitution Optimization	Emerging Risks
	NETWORK	production	Induction	
		use	Obsolescence	Rebound effects
		end of life	Substitution Optimization	Emerging Risks
	END-USE	production	Induction	
		use	Obsolescence	Rebound effects
		end of life	Substitution Optimization	Emerging Risks

Within study scope
If linked with end-use
Out of study scope

7 Research questions

What are the main technological and market trends of ICT? And what are their impacts (both positive and negative) from an environmental point of view?

What are the product lifecycle aspects (first order effects) that will need more attention in the next years? (e.g. use of materials, manufacturing processes, energy consumption in the use phase, lifetime extension, end-of life management). How can these first order effects be addressed by product policy (i.e. Ecodesign Directive)?

The importance of seeing the effects outside the device boundary: How relevant are higher order effects from an environmental point of view? (e.g. induction and obsolescence from the negative side, substitution and optimization from the positive side)?

More specifically, on induction: Does the use of ICT devices / services contributes to relevant impacts outside the end-user device life cycle (e.g. telecommunication network and data centres)? If these effects are relevant, at what extent can be addressed by product policy (i.e. Ecodesign Directive)? What could be the role of consumers and consumer policy?

Obsolescence: are the obsolescence effects of a fast evolving ICT sector relevant from an environmental point of view? Is product lifetime limited by technical devices issues or by more systemic functional obsolescence issues as incompatibility, software updates, or storage/memory needs? Or by consumer preference for new device? If these obsolescence effects are relevant, at what extent can be addressed by product policy (i.e Ecodesign Directive)? What could be the role of consumers and consumer policy? And what can be done at waste policy level?

Substitution and Optimisation effects: how are these effects considered in the global environmental assessment of ICT? Are the benefits from these effects relevant? If yes, how the EU can support these positive effects? at what extent this can be addressed by product policy (i.e. Ecodesign Directive)? What could be the role of consumers and consumer policy? And what can be done by other policy tools.

Also in terms of first order effects, does efficiency of devices compensate for the increased data demand (access, network) deriving for e.g. from higher resolution video streaming? Which of these effects can be addressed by product policy tools? Which of these aspects need different policy approaches? (e.g. physical and technical aspects vs. business drivers, consumer behaviour)

8 Potential for energy saving

Energy consumption of ICT devices is to an extent already being considered in EU product policy. Ecodesign implementing measures have introduced mandatory energy efficiency requirements for ICT products as computers, electronic displays, servers. Other product groups as Complex Set Boxes, Imaging Equipment and Game Consoles implemented voluntary agreements according to the Ecodesign Directive.

Energy labels too have proved successful in encouraging consumers to buy more energy efficient models and manufacturers have responded by producing ever more energy efficient products[6]. Regulated ICT products, such as electronic displays and desktop computers, have significantly improved their efficiency and reduced their energy consumption in the last few years.

The aforementioned approaches have considered energy consumption of ICT devices at their use phase and also on a product-by-product basis. However, with the digital revolution having taken place and still affecting every aspect of economic activity, technological trends such as miniaturisation and cloud infrastructure deployment deem necessary not only the investigation of other phases of ICT lifecycle, but also their consideration at system level.

While using ICT devices is becoming more energy efficient, increasing trends in the energy and carbon footprint related to their production phase (embodied impacts) have received, until now, less attention at both scientific and policy level. At the same time, manufacturing of ICT devices is not currently regulated under the EU Industrial Emission Directive (IED)[7]. It is important to consider that a relevant part of the ICT manufacturing industry is concentrated in Asia, in countries as Taiwan and South Korea, China and Japan, among others.

Several studies reviewed show how the manufacturing process is an environmental hot spot for battery-powered ICT devices and for ICT components as sensors / actuators that are going to be massively deployed in the IoT and Industry 4.0. For these products a dominant part of energy consumption and carbon footprint is related to the production process. Production energy/ embodied carbon can be still relevant for other end-use devices as well, such as electronic displays and desktop computers, especially as integrated circuits such as microprocessors and memory chips are built with increasing transistor density, faster and higher performance. According to Standard & Poor's (2019), the technological hardware and semiconductor industry (the driving force behind the wider electronics industry) is classified among the sectors with the highest environmental and social exposure due to the significant exposure to water and waste management, social and environmental risks related to sourcing minerals such as tin, tantalum, tungsten, gold, and cobalt, which are key materials used in electronic equipment, poor working conditions, and occupational safety standards.

Chapter 10 of this report provides an overview of the energy demand and carbon emission impacts from the ICT manufacturing stage, focusing mainly into the energy consumption / carbon footprint associated to key components as ICs and sensors. Also other environmental aspects and impacts linked to the manufacturing stage are presented, even though they are not the main focus of this Task.

Several recent studies highlight the lack of transparency in terms of primary manufacturing energy data and the lack of sufficient high-quality inventory data along the lifecycle of ICT devices. Energy use in manufacturing of semiconductors, chips, printed circuit board manufacturing are considered very sensitive parameters for the estimation of the carbon footprint of ICT, especially for battery-powered ICT devices.

The second aspect with regards to energy consumption that is being considered in this study is an examination of ICT systems as a system. As indicated Chapter 3, studying the energy consumption and demand of ICT systems also requires an examination of the wider range of products and telecommunication services associated with a specific ICT device or service. Furthermore, ever more evident become the trends of digitalization, Internet of Things and subsequently increased data demand which in turn are associated with energy consumption. Indeed, the IEA (2020) points out that, at global level, demand for data centre and network services is expected to grow strongly in the next years, driven, in particular, by the rapidly growing demand for video streaming and gaming. That deems necessary the examination of the sources of this data demand and other future trends related to how ICT systems are used and interact with each other. At the same time, technological development leads to more efficient ICT hardware and equipment used to provide

[6] SWD(2015) 139 final

[7] Directive 2010/75/EU of the European Parliament and the Council on industrial emissions (the Industrial Emissions Directive or IED) is the main EU instrument regulating pollutant emissions from industrial installations.

ICT services. Chapter 10 of this Task examines the opposite trends around the question of whether ICT as a system leads to an overall increase or decrease of energy consumption. Arriving to reliable forecasts is a challenging task, on one hand due to the dependency of the estimations on the methodology used, and, on the other, the difficulty to grasp the uncertainties associated with a wealth of new technologies and applications that characterise the sector.

Finally, a qualitative assessment of ICT systems in terms of the optimisation effects observed is being provided. The ever-increasing use of Internet of Things devices can lead to energy efficiency gains with the use of sensors, communication protocols and smart devices, These technologies are already revolutionising a number of sectors, with applications ranging from optimisation in industrial manufacturing and the facilitation of RES in energy systems, to consumer engagement in the energy use of home devices and route optimisation in the field of transport. In many cases such applications have already started to take place, such as the wide use of sensors and smart functions in products, while the use of artificial intelligence and energy harvesting are considered expected trends for the future.

9 Assessment of energy consumption from an LCA perspective

9.1 Impacts of manufacturing of ICT

9.1.1 Embodied energy and carbon footprint

Manufacturing of ICT requires energy intensive processes that can have relevant impacts in terms of embodied carbon footprint. From a methodological point of view, the production energy of ICT devices (and the related embodied carbon footprint) can be estimated by a careful lifecycle analysis (LCA) that includes a full inventory of the materials and processes involved, from the material extraction and processing, and the manufacturing of components and assembly, up to the shipment to the final customer.

Most of the ICT manufacturing energy use is associated with the manufacturing of semiconductor components, such as Integrated Circuits (ICs), and other complex components, such as electronic displays and Printed Circuit Boards.

An integrated circuit or monolithic integrated circuit (also referred to as an IC, a chip, or a microchip) is a set of electronic circuits on one small flat piece of semiconductor material that is normally silicon. Digital ICs are the more common variety, mainly because of the vast number of digital devices (not just computers) that make use of them and mainly include MOS memory cells, microprocessors (MPUs), microcontrollers (MCUs), and digital signal processors (DSPs). Perhaps, the single most important digital IC to evolve has been the MPU. This important device, incorporating hundreds of thousands of transistors in an area of about 1-2 square cm^2 or less, has truly revolutionized digital electronic system development. An MPU is the operational core of a microcomputer and digital control system and has broad applications in automotive electronic systems. The MPU incorporates a relatively complicated combination of digital circuits including an ALU or CPU, registers, and decoding logic. It is worth noting that a MCU is different from an MPU in that an MPU contains only CPUs and needs additional peripherals to perform tasks, while an MCU contains CPU, RAM, ROM, etc., that allow it to perform simple tasks independently (Das and Mao, 2020).

The production of ICs is a highly complex sequence of photographic and chemical processing steps whereby electronic circuits are gradually created on a wafer made of pure semiconducting material. From raw material to completion can involve hundreds of steps and can take weeks to complete. This is a highly resource-intensive production process with substantial energy (electricity) and resource use with among the highest environmental impacts per mass unit that exist today for mass produced products (Gupta et al. 2020).

According to Chen et al. (2013) a typical semiconductor fabrication plant can use as much power in a year as about 50,000 homes. In fact, large “megafabs” can consume more electricity than auto plants and refineries. Some facilities have even built their own captive power plants. While the power consumed by semiconductors chips has been reduced significantly in the past decade, improvements in the energy used during the chip production process have lagged behind.

Ultra-pure water is used in semiconductor manufacturing. Water is devoid of organic and inorganic contaminants before being used. This purification process requires energy intensive filtering and treatment. The electricity consumed by pumps, motors, drives and other infrastructure that moves the ultrapure and waste water in, around and out of the wafer fabrication facility is also significant (Water-Energy nexus).

As semiconductor manufacturers are confronted with the need to produce chips with ever smaller feature sizes, operations-driven resource usage is likely to increase dramatically. For instance, the next generation of steppers under development for use in the most advanced wafer fab manufacturing processes employ extreme ultraviolet lithography (EUV). These technologies may require 10 times the power of the previous generation, in part because of a low conversion efficiency (of only a few percent) of an infrared pump laser into the desired ultraviolet output. (Schneider Electric, 2019)

Also display and Printed Circuit boards’ production can be an important contributor of primary energy and electricity consumption for ICT devices’ manufacturing. In general, the manufacturing of these electronic components is much more energy intensive than processes for production of metals (with the exception of advanced processes), plastics and processing of many composites. Indicatively, while production of the latter products roughly falls within a range of 1 to 30 MJ/kg (Duque Ciceri et al., 2010),the primary energy for the manufacturing of a single IoT connectivity IC chip is estimated to be around 40 MJ according to Das and Mao (2020). Furthermore, Annex I reports examples of literature data for the primary energy (and electricity consumption) of semiconductor component production such as ICs and LCD screens, which fall within a range of 200 to 27.000 MJ/cm^2.

At the life cycle level of an ICT device, carbon footprint has two main sources: operational energy consumption (use carbon footprint), and hardware manufacturing (embodied carbon footprint) (Malmodin et Lunden, 2018; Gupta et al., 2020). According to Malmodin and Lunden (2018) the manufacturing stage is more relevant for many end-user ICT devices as this life cycle stage can represent around 50% of the total footprint. This is demonstrated in the Figure 3 below, where embodied carbon footprint is found to be relatively dominant for small battery-powered ICT devices, but also relevant for larger ICT devices as laptops, desktop computers and even for televisions.

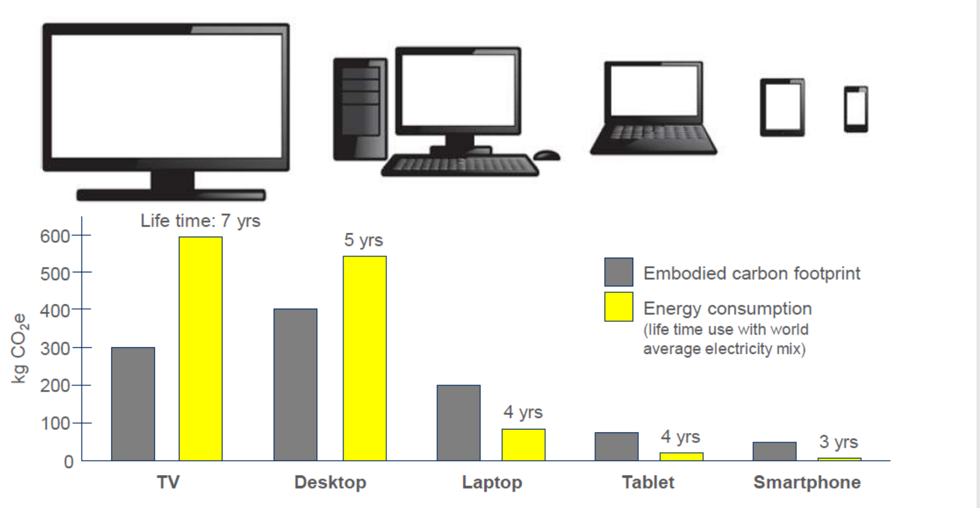


Figure 3: Estimated embodied carbon footprint and use (active lifetime) carbon footprint for common end user ICT devices. Source: Malmodin and Lunden (2018)

As for the embodied energy, according to Malmodin and Lunden (2018), the Integrated circuits (ICs) represent the largest contributor to the carbon footprint for ICT devices. Material extraction, mechanics, displays, and assembly also are responsible of significant carbon footprints (see Figure 4).

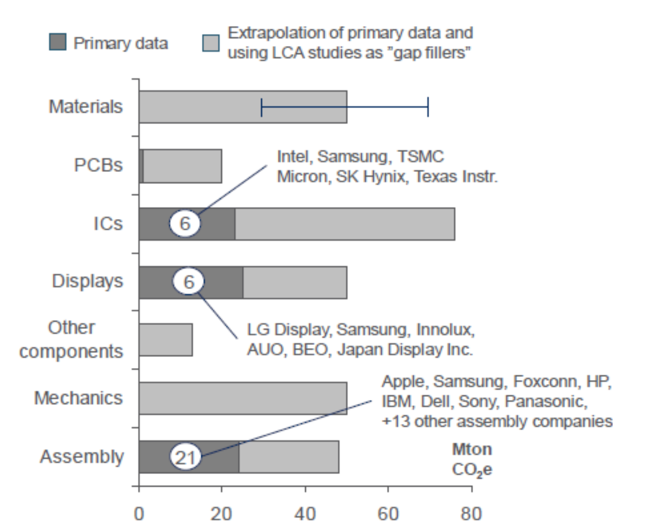


Figure 4: Total Carbon Footprint of the material acquisition and production stage for ICT user devices. The range indicated in materials shows the impact of recycling. Source: Malmodin and Lunden (2018).

The hardware manufacturing stage is the main contributor of the total carbon footprint of battery-powered end-user devices, with roughly 75% of the carbon footprint from hardware manufacturing (Gupta 2020). In particular, most of the emissions come from manufacturing of integrated circuits (e.g., SoCs, DRAM, and storage) (Gupta et al., 2020). That has led to the fact that although carbon emissions from the use phase at device level are decreasing thanks to algorithmic, software, and hardware innovations that boost performance and power efficiency, the overall carbon footprint of computer systems continues to grow for many devices (Gupta et al., 2020).

For several battery-powered devices, the carbon footprint has increased from generation to generation (see Figure 5) mainly due to the increased embodied footprint and from production and manufacturing. Figure 5 shows the carbon breakdown over several generations of battery-powered devices: iPhones (from 2008's 3GS to 2018's XR), Apple Watches (2016's Series 1 to 2019's Series 5), and iPads (2012's Gen 2 to 2019's Gen 7). According to Gupta et al., 2020 (figure 5 (top)), the fraction of carbon emissions devoted to hardware manufacturing accounts for 40% of emissions in the iPhone 3GS and 75% in the XR; for Apple Watches, it accounts for 60% in Series 1 and 75% in Series 5; and for iPads, 60% in Gen2 and 75% in Gen 7.

Figure 5 (bottom) shows the absolute carbon output across generations for the same devices. As performance and energy efficiency of both software and hardware have improved over the past few years, the use phase related carbon footprint from energy consumption has decreased. Despite the energy-efficiency increases over iPhone and Apple Watch generations, however, total carbon emissions grew steadily. The increasing outputs owe to a rising contribution from manufacturing as hardware provides more flops, memory bandwidth, storage, application support, and sensors (Gupta et al., 2020).. The opposing energy-efficiency and carbon-emission trends underscore the inequality of these two factors.

Reducing carbon output for the hardware life cycle requires design for lower manufacturing emissions or engagement with hardware suppliers. Alternative/complementary strategies can aim to extend the lifetime of the devices. (Gupta et al., 2020).

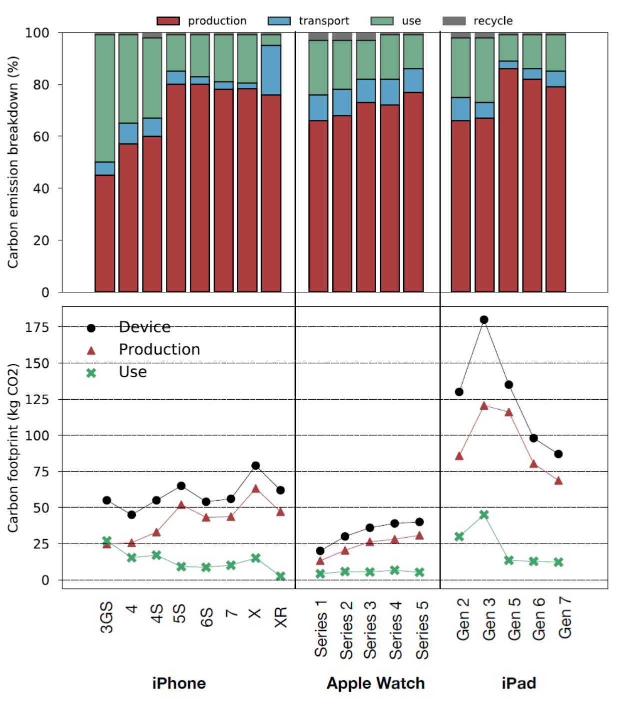


Figure 5: Carbon emissions and breakdown of emissions across generations for Apple iPhones, Watches, and iPads. Source: (Gupta et al., 2020).

From 2017 to 2019, software and hardware optimizations primarily focused on maximizing performance, overlooking the growth trend of carbon footprint.

Figure 6 illustrates the trade-off between performance, measured as MobileNet v1 throughput (i.e., inference images per second) and the manufacturing carbon footprint.

Gupta et al (2020) illustrated the trade-offs (pareto frontiers) between performance and carbon footprint of these devices. Higher performance is achieved through more-sophisticated System-on-Chips (SoCs) and specialized hardware. As highlighted by Gupta et al. (2020), while greater performance is important to enabling new applications and improving the user experience, moving the Pareto frontier down is crucial to design workloads and systems with similar performance but lower environmental impact.

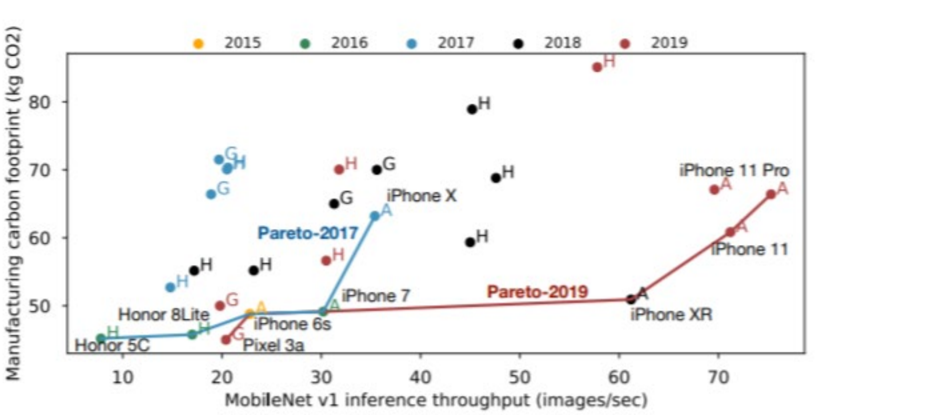


Figure 6. Performance vs. carbon footprint by mobile generation (A represents Apples, G Google and H Huawei).

In the specific case of smartphones, a wider review of carbon footprint studies carried out by Clement et al. (2020) also highlights the relevance of the production phase: 70 ± 12% of the total carbon (Figure 7). The Figure 7 also shows clearly that the ICs, the display and the PCBs are the top contributors for these devices, followed by the casing and the battery. The sources of energy is a major source of variation for the production footprint. Electricity is required at every step of the production, and its share in the IC and PCB production processes is around 50%.

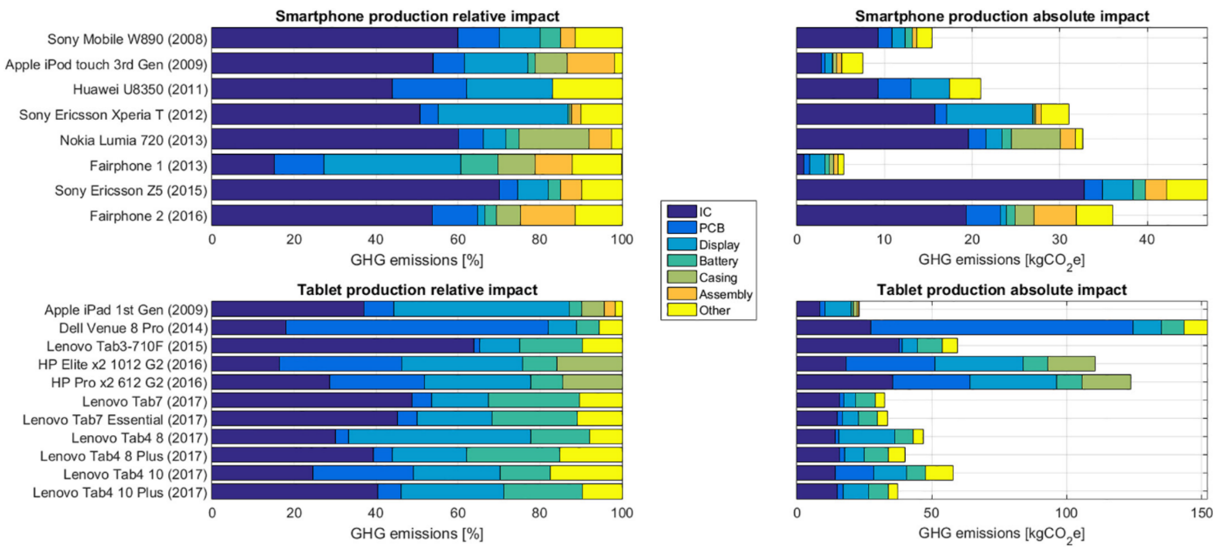


Figure 7: Sub-components production impact. Source: Clement et al. (2020)

Regarding tablets, Alcaraz et al. (2018) also found that the life cycle environmental impact of tablets is driven by the materials and manufacturing phase, and more specifically the manufacturing of electronic components such as integrated circuits and printed wiring board. The activities that contribute most both to the uncertainty and to the total greenhouse gas emissions are the display and, particularly, the ICs. This result is consistent with other relevant studies in literature that have used a conventional LCA approach. Alcaraz et al (2018) suggest that industry should focus further data collection efforts on integrated circuits, displays, and on improving the granularity of the data.

For data centres devices such as servers, mostly operated by cloud service providers at almost full capacity, the energy consumption of the device during use phase is still considered the most relevant factor affecting the total carbon footprint (Malmodin and Lunden, 2018). Finally, the location of the production plants is crucial as electricity generation accounts for a significant part of the GWP. It has to be considered that consumer's ICTs and components are mainly manufactured in countries such as the Republic of Korea, Taiwan, China, or Singapore, where energy systems are still largely dominated by fossil fuels (resulting in relevant GHG emissions).

According to Itten el al. 2020, switching to cleaner electricity production is essential, particularly in China, where 60% of the material-related climate change impacts of ICT manufacturing are caused. Improved supply chain management is crucial for other regions, which have increasingly outsourced their consumption-based impacts to China (e.g. EU, USA).

9.1.2 Sensors as main drivers of increased primary energy footprint of IoT devices

The deployment of sensors has been characterised as a "sensor tornado", with a growth from 10 million sensors in 2007 to 15 billion micro-electro-mechanical system (MEMS) sensors in 2015[8]. These sensors have enabled the Internet of Things (IoT), in which they act as converters of physical object attributes into representative digital data in the virtual world. The data captured by the MEMS of the IoT, is used to monitor and control the functions and interactions of these objects and is transmitted via internet protocol to the "Edge" or the "Cloud", where the data is stored, categorized, analysed and retrieved from, on demand (Patsavellas and Salonitis, 2019).

An IoT device contains either a sensor or an actuator that interfaces to wired/wireless internet communication, as shown in Figure 8. The key difference between sensors and actuators is that the former changes a physical parameter to an electrical output, whereas it is just the reverse for the latter.

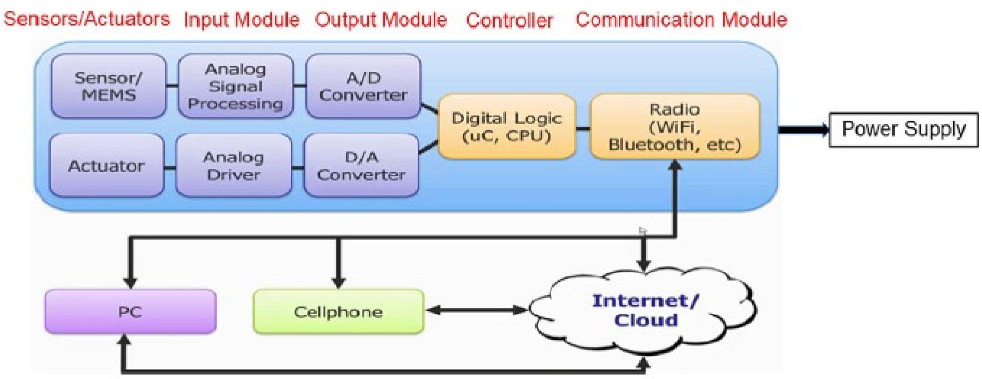


Figure 8: Schematic of an IoT device components flow in a connected economy

An I/O module acts as a mediator and interfaces between the processors (programmable automation controller) and I/O devices such as sensors (input) or actuators (output), and the data type could be either analog or digital. The common types of signal are temperature, humidity, light, pressure, motion, magnetic, vibration, etc.

According to Das and Mao (2020) the total global IoT semiconductor primary energy demand is projected to increase from 2 EJ in 2016 to 35 EJ by 2025, resulting mainly from a substantial projected increase in the manufacturing energy of sensors and connectivity ICs (see Figure 9). According to Das and Mao (2020), IoT connectivity ICs have a significantly higher primary manufacturing energy, e.g., 40 MJ/chip compared with 20 MJ/chip for IoT processor ICs, as Complementary Metal-Oxide-Semiconductor (CMOS) logic chip type is assumed in the former case and a MPU chip for the latter case. With an increasing trend in the technology node of the CMOS logic chip, the increase in its manufacturing energy is projected to be significantly higher in this case, despite market forecasts for both these chip types are projected to be similar by the end of projected period (see Figure 9).

[8] Colin Johnson, C. (2015) "Roadmap to Trillion Sensors Forks", *EE Times*, Available at: https://www.eetimes.com/document.asp?doc_id=1328466#

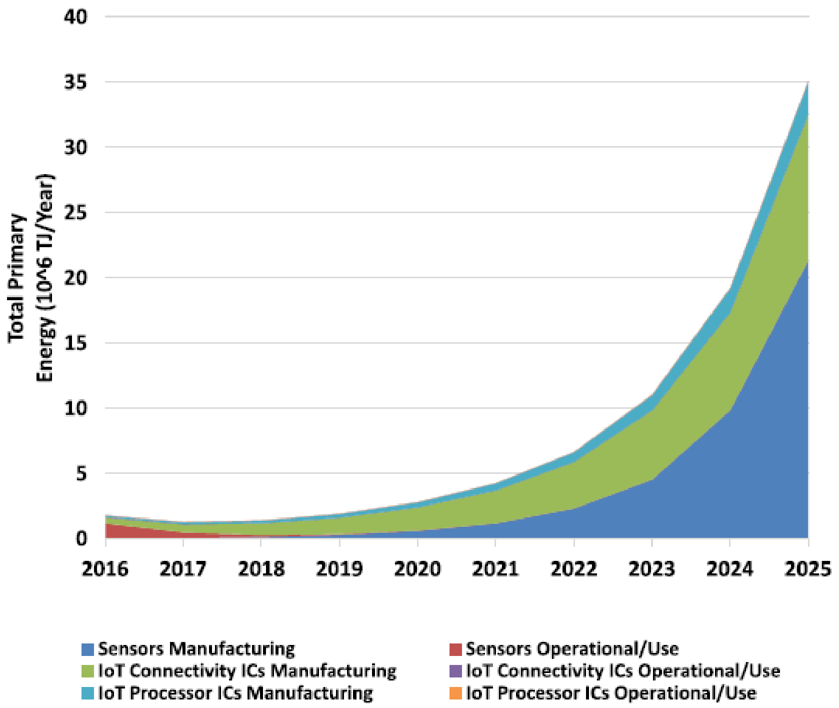


Figure 9: Global total primary energy footprint of electronics in IoT devices.

Additionally, a significantly higher pin count future trend in IoT ICs is assumed that will result in an annual manufacturing energy increase of 0.75 MJ/chip maximum in the case of IoT sensor ICs. The primary energy demand for different IC package methods is shown in Figure 10 (Das and Mao, 2020).

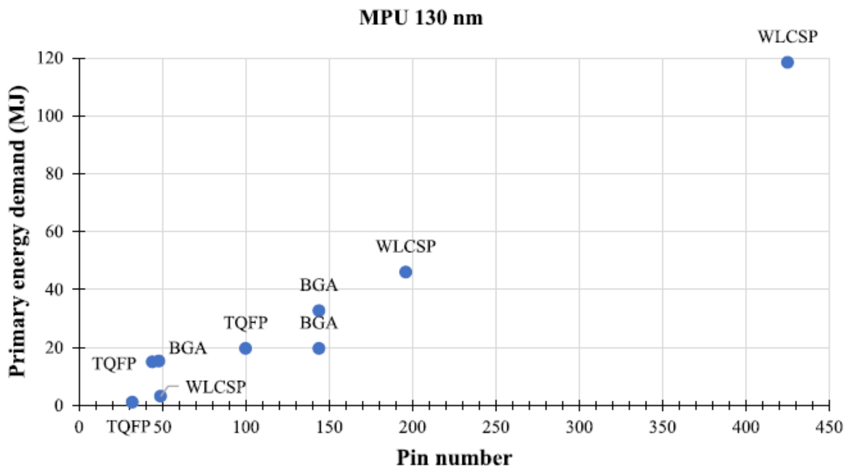


Figure 10: Primary energy demand of 130 nm MPU with different package methods.

9.1.3 Challenges in assessing carbon footprint of semiconductors

According to Clemm et al. (2019) semiconductors, despite contributing to a significant share of the total environmental impacts incurred by the manufacturing of electronic equipment, are frequently challenging to model in LCA studies, also as manufacturers of electronic equipment do not commonly publish detailed data on the latest fabrication processes. Also in the case of Das and Mao (2020), primary manufacturing energy data on chips has been limited to date due to difficulties in obtaining manufacturing-process level data on the dynamic technology nature and the increasing complexity of the technology.

Vasan et al. (2014) found reasons to believe that embodied carbon footprint could be underestimated in individual LCAs of electronics as a result of the inconsistencies arising from the system boundary selection methods and databases, the use of outdated LCA approaches, and the lack of supplier's emissions-related data.

Alcaraz et al. (2018) consider that the amount of information required to model the carbon footprint can be reduced by targeting the activities that have the most leverage to reduce uncertainty,

Integrated circuits (ICs) are frequently packaged into polymeric housings, which complicates the process of gathering information on the semiconductor itself. To appropriately model semiconductors in LCA studies, the area of silicon contained within the IC package needs to be known, as the area of processed semiconductor material is considered the most appropriate parameter to estimate environmental impacts of the complex clean room production processes including lithography, etching, and metallization steps. Clemm et al. (2019) describe various techniques that can be applied to obtain such information to differing degrees of certainty. **Error! Reference source not found.**Figure 11 shows the photo of a packaged IC from a smartphone mainboard as well as an X-ray image of the same IC, revealing the internal structures that can be used to estimate the semiconductor area contained in the package. In this particular case, the X-ray image shows that an estimation made from only judging the package itself would easily lead to an overestimation of the actual area. Destructive methods, such as decapping, can reveal the actual die size, however, the X-ray image is a good starting point to reduce uncertainty of assumptions regarding semiconductor area in an IC.

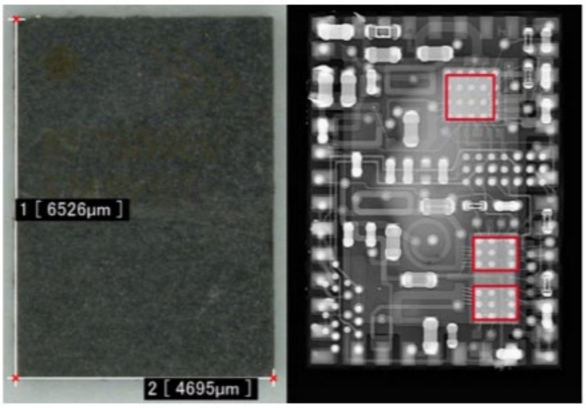


Figure 11: Photo of a packaged 3G/4G power amplifier IC from a smartphone mainboard (left) and X-ray image of the same component indicating it is a module with three smaller dies (highlighted in red boxes) and various passive components. Source: Clemm et al. 2019

During the Ecodesign Preparatory Study for Smartphones, Fraunhofer IZM et al., (2020) remodelled semiconductor datasets based on data by highly relevant semiconductor manufacturers (Table 4). Data furthermore is scaled per cm² of die area, which is considered a much more accurate scaling parameter than the packaged IC weight as applied in the standard EcoReport datasets. This is particularly the case for storage chips where several dice are stacked in one package and actually the package size (and weight) is actually the same across all storage specs, but differing in size of integrated semiconductor area. Data for upstream wafer manufacturing is based on industry data compiled in ongoing research projects. Notably, the ICs are much more primary energy and carbon footprint intensive than the other components. More literature data are available in Annex 1.

Table 4: Additional datasets specific to the product group mobile phones, smartphones and tablets, per kg or per 1000 cm²

	Name material	Recycle %*	Primairy Energy (MJ)	Electr energy (MJ)	feedstock	water (process)	Water (cooling)	Hazardous waste	Non Hazardous Waste	Greenhouse Gases in GWP100	Acidification (emissions)	Volatile Organic Compounds (VOC)	Persistent Organic Pollutants (POP)	Heavy Metals	Polycyclic aromatic hydrocarbon	Particulate Matter (PM, dust)	Heavy metals (to water)	Eutrophication
unit	New Materials production phase (category '**Extra**')	%	MJ	MJ	MJ	L	L	g	g	kg CO2 eq.	g SO2 eq.	mg	ng i-Teq	mg Ni eq.	mg Ni eq.	g	mg Hg/20	mg PO4
100	**Flex PCB Ni/Au-Finish 1-layer per cm²**	**0**	163.70	70.88	-	1,787.50	-	0.00	91.18	7.80	28.33	2.69	-	72.21	-	1.29	3,459.79	45,156.88
101	**Flex PCB Ni/Au-Finish 1-layer, double-sided per cm²**	0	228.43	130.52	-	1,868.75	-	0.00	122.41	10.36	38.32	3.02	-	76.88	-	1.31	4,685.63	45,983.06
102	**FR4 PCB Ni/Au-Finish 4-layers per cm²**	0	345.01	227.96	-	2,087.50	-	0.00	173.34	15.13	51.85	3.72	-	84.51	-	4.41	6,690.93	47,637.17
103	**FR4 PCB Ni/Au-Finish 6-layers per cm²**	0	491.79	354.38	-	2,256.25	-	0.00	239.38	21.05	68.64	4.57	-	93.52	-	5.61	9,279.42	49,596.40
104	**FR4 PCB Ni/Au-Finish 8-layers per cm²**	0	631.82	480.80	-	2,431.25	-	0.00	305.43	26.57	84.28	5.38	-	101.79	-	6.44	11,853.28	51,335.00
105	**FR4 PCB Ni/Au-Finish 10-layers per cm²**	0	771.85	607.22	-	2,606.25	-	0.00	371.47	32.09	99.92	6.19	-	110.07	-	7.26	14,427.14	53,073.60
106	**FR4 PCB Ni/Au-Finish 12-layers per cm²**	0	918.64	733.64	-	2,775.00	-	0.00	437.52	38.01	116.71	7.03	-	119.08	-	8.46	17,015.63	55,032.82
107	**FR4 PCB HAL-Finish 1-layer per cm²**	0	152.39	72.56	-	343.75	-	0.00	92.04	7.12	21.79	1.68	-	54.94	-	3.33	1,730.83	3,787.96
108	**FR4 PCB HAL-Finish 1-layer, double-sided per cm²**	0	217.12	132.20	-	425.00	-	0.00	123.28	9.68	31.78	2.01	-	59.60	-	4.05	2,956.67	4,614.14
109	**LCO-Battery (Lithium-Cobalt-Oxid)**	0	267.31	-	-	-	-	-	453.21	22.88	136.38	57.23	-	235.39	-	15.82	1,825.35	18,959.24
110	**NiMH battery (AAA)**	0	230.00	-	-	34.66	55.00	19.60	600.54	19.00	764.00	0.12	2.16	7.66	204.65	35.61	74.23	27,400.00
111	**LCD display, smartphone, per cm²**	0	255.83	245.15	-	93.33	-	91.20	112.68	19.59	64.98	5.09	-	119.05	-	6.50	-	12,211.47
112	**LCD display, tablet, per cm²**	0	213.19	204.29	-	77.78	-	76.00	93.90	16.33	54.15	4.24	-	99.21	-	5.42	-	10,176.22
113	**AMOLED panel per cm²**	0	363.93	245.15	-	93.33	-	91.20	112.68	14.27	64.98	5.09	-	119.05	-	6.50	-	12,211.47
114	**Glass per g**	0	27	21.816419	0	24.725275	0	0.8065028	40.580514	2.45	9.012502967	0.0131819	0.2294104	0.5305702	0.000859	0.1925659	0.1186721	1.076105625
115	**Silicone**	0	156.63	24.56	42.64	19.00	384.00	0.00	1,434.00	6.86	14.82	-	-	-	0.12	15.00	0.04	1,860.00
116	**NdFeB magnet**	0	330.00	3.42	0.11	39.33	-	-	2,582.28	27.60	440.00	0.20	39.00	36.00	0.10	124.00	2.00	79.00
117	**IC, SoC per cm² die area**	0	33,764.43	27,050.65	-	22,975.39	27,132.00	42,695.42	52,041.86	3,017.45	56,582.32	658.01	-	84,879.02	-	1,216.30	124,862.73	1,556,788.39
118	**IC, DRAM (50% of SoC) per 1cm² die area**	0	16,882.22	13,525.32	-	11,487.69	13,566.00	21,347.71	26,020.93	1,508.72	28,291.16	329.00	-	42,439.51	-	608.15	62,431.37	778,394.19
119	**IC, NAND (60% of SoC) per 1cm² die area**	0	20,258.66	16,230.39	-	13,785.23	16,279.20	25,617.25	31,225.12	1,810.47	33,949.39	394.80	-	50,927.41	-	729.78	74,917.64	934,073.03
120	**Generic IC per 1cm² die area**	0	26,730.18	21,415.10	-	18,188.85	21,479.50	33,800.54	41,199.81	2,388.81	44,794.34	520.92	-	67,195.89	-	962.90	98,849.66	1,232,457.47

Please note that although the dataset reads per cm² / per g in column “Name Materials” the values in this table are actually expressed per 1000 cm² or per kg.

9.2 Other environmental impacts

The manufacturing of semiconductor components that are present in all ICT devices is not only relevant from the primary energy and global warming point of view. Other environmental issues, including the water-energy nexus, should be considered.

Villard et al. (2015) conducted eight interviews with actors of environment strategies and policies in a leading semiconductor company and based on this interview results (tables below) also additional environmental impacts as water stress / water toxicity and resource depletion are highlighted as relevant impacts from the semiconductor industry (see Table 5).

Table 5 Expert ranking of environmental concerns in manufacturing plants. Source: Villard et al. 2015

IMPACTS	REPORTING	FRONT END SITES	BACK END SITES	REASON FOR IMPACT CONTROL: DESIRABLE LEVEL OF SITE RESPONSIBILITY
Toxicity in water	1	++	+++	Many dangerous chemicals are consumed; the risk of toxic effects on health and ecosystems by waste water exists
Global warming	1	+++	+++	Direct - perfluorocarbons (PFCs) - or indirect – energy - emissions The level of severity depends on the efficiency of PFC treatment units Intensive use of electricity
Resource depletion	1	+++	+++	Intensive use of raw materials
Water stress	0	+++	+	Intensive use of ultrapure water
Water Acidification	0	++	+	Many acids are consumed; the severity level depends on the sensitivity of local ecosystems and the efficiency of waste water treatment plants
Eutrophication	1	= / ++	+	Many acids are consumed; the severity level depends on the sensitivity of local ecosystems and the efficiency of waste water treatment plants
Air acidification	1	+ / ++	=	A few acidifying gases are used; the majority of emissions is controlled by air treatment units; site-dependent
Summer smog	1	++/+++	++	Emissions in air due to general plant functioning; the severity level depends on the sensitivity of local ecosystems and the efficiency of Volatile Organic Compounds (VOCs) treatment units
Human health	0	+	+	A few dangerous substances have to be managed for worker safety
Waste	1	=	+	Considerable quantity of plastic waste; variable rate of recycling
Noise	0	=	=	
Ozone layer depletion	0	=	=	
Toxicity in air	0	=	=	A few toxic gases are consumed; All are under control by air treatment units
Land occupation	0	=	=	
Toxicity (soil)	0	=	=	
Smell	0	=	=	

9.3 Performance indicators and benchmark

The evidence from scientific literature described above indicates the necessity of having more transparent data on the energy demand and environmental performance of the semiconductor manufacturing, including the size and type of the ICs included in ICT devices.

The Commission (European Commission, 2019) has recently produced sectoral best environmental management practices (BEMP) (Commission Decision (EU) 2019/63) applicable to electrical and electronic equipment manufacturing sector, have established some environmental performance indicators for electronic equipment manufacturing, even though benchmarks of excellence have not been established (Table 6).

Table 6: BEMP applicable to electrical and electronic equipment according to the Commission Decision (EU) 2019/63

	Environmental performance indicators	Benchmarks of excellence
Cleanroom activities	(i1) Energy use in the cleanroom for printed circuit board manufacturing (kWh/m^2 of processed printed circuit board) (i2) Energy use in the cleanroom for semiconductors and/or integrated circuits manufacturing (kWh/cm^2 of silicon wafers) (i3) Air Change Rate (number/hour) (i4) COP (Coefficient of Performance) of the cooling equipment installed (kWh cooling energy produced/kWh energy used) (i5) Water conductivity (µS/cm)	Not available
Cooling	(i6) Coefficient of Performance (COP) for individual cooling equipment (kW of cooling power provided/kW of power used) (i7) Coefficient of System Performance (COSP) including the energy required to run the supplementary equipment of the cooling system, e.g. pumps (kW of cooling power provided/kW of power used) (i8) Use of cooling cascades (Y/N) (i9) Use of free cooling (Y/N) (i10) Use of heat recovery ventilators (Y/N) (i11) Use of absorption chillers (Y/N) (i12) Energy use of the cooling system per unit of turnover (kWh/EUR)	Not available
Soldering operations, (especially relevant for the production of printed circuit boards (PCB)).	i13) Total energy demand per surface unit of printed circuit board processed (kWh of electricity/m^2 of PCB) (i14) Nitrogen consumption per surface unit of printed circuit board processed (kg of nitrogen/m^2 of PCB)	Not available

9.4 Discussion

Several life cycle studies show that, for small ICT (battery powered) devices as smartphones and tablets, the energy and carbon footprint impacts are mostly related to the production stage (embodied carbon footprint >75% of the total carbon footprint). Similar results are expected for IoT devices with high-tech sensors that are expected to increase their embedded energy and embodied carbon footprint of ICT despite a clear trend for energy efficiency improvements in their use stage.

For other ICT devices, such as servers for cloud services, operated at almost full capacity, the energy consumption of the servers during use phase is by far the most relevant aspect to be addressed (discussed in the following section). As general rule, manufacturing dominates emissions for battery-powered devices, whereas operational energy consumption dominates emissions from always-connected to the mains devices (Gupta et al., 2020).

In order to better understand the relevance of embodied impact for other ICT more data are needed related to the production Energy (PE) of device components and impacts of key components as Integrated Circuits, sensors, PCBs, screen.

However, based on the discussion above, Table 7 provides a qualitative assessment of the relative relevance of the embodied energy / carbon footprint compared to the energy / carbon footprint due to the use phase is presented below (see Table 7).

Table 7: Relative relevance of the embodied energy / embodied carbon footprint compared to the energy / carbon footprint due to the use phase for the products in the scope of this study

Product Group		Embodied energy and embodied Carbon Footprint Relevance (see note below)
Data Centre Devices (e.g. servers, storage devices, Networking devices as switches/routers)		Low
Telecommunication Network Broadband communication equipment		Low
End use Devices	Electronic displays	Medium
	Audio/video devices	Medium/High (High relevance for small battery powered devices as mp3 players or cameras)
	Computers	Medium/High (High relevance for small battery powered devices as notebooks and tablets)
	Imaging Equipment	Low
	Home / Office Network Equipment	Low
	ICT in public Space (e.g. ATMs, cash registers, security camera)	Low
	Building Automation and Control	High
	Industrial Sensors	High
	Uninterruptible Power Supply (UPS)	Low
	Audio Equipment (e.g. loudspeakers, wireless speakers, smart speakers, soundbars ...	High

Explanatory note: Relevance of embodied energy and carbon footprint

The relevance of the embodied energy and embodied carbon footprint is expressed in relative terms, compared to the energy consumption in the use stage:

- "Low" means that indicatively < 25% of the device embodied energy / carbon footprint is related to the production stage of the ICT device
- "Medium" means that between 25% and 50% of the device embodied energy / carbon footprint is related to the production stage of the ICT
- High means that more than (>50%) of the device embodied energy / carbon footprint is related to the production stage

10 Analysis of the energy consumption linked to the use of the ICT

10.1 The challenge of capturing the energy use of the internet

Different parts of ICT systems communicate via networks, and each action instigated by an end device user (from messaging and uploading files to streaming videos and games) mobilizes not only the end device itself, but also the network infrastructure that provides the connection and the data centre infrastructure that computes, stores and transmits data related to deliver the requested service. As different parts of the ICT system operate to deliver the service, each one is associated with energy consumption. According to Andrae and Edler (2015), electricity usage from ICT is divided into four principle categories:

(i) consumer devices, including personal computers, mobile phones, or TVs;

(ii) network infrastructure;

(iii) data center computation and storage; and lastly

(iv) production of the above categories[9].

In an attempt to examine the energy consumption of ICT systems overall, a methodological challenge arises. How is this energy consumption associated with internet use and applications allocated amongst parts of the ICT system? In other words, as several parts of an ICT system contribute to the delivery of a service (be it data production, computation or transmission), how much does each part contribute to the energy use of the whole system?

Using the example of video streaming, which, as noted above, has a major impact on data demand, Coroama and Hilty (2014) underline the importance of system boundaries. Three different approaches in the literature are identified:

- Top–down approaches, taking into account the total electricity consumption estimated for the Internet and the Internet traffic for a region or a country within a defined time period. Dividing the former quantity by the latter yields the average energy consumption per data transferred.
- Model-based approaches, which combine modelling parts of the Internet (i.e., deployed number of devices of each type) with manufacturers' consumption data on typical network equipment to arrive to the overall energy consumption.
- Bottom–up analyses, which are based on direct observations made in one or more case studies, leading to energy intensity values for specific cases, and a discussion of the generalizability of the results.

The difference in methodology and the variation in terms of results are one of the reasons that make future estimations on energy use challenging. On one hand, bottom-up studies better account for factors such as service demand growth, different types of equipment, energy efficiency, and market structure (Masanet et al 2020). On the other hand, capturing bottom-up services (e.g. data download) does not reflect the totality of potential consumption, if not accounting for elements such as stand-by, backup data centres or under-utilisation..

Related to these challenges are also uncertainties related to whether all data flows are captured by studies, considering data centres come in different types and sizes, networks of different ownership status (private vs public) are used and ICT system parts have multiple functions not easily attributed to one action (e.g. data centers are used for data storage and transmission but also computing) (Bashroush, 2020; Mayers et al, 2015).

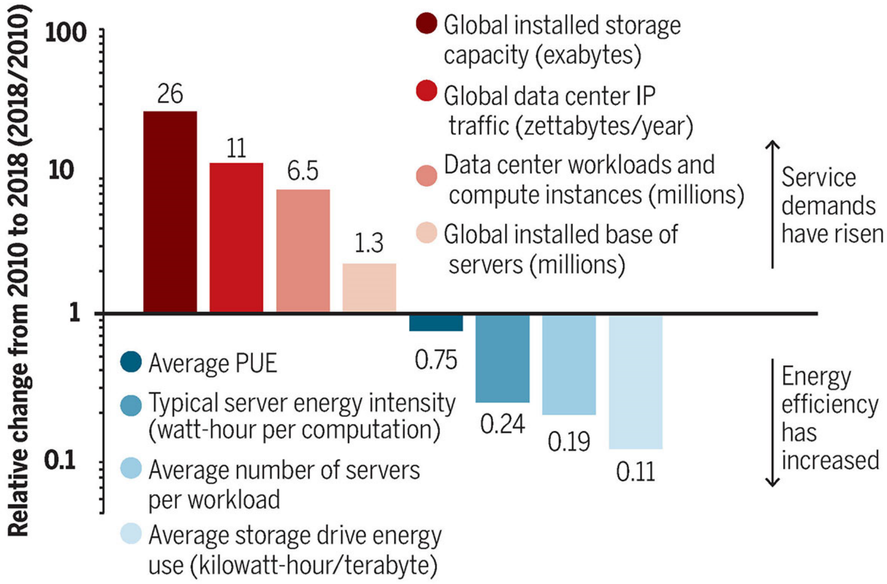
The following section presents data from studies following both top-down and bottom-up approaches, and examines major technologies that shape future energy consumption trends.

[9] The energy demands for the production of the product categories have been studied in part 3a

10.2 Trends in ICT system energy use

Whether the ICT sector's total energy consumption increases or decreases depends on which of the two effects prevails – the **growth of the sector** or the **increases in energy efficiency** (Lange et al, 2020). It is therefore an issue of whether the level of decoupling of energy use from growth is sufficient.

A useful basis for the investigation of elements of each trend (or "drivers") is provided by Masanet et al (2020) in Figure 12, which refers to energy use of data centres globally. However, due to the central role that data centres play in determining and delivering data growth, as well as the interrelations between the parts of an ICT system devices and network, these drivers can be considered for the entire ICT system, as presented in 10 below.



PUE, power usage effectiveness; IP, internet protocol.

Figure 12: Trends in global data center energy-use drivers

This structure can be extrapolated to the entire ICT system as demonstrated in Table 8. (Masanet et al, 2020)

Table 8: Trends in global ICT system energy-use drivers (adapted from Masanet et al (2020))

	Data Centers	Network Infrastructure	Consumer Devices
Growth demand	Installed storage capacity	Fixed broadband speeds	Internet users / subscribers
	Data centre IP traffic	Mobile network speeds	Networked devices/connections
	Workload/ compute instances	Network data traffic	Video Resolution
	Installed base of servers		Traffic growth driven by gaming and cryptocurrency
Efficiency	Power Usage Effectiveness	Energy intensity of data transmission	Device energy efficiency
	Typical server energy intensity	Energy efficiency of antenna base stations	
	Average number of servers per workload		

	Average storage drive energy use		

Following a top-down approach, Andrae and Edler (2015) expect an increase of annual energy consumption mainly driven by the transfer of use-stage electricity from consumer devices to the networks and data centers (see Figure 13).

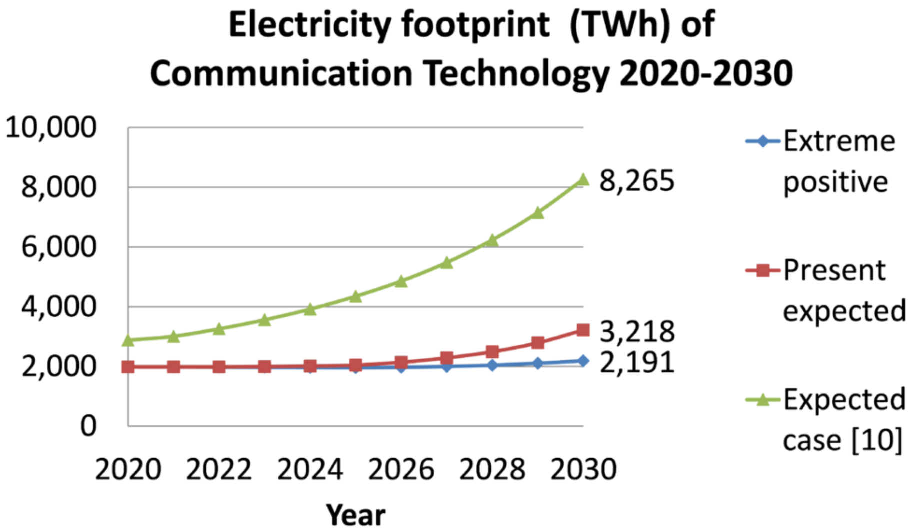


Figure 13: Expected electricity consumption scenario from ICT sector according to Andrae (2020)

At the very best scenario (the one cited as "extreme positive" in the figure above) consumption remains more or less stable between 2020 and 2030, despite increases in data traffic by 14 times, with the assumption that electricity intensity improvements continue after 2022 and that 20% improvements happen in networks and data centres until 2030.

Other sources argue that the aforementioned growth in data demand is compensated by increase in efficiency, driven by technical developments across all parts of the Internet, as well as use of improved energy management techniques in data centres and network operators (Policy Connect, 2018). Such efficiency refers firstly to energy efficiency of IT devices themselves, including servers and storage drives which has improved substantially. Secondly, the energy intensity of the internet use has been significantly reduced. Third, most compute instances have migrated from traditional data centres to much more efficient cloud and hyperscale data centers. (Energy Innovation, 2020). Figure 14 below demonstrates these efficiency gains when assuming a doubled (relative to 2018) computing demand (Masanet et al 2020).

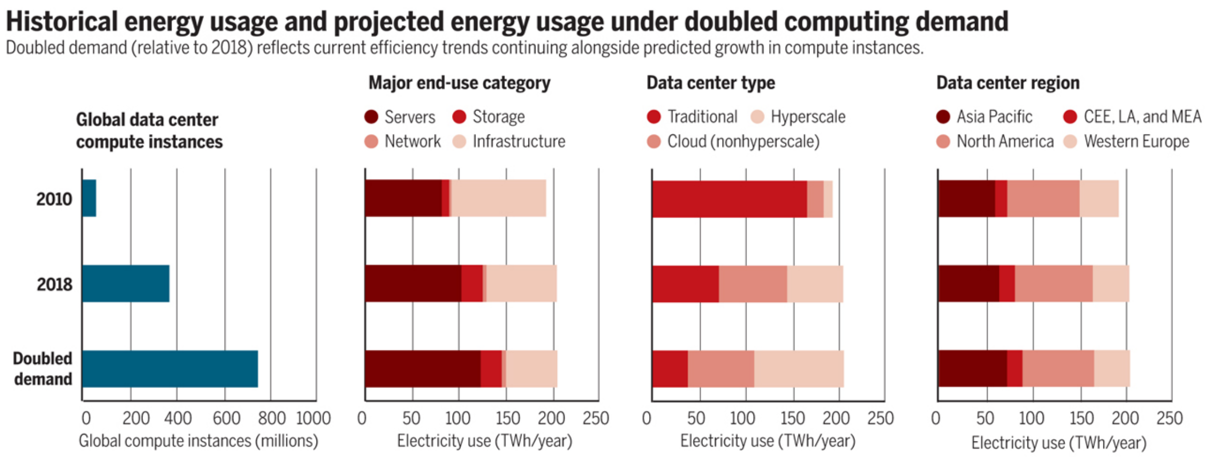


*Figure 14: Historical energy usage and projected energy usage under doubled computing demand**
**Doubled demand (relative to 2018) reflect current efficiency trends continuing alongside predicted growth in compute instance*

In the following sub-sections, parts of ICT systems are examined separately.

10.3 Data centres

Data centres comprise of a number of IT devices in order to provide the services of data computation, storage and connection to the network. Energy use is also associated with cooling equipment necessary to remove the heat generated by the aforementioned devices, as well as the infrastructure necessary to power them (Energy Innovation, 2020). In fact, around 55% of data centre energy consumption originates from its IT devices, while 45% from supporting equipment, as demonstrated in Figure 15 below (AGCoombs, 2018).

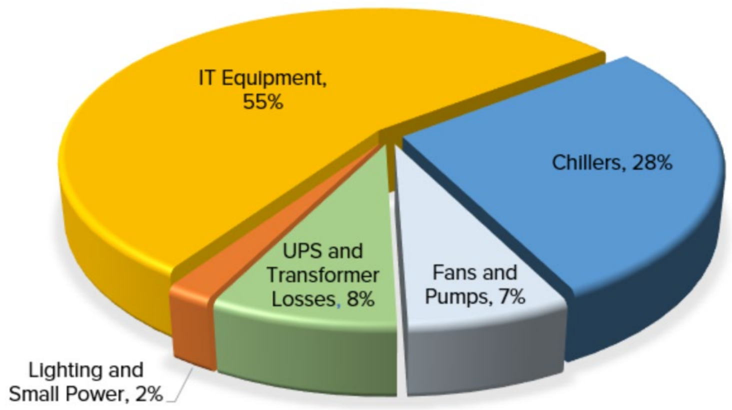


Figure 15: Average allocation of energy consumption between the different components of a data centre. Source: AGCoombs, 2018

Estimations stemming from literature are not conclusive with regards to future energy consumption of data centres. That difference in results can be explained by the variations in methodological approaches described in Section 2, with bottom-up studies showing reductions in energy use. Figure 15 above illustrates the efficiency improvements in data centres which have resulted in small annual electricity use despite increases of computational instances in recent years.

Two main factors are identified as keeping energy demand approximately flat.

One factor is efficiency improvements for servers, storage devices and network switches, as well as in terms of infrastructure related to equipment other than IT.

With regards to IT equipment efficiency, Masanet et al (2020) report that despite the increase in compute instances (demonstrated in Figure 14 above and also in Table 9 below), the energy use per compute instance, the energy consumption did not increase proportionally, leading to the conclusion that the energy intensity of global data centers having decreased by 20% annually since 2010.

Table 9: Global workload and compute instances 2014-2021. Source:VHK and Viegand Maagøe, 2020

Workload and compute instances (in millions)	2014*	2015**	2016	2017	2018	2019	2020	2021	CAGR 2016-2021
Traditional DC	46	44.9	42.1	41.4	40.8	39.1	36.2	32.9	-5%
Cloud DC	83.5	136.0	199.4	262.4	331.0	393.3	459.2	533.7	22%
Total DC	***129.5***	***180.9***	***241.5***	***303.8***	***371.8***	***432.4***	***495.4***	***566.7***	***19%***
Traditional DC	36%	25%	17%	14%	11%	9%	7%	6%	
Cloud DC	64%	75%	83%	86%	89%	91%	93%	94%	

In terms of the number of data centres, that is not a representative metric in itself, as data centres vary in size. With regards to infrastructure efficiency, indeed one metric that has been proposed to assess efficiency of data centres is Power Usage Effectiveness (PUE), which is the ration of power consumption of IT equipment (all equipment used to manage, process, store or route data in the data center) by the total power needed by the data center including infrastructure such as the power supply system, the lighting system and the cooling system. There have been studies forecasting a constant reduction in the PUE metric, meaning an optimisation of data centre efficiency based on equipment other than IT (Liu et al, 2020). Furthermore, reported trends among some of the world's largest data center operators of increasingly moving toward renewable energy procurement can also lead to a reduction of carbon emissions. (Energy Innovation, 2020)

A second factor is the change of technology towards hyperscale data centers, which are larger and more efficient. Hyperscale data centres are very efficient large-scale cloud data centres that run at high capacity, owing in part to virtualisation software that enables data centre operators to deliver greater work output with fewer servers (IEA, 2020). Furthermore, due to their efficiency and size, hyperscale data centres demonstrate low levels of PUE which in turn, lowers the energy demand of data centre infrastructure even further.

The emergence of hyperscale data centres has been credited as a main reason for the stabilisation of demand over the past half-decade. It is reported that around 400 hyperscale data centres are installed worldwide, servicing small corporations or universities that in the past would have had their own servers, and already account for 20% of the world's data-centre electricity usage (Nature, 2018).

In their estimations study for the energy use of data centers in the US, Shehabi et al (2016) identify a number of efficiency trends which explains a rather static energy consumption between 2010 and 2020:

- Average server utilization
- Server power scaling at low utilization
- Average power draw of hard disk drives
- Average power draw of network ports
- Average infrastructure efficiency (i.e., PUE)

They also present Figure 16 below, which demonstrates the static electricity use from 2010 to 2020 under current efficiency and growth rates, the trajectory of electricity use that would have materialised had there not be energy efficiency strategies, and estimations of electricity use reductions should further efficiency scenarios be implemented.

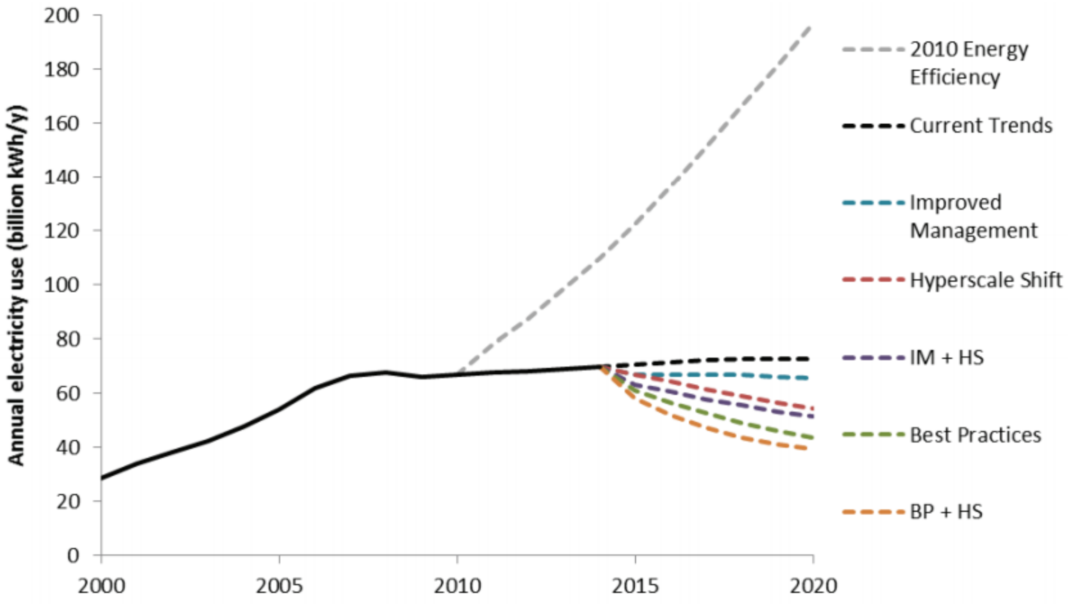


Figure 16: Effect of energy efficiency strategies on energy consumption scenarios for data centres in US. Source: Shehabi et al (2016)

The strategies range from improving the least efficient components of the data center stock ("Improved Management" scenario) and assuming an aggressive "Hyperscale Shift" of data centers to adopting the most efficient technologies ("Best Practices"), and combinations of the above scenarios Shehabi et al (2016).

The impact of both factors of increased efficiency on energy use is demonstrated in the following Table 10 (Masanet et al, 2020). The results in the table on one hand suggest an increase in the number of data centre servers, as well as an increase in the energy consumption for servers, storage and network port usage of the data centres. However, a significant reduction in energy use associated with data centre infrastructure and cooling needs brings the projection to a reduction of energy use in 2023 compared to both globally and in Western Europe.

Table 10: Efficiency trends for data centres in Western Europe according to Masanet et al, 2020.

Western Europe	**2010**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
1. Traditional data centre servers (thousands)	7386	2831	2531	2266	2026	1759	1528
2. Cloud (non-hyperscale) servers (thousands)	117	2700	2536	2510	2413	2750	3130
3. Hyperscale servers (thousands)	437	3155	3801	4292	4943	5510	6143
	7940	*8687*	*8868*	*9068*	*9382*	*10019*	*10801*
SERVERS							
1. Traditional data centre server energy use (TWh)	15.06	5.96	5.49	5.14	4.87	4.48	4.17
2. Cloud (non-hyperscale) server energy use (TWh)	1.54	6.78	6.34	6.15	5.81	6.33	6.91
3. Hyperscale server energy use (TWh)	1.02	7.06	8.45	9.46	10.79	11.89	13.12
	17.6	*19.8*	*20.3*	*20.8*	*21.5*	*22.7*	*24.2*
STORAGE							
1. Traditional data centre storage energy use (TWh)	1.51	1.00	0.76	0.58	0.53	0.52	0.51
2. Cloud (non-hyperscale) storage energy use (TWh)	0.05	1.56	1.34	1.30	1.18	1.22	1.26
3. Hyperscale storage energy use (TWh)	0.17	1.82	2.01	2.21	2.41	2.44	2.47
	1.7	*4.4*	*4.1*	*4.1*	*4.1*	*4.2*	*4.2*
NETWORK PORT USAGE							
1. Traditional data centre network port energy use (TWh)	0.47	0.17	0.14	0.12	0.11	0.10	0.08
2. Cloud (non-hyperscale) network port energy use (TWh)	0.01	0.23	0.19	0.17	0.16	0.19	0.21
3. Hyperscale network port energy use (TWh)	0.04	0.36	0.40	0.41	0.48	0.54	0.61
	0.5	*0.8*	*0.7*	*0.7*	*0.7*	*0.8*	*0.9*
PUE							
1. Traditional data centre PUE	2.23	2.06	1.99	1.93	1.87	1.81	1.76
3. Cloud (non-hyperscale) data centre PUE	1.75	1.62	1.58	1.55	1.52	1.49	1.46
4. Hyperscale data centre PUE	1.23	1.18	1.17	1.17	1.16	1.16	1.15
COOLING etc.							
1. Traditional data centre infrastructure energy use (TWh)	20.93	7.53	6.32	5.43	4.80	4.13	3.62
2. Cloud (non-hyperscale) infrastructure energy use (TWh)	1.20	5.29	4.56	4.19	3.72	3.79	3.86
3. Hyperscale infrastructure energy use (TWh)	0.28	1.67	1.90	2.04	2.23	2.34	2.46
	22.4	*14.5*	*12.8*	*11.7*	*10.7*	*10.3*	*9.9*
TOTAL ENERGY USE (TWh)	***42.3***	***39.4***	***37.9***	***37.2***	***37.1***	***38.0***	***39.3***
EU27 (Western Europe x 1.06)	*44.8*	*41.8*	*40.2*	*39.4*	*39.3*	*40.3*	*41.7*

Overall, VHK and Viegand Maagøe (2020) conclude that the growth and efficiency effects for data centres cancel each other out leading to energy use remaining stable until 2025 (see Figure 17).

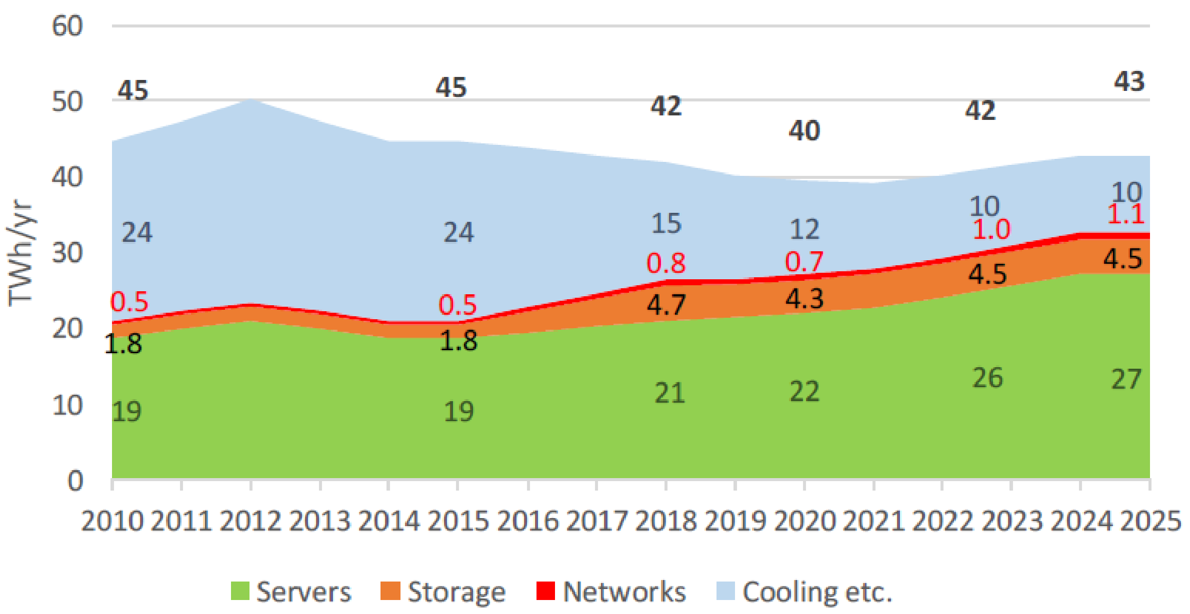


Figure 17: Trends and forecasts for the data centres electricity use in EU27 (in TWh/yr). Source: VHK and Viegand Maagøe, 2020

The above efficiency trends illustrate that the stabilisation of energy consumption for data centres is mainly driven by the reduction and then stabilisation of the energy needs for cooling. Furthermore, PUE is already reaching low values (for hyperscale data centers even approaching the value 1.1 as demonstrated in Table 7). Therefore forecasts based on those metrics may give misleading signals, due to their focus on efficiency improvements for non-IT equipment (VHK and Viegand Maagøe, 2020). Indeed, pressures on IT equipment and related to aforementioned data demand growth trends seem more indicative of the direction that consumption may take in the future. It can therefore be argued that for the purposes of this study, this metric should be considered with caution. In fact, despite the overall reduction in the period 2010-2023, the table above still predicts an increase as from 2021. This increase is in line with estimations looking at the electricity usage of data centres from a top-down approach and with a wider future horizon. The Figure 18 below from Andrae (2020) indeed demonstrates a more alarming trend.

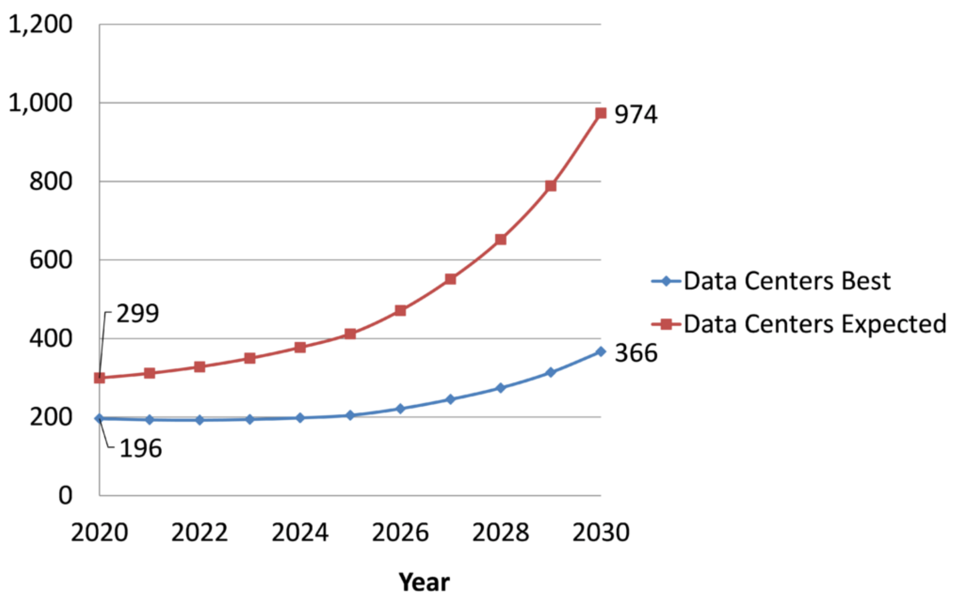


Figure 18: Electricity usage (TWh) of Data Centres (2020-2030) according to Andrae (2020)

Looking closely into the elements that contribute to shaping energy use trends might provide additional insights, with main energy consumption increase factors being increased data demand and installed storage capacity, examined below in Figure 19. (Statista, 2021).

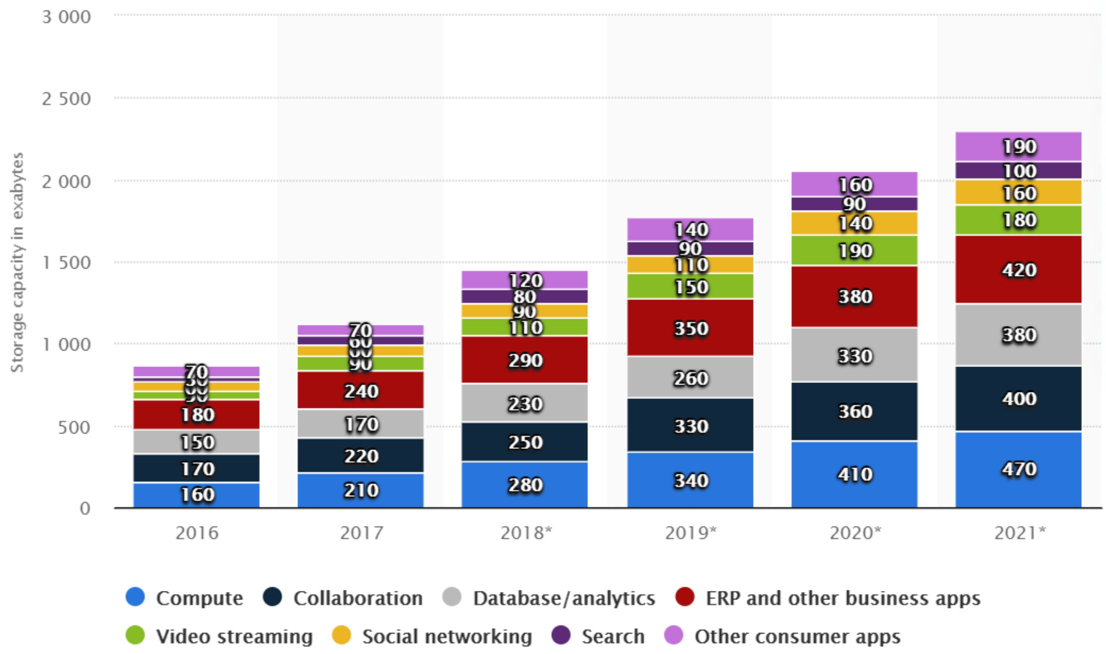


Figure 19: Trends in the installed storage capacity in exabytes (10^{18} bytes). Source: Statista, 2021

Table 11 below originating from Cisco 2016 (via VHK and Viegand Maagøe, 2020), demonstrates the increase in data centre traffic in the last years, predicting further increase.

Table 11: Trends in Global data Centre Traffic. Source: Cisco 2016 (via VHK and Viegand Maagøe, 2020)

	2016	2017	2018	2019	2020	2021	CAGR 2016-2021
	By type (EB per year)						
DC to user	998	1280	1609	2017	2500	3064	25.2%
DC to DC	679	976	1347	1746	2245	2796	32.7%
within DC	5143	6831	8601	10362	12371	14695	23.4%
	By segment (EB per year)						
Consumer	4501	6156	8052	10054	12401	15107	27.4%
Business	2319	2931	3505	4070	4716	5449	18.6%
	By type (EB per year)						
Cloud DC	5991	8190	10606	13127	16086	19509	26.6%
traditional DC	828	897	952	997	1030	1046	4.8%
Total DC	6819	9087	11557	14124	17116	20555	24.7%

IEA (2020) also expect the continuation of this exponential growth, with global internet traffic expected to double by 2022 to 4.2 zettabytes per year (4.2 trillion gigabytes).

This trend is attributed to the number of mobile internet users projected to increase from 3.8 billion in 2019 to 5 billion by 2025, and the number of Internet of Things (IoT) connections is expected to double from 12 billion to 25 billion (see also section 3.5 below). This increased traffic, and especially in mobile networks, may be a cause of concern from an energy efficiency perspective as mobile networks are currently more energy-intensive (even more so in video streaming) and also growth in traffic in "busy hour" may lead service provides to see network capacity increases (Morley et al, 2018; Cisco 2017)

These increase trends may have been exacerbated by the unforeseen even of the Covid-19 pandemic. IEA (2020) report that global internet traffic surged by almost 40% between February and mid-April 2020, driven by growth in video streaming, video conferencing, online gaming, and social networking.

10.3.1 Edge network and computing

Another area worthy of focus is the emergence of the edge network and computing, which, as a response to increasing digitalisation and data demand growth, decreases data processing costs and latency by bringing "high-performance compute, storage, and networking resources closer to users and devices" Montevecchi et al (2020). Figure 20 below presents the range of applications where edge computing is used (Cisco, 2020)

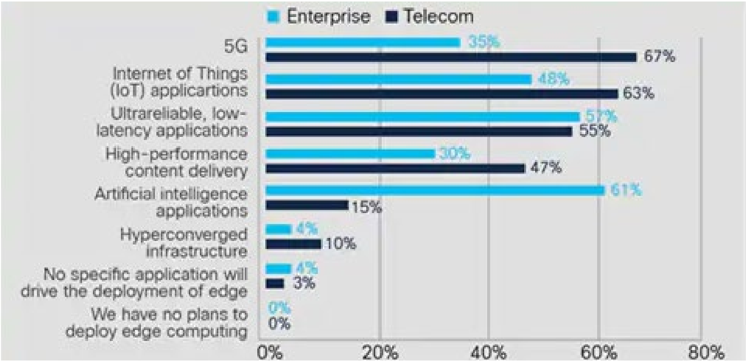


Figure 20: Edge Computing use cases. Source: (Cisco, 2020).

Edge data centres may operate less efficiently than large cloud data centres due to their size and architecture. Even though edge computer currently plays a minor role in energy consumption of data centres, Montevecchi et al (2020) forecast that edge data centres will account for around 10% of the server capacity installed in the EU28 in 2025, and therefore account for 12% of the energy demand of all data centres in the EU28. For the year 2030, it is assumed that edge data centres will account for 40% of the total server capacity (Figure 21). With the expansion of 5G mobile networks and hightech developments such as industry 4.0 and autonomous driving, the demand for small decentralised edge computing centres could see a massive increase. In such scenario, the study forecasts that energy consumption of all data centres in the EU28 could rise to approx. 120 TWh/a.

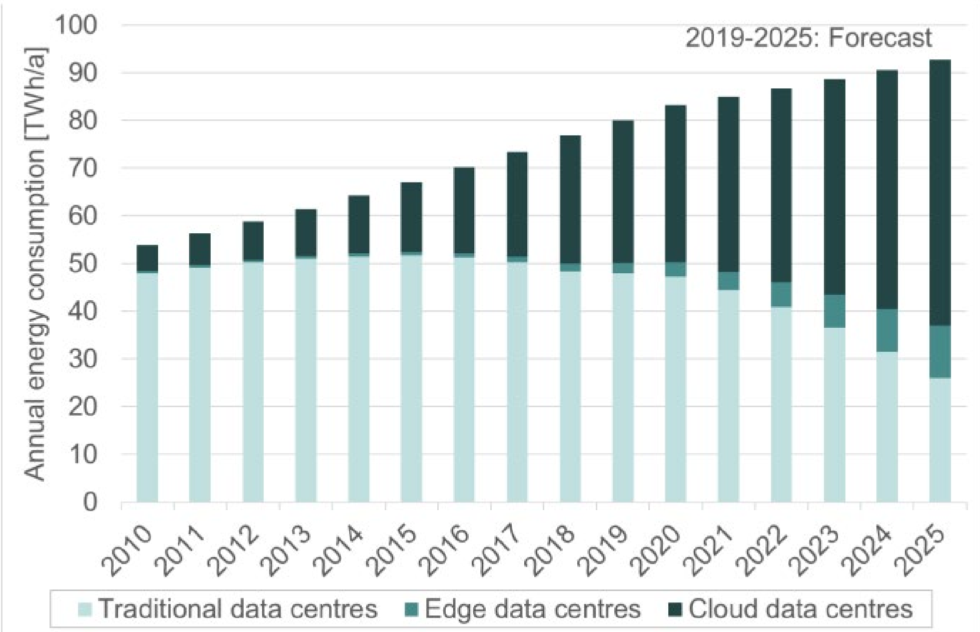


Figure 21: Trends and forecasts in terms of energy consumption by data centre type in EU28. Source: Montevecchi et al (2020)

10.4 Network Infrastructure

Similar trends of technological improvements leading to increased efficiency and data demand growth are seen in network infrastructure equipment as well.

IEA 2020 reports that energy efficiency of data transmission networks is improving rapidly, with fixed-line network energy intensity having halved every two years since 2000 in developed countries, and mobile-access network energy efficiency having improved by 10-30% annually in recent years.

At the same time, the same source expects data network consumption to rise to around 270 TWh in 2022 from around 250 TWh in 2019.

According to Andrae 2020 models, consumption is expected to increase further in the next years leading to 2030 in fixed access networks, both wired networks (Figure 22) and wireless access networks (Figure 23), both attributed to growth in data traffic.

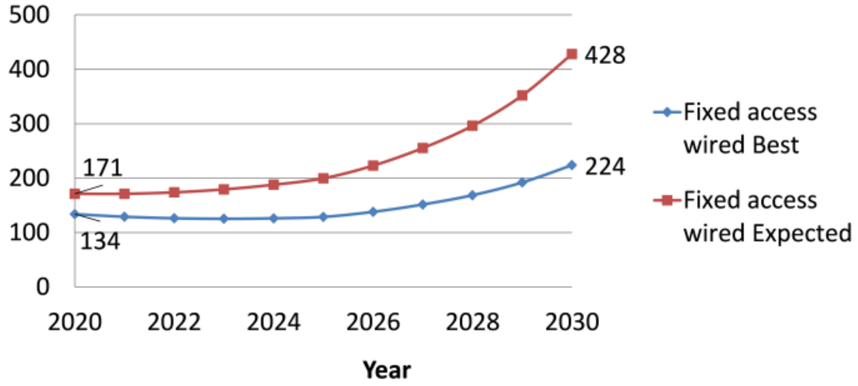


Figure 22: Electricity Usage (TWh) trends for fixed access wired networks 2020 to 2030 according to Andrae 2020

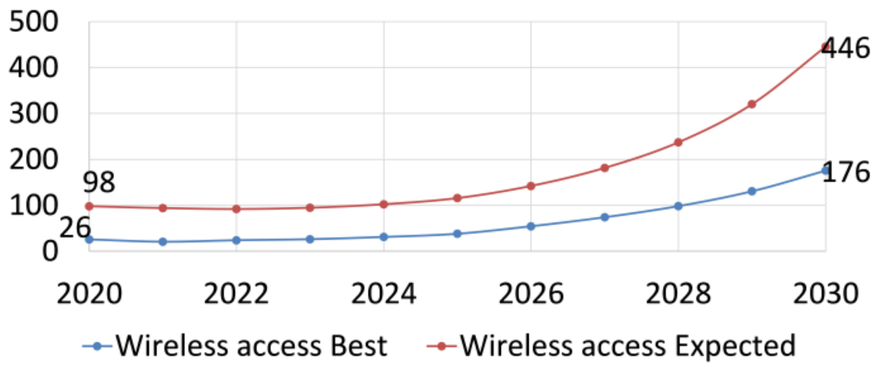


Figure 23: Electricity Usage (TWh) trends for wireless access networks 2020 to 2030 according to Andrae 2020

Estimations contained in the Recommendation ITU-T L.1470, and demonstrated in Figure 24, arrive to different results for fixed networks, forecasting a stabilisation of energy consumption until 2030, rather than the increase expected by Andrae (2020).

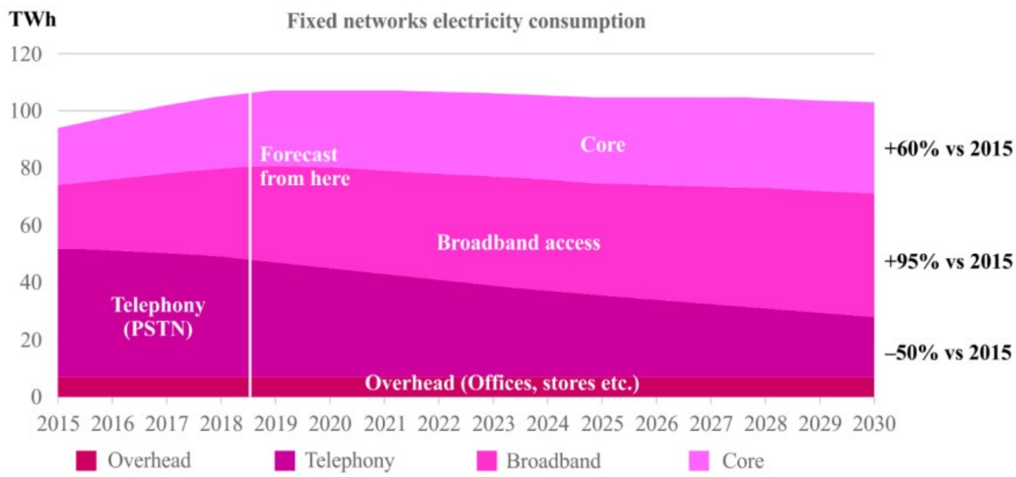


Figure 24: Fixed networks electricity consumption (ITU-T, 2020)

With regards to mobile networks, the estimations again contained in L.1470 are very much in line with those of Andrae (2020), forecasting an increase of consumption reaching the levels of 170-180 TWh in 2030 (Figure 25).

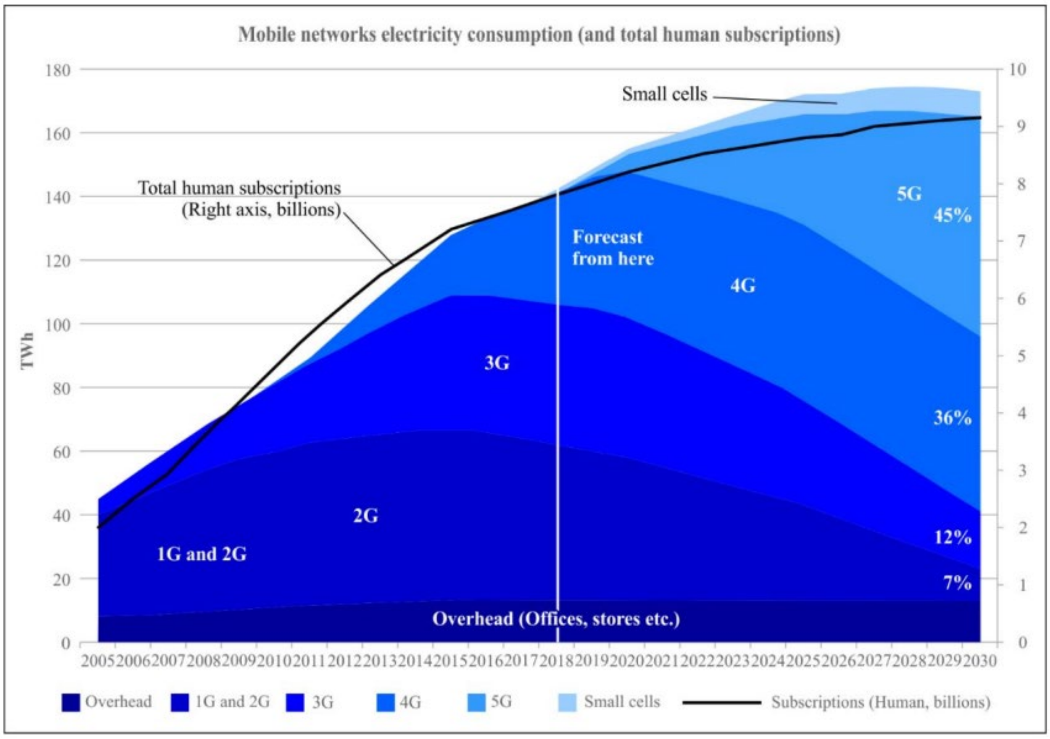


Figure 25: Mobile networks electricity consumption (ITU-T, 2020)

Network speed is another driver of internet traffic. According to Cisco (2020), anecdotal evidence supports the idea that overall use increases when speed increases, and broadband-speed improvements result in increased consumption and use of high-bandwidth content and applications. Table 12 and Table 13 below demonstrate the increase in fixed and mobile network speeds (in Mbps) both in Europe and globally almost, or in some cases above, threefold.

Table 12: Fixed broadband speed (on Mbps), 2018-2023

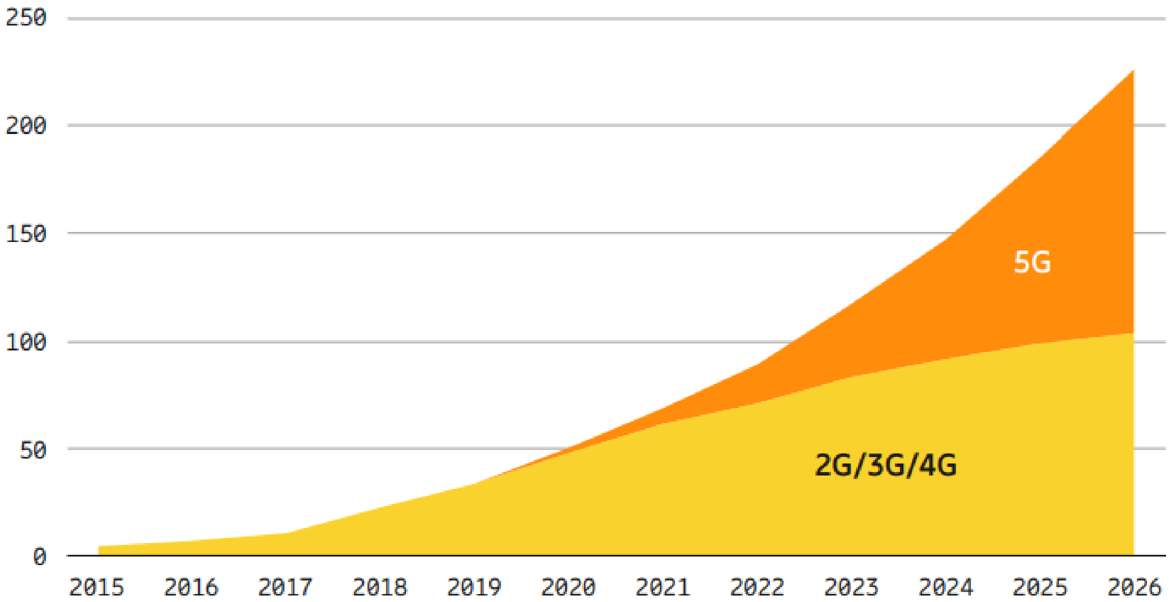
Region	2018	2019	2020	2021	2022	2023	CAGR (2018–2023)
Global	45.9	52.9	61.2	77.4	97.8	110.4	20%
Asia Pacific	62.8	74.9	91.8	117.1	137.4	157.1	20%
Latin America	15.7	19.7	34.5	41.2	51.5	59.3	30%
North America	56.6	70.1	92.7	106.8	126.0	141.8	20%
Western Europe	45.6	53.2	72.3	87.4	105.6	123.0	22%
Central and Eastern Europe	35.0	37.2	57.0	65.5	77.8	87.7	20%
Middle East and Africa	9.7	11.7	25.0	29.0	34.9	41.2	33%

Table 13: Average mobile network connection speeds (in Mbps) by region and country

Region	2018	2019	2020	2021	2022	2023	CAGR (2018–2023)
Global speed: All handsets	13.2	17.7	23.5	29.4	35.9	43.9	27%
Asia Pacific	14.3	18.0	24.7	32.4	39.0	45.7	26%
Latin America	8.0	11.2	15.7	21.1	24.8	28.8	29%
North America	21.6	27.0	34.9	42.4	50.6	58.4	22%
Western Europe	23.6	31.2	40.1	48.2	54.4	62.4	21%
Central and Eastern Europe	12.9	15.7	21.3	30.3	36.1	43.0	27%
Middle East and Africa	6.9	9.4	13.3	17.6	20.3	24.8	29%

Another factor of future IP traffic increase is the evolution of mobile devices from lower-generation network connectivity (2G) to higher-generation network connectivity such as 3G, 3.5G, 4G or LTE and now also 5G). More capable device and faster, more intelligent networks will facilitate the adoption of advanced multimedia applications that contribute to increased mobile and Wi-Fi traffic. Cisco 2020

Ericsson (2020) reports that 5G is estimated to cover around 60% of the population in 2026 compared to 15% in 2020, a trend exacerbated by COVID-19, making it the fastest deployed mobile communication technology in history. As shown in Figure 26, the same study predicts that in 2026, 5G networks will carry more than half of the world's mobile data traffic.



Note: This graph does not include traffic generated by fixed wireless access (FWA) services.

Figure 26: Trends and forecasts for global mobile data traffic (Exabites for months). Source: Ericsson (2020)

With such increase in traffic, what is the impact on energy consumption? Again studies focus on the question of whether energy efficiency potential of the new 5G protocol can compensate for the increased traffic generated.

In terms of efficiency, reports agree that the 5G protocol has the potential to achieve higher energy efficiency than legacy protocols. A new study by Nokia and Telefónica (Nokia, 2020) has found that 5G networks are up to 90 percent more energy efficient per traffic unit than legacy 4G networks, with more data bits per kilowatt of energy than any previous wireless technology generation. Montevecchi et al (2020) point out that 5G brings promising opportunities through new technologies that improve energy-efficiency. On the one hand within the RAN, the data volume transferred per energy consumed can be improved through high data transmission rates, which allow more data to be transmitted from a single transmitter with comparable power consumption. On the other hand, 5G brings other possibilities like small cell offloading and mobile edge caching (Yan et al., 2019) that can reduce the overall energy consumption of cloud application. Manufacturer of mobile network equipment aim to reduce the energy intensity of mobile data transmission (kWh/GB) by the factor 10 until 2022 compared to 2017.

However, for those efficiency levels to be realised, actions are necessary. According to Emil Björnson, an associate professor at Linköping University, (Clari et al, 2020) two fundamental aspects of 5G are an increase in the number of small cells and the rise of massive multiple-input multiple-output (MIMO) antennas. The increased number of small cells will logically imply higher energy consumption, but it has been pointed out that the individual energy consumption of each small cell is much lower than in a conventional cell. Concerning massive MIMO, it involves the use of arrays with many more antennas at each base station, which requires many more hardware components per base station and therefore more energy. A white paper released by Nokia (2016) base stations should be the subject of focus as they consume 80% of the energy used (only 15% of the energy is used to forward bits). Most of the energy is used for system broadcasts and running idle resources, to power fans and cooling systems (over 50% of the energy consumption), for heating and lighting, and to run uninterruptible and other power supplies. However, as the MIMO technology develops, its energy efficiency may also improve over time: the MAMMOET project has predicted that future massive MIMO base stations will consume less energy than 4G base stations, despite the fact that they will contain more hardware. A second solution is the possibility to put the base stations in "sleep mode" when there are no active users is one of the main ways to reduce energy consumption. Indeed, it is expected to reduce energy consumption by almost 10 times compared to current systems.

Montevecchi et al (2020) find that despite the optimism about the services and the interplay with edge computing enabled by 5G, there are significant concerns about rising costs. The move to 5G is likely to increase total network energy consumption by 150 to 170 % by 2026. Looking at the total energy consumption of mobile networks, these efficiency gains can be reduced or even erased by heavily increasing data transmission through the mobile networks. Increasing data volumes and the development of 5G mobile networks are also likely to boost the demand for decentralised computing capacities in edge data centres.

10.5 Consumer Devices and application software

As referenced above, the trend in electricity consumption in ICT systems will see consumption moving from the end-user devices to the network and data centre infrastructure. Looking at consumer devices independently from the ICT system and from a top-down approach, it is estimated by Andrae (2020) that the electricity usage that can be attributed directly to consumer devices (including wi-fi devices) will remain more or less stable or at best trend towards reduction onto 2030 (Figure 27).

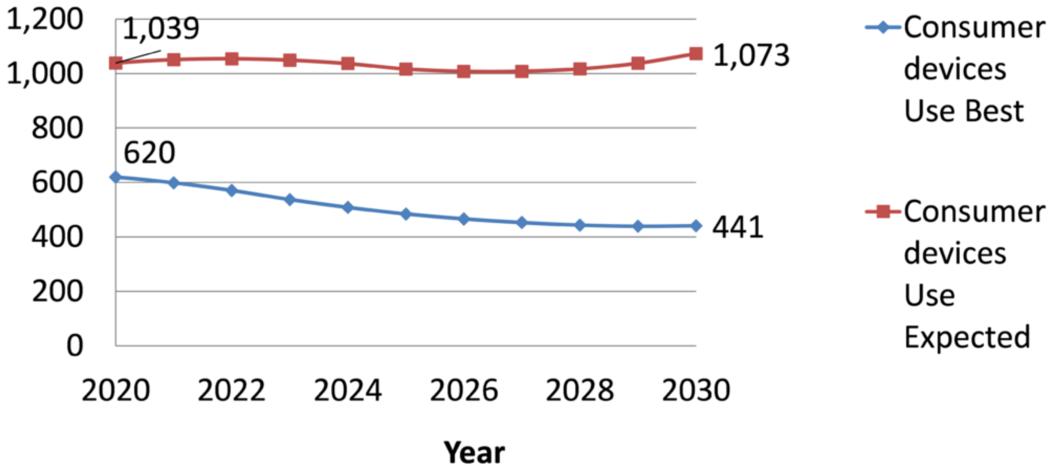


Figure 27: Electricity usage (TWh) of Consumer Devices 2020 – 2030. Source: Andrae 2020

However, as it becomes evident by the methodological challenges presented in section 3.1, such reduction or stabilisation alone does not mean devices do not contribute to increasing energy consumption of ICT systems as a whole. Therefore, trends in consumer device use and factors that influence consumption could still offer insight into the increasing energy use associated with the mobile access network presented above.

Projections from Cisco (2020) demonstrate an increase in the number of internet users, mobile users, networked device connections by 2023 compared to 2018 in both "Western Europe" and "Central and Eastern Europe" regions (see Table 14).

Table 14: Internet users, mobile users, networked device connections in the period 2018-2023 in different European Regions. Source: Cisco (2020).

	Western Europe		Central and Eastern Europe	
	2018	2023	2018	2023
Internet users	345 million	370 million	323 million	388 million
Mobile users	357 million	365 million	394 million	404 million
Networked devices/connections	2.4 billion	4.0 billion	1.2 billion	2.0 billion

The number of devices themselves are also growing globally, with this trend mainly driven by the growing number of Machine-to-Machine (M2M) applications, such as smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking, are contributing in a major way to the growth of devices and connections. Second most-growing type of devices are smartphones, followed by connected TVs (Cisco, 2020) (Figure 28).

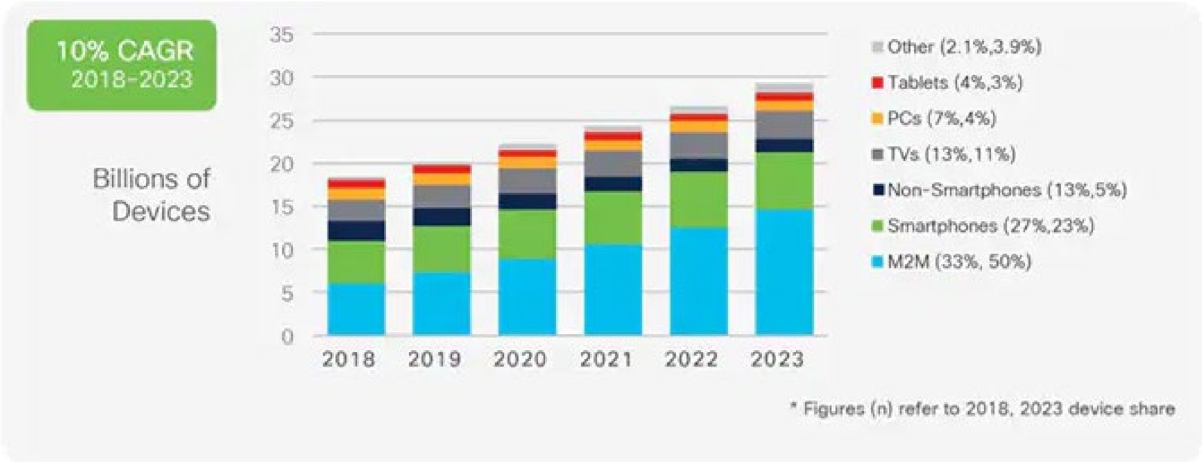


Figure 28: Number of connected devices in billions. Source: Cisco (2020)

M2M applications (i.e. the main driver of growth of IoT devices) are expected to grow to such an extent that IoT devices will account for 50 percent (14.7 billion) of all global networked devices by 2023 (Figure 29). Trends in the area of IoT and M2M may provide indications and explanations for the rise in network access connections presented above. (Cisco, 2020).

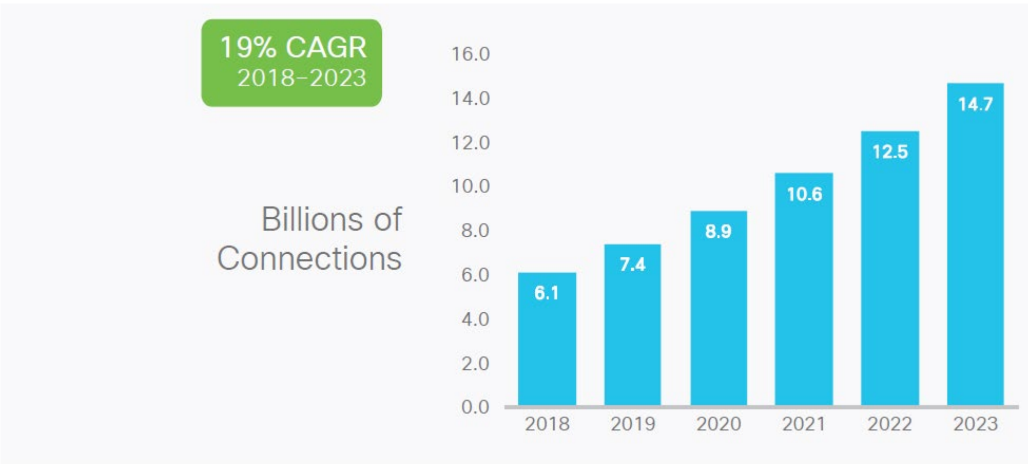


Figure 29: Global M2M Connection Growth. Source: Cisco (2020).

The Internet of Things (IoT) has been defined in Recommendation ITU-T Y.2060 (06/2012) as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies. (ITU, 2012)

As Figure 32 demonstrates, the energy consumption enabled by the semiconductors (here integrated circuit chips, i.e. sensors, processor integrated circuits (ICs), and connectivity ICs) themselves used in IoT devices is expected to reduce to insignificant levels (Das and Mao, 2020).

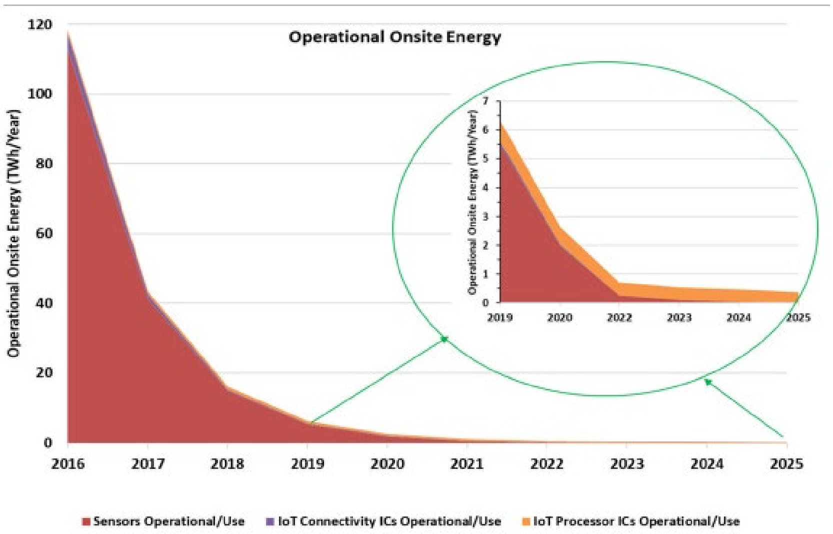


Figure 30: Projection of the operational energy consumption of semiconductors in the IoT (sensors, connectivity ICs, Processors ICs). Source: (Das and Mao, 2020)

What is more relevant is the effect that IoT technologies can have on the energy consumption of ICT systems via second-order effects. On one hand, smart functionalities can allow devices to operate in ways that save energy via optimization effects, and on the other, enable energy consumption of ICT systems via a large amount of data transfer and remote processing, i.e. induction effects. Optimization effects are studied in part 3a.

The applications that currently drive internet traffic growth are video streaming, social networking and gaming (Figure 34). Video streaming in particular not only holds the lion's share of internet traffic with 57.6% of share in year 2020, but also demonstrates the highest percentage of increase, having grown its share by 2.2% compared to the year before. Social networking applications are responsible for 10.7% of internet traffic, an increase of 1.78% compared to 2019. Finally, even though still in 7th place, gaming poses as a main driver for internet traffic in the future with 4.2% of the share, which has almost doubled since 2019 (Sandvine, 2020).

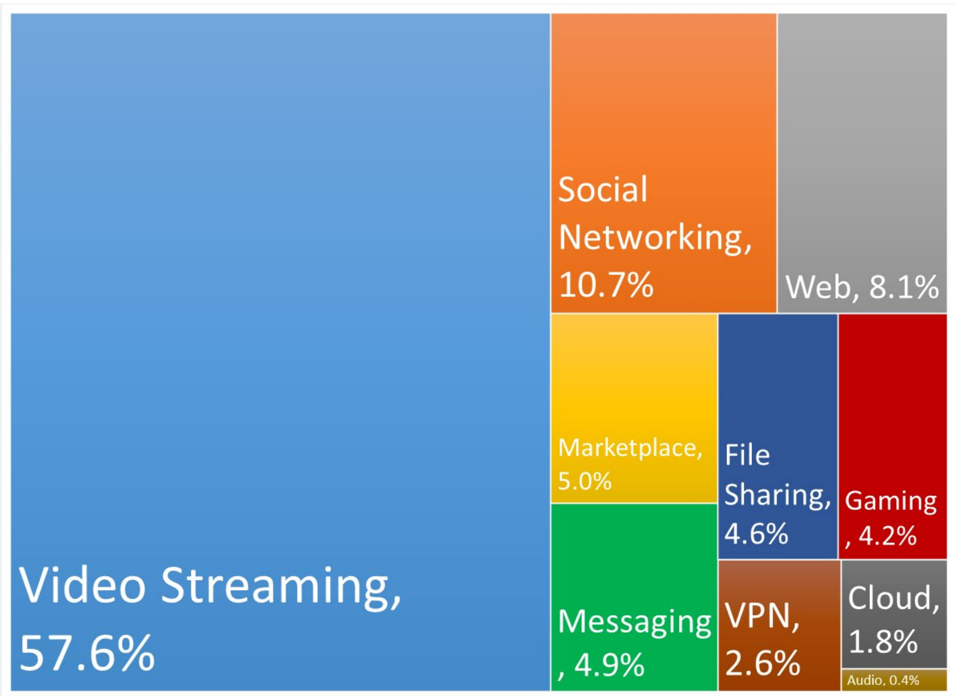


Figure 31: Global Application Category Total Traffic Share [data from Sandvine 2020]

Being dominant in terms of traffic share, video streaming offers an application worth investigating. Firstly, video streaming from the internet can have a substantial effect on traffic. One contributing factor is the resolution used for the streaming. The potential for traffic increase due to resolution increase can be demonstrated by Figure 32 below, whereby Cisco (2020) estimate that by 2023, two-thirds (66 percent) of the installed flat-panel TV sets will be UHD, up from 33 percent in 2018. The same source indicates that the bit rate for a UHD, or 4K, video is about 15 to 18 Mbps, meaning more than double the HD video bit rate and nine times more than Standard-Definition (SD) video bit rate (Cisco, 2020).

Figure 32: Increasing video definition. By 2023, 66% of connected flat panel TV sets will be 4K. Source: Cisco 2020

A characteristic example of the impact that video resolution has on internet traffic is the fact that at the early stages of the Covid-19 pandemic in Europe in March 2020, and after discussions with the European Commission, Netflix announced to reduce bit rates across all streams in Europe for 30 days, (thus reducing Netflix traffic on European networks by 25 percent), while YouTube committed to temporarily switch all traffic in the EU to Standard Definition by default (European Commission, 2020a)[10]. Sandvine (2020) predicts that if this change had not been made, video might have even touched 70% of overall bandwidth, having a mighty impact on many networks.

Another determining factor for the contribution of video streaming to traffic is the type of device used. Schien et al., 2013 attempt to bring the factors of type of device and type of network connection and Energy Consumption during the Use Stage of Online Multimedia Services Several studies (Schien et al., 2013; Shehabi et al., 2014) argue that estimated the energy demand of digital media including video streaming is very much dependent on the end device and the access network (Figure 33).

[10] YouTube and Netflix are the two applications with the largest traffic share at 15.94% and 11.42% respectively (Sandvine, 2020)

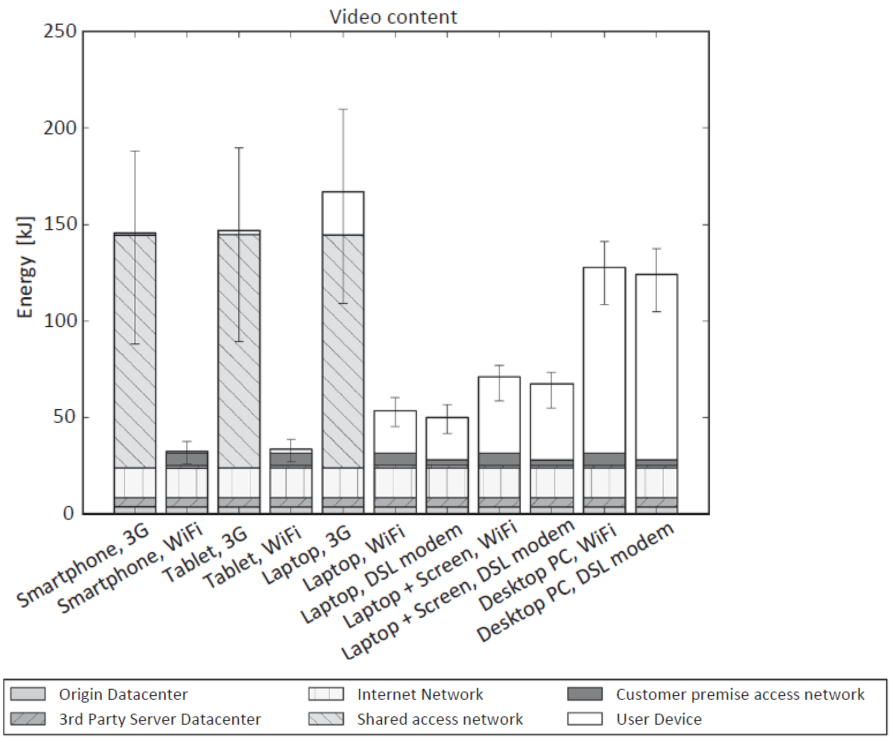


Figure 33: Energy consumption from video streaming in different configurations of access network and user device.

One device not considered in the study above is TVs whose increase connectivity combined with a higher energy consumption compared to other devices [Malmodin, 2014]. This observation plays an important role if one considers the future trends of device use for video streaming. In 2018, Netflix said that 70% of its streams end up on connected TVs instead of phones, tablets or PCs (Recode, 2018). Similarly, in 2017, YouTube reports that viewing on actual TV sets is up 70% in the last year (Recode, 2017). Kamiya (2020) concludes that viewing devices account for the majority of energy use (72%), followed by data transmission (23%) and data centres (5%).

In addition to the type of device, Figure 33 reveals another influencing factor for consumption, namely the type of network, especially in light of video traffic over mobile networks alone growing by 55% per year (Cisco, 2020). Andrae (2020) uses an electricity intensity factor (kWh / GB) for the influence of network type in energy consumption. This is presented in

Table *15* below, which demonstrates that currently wireless access networks are much more energy intensive compared to fixed access networks, however a very significant intensity decrease is forecasted by 2030, attributed to potential improvements in wireless networks.

Table 15: 2020 and 2030 key electricity intensity in kWh/GB, relevant for video streaming. Source: Andrae (2020)

Entity used in video streaming	Year 2020	Year 2030
Wireless access network	0.18	0.0144
Fixed access wired networks	0.07	0.017

Suski et al (2020) identify viewing duration of online video as another factor for the increase of online video traffic, due to user-behavioural rather than technical characteristics, such as the rise of mobile internet which can enable the parallelization of activities such as watching online video while commuting or waiting and ‘All-you-can-stream’ flat rates.

Considering above-mentioned factors, Carbon Trust (2021) estimated the energy consumption from one hour of video streaming on the basis of an average speed and a representative mix of devices used in Europe. They arrive to a European average of 188Wh per hour of video streaming, as presented in Figure 34.

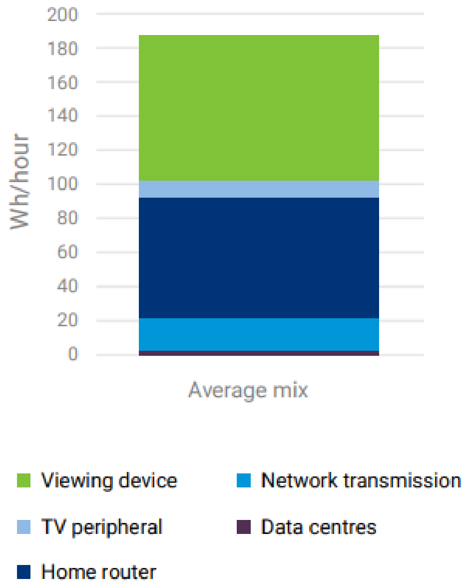


Figure 34: Estimated energy consumption from one hour of video streaming (European average in 2020)

While taking the above-mentioned factors and studies into account, the challenges of quantifying the energy consumption of video streaming systematically are similar to those described above for the other parts of the ICT system. A video is projected in a device, but it is stored in a data center facility. The streaming is achieved via the internet which is provided by a network infrastructure. Figure 35 demonstrates the ICT system devices and processes used to provide a streaming video service to a viewer (Shehabi et al 2014).

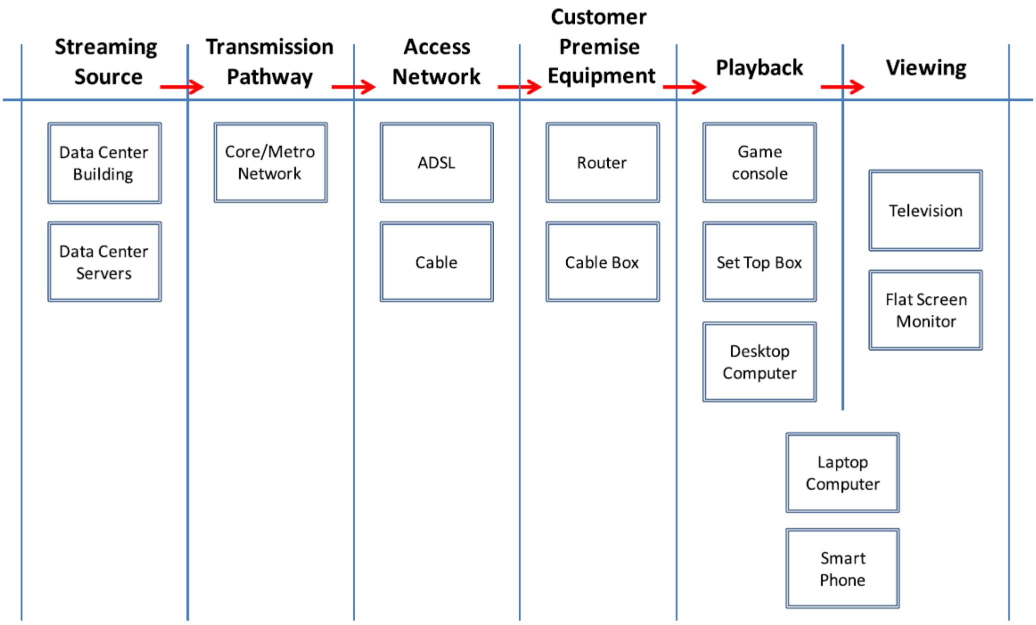


Figure 35: ICT system devices and processes used to provide a streaming video service to a viewer. Source: Shehabi et al 2014.

Therefore, as noted in section 3.1, allocating the energy consumption (and overall environmental impact) of video streaming and other application categories to one part of the system alone, or investigating only the energy consumption of end use devices, poses the risk of not only a misrepresentation of energy use reality, but also an inability to identify future trends.

Coroama and Hilty (2014) conclude that in order to determine the energy consumption caused by streaming and watching a video from the Internet, the system under study should include and separately consider:

(a) a properly allocated share of the consumption of the server providing the video (energy per time, i.e. just power)

(b) the consumption caused in the Internet by transmitting the data

(c) the end-user device's electricity consumption for the duration of the video being watched, *(measure energy intensity in energy per data)*

They further deem arguable whether devices should be considered relevant when defining the system boundary for the energy intensity of the Internet, because on one hand different types of devices have different energy consumption levels, and also consumption would be dependent on the applications used in those devices. However, they do argue in favour of considering customer premises equipment (CPE), which are mainly WiFi routers and modems.

Data from the previous section do not bring us to a conclusive answer to the question of the future of data centre energy use. Beyond methodological divergence, there is again the challenge of scope. Indeed, Bashroush (2020) maintains that bottom-up studies projecting energy efficiency gains enough to maintain a static energy consumption suffer from methodological uncertainty, and may potentially have excluded from the scope energy use associated with small to medium data centres, bitcoin mining and edge computing demands. Further trends supporting this challenge are the large increase in video streaming demand and mobile traffic, and the levels of electricity consumption increases report by some of the biggest streaming services. According to Google's published data, their electricity consumption went up by 33% between 2017 and 2018 (Google, 2019). Similarly, Netflix energy consumption (direct and indirect) went up by 84% between 2018 and 2019 (Netflix, 2019; Netflix, 2020).. Although the different approaches and methodologies between studies has to again be highlighted when reading those results.

Gaming is another area which is also expected to constitute a major driver of future IP traffic growth, driven by the development of cloud gaming. As is the case with video streaming, cloud games transfer graphics processing, and therefore energy consumption needs, to data centres and the ICT system.

A 2019 study (Mills et al, 2019) concludes that cloud-based gaming requires significantly more energy than similarly powerful equipment located in the gamer's home. Further investigation into two scenarios for cloud gaming in the United States - one assuming only 20% of cloud gaming by 2021 and another 75% - reveals higher energy use by 17% in the second scenario in the five years between 2016 and 2021.

A similar study (Marsden et al 2020) with a wider focus on carbon emissions examined three scenarios - one where streaming remains niche, a scenario where 30% of gaming moves away from conventional and into streaming platforms, and one assuming 90% of gaming switches to streaming over the next decade. It is estimated that emissions would be 30% higher per year from 2030 in the high-streaming scenario compared to a low-streaming one (Figure 36).

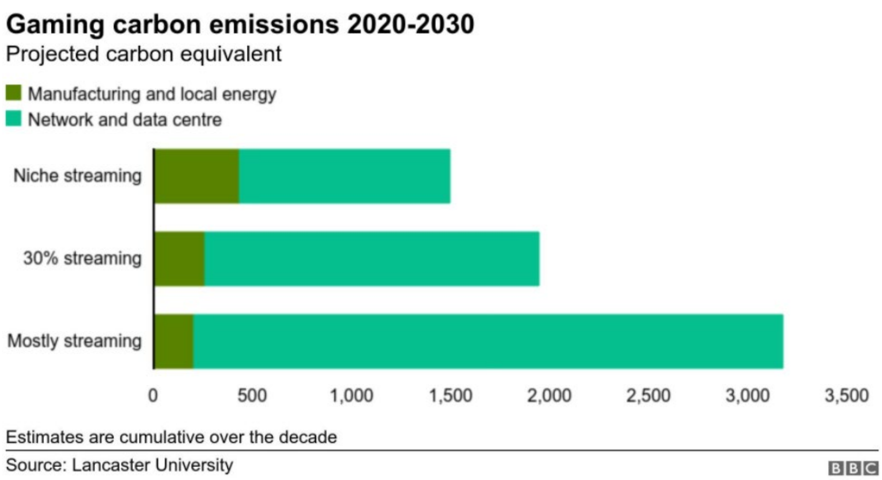


Figure 36: Cloud gaming: Are game streaming services bad for the planet? Figure source: BBC (2020). https://www.bbc.com/news/technology-53838645

Another area of interest that can affect the energy consumption of ICT systems is the mining of Bitcoin and other cryptocurrencies.

A summary of studies (Koomey, 2019) suggests that Bitcoin electricity consumption accounts for 44 TWh annually, or about 0.2% of global electricity use. That number seems to be in agreement with another study of the same year by Stoll et al (2019) who suggest a consumption of 45.8 TWh of electricity per year as of November 2018, accounting again for about 0.2% of global electricity consumption.

However, it has to be noted that those results are associated with a high level of uncertainty. IEA (2019b) notes that bitcoin's electricity consumption are wide-ranging, presenting results from a number of studies which range from 20-80 TWh annually, or about 0.1-0.3% of global electricity use. Another study by de Vries (2019) raises the number of energy consumption from mining operations to 0.5% of worldwide electricity use by the end of 2018—and eventually as much as 5%.

Such wide divergence derives from the fact that bitcoin and other cryptocurrencies exhibit rapid rates of change, even faster than growth in normal IT. This rapidity is driven in part by the volatile nature of cryptocurrency prices (Koomey, 2019). Furthermore, details about mining facilities, the hardware, and software use, are scarcely revealed, making estimations difficult.

And all that without account for other cryptocurrencies beyond Bitcoin.

10.5.1 **Software efficiency**

The efficiency of ICT devices can also be dependent on software. Although it is the hardware that consumes energy, the software triggers the consumption of the energy of a device. Kern et al., (2018) describe the interaction between software and hardware lifecycles according to Figure 37. Software design can influence several aspects of the hardware, including the processing power (energy consumption), but also some aspects related to the use of material resources as memory and storage capacity or specific peripheral devices and also have impacts on the obsolescence and disposal of the device.

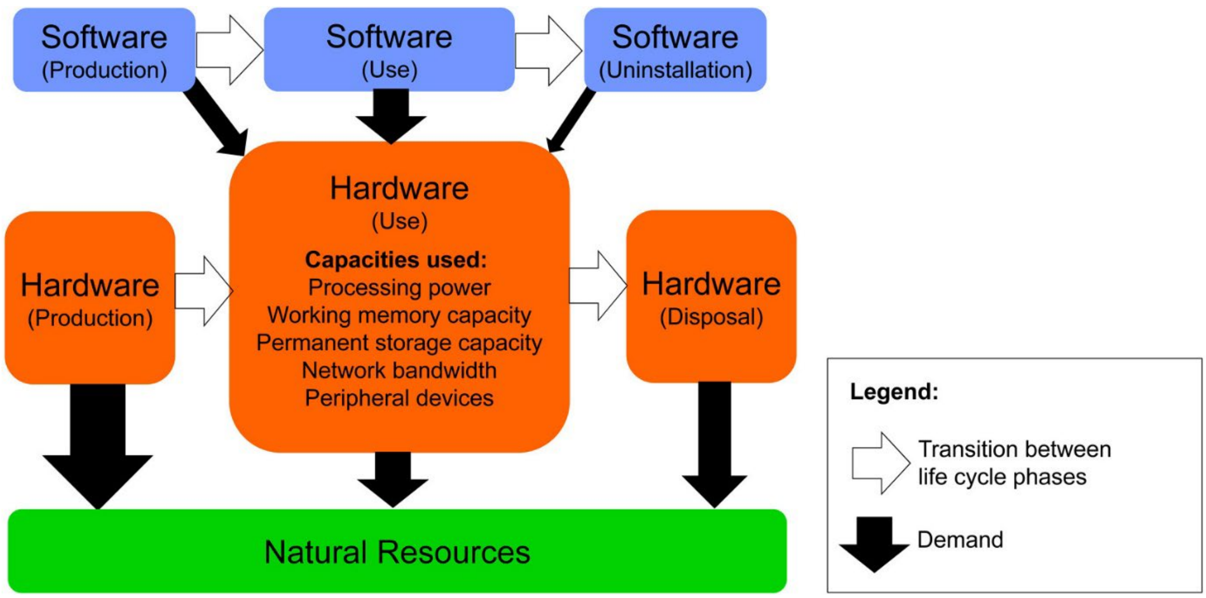


Figure 37: Life cycles of hardware and software (horizontal dimension) and the resource demand induced by the life cycles (vertical dimension)

In abstract terms. Kern et al., (2018) describe two essential flows caused by the use of a software product (Figure 38):

- the flow of energy through the hardware running the software (electricity to waste heat),
- the flow of hardware through the organization using it (new hardware to electronic waste).

If a software product causes significantly lower hardware and energy flows than competing products with similar functionality, it can be considered “relatively sustainable”.

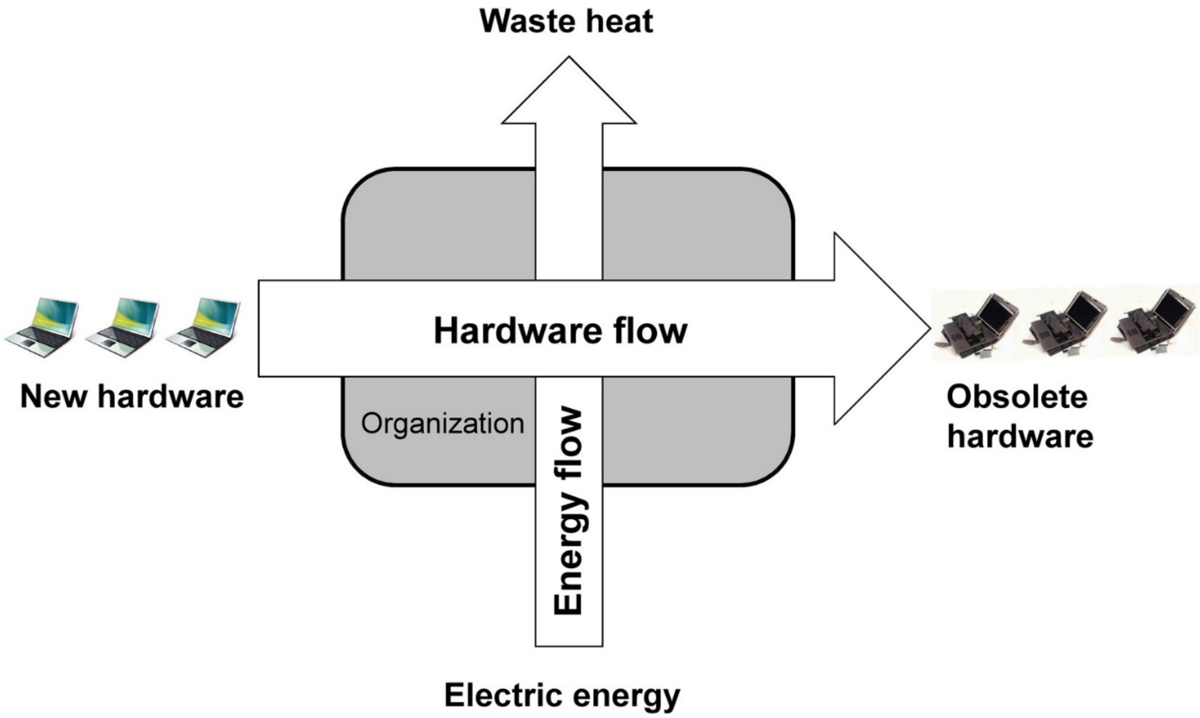


Figure 38: The two main physical flows to be reduced by sustainable software.

In terms of energy efficiency, the key question is: “how much electricity does the hardware consume when the software product is used to execute a standard usage scenario? Interaction of the software with material efficiency aspects will be further discussed and analysed in the following Tasks of this study (Task4 to Task6). How relevant is the impact from the “active use” of these application software to the hardware energy consumption compared to the idle/sleep mode scenario?

In order to better describe the issue of the “”active use” energy, Figure 39 describes the measured power and energy use for a “gaming computer plus display” in different modes of operation (Mills and Mills, 2016). This example shows that the level of energy consumption is highly dependent from the type of usage / application software and, in some circumstances, the application software can be responsible for a relevant part of the energy consumption of the hardware device.

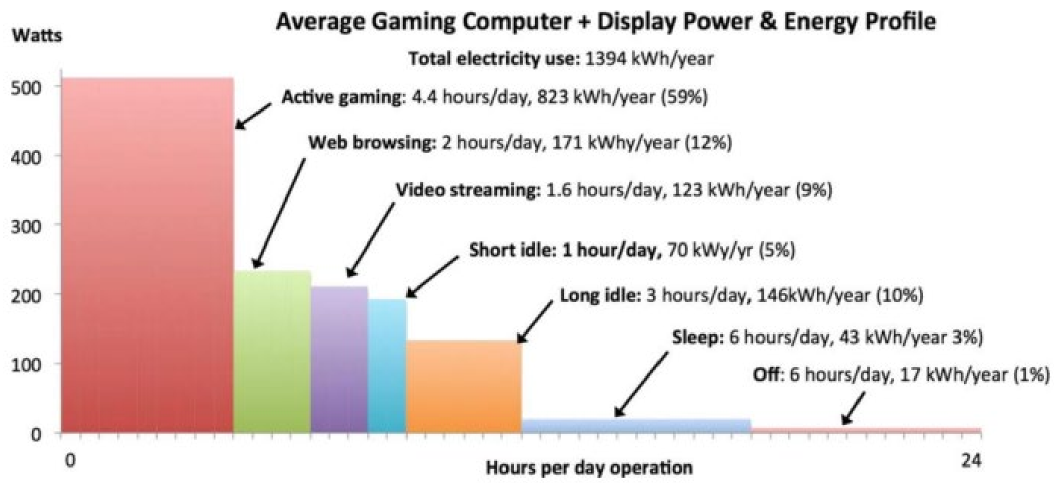


Figure 39: Measured power and energy use for different modes of operation

While “embedded” system software and firmware are normally considered as part of a product and addressed in product policy tools as the Ecodesign Directive (e.g. the efficiency of a washing machine is also related to the performance of its embedded software), less attention is paid to the “application software” that are commonly linked to ICT devices and applications. In the ICT context, application software can be defined as the software that uses the ICT system to perform special functions for end-users beyond the basic operation of the device itself (Viegand Magoe et al., 2021). They can be placed on the market / sold separately and may compatible with various device models or operating systems.Examples of application software in the ICT sector include word processors, databases, image or video editing for computers, video sharing and/or streaming applications for smart TVs, computers, tablets, smartphones, game applications for gaming consoles…

Within the research project "Development and application of criteria for resource-efficient software products with consideration of existing methods", sponsored by the German Federal Environment Agency, Gröger et al. (2018) has developed a methodological basis for determining the use of resources by software, comparing application software products with each other and making efficiency demands on them.

In Viegand Magoe et al., (2021), standard usage scenarios were defined for software product groups to be used as reference unit for all measurements of energy consumption and hardware usage. For the System Under Test (SUT), first the basic load of the device was determined by measurement, i.e. the average utilisation of the CPU, working memory and permanent storage, and the amount of data transmitted via the network without the application software to be tested. The application software to be measured was then installed and started on the device. As long as the software was still in an idle state, i.e. after the start but without execution of a usage scenario or interaction with the user, the idle load was measured. The third measurement was used to determine the (gross) utilisation of the system during the active operation of the application software by a standard usage scenario. Standardised evaluations ensured that software products that have gone through the same usage scenarios could be compared in terms of their energy efficiency and their use of hardware capacities. During the course of the scenario, usage of the hardware capacity and energy consumption were measured and the active tasks were recorded in the activity log of the load driver. It was possible to monitor and record the CPU, main and hard disk storage, network load and total system energy consumption.

The measurement results pointed out clear differences in energy consumption between the tested application software products with same functionality during their actual operation, see following Figure 40 and Figure 41.

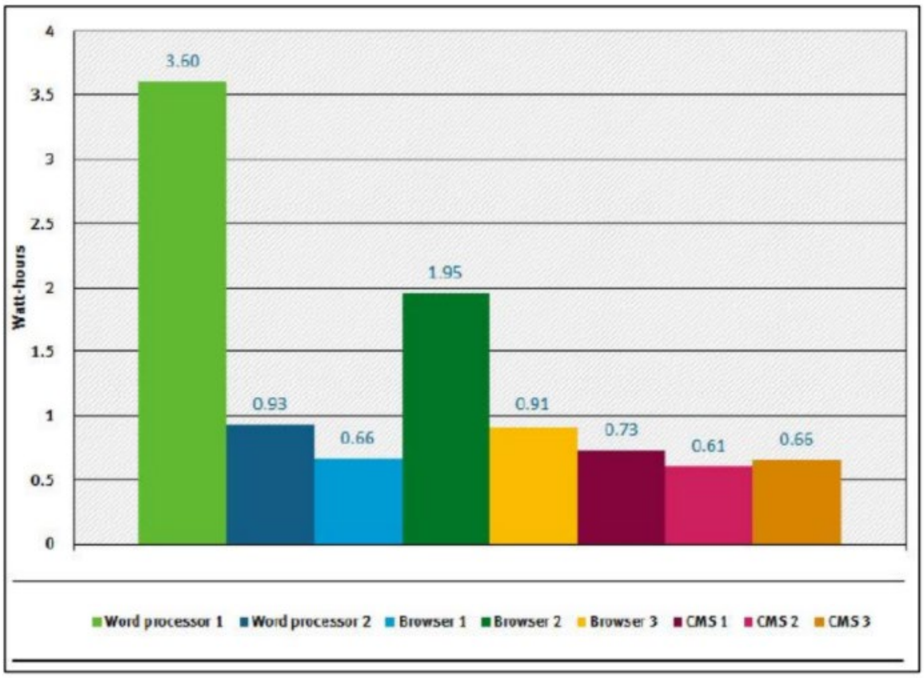


Figure 40: Comparison of energy consumption of the local device (SUT(Client)) during the execution of the standard usage scenario; source: Gröger et al. (2018)

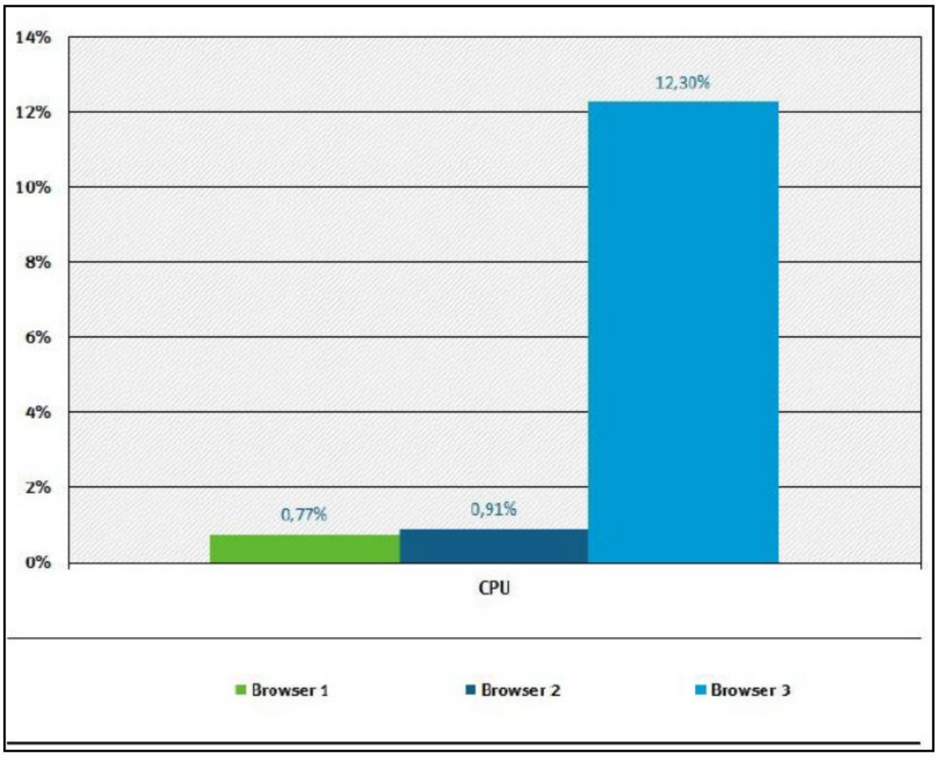


Figure 41: Hardware Utilization (CPU) of three web browsers in idle mode; source: Gröger et al. (2018)

Currently there are no legal requirements for the energy efficiency of application software products. During the development of the Ecodesign Working Plan 2020-2024 evidence and examples of improvement potentials in terms of efficiency have been provided. However no estimations in terms of saving potential were provided. The Commission has concluded, in the final Ecodesign Working Plan that the possibility of establishing more product-specific requirements on aspects related to durability, firmware and software may also be explored (European Commission, 2022).

However, at voluntary level, it is important to highlight that the Ecolabel Type I label “Blue Angel” has introduced in 2020 a first version of ecolabel criteria for Resource and Energy Efficient Software Products[11]. Among the criteria applied there are criteria addressing the use of energy in both idle and active mode and the interaction of the software with the energy management service of the device (see Table 16 below).

Table 16: Resources and Energy-Efficient Software Products (DE-UZ 215). Energy Efficiency criteria

Criterion Title	**Criterion Description**
Hardware utilisation and electrical power consumption in idle mode	The following information when the software product is in idle mode must be stated: • Average processor utilisation in idle mode (%) • Average working memory utilization in idle mode (MByte) • Average permanent storage utilization in idle mode (MByte/s) • Average bandwidth utilization for network access in idle mode (Mbit/s) (only contains the additional load, not the percentage share of the base load) • Average electrical power consumption (net) (W)
Hardware utilisation and energy demand when running a standard usage scenario	The following information must be provided when executing the standard usage scenario under the standard configuration: • Processor utilisation (%*s) • Working memory utilisation (MByte*s) • Permanent storage utilisation (reading and writing) (MByte/s*s) • Volume of data transferred for network access (Mbit/s*s) • Average energy demand (net) (Wh)
Support for the energy management system	A software product must not require that an already existing energy management system on the computer (e.g. standby mode/idle mode) is deactivated/uninstalled for it to operate perfectly. The energy management system on the computer must not be negatively influenced by the software product. The functionality of the software product must not be influenced by the energy management system (e.g. loss of data, impaired usability).

10.6 Conclusions

The question is a matter of new energy efficient technologies driving energy consumption reduction, and data traffic increases driving consumption up. The main drivers of higher energy efficiency include the shift to larger and more efficient hyperscale data centres, as well as technological improvements in terms of computation and network devices. On the other hand, exponential increases expected in terms of the number of devices, connections, subscriptions, streaming and, subsequently, data demand and IP traffic, may deem efficiency improvements insufficient to curb the consumption trajectory. Indeed, several studies (especially ones using a top-down approach) conclude that energy consumption of ICT systems will increase, while more optimistic studies (especially those using a bottom-up approach) argue that it will remain more or less the same due to higher efficiency. Due to fast tech cycles, these estimations are associated with some level of uncertainty, especially when it comes to the impact of technologies and applications such as bitcoin mining, video streaming resolutions etc.

[11] Resources and Energy-Efficient Software Products (DE-UZ 215). Available at https://www.blauer-engel.de/en/productworld/resources-and-energy-efficient-software-products/resources-and-energy-efficient-software-products

11 Qualitative contribution of ICT to energy efficiency in systems ("Internet of Things")

11.1 IoT market penetration and effects

The importance of Internet of Things (IoT) is demonstrated by its projected increasing use in the following years, as depicted in Figure 29 above.

The first order effects deriving from IoT deployment (i.e. contribution to energy consumption) are described in 3b. In this section 4, second order effects associated with the use of IoT and digitalisation are presented, namely in terms of system optimisation and increase of system efficiency. This efficiency is achieved in various sectors where IoT is utilised, ranging from the energy system to buildings and from industrial applications to transport. It also materialises with the use of various technologies, from sensors and connection protocols to energy meters and data analysis.

11.2 IoT Applications

11.2.1 Application Taxonomy

Shaikh et al(2017) offer a useful taxonomy of Green IoT applications in Figure 42. Green IoT can be defined as "the energy efficient procedures (hardware or software) adopted by IoT either to facilitate reducing the greenhouse effect of existing applications and services or to reduce the impact of greenhouse effect of IoT itself".

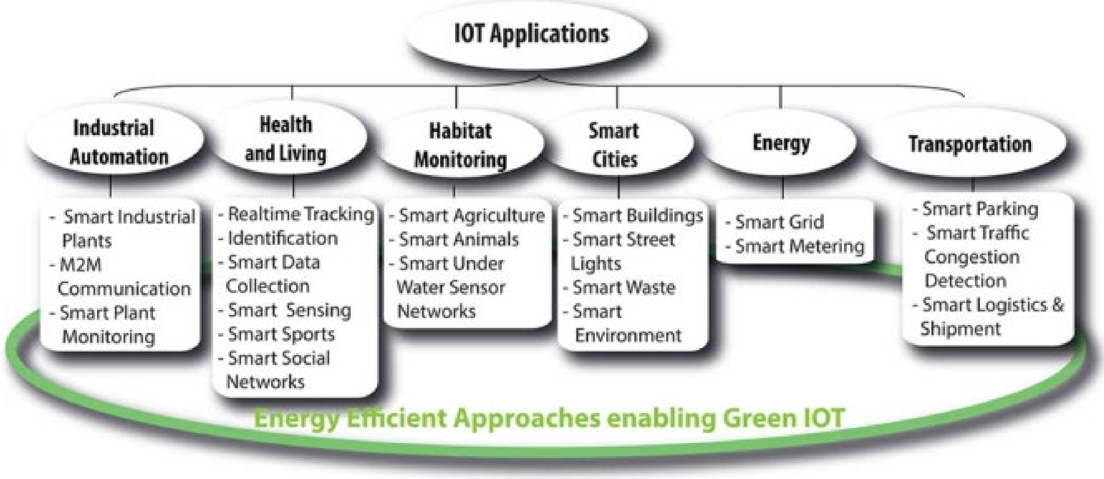


Figure 42: Energy efficiency approaches enabling Green IoT

1. Industrial Automation, including applications such as smart industrial plants and M2M communication, which help improve automation of industrial plants and improve energy efficiency by monitoring various parameters, such as temperature, air pollution and machine faults.

2. Health and Living, whereby applications such as smart data collection in the healthcare sector can achieve energy efficiency by reduction of processing time, automated hospital admission processing, and automated care and procedure auditing.

3. Habitat Monitoring, and smart agriculture with the deployment of smart underground sensors and smart insect detection and monitoring of irrigation systems and environmental impacts.

4. Smart Cities, encompassing a wide range of applications within urban spaces such as smart buildings Smart homes and offices use IoT devices to optimize HVAC or lighting management, but also support energy demand and renewables integration (Hittinger and Jaramillo 2019). In street lighting,conventional street lighting systems which remain turned on until morning, and often in areas without presence of people can be replaced by energy efficient monitoring systems. Digital technologies can also enable smart waste management systems, by improving recycling, facilitating

the use of recyclates by producers, enabling better purchasing and sorting decisions by consumers, and improving waste sourcing options for recyclers (EEA, 2021).

5. Energy system applications, such as smart metering. Smart meters enable two-way communication between the smart meter and the utility company by recording the consumption of electric energy and transmitting that information for billing purposes.

6. Transportation, including solutions such as Smart Parking, Smart Traffic Congestion Detection and Smart Logistics/Shipment applications which can reduce traffic congestion, help enterprises to respond to changing markets in the shortest possible time and improve the efficiency of the food supply chain.

Figure 43 from Horner et al 2016 provides examples of impacts from ICT services which are related to the positive effects of substitution and optimisation ("efficiency").

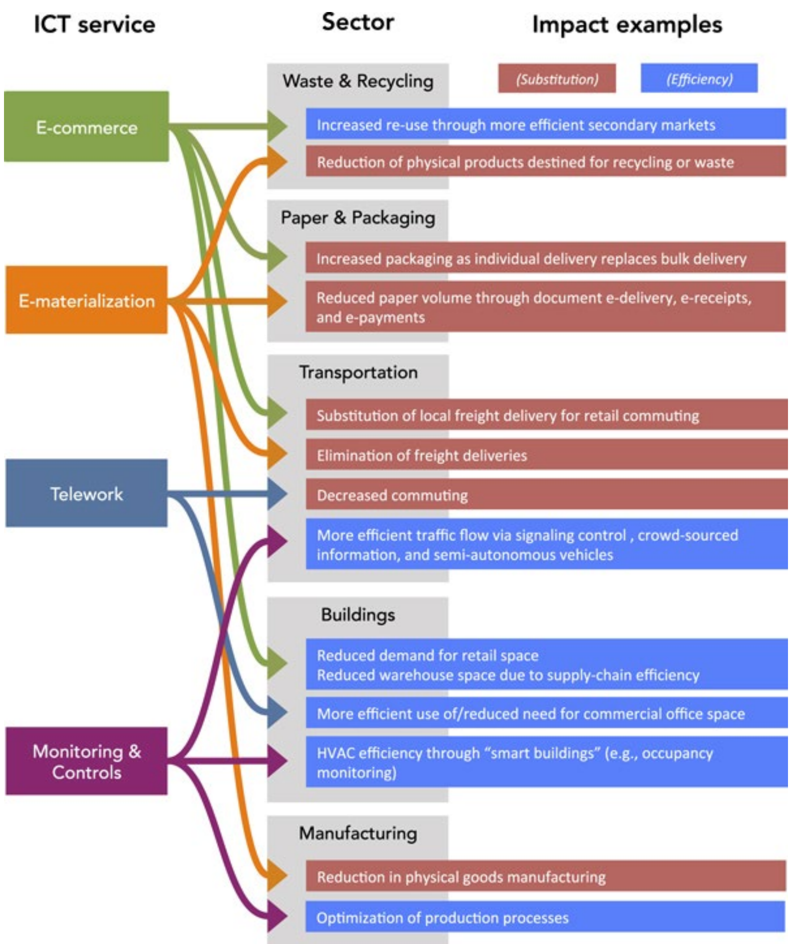


Figure 43: Impact of ICT Services in different sectors

The impacts span across many sectors, and also refer to impacts which may go beyond those considered as second-order effects and within those considered third-order effects (e.g. impacts on transportation, reduced demand/need for building space). For the purpose of this study, our focus is on the effects on the Manufacturing, Energy and Buildings sectors.

11.2.2 Industry / Production Management

Digital technologies are changing the face of industry and the way we do business. They create new business models, allow industry to be more productive, provide workers with new skills and support the decarbonisation of our economy. The digital sector will also contribute to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint (European Commission, 2020b).

In industry, many companies have a long history of using digital technologies to improve safety and increase production. Further cost-effective energy savings can be achieved through advanced process controls, and by coupling smart sensors and data analytics to predict equipment failure (IEA 2019a).

IoT technologies provide awareness of energy consumption patterns by collecting real-time energy consumption data that offer several opportunities to reduce energy consumption by enabling and enhancing energy-efficient practices in production management. (Shrouf and Miragliotta 2015.)

IoT technologies have a key role in smart industry (also called Industry 4.0[12]), where fully-integrated, collaborative manufacturing systems respond in real time to meet changing demands and conditions in the smart factory and even in the supply network, and in customer needs.

According to Rogers (2014) smart manufacturing is related to intelligent efficiency, as they both use ICT to achieve efficiency goals. Intelligent efficiency is energy efficiency made possible by the deployment of affordable next-generation sensor, control, and communication technologies that gather, manage, interpret, communicate, and act upon disparate and often large volumes of data to improve device, process, facility, or organization performance. The energy efficiency improvements can be at multiple layers as showed in Figure 44.

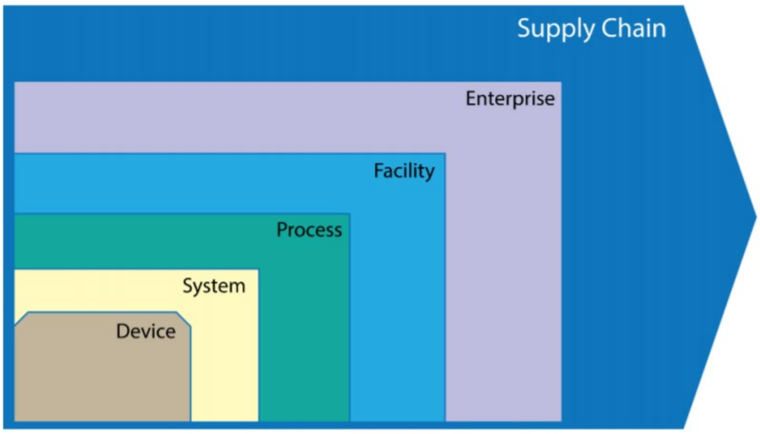


Figure 44: Order of energy savings in manufacturing. Source: Rogers (2014)

The integration of energy data into production management decisions requires not only a network of sensors but also requires e-DSS (energy-Decision Support Systems), the definitions of a set of e-KPIs, visualization tools, optimisation techniques to support energy aware decision-making (Shrouf and Miragliotta 2015).

According to Wang et al. (2018), in order to increase the energy efficiency, a manufacturing company should achieve real-time and seamless dual-way connectivity and interoperability between physical manufacturing systems and enterprise information systems. With the real-time status of machine operation being tracked, the abnormal events of machines such as tool wear, breakdown and efficiency reduction can be also found and managed easily and timely.

Shrouf and Miragliotta (2015) described six main energy related benefits from the adoption of Internet of Things in production management (see Table 17). These optimization areas go beyond the equipment level and include system and process levels (machine scheduling, environmental conditions, resources assignment, operation planning).

Finally, in the evaluation of the net benefits of IoT in industry, the negative effects discussed in the previous chapters of this study should be also taken into account. In particular:

- The generation of large volume of data destined to be transmitted to Cloud Data Centres (and related impacts
- The manufacturing of increasing number and variety of IoT electronic devices in a wide range of uses to support the IoT infrastructure.

[12] Industry 4.0: Digitalisation for productivity and growth. Available at https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568337/EPRS_BRI(2015)568337_EN.pdf

Table 17: Energy efficiency benefits of IoT adoption in production management. Source: Shrouf and Miragliotta 2015

Benefits of IoT adoption (energy efficiency related)	Practices enhanced or enabled by IoT which lead to those benefits
1. Finding and reducing energy waste sources	Comparing energy consumption with production level to find the waste source. Comparing energy consumption for the same process (e.g. heating, molding) in different environments, and then improve.
2. Improving energy-aware production scheduling	Integrating energy consumption data into manufacturing systems to optimize production scheduling Energy efficient jobs routing, when there is sufficient machine flexibility to do so Defining energy consumption for a machine in different configurations (e.g. speed), and then choosing the more efficient machine configuration. Reducing idle time by switching a machine off, if energy consumption in Off/On transition is less than energy waste during idle time.
3. Reducing energy bill 3.1 Avoiding a financial penalty due to breach of the maximum consumption levels 3.2. Reducing energy purchasing cost	Reducing energy consumption at peak time (e.g. load balancing) Negotiating with energy providers and buying energy from several suppliers Making energy purchasing decisions (i.e. determining quantity to purchase) based on real consumption data
4. Efficient maintenance management 4.1 Shifting to condition-based maintenance 4.2 Increasing energy-efficient maintenance 4.3 Increasing accuracy and reliability of equipment by ensuring it is in good condition based on real-time data.	Maintenance based on energy use pattern (e.g. predictive, proactive maintenance).
5. Improving environmental reputation 5.1 Meeting customers' expectations and environmental regulations 5.2 Obtaining environmental certifications (e.g. ISO 50001)	Measuring and reducing the CO_2 footprint coming from production processes, and making such data available to stockholders
6. Supporting decentralization in decision-making at production level to increase energy efficiency.	Using several energy KPIs to evaluate energy usage in production Using visual dashboards on the shop floor to enhance decentralized visual management

11.2.3 Energy systems

IoT can provide a variety of services to energy systems, enabling optimal decisions at both the supply and demand side, and turning them from centralised and one-directional to smart and integrated (Motlagh et al, 2020).

The Figure 45 below demonstrates the plethora of IoT applications in energy systems, which allows for bringing together its subparts into a synergic system.

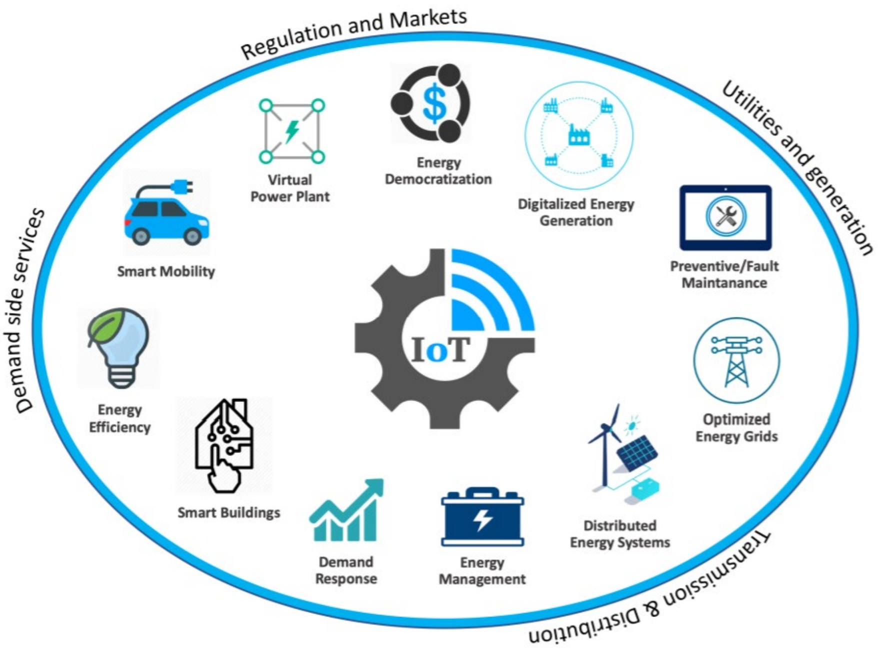
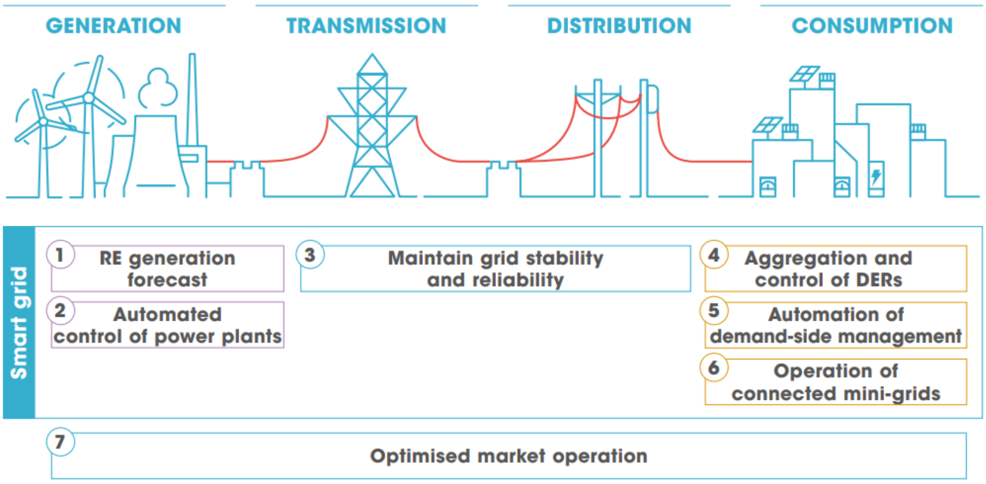


Figure 45: Application of IoT in an integrated smart energy system

Central to a smart energy system integration are smart grids. A smart grid is a concept that integrates information and communication technologies (ICT) with grid power systems, in order to achieve efficient and intelligent energy generation and consumption (Iyer and Agrawal, 2010). IoT can help the energy sector to transform from a centralized to a distributed, smart, and integrated energy system. This can provide major benefits in terms of renewable energy sources (RES) integration, as well as grid stability (Motlagh et al 2020).

Deployment of RES, such as wind and solar, is key towards reaching decarbonisation objectives. However, it is also characterised by challenges related to prediction and control of energy supply (i.e. the intermittency challenge): in an energy system with a high share of Variable Renewable Energy (VRE), matching generation of energy with demand is a big challenge due to variability of supply and demand resulting in mismatch in different time scales (Motlagh et al. 2020).

A lack of management of energy supply and an imbalanced electricity system can lead to energy and material waste due to long distance electricity transportation, electricity network losses, and ultimately, thermal heating and degradation of energy system equipment (Más and Kuiken, 2020). This challenge could be addressed by increasing the physical capacity of the electricity system, but at the same time leading to more resource use (more reserve capacity, cables, transformers, etc.). IoT, on the other hand, can address these challenges and play a vital role in RES integration, by facilitate grid stability by optimising energy demand and supply and address the aforementioned challenges more efficiently (Más and Kuiken, 2020). IRENA (2019) outline the effects of digitalisation and grid smartness across the entire energy system from energy generation from RES to consumption (Figure 46).



DER = distributed energy resources
Source: IRENA, IRENA, adapted from BNEF, 2017

Figure 46: Current state of digitalisation of the energy value chain

In terms of renewable energy generation, the study of weather patterns and collection of real-time data can address the issue of energy generation predictability. General Electric estimates that by implementing digital systems and data analytics, forecast accuracy can increase up to 94% from around 88% today (IRENA 2019). The use of sensors and control systems on power plants such as wind turbines can enable responses to weather and network conditions and optimise generation efficiency.

When it comes to transmission and distribution, IoT can contribute to grid management and network system health, by smoothening out peak load demand that stress and imbalance the system. It can also be used in the context of preventive maintenance, with the use of smart devices and sensors that can indicate and inform about equipment failures.

On the consumption side, digital tools can enable forecasting of energy demand and generation, optimisation of energy reserves, control voltage and frequency, and connect or disconnect from the main grid, facilitating local energy generation when sites are in remote areas and not connected to the main grid. (IRENA 2019). IoT offer solutions for the automation of demand-side management and contribute to the establishment of a smart grid.

Mas and Kuiken (2020) also recognise the role of IoT in improving the matching of demand with the available supply. Demand Side Response (DSR) could consider not only the timing of production and consumption, but also the location of consumption and production, potentially bringing even more efficient results. Considering the growing amount of distributed RES (e.g. solar panels or – onshore – wind turbines), local demand and supply matching could reduce network losses: in general, the less electricity must be transported, the less electricity will be wasted. Also, DSR could reduce the need for spinning reserves[13], which could reduce the amount of energy wasted for balancing the electricity system.

In order to apply DSR, sufficient data on consumption and production patterns need to be available on the (expected) production and consumption, and the local network status (Más and Kuiken, 2020). Moreover, a response mechanism should be present. Such a mechanism could simply be a consumer, switching on or off equipment at exactly the right moment, but will more likely be an automated mechanism, a configuration in which e.g. an appliance (or a management interface connected to the appliance) is able to switch itself (or it) on or off, or to reduce or increase the consumed loads by the appliance.

Heat pumps are considered to be a major technology to provide flexibility to the power system meanwhile providing efficient heating and cooling solutions to residential buildings. The technology is supported by increasing efficiency, the deployment of computing and communication technology and increased renewable electricity generation. Potential benefits of peak reduction on an aggregate level involve lower electricity

[13] The spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system

generation costs (which is called merit order effect), less need for peak generation reserve power plants and less need for transmission capacity (Fischer and Hadani, 2017).

Such optimisation is also achieved with the use of smart appliances and devices; such technologies are further studied in the following section.

Table 18 summarises the benefits of different applications of IoT in the energy sector. Motlagh et al. 2020 identifies possible benefits both in the field of the energy supply regulation and markets and in the field of energy supply (see table below).

Table 18: Benefits of the applications of IoT in the energy sector (1): regulation, market, and energy supply side. Source: Motlagh et al., 2020.

	Application	Sector	Description	Benefits
Regulation and market	Energy democratization	Regulation	Providing access to the grid for many small end users for peer to peer electricity trade and choosing the supplier freely.	Alleviating the hierarchy in the energy supply chain, market power, and centralized supply; liquifying the energy market and reducing the prices for consumers; and creating awareness on energy use and efficiency
	Aggregation of small prosumers (virtual power plants)	Energy market	Aggregating load and generation of a group of end users to offer to electricity, balancing, or reserve markets.	Mobilizing small loads to participate in competitive markets; helping the grid by reducing load in peak times; Hedging the risk of high electricity bills at peak hours; and improving flexibility of the grid and reducing the need for balancing assets; Offering profitability to consumers.
Energy Supply	Preventive maintenance	Upstream oil and gas industry/ utility companies	Fault, leakage, and fatigue monitoring by analyzing of big data collected through static and mobile sensors or cameras.	Reducing the risk of failure, production loss and maintenance downtime; reducing the cost of O&M; and preventing accidents and increasing safety.
	Fault maintenance	Upstream oil and gas industry/ utility companies	Identifying failures and problems in energy networks and possibly fixing them virtually.	Improving reliability of a service; improving speed in fixing leakage in district heating or failures in electricity grids; and reducing maintenance time and risk of health/safety.
	Energy storage and analytics	Industrial suppliers or utility companies	Analyzing market data and	Reducing the risk of supply and demand imbalance; increasing profitability in energy trade by optimal use of flexible

			possibilities for activating flexibility options such as energy storage in the system.	and storage options; and ensuring an optimal strategy for storage assets.
	Digitalized power generation	Utility companies & system operator	Analysing big data of and controlling many generation units at different time scales	Improving security of supply; improving asset usage and management; reducing the cost of provision of backup capacity; accelerating the response to the loss of load; and reducing the risk of blackout.

11.2.4 Homes and Offices Buildings

The importance of improving the energy efficiency at homes and offices derives not only from the fact that buildings are responsible for approximately 40% of energy consumption and 36% of CO2 emissions in the EU[14], but also from future trends: the IEA Central Scenario (IEA 2019a) suggests that electricity use in buildings is set to nearly double from 11 petawatt hours (PWh) in 2014 to around 20 PWh in 2040 globally.

As indicated in the previous section, IoT at building level can offer a variety of benefits in terms of energy efficiency, not only for the building itself but the energy system as a whole.

The concept of Smart Building could be defined as a set of communication technologies enabling different objects, sensors and functions within a building to communicate and interact with each other and also to be managed, controlled and automated in a remote way (European Commission, 2017).

Building Automation and Control Systems (BACS) with the use of sensors, communication protocols and automated processes allow for the control of the building's operations, including adjusting HVAC (Heating, Ventilation, Air Conditioning) systems according to ambient conditions, or adjusting lighting levels based on room occupancy. Thus, they provide various services ranging from comfort to safety, but also energy efficiency within the building.

At the same time, and as described in the previous section, such automation and connectivity allows an interaction with the wider grid and all the way with the energy production source.

The following graphs Figure 47) demonstrates the increased development in smart homes in millions and also the penetration rate in Europe.

[14] https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

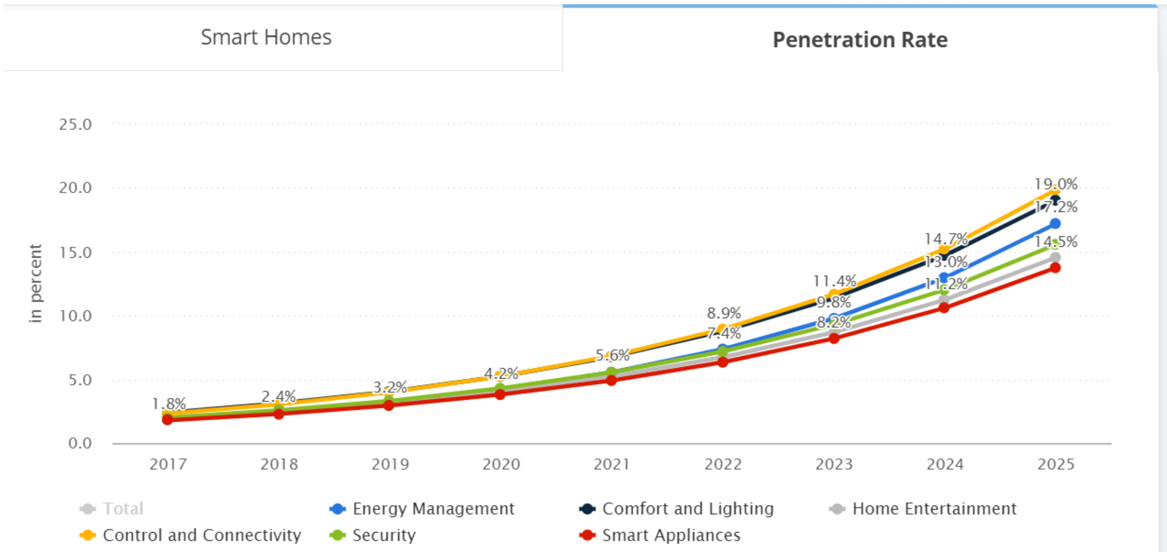


Figure 47: Penetration Rate of smart home devices. Source: Statista, November 2020, https://www.statista.com/outlook/279/102/smart-home/europe

Despite the expected increase in the coming years, the penetration rate of smart homes is still at a stage of early, tech-oriented adopters (Serrenho and Bertoldi, 2019).

Table 19 offers a list of various BAC system products and also components that are providing data input to the system (VHK and Viegand Maagøe, 2020):

Table 19: BACS products and related components / sensors providing data inputs

BAC system product	Components providing data input
heating, ventilation (including window openings) and air conditioning (HVAC)	Temperature sensors
domestic hot water (DHW)	CO2 sensors
solar shades	Humidity sensors
lighting	Presence detectors
electrical power distribution	Solar radiation sensors
access control & security	Outdoor wind speed meter
fire safety	Light meter
	Domestic cold and hot water meters
	Electricity meters
	Heat and other energy meters
	Door and window opening sensors
	Smoke and fire detectors
	Access control detectors
	User setting for desired indoor quality level, scheduling

A main feature of smart buildings is the use of smart appliances, meaning appliances that are communication enabled (VITO, 2016). This is achieved with the use of IoT technologies, which can contribute to energy efficiency by containing energy saving features (e.g. alerting when the refrigerator door is left open or allowing for demand response flexibility. Such IoT technologies and systems are described below.

Sensors, as can also be derived from the table above, are a key technology for the implementation of BACS and smart buildings. Temperature sensors, for instance, generate data of ambient conditions, while Passive Infrared (PIR) sensors can detect the presence of humans inside spaces. Such data can determine the best time for turning on or off the ventilation and cooling systems or the lighting system, thus saving energy Motlagh et al 2020.

Data generation alone is only part of a connected system. Another technology crucial for the composition of a smart building are **wireless communication systems**. Those systems communicate data from the sensors to other IoT devices, sensors and mobile app controllers or displays that offer an interface with consumers. Depending on the application various protocols are used. Beyond the power demanding Wi-Fi, other communication technologies are deployed, such as ZigBee, Bluetooth low energy (BLE), or LoRa, which offer low power, interoperable and energy efficient solutions (VHK and Viegand Maagøe, 2020; Motlagh et al 2020).

At the other end of the system are **consumers** who still play a central role in the delivery of energy efficiency by those systems. Serrenho and Bertoldi (2019) point to the correlated of potential of energy savings in smart homes with the feedback being provided to final energy consumers. An example of such interaction takes place via In-Home Displays, which are platforms allowing access to information related to the consumption of connected devices, energy prices and utility load fluctuations, as well as the ability to remotely control appliances for a customised service and optimised efficiency. This review of 46 studies where consumers interacted registered energy savings reaching up to more than 15%. This is consistent with Darby (2016), reporting a norm of savings from direct feedback (from meters to an associated display monitor) that range from 5-15%.

Horner et al 2016 point out that energy waste in buildings can be addressable by ICT interventions, such as the use of smart meter technology coupled with displays can provide real-time load information, which should cause a rational (in the classical economic sense) customer to reduce consumption. Building energy management systems (BEMS), including technology like programmable thermostats and occupancy sensors, can reduce the need for human hands (and minds) to make routine energy-saving interventions. BEMS match heating, ventilating, and air conditioning (HVAC) operation to required load and analyze consumption patterns to detect faults. Empirical studies of BEMS have found energy savings of 7%–23%.Such benefits, on the other hand, depend on various factors, and therefore cannot be taken for granted, as the concept of smart buildings does not itself necessarily translate into energy savings. Firstly, it is important to distinguish devices which are smart, in the sense that they can be connected and controlled remotely, from those that are intelligent, meaning those with an ability to make decisions based on daily habits of human beings (CarbonTRACK, 2020).

Furthermore, studies point out that the use of home management systems and their ability to stimulate on energy-saving user behaviour, depends on a households' willingness and an ability to engage to the information and features provided (Buchanan et al 2015; Nilsson et al 2018; Vassileva et al, 2013). Furthermore, several studies reporting energy savings are based on consumer surveys, which could suffer from the Hawthorne effect, according participants alter their behavior simply because they are aware that the study is taking place (Horner et al 2016; Schwartz et al 2013).

Another factor refers to the type of information provided and the way the information is presented to users. Darby 2016 indicates the difference between direct and indirect feedback, i.e. feedback that has been processed in some way before reaching the energy user, normally via billing. High energy users may respond more than low users to direct feedback. Indirect feedback, on the other hand, is usually more suitable for consumption of changes in space heating, household composition and the impact of investments in efficiency measures or high-consuming appliances.

Another factor with a role in the delivery of actual efficiencies is the way systems are installed. Studies from the US note that even if programmable thermostats for heating and cooling control could theoretical deliver 5–15% energy reductions compared to manual thermostats (Peffer et al 2013), factors such as poor installation, design and usability (such as difficult to understand interfaces, small buttons, inaccessible installation location) could discourage consumer engagement and cancel those savings out (Meier et al. 2011, Pang et al 2021).

Lastly, beyond the direct consumption of such systems (first-order effects) and the uncertainty of second-order effects presented above, third-order effects (not further examined in this study) could also emerge, such as the rebound effects. An example is the likelihood of advanced lighting control technologies leading to the installation of more lights in the system Aebischer and Huser (2000).

IEA (2019a) suggests that, assuming limited rebound effects in consumer energy demand, digitalisation in residential and commercial buildings, including smart thermostats and smart lighting, could cut their total energy use between 2017 and 2040 by as much as 10% compared with the IEC Central Scenario Figure 48. Cumulative energy savings over the period to 2040 would amount to 65 PWh – equal to the total final energy consumed in non-OECD countries in 2015.

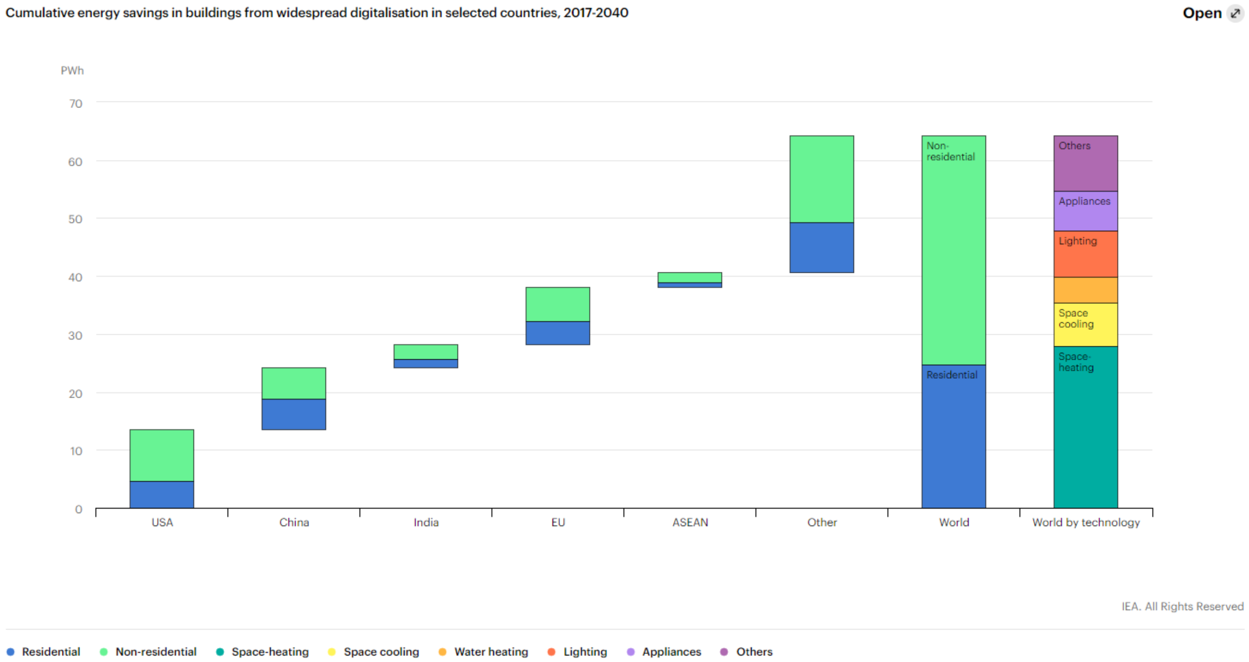


Figure 48: Cumulative energy savings in buildings from widespread digitalisation (in PWh).
EU; residential: 3.95 PWh; non-residential: 5.94 PWh
World; residential: 24.76 PWh; non-residential: 39.50 PWh
World; space heating: 27.94; space cooling: 7.53 PWh; water heating: 4.44PWh; lighting: 7.93PWh ; appliances: 6.87PWh; other: 9.55PWh

Assuming an optimal level of installation and operation of BAT/BEMS or BAT/HEMS in 100% of EU buildings, Waide (2014) estimates incremental annual energy savings which would peak at approximately 50 Mtoe in 2035 for service sector buildings and at approximately 100 Mtoe in the year 2029 in residential buildings (Figure 49).

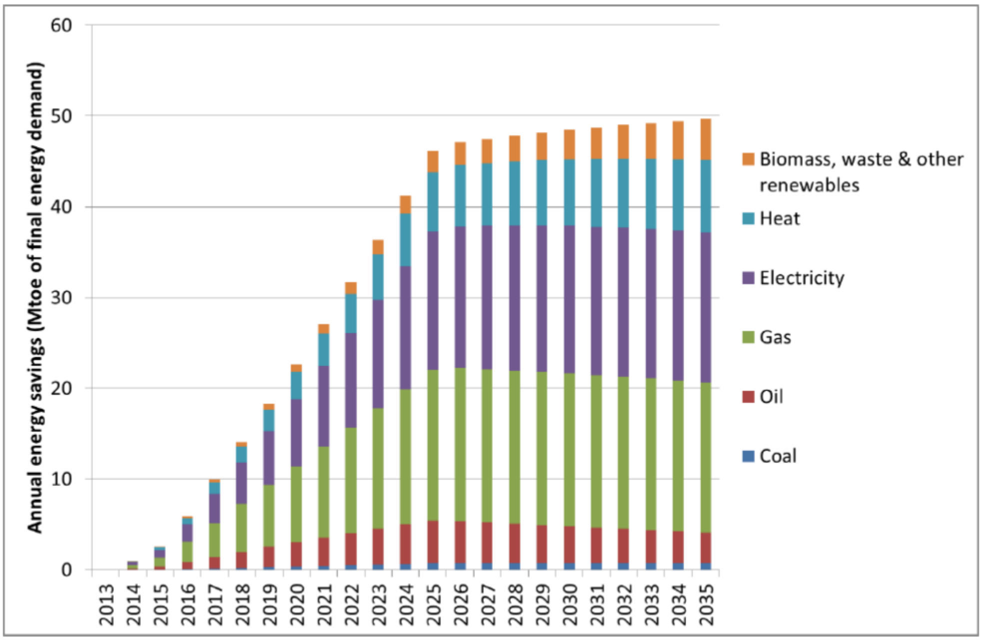


Figure 49: Service sector building additional energy savings under the Optimal Scenario compared with the Reference Scenario from 2013 to 2035.

11.2.5 Transport

IoT deployment could have a significant impact on transport systems as well. The use of sensors, advances in satellite communications and processing of data can optimise route planning and reduce fuel use in the sectors of commercial aviation and shipping (IEA, 2017).

However, the biggest changes could be witnessed in the digitalisation of road transport. Sensing, connectivity and automation technologies could fundamentally transform the movement of people and goods, with the uptake of automated, connected, electric and shared (ACES) mobility (IEC, 2017). Similarly to the case of buildings, IoT in transport can improve the driving experience and safety via automated driving technologies, while real-time traffic information, smart parking systems and eco-driving functions can lead to selecting optimal routes, and providing fuel savings (Motlagh et al 2020). An IEA study found that applying digital solutions to truck operations and logistics could reduce road freight's energy use by 20-25% (IEA, 2017).

The graph below Figure 50 (IEA 2019a) demonstrates the projected impact of digitalisation on energy use in road traffic for the period between 2015 and 2050.

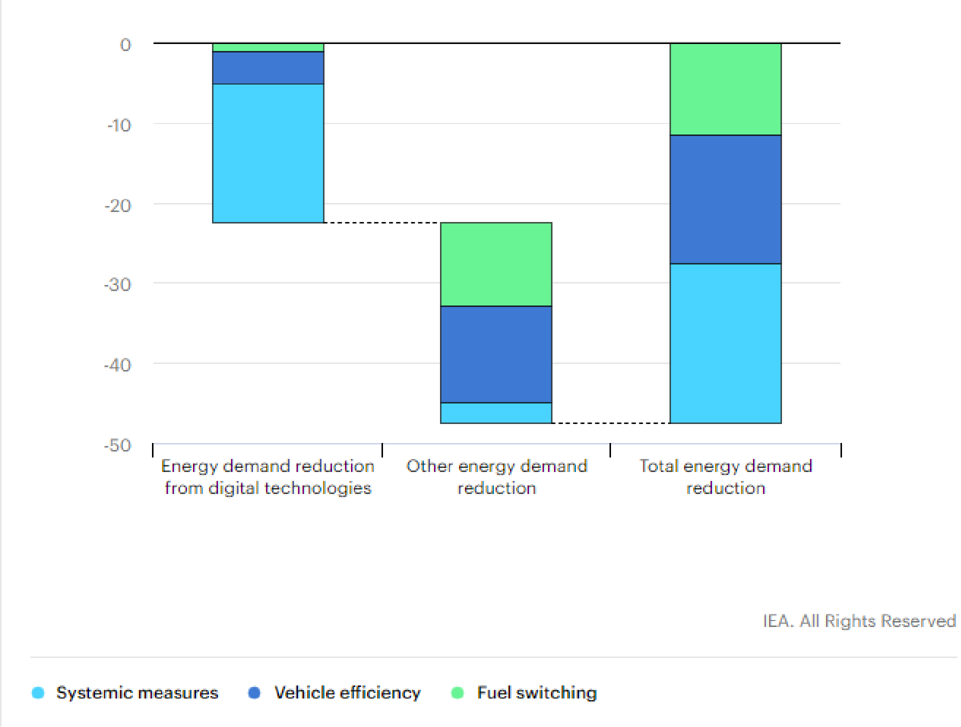


Figure 50: Impact of digitalisation on energy use in road freight 2015-2050.

These benefits are always presented keeping in mind potential associated rebound effects (IEA, 2017).

11.3 IoT trends and challenges

The application and position effects deriving from ICT use and digitalisation are also associated with challenges. A list of challenges and solutions are provided by Motlagh et al 2020 (see Table 20).

Table 20: Challenges and current solutions of using IoT in the energy sector.

Challenge	Issue	Example Solution	Benefit
Architecture design	Providing a reliable end-to-end connection	Using heterogeneous reference architectures	Interconnecting things and people
	Diverse technologies	Applying open standard	Scalability
Integration of IoT with subsystems	IoT data management	Designing co-simulation models	Real-time data among devices and subsystems
	Merging IoT with existing systems	Modelling integrated energy systems	Reduction in cost of maintenance
Standardization	Massive deployment of IoT devices	Defining a system of systems	Consistency among various IoT devices
	Inconsistency among IoT devices	Open information models and protocols	Covering various technologies
Energy consumption	Transmission of high data rate	Designing efficient communication protocols	Saving energy
	Efficient energy consumption	distributed computing techniques	Saving energy
IoT Security	Threats and cyber-attacks	Encryption schemes, distributed control systems	Improved security
User privacy	Maintaining users' personal information	Asking for users' permission	Enables better decision-making

A major challenge for the deployment of IoT solutions in energy systems is the energy consumption of IoT themselves. Section 3 of this report, presented challenges related to the generation and submission of large amounts of data and the impact on the ICT system that this entails. At the same time, efforts at achieving better efficiency are made, including setting sensors to sleep mode when not used and establishing efficiency communication protocols (Motlagh et al 2020).

Besides the challenges associated with the direct consumption of ICT, there are also uncertainties about the delivery of second-order effects, and the emergence of third order effects. Positive substitution effects, for instance, can often be “incomplete”, or their efficiency may be cancelled out by rebound effects. For example, the ICT-enabled benefits of e-commerce and optimised logistics might be overcompensated by increased volume of deliveries, or consumers using e-commerce only partly for their shopping without saving trips (Berkhout and Hertin (2001).

Noteworthy are of course other challenges too, which may not be energy-related, but are nevertheless considered. One challenge is related to user privacy of the data gathered by IoT and also security. For example, data generated by electric vehicles or smart appliances at home might reveal information about where the user is at a given time or what their sleeping patters are. On one hand, such data may be exploited commercially, and on the other and they might be susceptible to cyberattacks and security breaches (IRENA, 2019)

Finally, there is a challenge of standardisation for the protocols and procedures used to establish communications are large scale, related to data sharing to contracts and payments.

Amongst the solutions to aforementioned privacy and energy management challenges is blockchain technology. Blockchain allows for information exchange between people and devices without the involvement of a third party, whether this is related to energy distribution or payments (Motlagh et al 2020; IRENA, 2019). Provided that challenges such as reducing cost and ensuring privacy are considered, blockchain technology can bring multiple benefits from an energy management perspective. Consumers and prosumers can receive information about price signals and energy costs, and perform trades of their energy surplus or flexible demand in a decentralised and transparent way. Such platforms provide incentives for demand response and smart management of their energy needs, enabling the formation of local microgrids which in turn facilitates RES integration, reduces transmission losses and increases network stability. It has to be noted however, that the use of blockchain technology itself is associated with energy consumption, which can be high compared to the transactions performed. The energy demand for blockchain technology applications are very much dependent on the blockchain architecture used (Andoni et al, 2018; Sedlmeir et al, 2020).

Energy harvesting

The development of IoT is associated with the use of low-power sensors. Sensors are undertaking simple tasks such as measurement and communication that require small quantities of energy, but are present in large numbers and geographically dispersed. When grid connection is lacking, such applications have to rely on costly and often short-lived batteries that also have a considerable impact on the environment (Ellis et al, 2015 ; Zeadally et al 2020; Elahi et al 2020). Therefore, ensuring high efficiency of IoT applications is important. One solution to this problem is energy harvesting, i.e. the process of conversion of ambient energy into electrical energy (Figure 51) (Elahi et al 2020). Energy can be harvested by sources such as wind solar energy, wind energy, mechanical energy or radio frequency energy (Table 21).

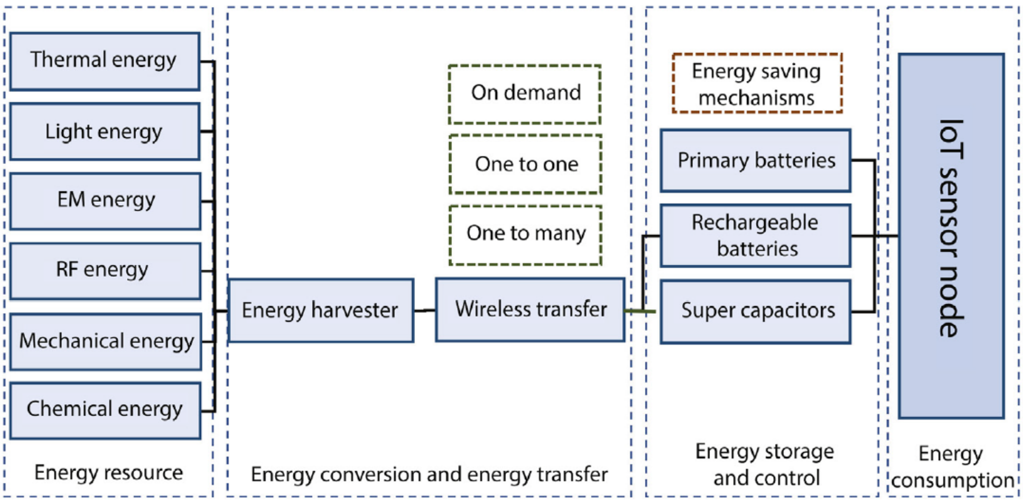


Figure 51: A block diagram of an energy harvesting system. Source: Zeadally et al 2020.

Table 21: Comparison of energy harvesting sources. Elahi, 2020

Source	Method	Merit	Power Density	Weakness	Applications
Aeroelastic energy	FSI and Piezoelectric	High efficiency Controllable	0.6 lW/cm^2 [48]	Material can break	Aerospace vehicle
Mechanical energy	Electromagnetic, and Piezoelectric	High efficiency Controllable	0.819 lW/cm^2 [32]	Material can break	PEH, road buffers, TENG
Light Energy	Photovoltaic	Predictable, Mature	[181] 5–100 mW/cm^2 (solar) [182] 0.5–1000 lW/cm^2 (Indoor)	Expensive, light not steadily available	Biometric, Agriculture, monitoring, ZNE building, indoor and portable devices
Wind energy	Piezo turbine	Low wind speed can work	[90] 4–50 lW/cm^2	Wind not steadily available	Agriculture
Sound energy	coherence resonance	Clean, sustainable	[85] 6.02 lW/cm^2	Big energy loss, highly variable	Structure monitoring, environment monitoring
Radio frequency energy	Rectenna	Continuous available, carry and process information simultaneously	[186] 0.01–0.3 lW/cm^2	Efficiency decrease with distance	Sensor, Nuclear, wirelessly powering
Pyroelectric energy	Pyroelectricity	waste heat Can be used	[187] 48.57 lW/cm^2	Low efficiency	waste energy Plants

IoT sensors can optimise their efficiency in various ways. One way is radio optimisation, whereby the power is tuned to low to consume less energy when the nodes are close and tuned to full when the nodes are far away. Another example of energy efficiency is the use of scheduling techniques, whereby the data is transmitted only when necessary, and when no data are to be sent, the nodes are put to sleep. Finally, different wireless standards are more efficiency than others and each appropriate for different applications. Therefore, making the right choice of standard wireless standard can deliver higher energy efficiency Table 22) (Zeadally et al 2020).

Table 22: Energy consumption of various components used in IoT. Source: Zeadally et al 2020

	Component	Power/Current consumption
Wireless technology	Wi-Fi	835 mW
	Zigbee node	36.9 mW
	MiMAX node	36.78–36.94 W
	Bluetooth	215 mW
	BLE	10 mW
	Cellular	0.1–0.5 W
	LoRa	100 mW
Typical sensing devices	Temperature/humidity	0.2–1 mA
	IR	16.5 mA
	Ultrasonic	4–20 mA
	PIR	65 mA
	Light	0.65 μA
	Camera	270–585 mA
IoT node/gateway	WASP mote	9 mA
	Pi	100–500 mA
	Xbow	17.5–19.7 mA
	Arduino	3.87–13.92 mA

Another interesting concept related to energy harvesting is the Zero Energy Appliance (ZEAP) (Ellis et al, 2015; Meier and Siderius, 2017). As technologies for energy harvesting are improving and efficiencies of products ZEAPs can be an attractive concept for IoT applications. Many ZEAPs, especially sensors, will replace battery powered devices or will be new devices and therefore will not have an impact on electricity consumption from the grid. For larger devices the qualitative impact is that developments towards ZEAPs could also stimulate the development of more efficient components and devices. (Ellis et al, 2015; Meier and Siderius, 2017)

12 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 52 figure below (Wager et al. 2014)).

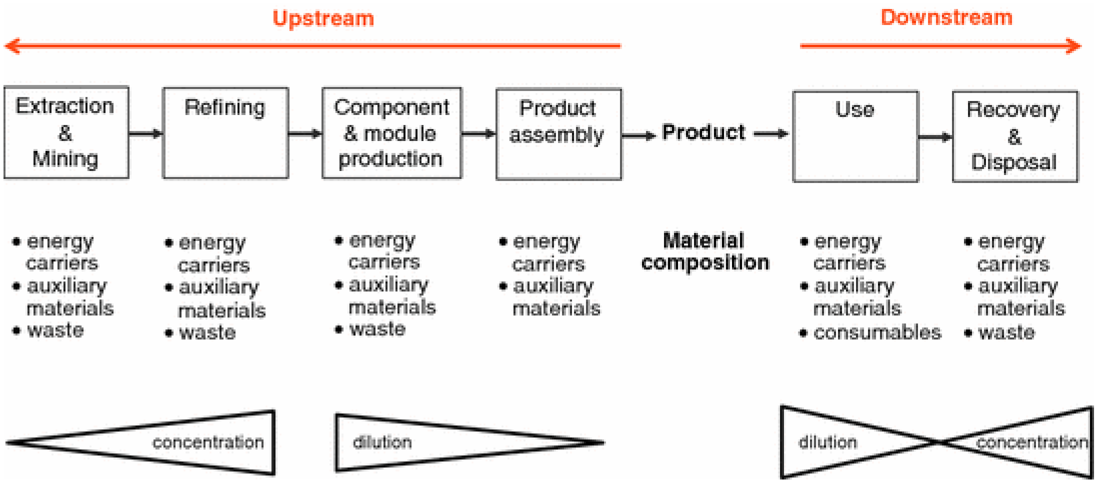


Figure 52: Processes and material flows in ICT life cycle. Source: Wagner et al. 2014

12.1 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 53).

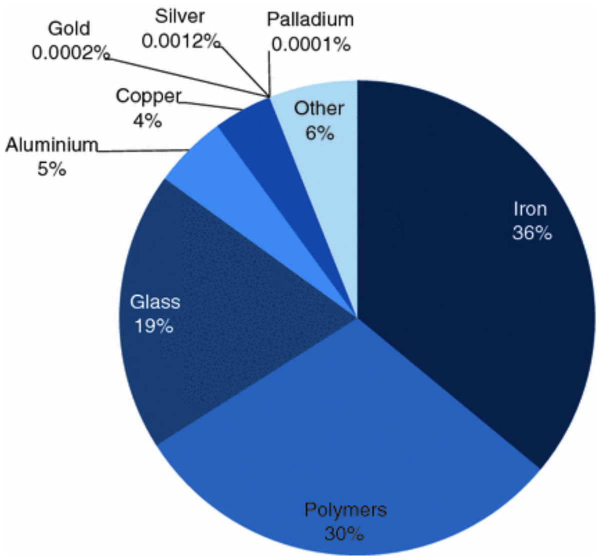


Figure 53: Relative mass distribution of the materials contained in EoL consumer ICT devices in Switzerland (reference year 2010).

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 54). 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[15]) between 13% and 48%, based on methodological assumptions. (Ericsson, 2018; Malmodin et al. 2018).

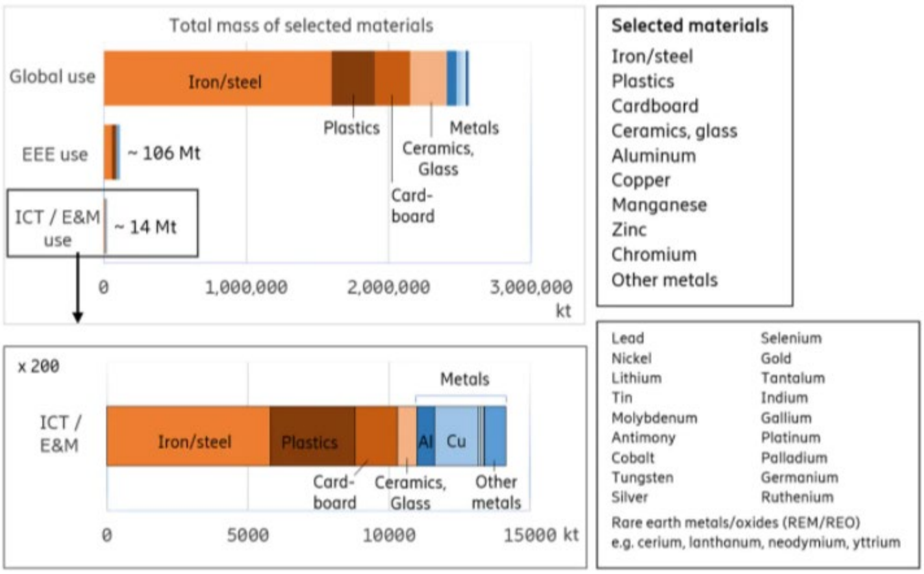


Figure 54: Relative mass distribution of the materials contained in EEE (above) and ICT / E&M devices. Source: Ericsson (2018)

[15] 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 55). 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 55: Example of product disassembly for a tablet (Samsung Galaxy Tab 4 SM-T530, 2014), illustrating the main components (Babbitt et al., 2020).

12.2 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 56 below.

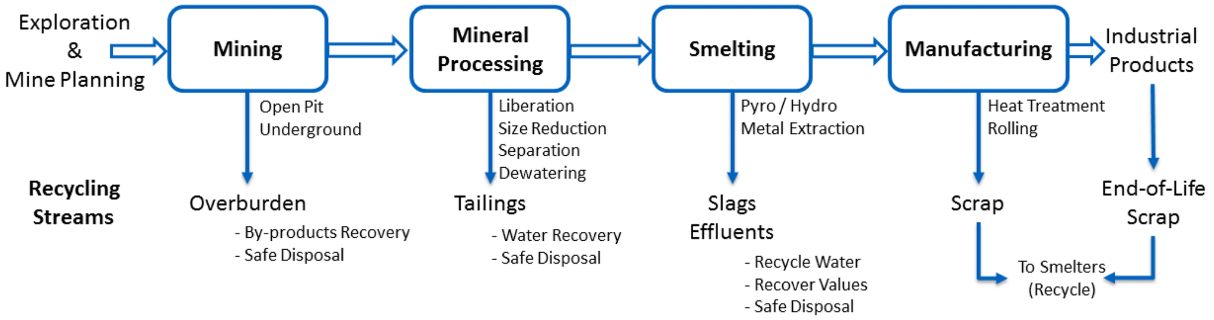


Figure 56: Cradle-to-cradle cycle for metals. Source: Pradip et al., 2019

Most of the materials used in the ICT sector are characterised by complex supply chains (example in Figure 57), 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 57: 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.

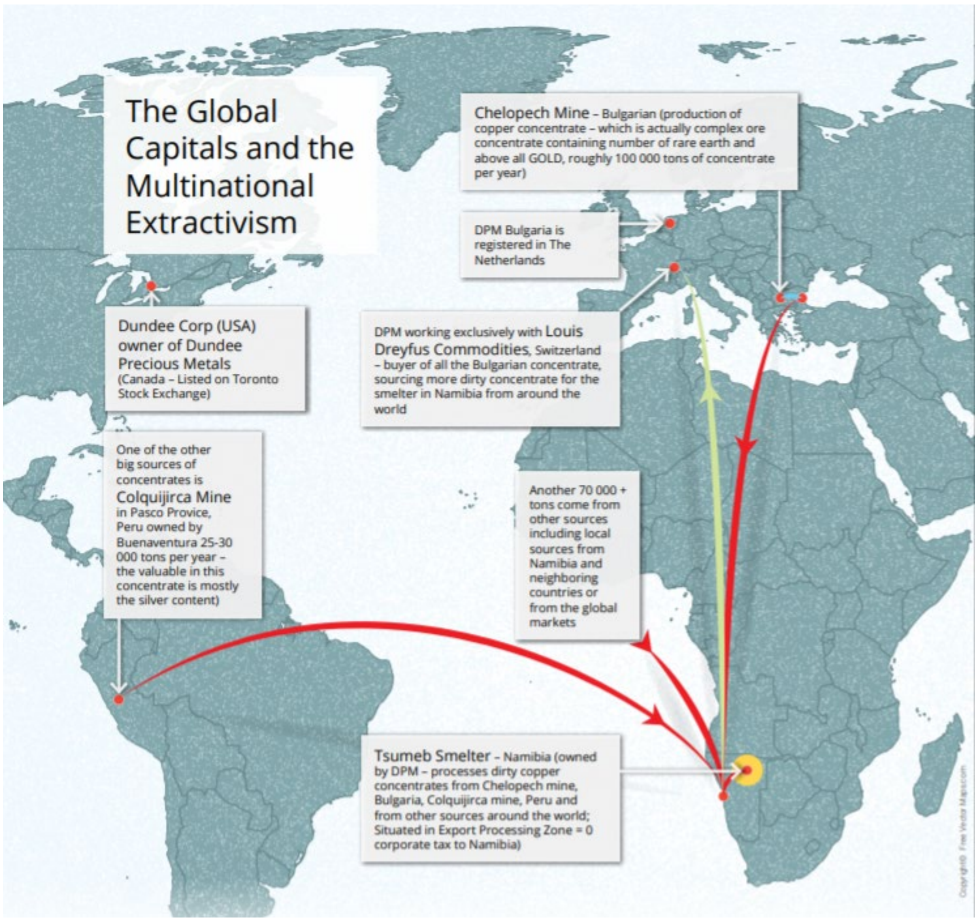


Figure 58 : Example of extractive activities involving several countries and continents. Source: CEE Bankwatch Networks, 2020).

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 59).

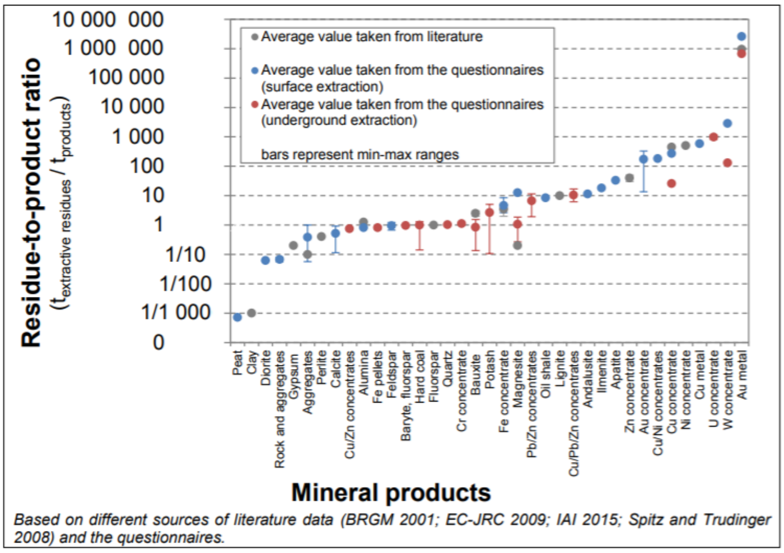


Figure 59: Residue-to-product ratio for the extraction of different mineral

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[16] 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 60 and Figure 61).

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

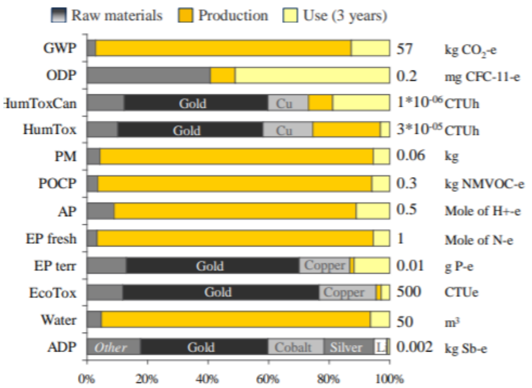


Figure 60: Total life cycle result for all impact categories for smartphone Z5 with accessories using Ecoinvent database and adopting a 50/50 recycling approach with 19% recycling of gold assumed.

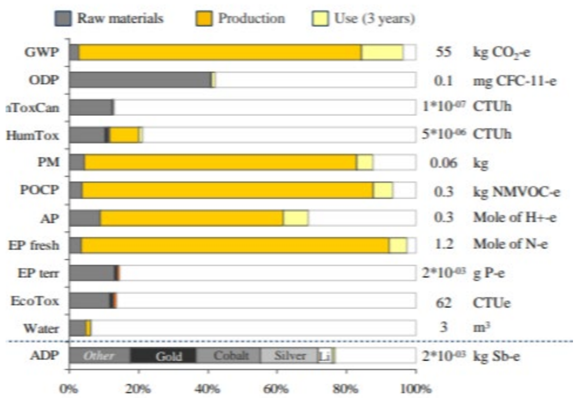


Figure 61: Total life cycle result for all impact categories for smartphone Z5 with accessories using GaBi database for gold and energy production and a 50/50 recycling approach with 83% recycling of gold assumed. Note that the figure shows relative results compared to Figure 60

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 23: 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[17] 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 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

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

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 23: 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[18].

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,

[18] 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[19] 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[20], aiming to evaluate potential supply, environmental, and social impacts in a single assessment and the Dragonfly Initiative by Fairphone[21]. 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 24 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 24 : materials used in ICT with highest criticality in terms of supply risk, environmental impacts and risk of conflicts.

Material	Raw Materials of	Raw Materials of	Conflict Minerals

[19] 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

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

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

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

12.3 Impacts from manufacturing processes

As introduced in chapter 3, 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 62). 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.

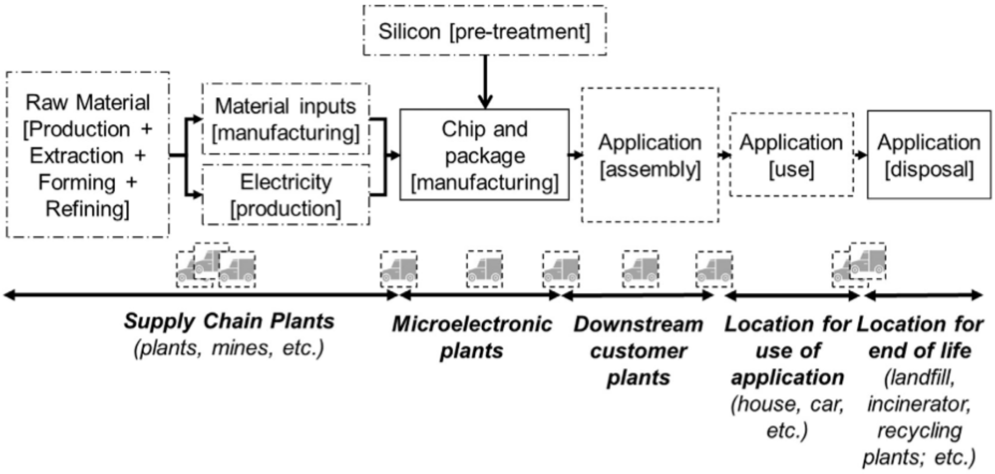


Figure 62: Cradle to grave lifecycle of chips. Source: Villards et al. 2015

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. 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

12.3.1 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[22,23]. 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.

12.3.2 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).

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

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

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

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[24].

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12.4 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 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.

12.4.1 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.

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

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

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[25], 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 63) 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 63: 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:

[25] 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 25: 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 64).

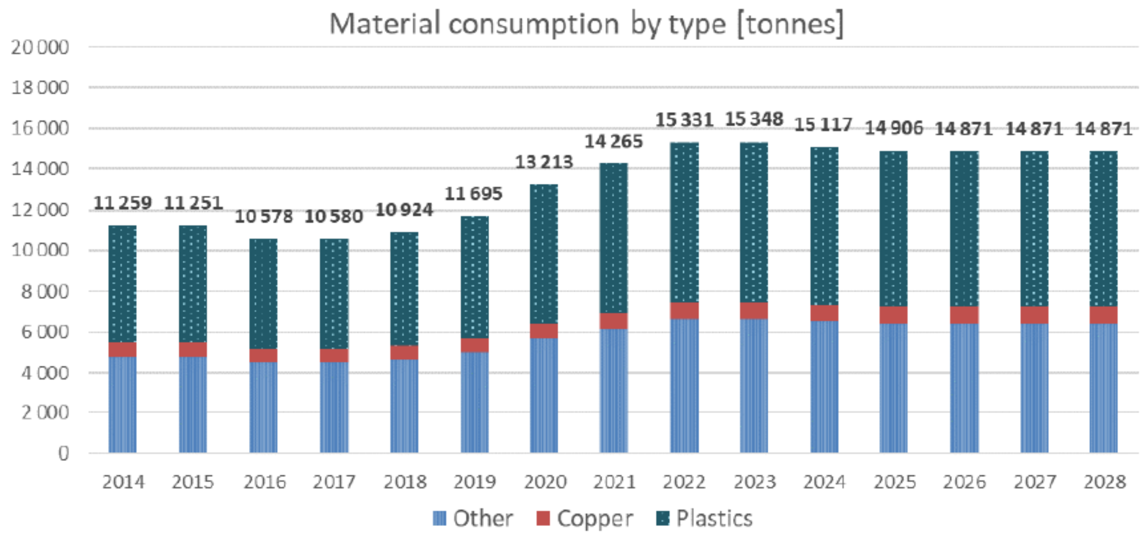


Figure 64: Material consumption of chargers sold each year in the baseline scenario, by material (tonnes), 2014-2018

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 65).

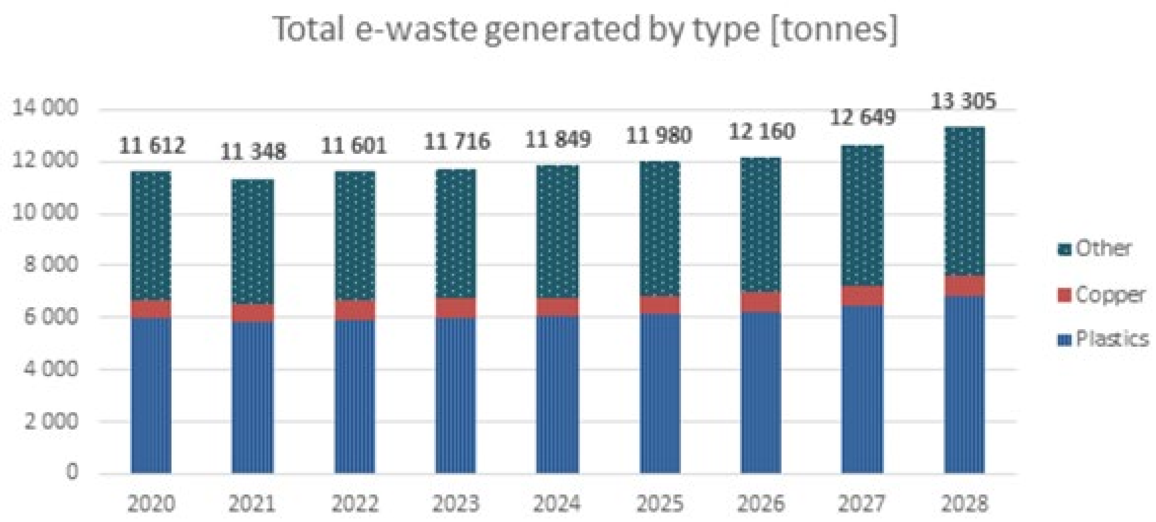


Figure 65: E-waste generation of chargers disposed each year in the baseline scenario, by materials (tonnes), 2020-2028.

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 66).

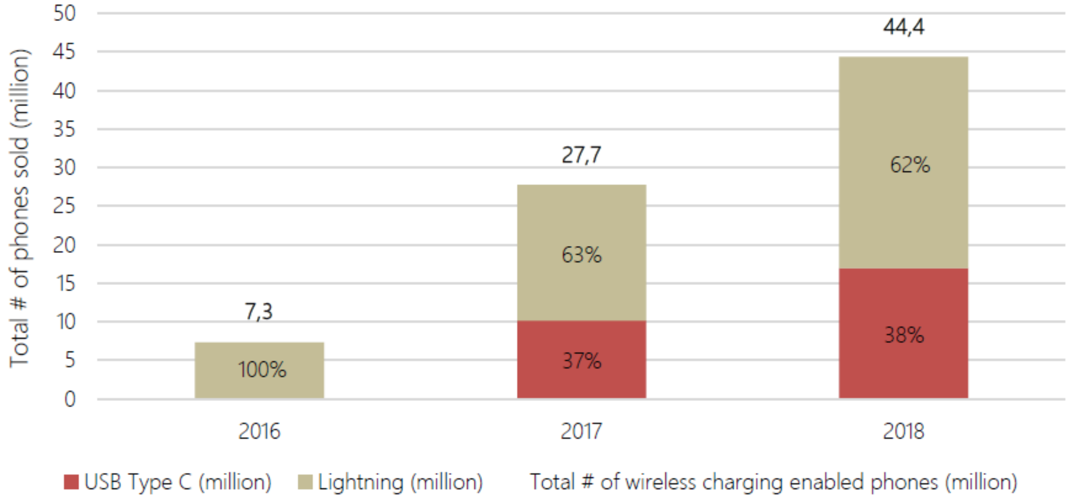


Figure 66: Shipments of wireless charging enabled phones (EU-28 2016-2018)

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 26). 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 26: 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 Change	32,4 kg CO_2 eq.	32,4 kg CO_2 eq.	32,3 kg CO_2 eq.	32,4 kg CO_2 eq.	6,24 kg CO_2 eq.	11,8 kg CO_2 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 67).

Figure 67: 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.

12.4.2 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).

12.4.3 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 68) are related to components as screens, keyboards, hard disks drives or solid state drives, batteries, adapters and ports/connectors (Cordella et al. 2019).

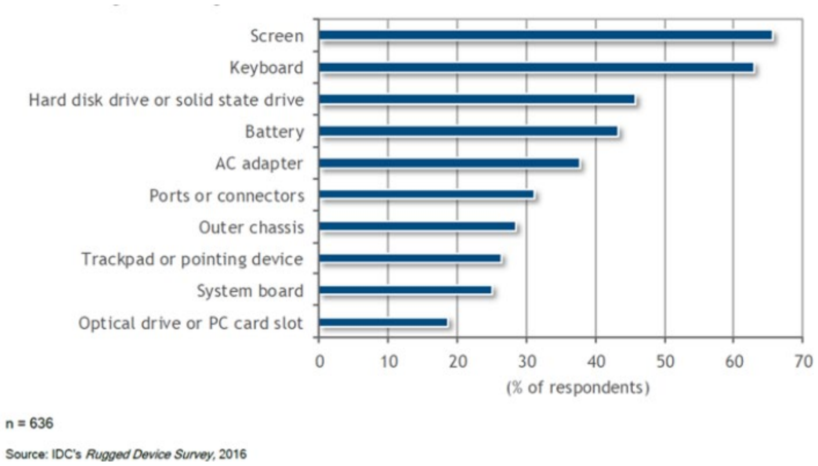


Figure 68: Common parts of notebooks reported to suffer damage.

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 27 and Table 28 (Fraunhofer IZM et al, 2020).

Table 27: 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 28: 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 29.

Table 29: Requirements on spare parts availability for electronic displays

Product Group	Spare parts availability		
	Which parts?	**To whom?**	**For how long?***
Electronic displays (EU)2019/2021	internal power supply, connectors to connect external equipment (cable, antenna, USB, DVD and Blue-Ray), capacitors, batteries and accumulators, DVD/Blue-Ray module and HD/SSD module	professional repairer	min 7 years
	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[26]. 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 69), the lifetime of small ICT devices tend to be limited by the technical lifetime of its battery.

[26] https://blog.izm.fraunhofer.de/the-weakest-link-aging-lithium-ion-batteries/

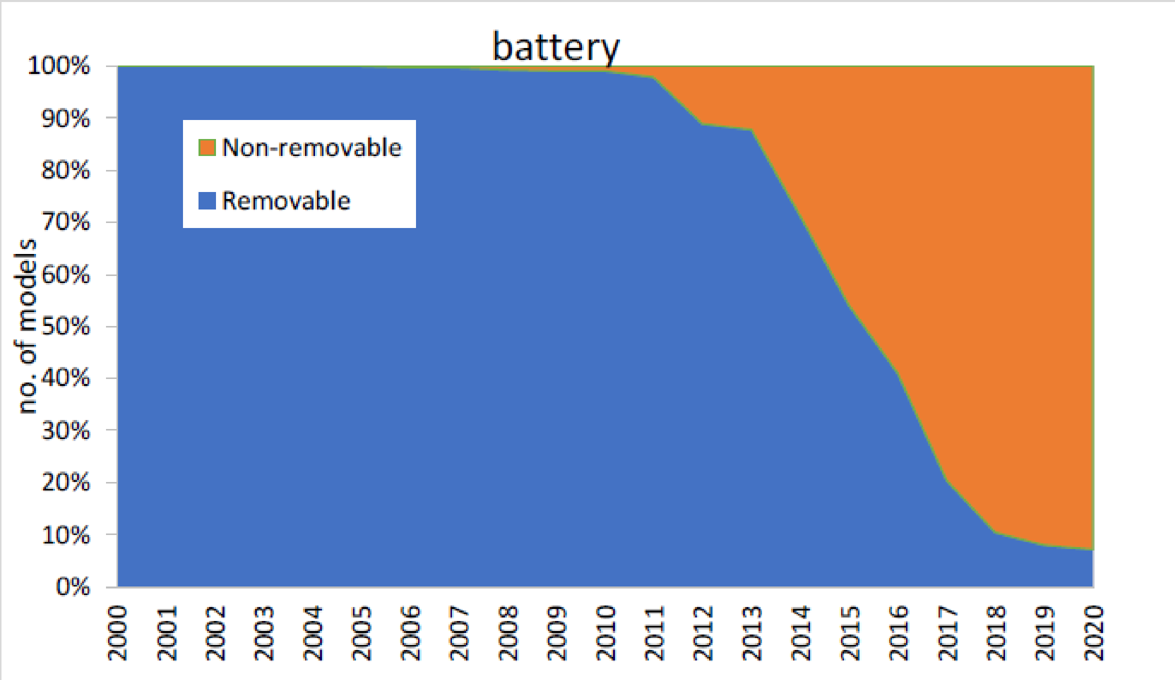


Figure 69: Share of removable and non-removable batteries in mobile phones 3 between 2000 and 2020 (Proske et al. 2020a)

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[27].

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[28] require the existence of software determining the battery/accumulator status and allowing the 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[29] and Blue Angel[30] requires the availability Battery/Accumulator Protection Software shall be able to limit the

[27] https://globalelectronicscouncil.org/
[28] https://produktinfo.blauer-engel.de/uploads/criteriafile/en/DE-UZ%20078-201701-en-Criteria-V4.pdf
[29] https://tcocertified.com/files/certification/tco-certified-generation-9-for-notebooks-edition-2.pdf

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.

12.4.4 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)[31] 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.

12.5 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[32]). 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

[30] https://www.blauer-engel.de/en/certification/basic-award-criteria
[31] https://eur-lex.europa.eu/eli/reg/2016/679/oj
[32]

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[33] 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 70 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 71).

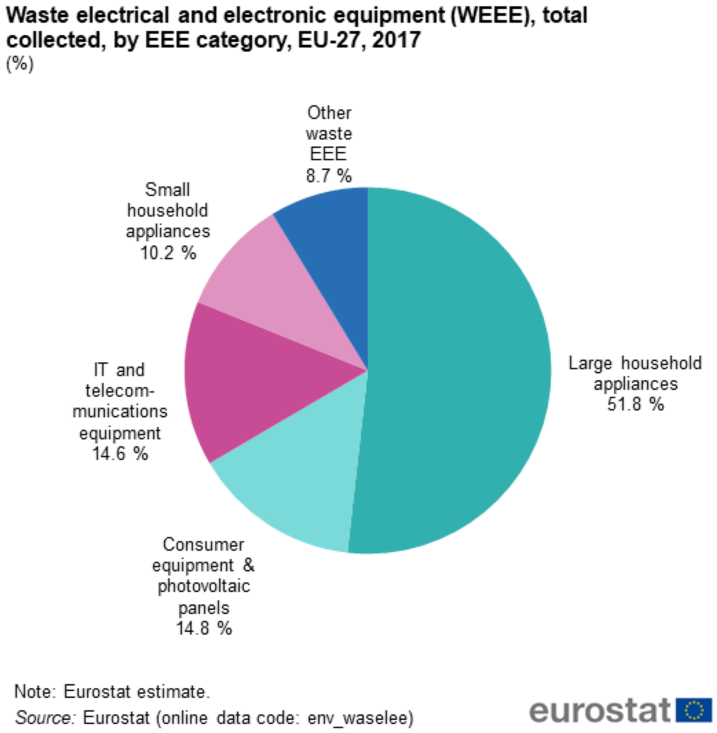


Figure 70: Collected Waste Electrical and Electronic Equipment (WEEE) by EEE Category (%), EU27, 2017. Source: Eurostat

[33] https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment

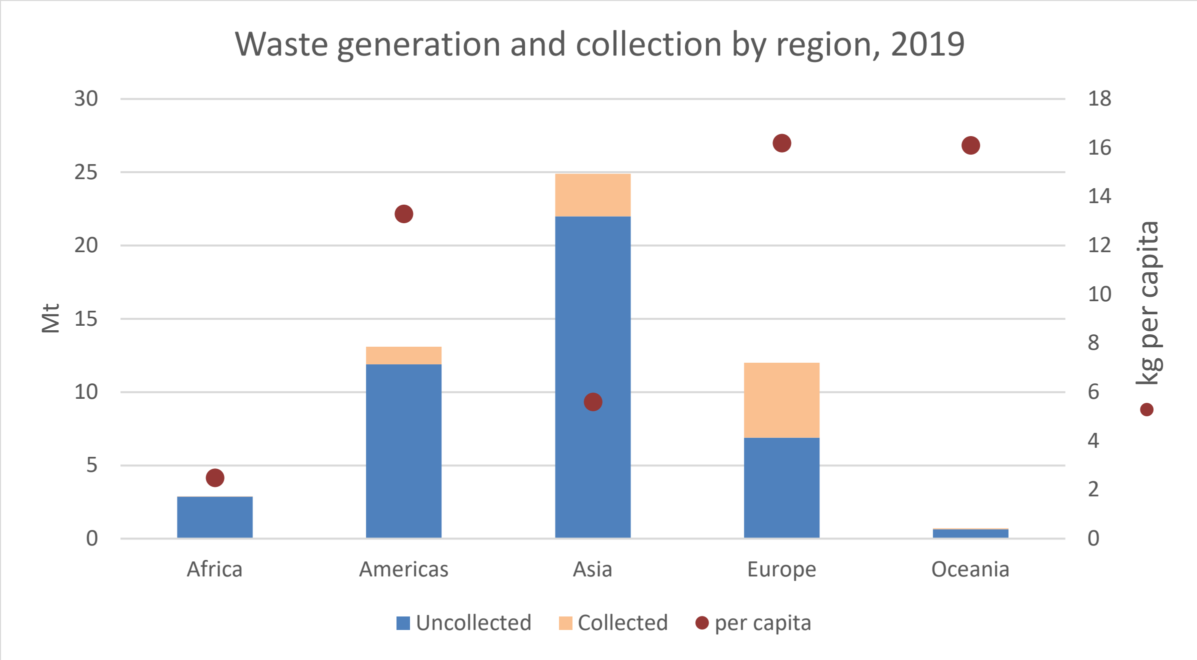


Figure 71: Waste generation and collection by region (2019). Source: own with data from the Global E-Waste Monitor 2020 (Forti et al., 2020)

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 72 .

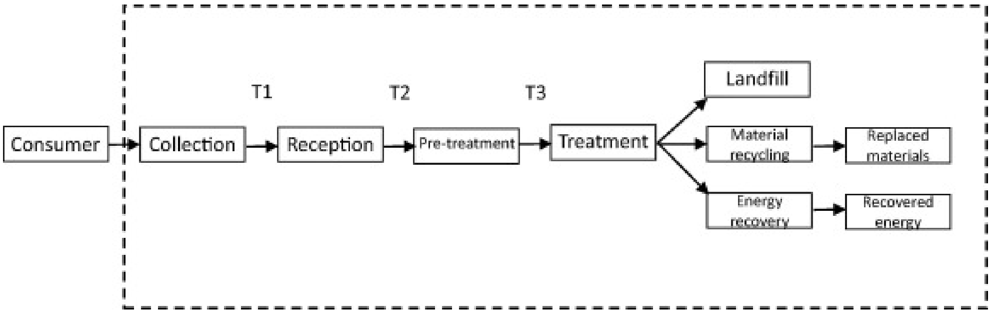


Figure 72: End-of-life processes. Source: Baxter et al 2016

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[34], identified the economic feasibility of a number of key CRMs typically found in ICT products, presented in the table below (CEWASTE, 2021).

Table 30: 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

[34] https://cewaste.eu/

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).

As a result, those materials are not recovered and fed back to the production stage sufficiently to meet demand. Figure 73 below describes the low contribution of recycling to meet the EU demand of CRM (SCRREEN, 2019).

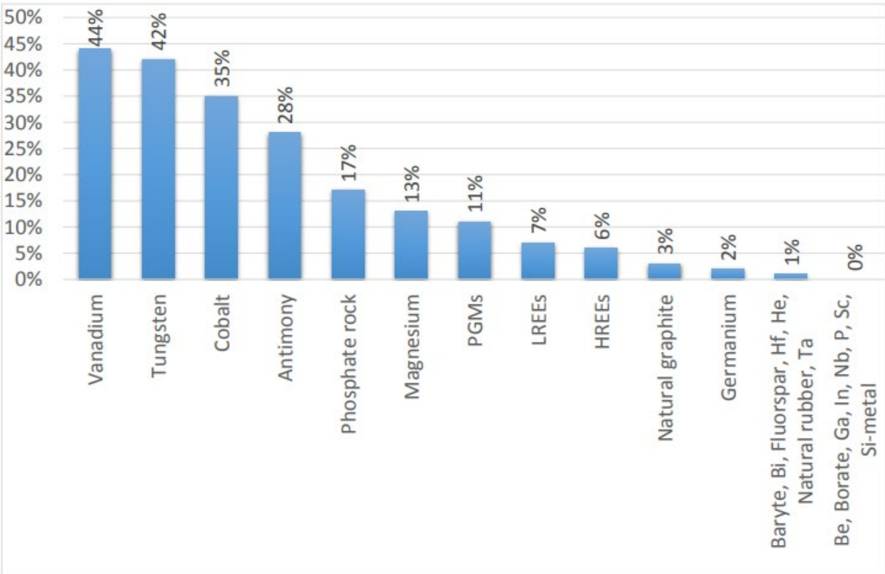


Figure 73: Contribution of recycling to meet EU demand of CRMs: End-Of-Life Recycling Input Rate (EOL-RIR). Source: SCRREEN (2019) (JRC elaboration based on the 2017 CRM study and on the MSA study 2015).

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 31.

Table 31: 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[35] 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[36] 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

[35] 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)

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

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.

13 Analysis of material consumption linked to the use of ICT

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.

13.1 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 32: 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[37]. 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	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

37

order effect)	is the transition from TVs to smart TVs
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).

13.2 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 74).

Figure 74: 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 33.

Table 33: Software induced obsolescence (direct) and software related obsolescence (indirect)

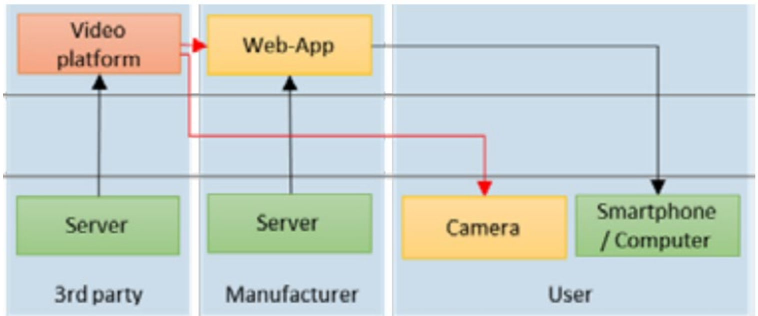
Casual Chain	Example
Direct (software induced obsolescence)	- Functional software failure - Built in software-controlled shutdown or counting devices - Software inefficiencies can lead to higher performance load (software bloat) and hardware degradation
Indirect (software related obsolescence)	- Functional 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)

13.2.1 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 34.

Table 34. 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[38]. After the criticism received Sonos removed Recycle Mode from its app[39]
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[40]. 

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.

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

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

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

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 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 35 below describes some case studies of software related issues for ICT devices on the market.

Table 35. 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[41] 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[42])
PSP, PS3, PS Vita: loss of functionalities	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

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

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

– Purchase of games	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 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[43], 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) [44]. 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 Figure 75 to inform them that the new part "isn't genuine" and even sometimes that it's not working.

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

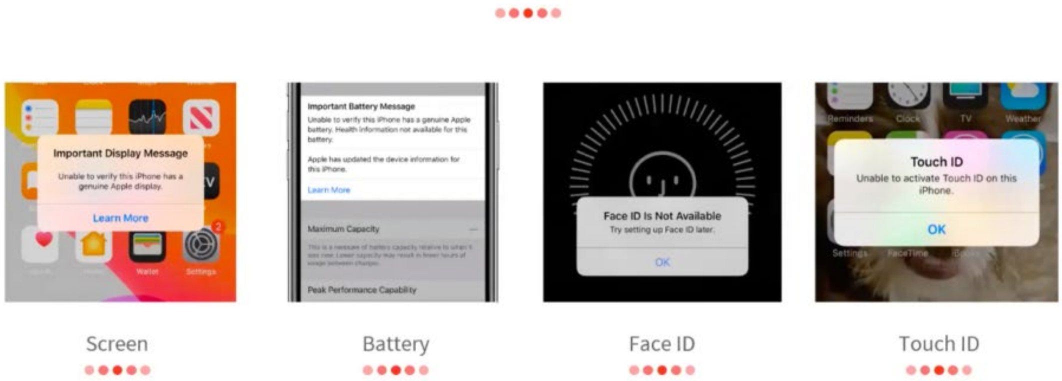


Figure 75: warning messages after replacing a part with a not paired one.

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 (Figure 76**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[45], 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”[46].

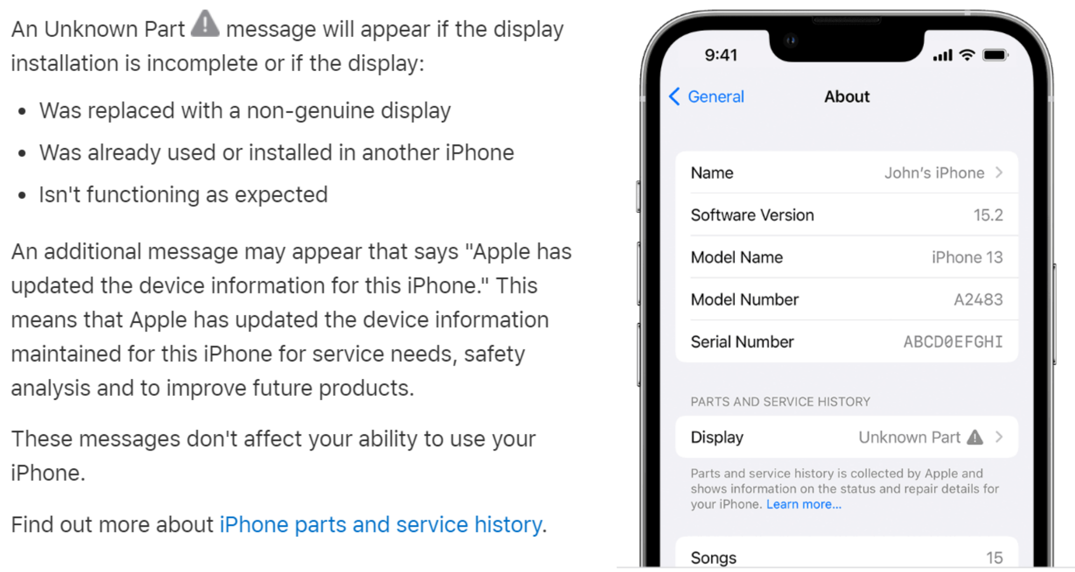


Figure 76: Unknown Part Message from Apple. Source: https://support.apple.com/en-au/HT210321

According to The Repair Academy[47] 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.

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[45] https://www.backmarket.com/
[46] Webinar recording available at https://youtu.be/CvCThm0tHCA
[47] https://therepairacademy.com/

13.3 Induction effects

The increased traffic and number of connected devices presented in Chapter 10 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 77 (McKinsey and Company, 2018).

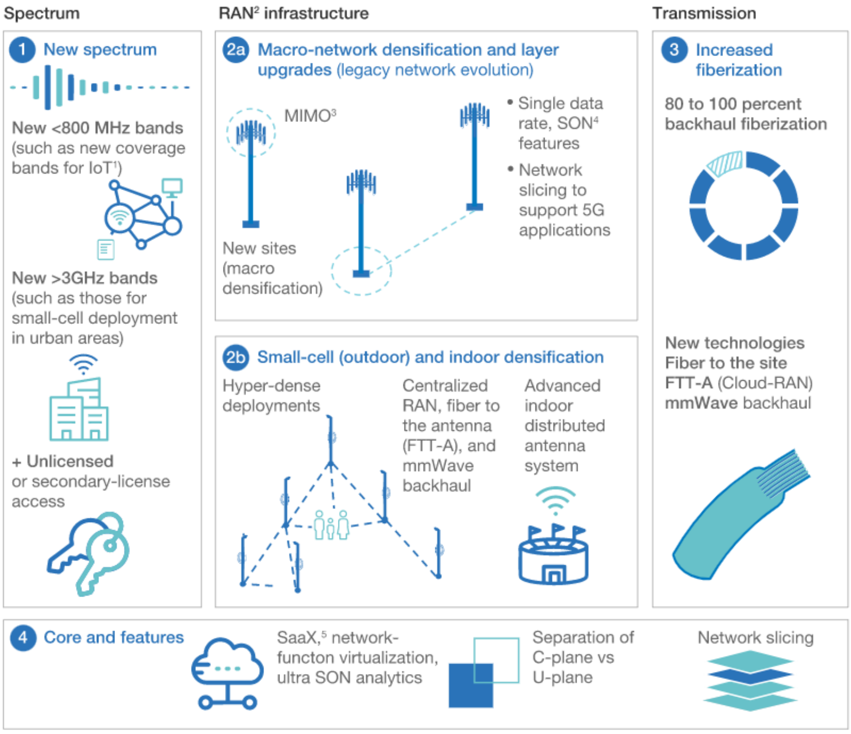


Figure 77: Growth in the ICT infrastructure related to the 5G rollout. Source: McKinsey and Company, 2018

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 78 below highlights main drivers enabling WEEE growth.

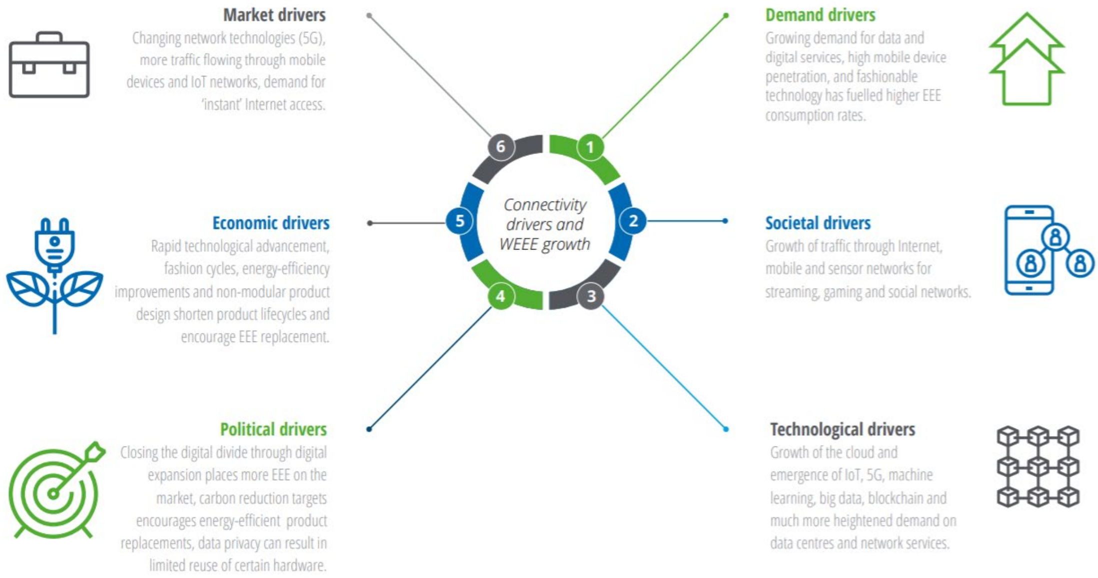


Figure 78: Main drivers enabling WEEE growth. Source: ITU and WEEE Forum, 2020.

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 79).

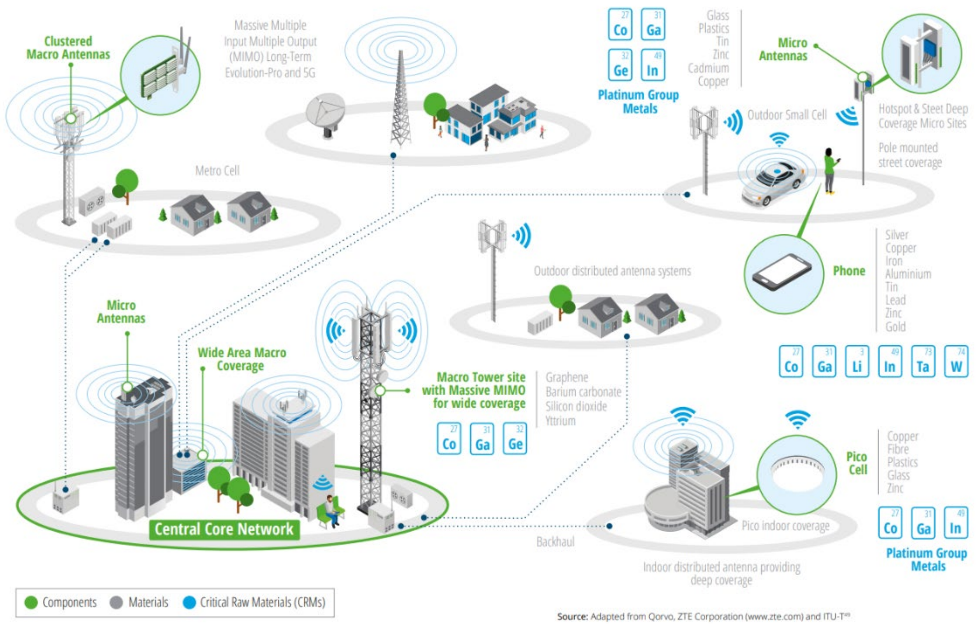


Figure 79: Overview of 5G network infrastructure and associated critical materials. Source: ITU and WEEE Forum, 2020.

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 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 chapters, 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.

13.4 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 80 present the ICT-related drivers and enablers leading to either an increase or decrease of resource use.

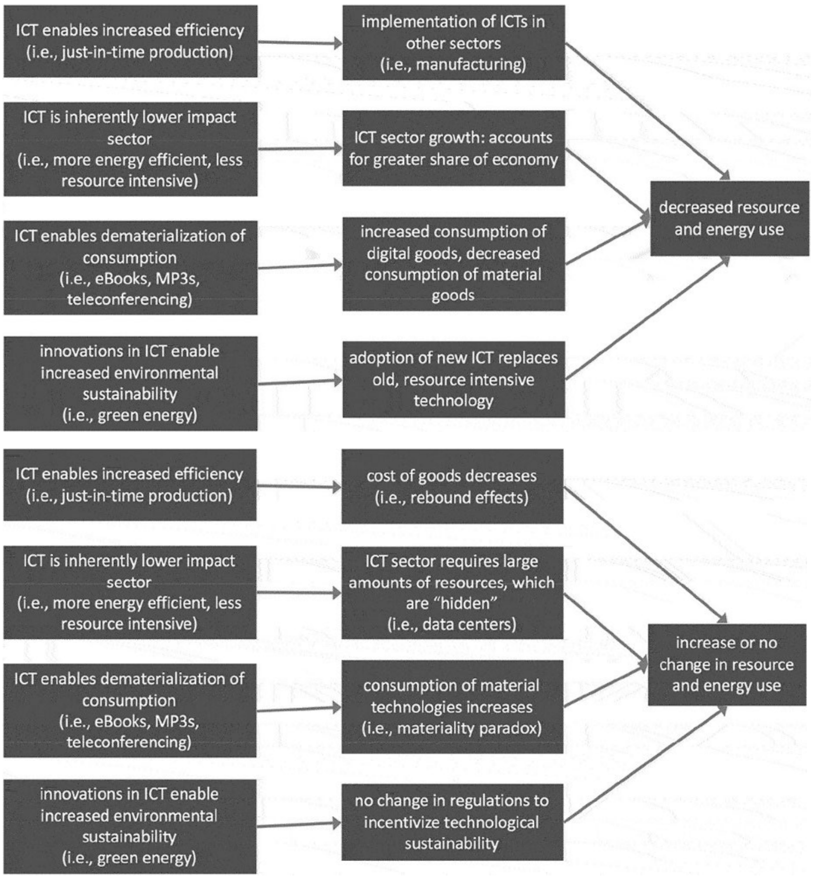


Figure 80: ICT sector as driver of reduction (or increase) in material and energy consumption

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 36 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 36: 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).

14 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 81 below.

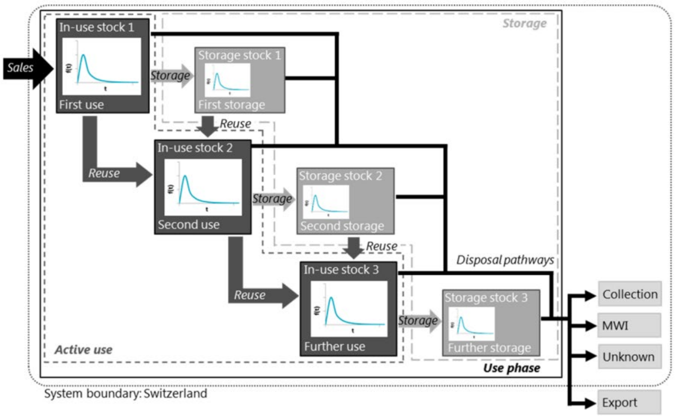


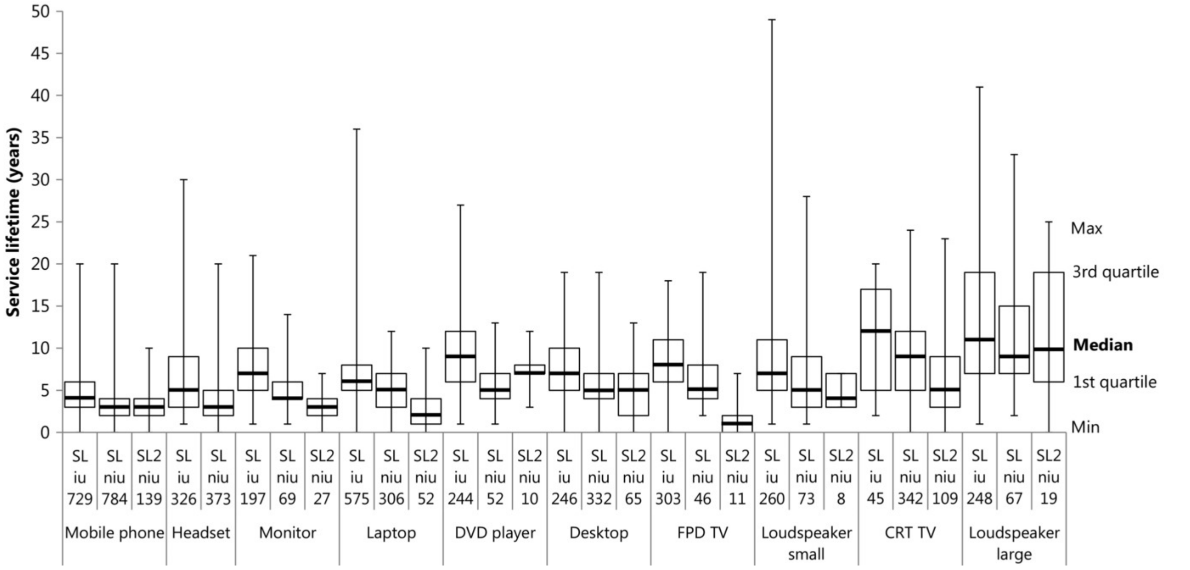
Figure 81: "Cascade model" of the use phase of ICT devices, including several active uses and storage periods. Cascade model of the process "use phase", divided into "active use", and "storage". Source: Thiébaud et al. (2017b)

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 82 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 82: 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.

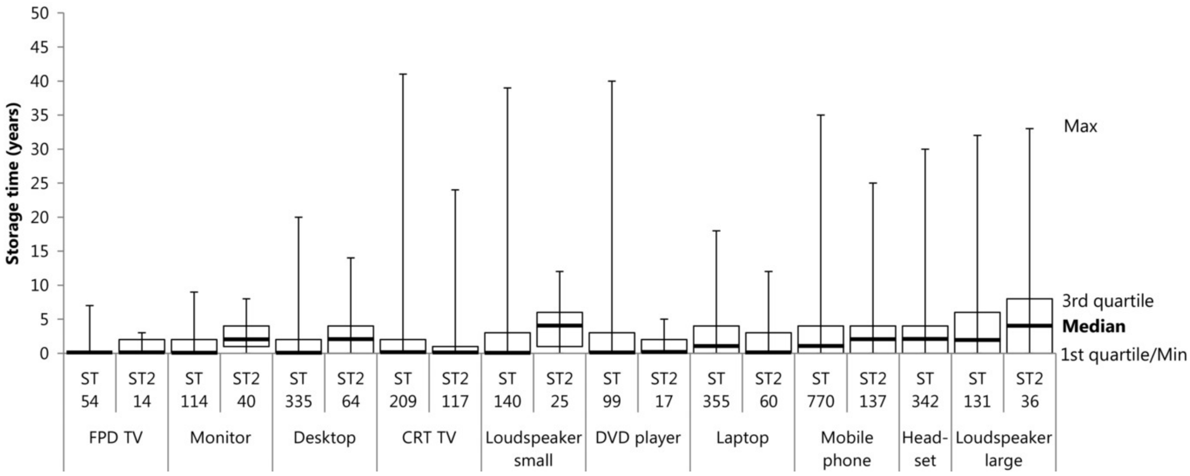


Figure 83: Comparison of the box plots of the storage time for ten different electronic device types.

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.

15 Strategies for material efficiency of ICT

15.1 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[48], 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[49] 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 84 below.

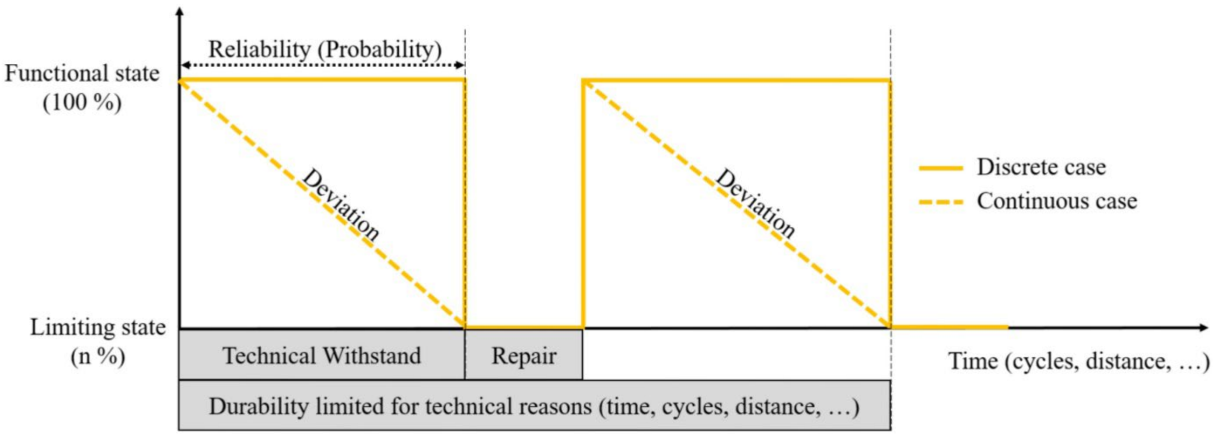


Figure 84: Relationship between reliability, repair and durability (adapted from EN 45552:2020). Source: Cordella et al. 2021)

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 37: Example of reliability provisions of ICT devices

Product group	Reliability aspect	Rationale

[48] EN45552:2020. General method for the assessment of the durability of energy-related products
[49] https://www.ecosmartphones.info/

Smartphones and tablets (proposals for reliability requirements).	Scratch Resistance - Screen of the device passes the hardness level 4 on the Mohs hardness scale.	Measures to increase the withstand of the glass used to cover the display do not only prevent 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 Regulation (EU) 2019/2021 and Commission Delegated Regulation (EU) 2019/2013	Firmware 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	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
	Info. on minimum guaranteed availability of software and firmware updates, and of product support more generally	

15.2 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 38). 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 38.

On this area, the "Directive (EU) 2019/771[50] 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[51] 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:

[50] 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.

[51] 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

- a longer compatibility of software updates with hardware
- 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)[52] 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 38: Example of software related provisions on ICT devices

Product group	Software Aspect	Rationale

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

Electronic Displays (Commission Regulation (EU) 2019/2021)	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	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
Commission Regulation (EU) 2019/424 of 15 March 2019 laying down ecodesign requirements for servers and data storage products		
Smartphones and tablets (proposal for software related requirements)	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.	

15.3 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[53] (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 85)

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

Figure 85: 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 Figure 86).[54]

Figure 86: 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).

15.4 Interoperability

ISO/IEC 2382-01[55] 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[56]. 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.

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

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

[56] 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

- 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 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[57] and a detachable (DC) output cable[58] to the ICT device (see Figure 87). 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.

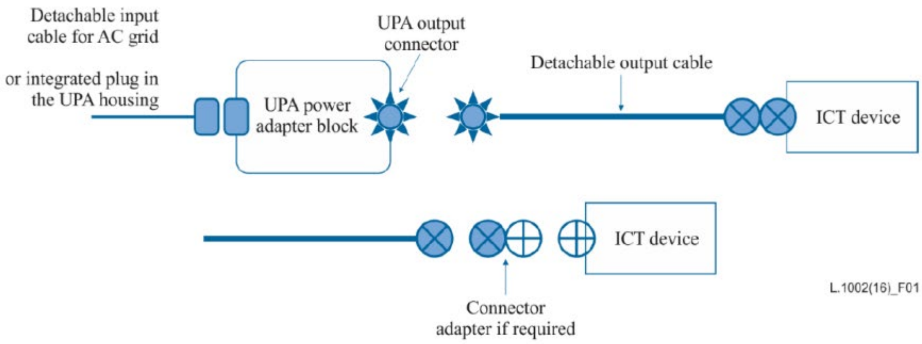


Figure 87: Basic Universal Power Adaptor (UPA) configurations and connection options (Source: ITU-T 2016)

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

[57] 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.

[58] 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.

proper end-of-life treatment results only in minor credits, if at all. Thus, the environmental argument for 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[59] 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[60].

15.5 Reparability and upgradability

According to the standard EN45554:2020[61] 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 39. Less attention has been paid until now to design for upgrading strategies.

Table 39: Examples of reparability / upgradability requirements applied (or proposed) for ICT devices in the EU Ecodesing and Energy Labelling framework.

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

Product group	Reparability / upgradability aspects	Rationale
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	

15.6 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[62] key[63] 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 40) 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 40: 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)	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

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

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

2019/424		hibernation.
Smartphone and slate tablets (proposal)	The devices include a software function, that resets the device to its factory settings and erases 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;	

15.7 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[64].

Refurbishment has often also a social inclusion mission. RECOSI[65] (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[66] 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[67], 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[68] 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 41

Table 41: Design strategies relevant for remanufacturing according to the EN45553:2020.

64 https://www.backmarket.com/

65 https://circulareconomy.europa.eu/platform/en/good-practices/recosi-refurbishing-ict-products-re-use
66 https://rreuse.org/about-us/
67 https://www.aliternetworks.com/
68 EN45553:2020 General method for the assessment of the ability to remanufacture energy-related products

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 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)

15.8 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[69], 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 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 42.

Table 42: 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

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

	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).

15.9 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

15.10 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 43 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 43: 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	Reparab ility	Reusabil ity	Upgradabi lity	Removabi lity	Replaceabil ity
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	Comprehensive		Yes		Yes	Yes	Yes
	Target Group		Yes		Yes	Yes	Yes

Table 44 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 44: Synergies and trade-offs between circularity strategies

	Reliability	Reparability	Upgradability	Reusability	Ability to be remanufactured	Recyclability	Recycled Content
Reliability		Synergies Products that are more reliable (or perceived to be more reliable) have more possibilities to be repaired (Makov and Fitzpatrick, 2021). Trade-offs Design measure to make product more reliable could come at expenses of reparability/disassemblability (e.g. use of glues for strong Ingress Protection) (Cordella et al. 2021)	Synergies Products that are more reliable are expected to have a longer lifetime and consumer are more willing to upgrade them. Trade-offs Products that are more disassemblable (for upgrade) are sometimes perceived to be less reliable. Some easy to upgrade design can have trade off with reliability	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	Synergies Higher quality material associated with reliability also increase recyclability. Trade-offs Design measures to make product more reliable could come at the expense of recyclability (e.g. use of adhensive for higher Ingress Protection)	Synergies High quality material (e.g. plastics) can offer both reliability, but also good quality material for a future product. Trade-offs Lower quality recycled material can hinder reliability. Certain materials may lose their reliability/quality the more times they are recycled.
Reparability			Synergies Easy disassembly facilitates both	Synergies Easy disassembly facilitates both Reset and data transfer/erasure facilitates both.	Synergies Easy disassembly facilitates both	Synergies Easy disassembly facilitates both	

Upgradability				Easy disassembly facilitates both	Easy disassembly facilitates both	Easy disassembly facilitates both	
Reusability		.			Easy disassembly facilitates both	Easy disassembly facilitates both	
Ability to be remanufactured						Easy disassembly facilitates both	
Recyclability							Legacy chemicals/ pollutants may deem recyclability less desirable/ feasible (Dalhammar et al., 2021)
Recycled Content							

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[70.]

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.

[70] C. Bakker, F. Wang, J. Huisman, M. Hollander (2014) Products that go round: exploring product life extension through design J. Clean. Prod., 69, pp. 10-16, 10.1016/j.jclepro.2014.01.028

16 Product Grouping

A categorisation of the different products subsumed under the wider category of 'ICT products' is proposed in Table 45 below. Grouping of products is based on their application in the context of ICT system (e.g. data centre, telecommunication network, end-use) but also based on functional similarities (e.g. audio video devices, wearable devices, among others). This categorisation will be the basis for the definition of the scope/product applicability of the policy recommendations presented in Chapter 18.

Table 45: Product grouping

<table>
<tr><td colspan="2">Product Groups</td><td>Sub categories</td></tr>
<tr><td colspan="2">Data Centre Devices</td><td>Servers; storage, networking (Networking (switches/routers), Uninterruptible Power Supply (UPS)</td></tr>
<tr><td colspan="2">Telecommunication Network Devices</td><td>Broadband communication equipment, Network in Offices (1GB/10+ GB LAN, WLAN), Mobile networks (mobile radio, aggregate/core, satellite TV, TETRA, 2G, 3G, 4G, 5G, Cable (fixed, landline) networks (i.e. PSTN/KSDN, TV-cable, ADSL, VDSL, FTTLA, FTTH/B, FTTH)</td></tr>
<tr><td rowspan="9">Consumer ICT devices (Consumer Electronics)</td><td>Electronic displays</td><td>Televisions, Monitors, Digital Signage Displays</td></tr>
<tr><td>Audio/video devices</td><td>video projectors / beamers, interactive whiteboards, videoconference systems, , complex set-top boxes; cameras, virtual reality headsets video players/recorders;</td></tr>
<tr><td>Audio Equipment</td><td>Loudspeakers, Radios, Players/recorders, Amplifiers, Receivers, Tuners, Microsets, Wireless speakers, Smart speakers, Soundbars, Network audio players MP3 players, stand-alone home audio, network connected home audio;</td></tr>
<tr><td>Personal ICT Equipment</td><td>Desktop PCs, Workstations, Notebooks/Laptops, Slate Tablets, Smartphones, Mobile Phones, Fixed Phones, video game consoles,</td></tr>
<tr><td>Accessories and peripherals</td><td>External power supplies (chargers), docking stations, external drives (hard drives, memory stick), and power banks, keyboards</td></tr>
<tr><td>Wearable ICT Devices</td><td>Smartwatches, Fitness trackers, Earbuds, Headsets, Virtual Reality</td></tr>
<tr><td>Imaging Equipment</td><td>Monochrome laser MFD (Multi-Functional Printer, Colour laser MFD, Monochrome laser printer, Colour laser printer, Colour inkjet MFD, Colour inkjet printer, Professional printer and MFD, Scanner, Copier, Facsimile (fax) machine, 3D Printers</td></tr>
<tr><td>Home / Office Network Equipment</td><td>Home/office network equipment, IoT Cellular Gateway, IoT Home/Office Gateway, Home Network-attached storage equipment (NAS)</td></tr>
<tr><td rowspan="3">Other ICT Devices</td><td>ICT in public Space</td><td>ATMs, Cash Registers and POS Terminals, Ticket Machines, Public WLAN hotspots, Toll-related ICT, Security cameras</td></tr>
<tr><td>Industrial Sensors</td><td>ICT devices for industrial monitoring & management</td></tr>
<tr><td>Building Automation & Control</td><td>ICT devices for building monitoring & management</td></tr>
</table>

17 Current policy landscape

The current EU sustainable product policy is based on a combination of policy instruments at mandatory and voluntary level.

At mandatory level, the Directive 2009/125/EC established a framework for the setting of energy and material efficiency ecodesign requirements for energy-related products (ErP), including the ICT devices under the scope of this study. The Energy Labelling Regulation (EU) 2017/1369 also applies to energy-related products placed on the market or put into service. It provides a framework for the labelling of those products and the provision of standard product information regarding energy efficiency, allowing the provision of 'supplementary information' regarding the functional and environmental performance of a product.

At voluntary level the most relevant EU initiatives are the voluntary European Ecolabel scheme (according to the Regulation (EC) No 66/2010) and the Green Public Procurement (GPP) Criteria, published as Staff Working Documents of the European Commission, and developed for different product groups and services.

In this policy framework the table below provide a summary of the ICT product groups already covered (or planned to be covered) by these complementary policy initiatives.

Table 46: Current product policy landscape

Product Group	Sub categories	Existing and planned EU product policies			
		Ecodesign Directive	Energy Labelling	EU Ecolabel	EU GPP
Data Centre Devices	Servers	Regulation (EU) 2019/424			SWD(2020)55 final
	Storage	Regulation (EU) 2019/424			
	Networking (switches/routers)				
	UPS				
Telecommunication Network	Broadband communication equipment				
	Network in Offices (1GB/10+ GB LAN, WLAN)	(EC) No 1275/2008 requirements for standby and off-mode			
	Mobile networks (mobile radio, aggregate/core, satellite TV, TETRA, 2G, 3G, 4G, 5G				
	Cable (fixed, landline) networks (i.e. PSTN/KSDN, TV-cable, ADSL, VDSL, FTTLA, FTTH/B, FTTH)				
Consumer Electronic	Televisions	Regulation (EU)	Regulation	Commissio	SWD(202

	displays	Monitors	2019/2021	(EU) 2019/2013	n Decision 2020/1804/EU	1) 57 final
		Digital Signage Displays				
		video game consoles	Voluntary Agreement (VA) COM/2015 /0178 and (EC) No 1275/2008			
	Audio/video devices	video players /recorders	(EC) No 1275/2008			
		video projectors / beamers				
		interactive whiteboards				
		videoconference systems				
		MP3 players				
		stand-alone home audio				
		network connected home audio				
		complex set-top boxes				
		cameras				
		Headsets and virtual reality headsets;				
		Loudspeakers				
	Audio Equipment	Radios	(EC) No 1275/2008			
		Players/recorders				
		Amplifiers				
		Receivers				
		Tuners				
		Microsets				
		Wireless speakers				
		Smart speakers				
		Soundbars				
		Network audio players				
		Desktop PCs,	Regulation (EU)			Commissi

			617/2013 (under revision)			on Staff Working Document SWD(2021) 57 final
	Personal ICT Equipment	Workstations	Regulation (EU) 617/2013 (under revision)	Under preparation		Commission Staff Working Document SWD(2021) 57 final
		Notebooks/Laptops				
		Smartphones	Under preparation			
		Slate Tablets	Under preparation	Under preparation		
		Mobile	Under preparation (limted to cordless)			
		Home/Office fixed phones				
		External Power Supplies	(EU) 2019/1782			
	Accessories and peripherals	docking station	(EC) No 1275/2008			
		external drive (hard drives, memory stick)				
		power bank				
		Keyboard, mouse				
		Monochrome laser MFD (Multi-Functional Printer)	(EC) No 1275/2008 and Regulation under preparation**	Regulation Under preparation		GPP (SWD(2020) 148 final)
	Imaging Equipment	Colour laser MFD	(EC) No 1275/2008 and Regulation under preparation**	Regulation Under preparation		GPP (SWD(2020) 148 final)
		Monochrome laser printer				
		Colour laser printer				
		Colour inkjet MFD				
		Colour inkjet printer				
		Professional printer & MFD				
		Scanner				
		Copier				

		Facsimile (fax) machine				
		3D Printers				
		Home Network-attached storage equipment (NAS)				
	Home / Office Network Equipment	Home/office network equipment	(EC) No 1275/2008			
		IoT Cellular Gateway				
		IoT Home/Office Gateway				
Other ICT Devices	ICT in public Space	ATMs				
		Cash Registers and POS Terminals				
		Ticket Machines				
		Public WLAN hotspots devices				
		Toll-related ICT				
		Security cameras				
	Building Automation and Control					
	Industrial Sensors					

In the existing product policy framework, there are other policies that have a more horizontal approach and can still be relevant for the ICT context. These initiatives include:

- The Regulation (EU) 1275/2008 laying down ecodesign requirements for off mode, standby mode of electrical and electronic household and office equipment (currently under revision in order to extend the scope to networked standby energy consumption)
- Radio equipment directive (Directive 2014/53/EU) with the ongoing amendment on common charger
- Directive 2006/66/EC on batteries and accumulator (currently there is a proposal for a concerning batteries and waste batteries, repealing and amending this directive)

Finally, JRC policy initiatives related to Code of Conducts help parties in the telecommunications sector to address the issue of energy efficiency by setting general principles and target consumption values. Among the Codes of Conduct currently in place are the Code of Conduct for Broadband Communication Equipment[71] (Bertoldi and Lejeune, 2023) and the Code of Conduct for Data Centres[72] (Acton et al, 2023).

[71] https://e3p.jrc.ec.europa.eu/communities/ict-code-conduct-energy-consumption-broadband-communication-equipment
[72] https://e3p.jrc.ec.europa.eu/communities/data-centres-code-conduct

18 Policy Recommendations

18.1 Addressing the multiple layers of the ICT system

Addressing the environmental impacts of ICT from multiple perspectives, through both supply and demand, and by deploying flexible and future-proof policy instruments reflects not only the multi-layer nature of ICT systems but also the fast pace of technological development and innovation.

Policies are recommended on the basis of two levels as depicted in Figure 88:

- the *device* level, represented by the blue area, which in turn refers to ICT hardware (dark blue shade) as well as software which is necessary for the functioning of the device, such as firmware or an operating system (light blue shade), and
- the *system* level, which crosses the boundaries of the device, and refers to application software (light orange shade), cloud services and other ICT services (dark orange shade).

Such distinction allows for the policy proposals to capture the technical complexity of ICT systems, but also facilitates policy-making by signalling potential boundaries for the "original equipment manufacturer (OEM)" of the device. In other words, policies at system level could also address areas where parties other than the OEM of the device operate.

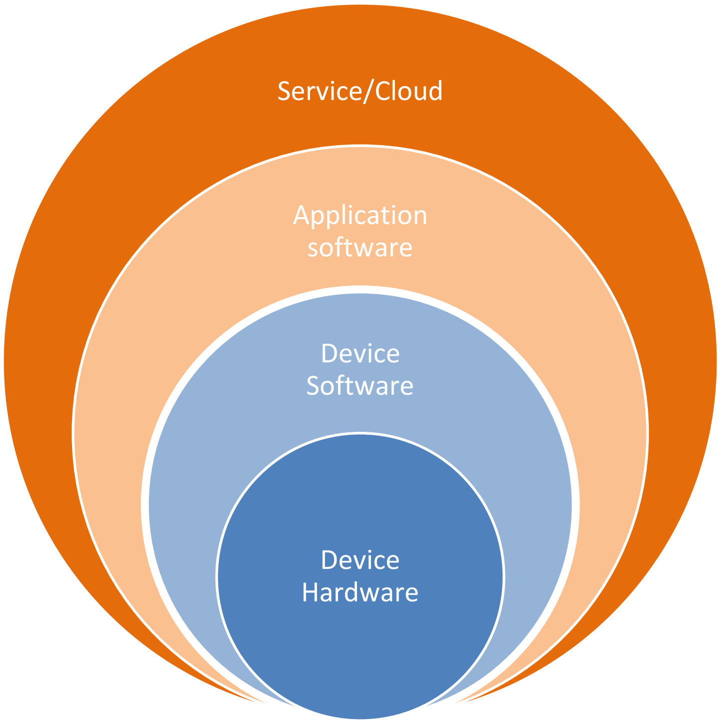


Figure 88: The multiple layers of ICT systems

Device-level policy options ensure that innovation continues at hardware level to improve energy and material efficiency. The ecodesign framework (under the Ecodesign Directive and the Energy Labelling Regulation) already establishes well-developed energy efficiency provisions, which can continue to be adjusted and updated to an ambition level that would effectively stimulate innovation, especially with regards to ICT products which remain energy intensive in the use phase. Some product group gaps can be addressed such as updated provisions for computers, the strengthening of provisions for imagining equipment and game consoles, and the introduction of policies for home and office network equipment other than the existing ones on standby, off mode and networked standby.

The ecodesign framework as a policy instrument has also been able to accommodate a wider range of provisions focused at improving material efficiency, an aspect which is very relevant for ICT products which are contain valuable and scarce materials, are manufacture-intensive, demonstrate short and reduced lifetime and contribute to e-waste generation. With regards to ICT material efficiency provisions, such as those aimed at increasing reliability, reparability and recyclability, have already been introduced for servers and electronic displays (and are being proposed for mobile phones and tablets), but should be expanded to a wider range of ICT products with the aforementioned characteristics. In order to enhance the role of consumers in the economic transition towards circularity, the extension of product guarantees and the provision of easy-to-understand information via circularity indices (e.g. durability or reparability scores), can be deployed and expanded. Moreover, policies that facilitate the development of the second-hand and refurbishing market, such as building consumer trust via information and labelling of the quality of refurbished products or refurbishers themselves, can also offer potential for circularity and retention of valuable materials in use.

However, policies at device level are insufficient to effectively capture the systemic nature of ICT products and the way in which environmental impacts take place. Induction effects, presented and analyse the previous Tasks of this study, leading to higher data storage, transmission and processing needs, mean that addressing efficiency alone may not be sufficient to enable energy and material savings overall. System/Cloud-based policies that target directly enablers of energy and material consumption, such as the efficiency of software applications and the settings of video streaming regardless of the medium of streaming (device, application or platform). Those can take the form of minimum requirements (e.g. in the case of software efficiency), or informational provisions such as clear communications to consumers on their data and settings usage.

The market shift towards service-based business models calls for policy design that also considers services. The current ecodesign framework maintains its focus on the product, meaning that other policy instruments may need to be deployed. Some such instruments already exist, such as the EU Green Public Procurement, which could expand their reach and impact through mandatory implementation (e.g. in the framework of the new Ecodesign for Sustainable Products Regulation (European Commission, 2022), and cover a wide range of criteria targeted at both device and service level. Other instruments may need to be considered, such as provisions that directly aim at telecommunication services. Provision of information to consumers on the environmental impact of the telecommunication services they are offered can enable them to make informed decisions and foster innovation at systemic level; both in the hardware deployed to deliver those services and the way they are marketed. Lastly, even though financial policies are not the focus of this report, tools such as pricing policies and taxation can be very effective in curbing data traffic and incentivising efficiency in data use and subsequently energy, in accordance with the polluter pays principle.

Policy recommendations are described in more detail in the sections below using the structure in Figure 88 (section 4.2. for the *device* level and section 4.3. for the *system* level). Comments from the stakeholders are summarised in the Annex I below.

18.2 Device Level

18.2.1 Energy Efficiency

#1 Extending the implementation of energy efficiency requirements

Energy efficiency requirements are currently enforced for a number of relevant ICT devices, namely electronic displays, servers and computers.

ICT in public spaces ("Public ICT") and Home network equipment are the only ICT categories where energy consumption is clearly rising. According to the study by VHK and Viegand Maagøe (2020). (2020), the electricity consumption of home/office network equipment has increased from 10.28 TWh/year in year 2010 to 16.61 TWh/year in year 2020. Furthermore, it is expected to further increase to 18.49 TWh/year by year 2025, constituting approximately 7.6% of the electricity consumption of ICT devices overall. This product group can also be considered together with similar network equipment devices, such as hotspot equipment. When combined, these products are expected to consume 25 TWh/year in year 2025, which would correspond to more than 10% of the energy consumption of ICT devices.

Neither category is currently regulated, nor included in the Ecodesign and Energy Labelling Working Plan 2022-2024. Relevant aspects would include energy efficiency in active move and material efficiency aspects, while stand-by and off mode consumption are already covered by the by Regulation (EC) No 1275/2008.

#2 Introduction of energy efficiency requirements based on "active mode" performance

The energy efficiency of ICT devices with high computing capacity (e.g. servers, computers, game consoles but also tablets, smartphones) is dependent on the active mode(s) the device is running on. Some active modes can require a more intensive use of CPUs and graphic cards (e.g. gaming), notably increasing the level of energy consumption of the device. Energy efficiency requirements in ecodesign regulations are based on tests performed on a combination of modes (e.g. "active", "sleep", "off", "idle") so as to reflect variable consumer behaviour during a products lifetime. However, in the case of computers, energy consumption under Regulation (EU) No 617/2013 is considered only for the power modes of "off", "sleep" and "idle" (see Table 47). In the context of the revision of the Ecodesing and Energy Labelling Criteria for computers, the Commission, CLASP/GTD offered support to fill this gap and have developed an open-source software for testing the energy-efficiency and performance of personal computers (Test Suite) as they perform a range of common tasks[73].

The main characteristics of the Test Suite developed by GTD are:

• It is based on the open-source Phoronix Test Suite

• It runs a series of worklets[74]

• It executes native binaries in Microsoft Windows, MacOSX, and Linux (incl. ChromeOS)

• Measuring power does not alter the performance or the power demand

• All the results are fused together in a single meta-efficiency metric value

Table 47: Modes considered under Regulation (EU) No 617/2013.

<table>
<tr><td>Mode</td><td>Definition</td><td>Minimum Requirement</td></tr>
<tr><td>Active mode</td><td>The state in which a computer is carrying out useful work in response to (a) prior or concurrent user input or (b) a prior or concurrent instruction over the network. This state includes active processing, seeking data from storage, memory or cache, including idle state time while awaiting further user input and before entering low power modes;</td><td>No</td></tr>
<tr><td>Idle state</td><td>A state of a computer in which the operating system and other software have completed loading, a user profile has been created, the computer is not in sleep mode, and activity is limited to those basic applications that the operating system starts by default;</td><td>Energy consumption threshold based on the combination of "off", "sleep" and "idle"</td></tr>
<tr><td>Off mode</td><td>'power demand level in the low power mode which cannot be switched off (influenced) by a user, other than through the movement of a mechanical switch, and which may persist for an indefinite period of time when the appliance is connected to the main electricity supply and used in accordance with the manufacturer's instructions. Where Advanced Configuration and Power Interface (ACPI) standards are applicable, off mode usually correlates to ACPI system level G2/S5 ('soft off') state;</td><td rowspan="2">Off mode and sleep mode power limits.</td></tr>
<tr><td>Sleep mode</td><td>Low power mode that a computer is capable of entering automatically after a period of inactivity or by manual selection. In this mode the computer will respond to a wake event. Where Advanced Configuration and Power Interface (ACPI) standards are applicable, sleep mode usually correlates to ACPI system</td></tr>
</table>

[73] https://www.clasp.ngo/tools/on-mode-computer-testing-tool/

[74] A worklet is a set of tasks, placed in a workflow, that is, in a sequence of activities that can be easily reproduced on a regular basis

	level G1/S3 (suspend to RAM) state;	

Similarly, in the case of game consoles, power cap established under the voluntary agreement (VA) Self-Regulatory Initiative for Energy Efficiency of Games Consoles (4.0) are not set for the "Active Gaming Mode". The VA set requirements only for "Navigation Mode" and "Media Playback Mode" (see table below).

Table 48: Modes considered in game consoles

Mode	Definition	Minimum Requirement
Active Gaming Mode	Active Gaming: Mode in which the Games Console is actively performing its primary function of game playing.	NO
Media Playback:	Mode in which there is decoding and playing of video files and codecs up to UHD content, on the Games Console's own optical discs, and streaming media players.	YES
Navigation: Mode	C. in which no other mode is engaged and the Games Console is displaying a menu of functions (the "Home Menu").	YES
Off, Standby, Networked Standby	As defined in EU Regulation (EU) No 1275/2008 (as amended by EU Regulation (EU) No 801/2013);	YES

It is suggested to:

- Establish minimum energy requirements based on a combination of modes as representative as possible of actual use and/or;
- set specific requirements for each representative active mode

18.2.2 Material efficiency

#3: Material efficiency of consumer electronics

The proposed measure includes a range of provisions (see Table 49 below) related to a number of material efficiency aspects to be applied horizontally across the scope of consumer electronics (see product scope in Table 46). The existence of potential trade-offs and synergies between these different strategies, make recommendable the development of a single horizontal measure covering all these aspects and potential provisions. Moreover, different provisions could be suitable/applicable to different product groups included in the scope of this proposal.

The proposed measure covers "consumer electronics" and refers to any electronic devices designed, tested and marketed for household and office environment.

The overall aim of this measure is to increase the product durability, reusability, and recyclability, according to the waste hierarchy of priorities reduce-reuse-recycle.

Table 49: Material efficiency provisions

Aspect	Provisions
Hardware durability and reliability	• Resistance to stresses/ageing mechanisms (e.g. drop/shock/ scratch resistance, ingress protection from water/dust) • Battery endurance in cycles, battery protection software, intelligent charging, information on battery state of health • Minimum / Expected lifetime • Durability/reliability score

Software related durability and device performance impact	• Minimum requirements for availability of software functionality / corrective / security updates • Availability and durability of cloud based services associated to the product. • Decoupling of the electronic device from cloud services • Software update impact on device performance
Reparability, Upgradability and Reusability	• Introduction of a Reparability Scoring Index / Label • Availability of repair/upgrade/maintenance info to independent operators/end-users • Prevention of part pairing • Spare part availability and delivery time • Disassembly generally or related to Disassembly Depth, Tools, Fasteners, Working • Environment and Skill Level • Use of coding standards for identification of components and materials • Standardisation of certain relevant spare parts • Reusability/Upgradability specific provisions
Ability to be refurbished and remanufactured	• Ability to be identified of products/parts • Ability to locate access points and fasteners • Accessibility of parts • Ability to be disassembled/ assembled • Wear and damage resistance during the remanufacturing process steps
Recyclability	• Ability to easily separate the product into different materials (e.g. metals, plastic, CRMs) • Choice of materials and restrictions on substances (e.g. choice and combination of polymers, additives) • Condition for the access to product data relevant for the recycling, • Recyclability information • Recyclability Score

Hardware durability and reliability

Resistance to stresses/ageing mechanisms

Proxy examples of provisions related to resistance to stresses or ageing mechanisms include:

- Drop/shock resistance
- Scratch Resistance
- Ingress protection

These elements should define how long a particular product/part function would endure, after preparing and/or using the product under recommended operational conditions and be submitted to known stresses and/or aging effects.

Battery endurance, protection software, intelligent charging, State of Health

Batteries are a key component of portable ICT devices. Provisions related to battery durability can cover design aspects (e.g. endurance), information/instructions and battery power management. In particular:

- Battery endurance in cycles: measures to ensure that the batteries used in the devices achieve at least X cycles at Y percent of the initial 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;
- Battery Protection Software: Pre-installed battery protection software that can limit the maximum battery charge (e.g. at 80%) when the electronic device is used plugged-in mode, reducing the degradation of the battery.
- Intelligent charging software: the availability of this functionality allow 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.
- 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.

Minimum / Expected Lifetime

A horizontal measure would go beyond the consumer guarantees under the existing EU regulations and set the harmonised rules regarding the products life expectancy. There are various approaches that could be followed in this context, from the information requirements, labelling on the expected (technical) lifespan or lifespan guarantees that consider the durability of the product.

Regulating "durability" as a horizontal measure requires use of different parameters (e.g., number of years/hours/cycles, kilometres, Mean Time Before Failure (MTBF), etc.) and different testing methods per product group.

Also, for some ICT products, there is no standard for assessing accurately product lifespans. The definition of the lifespan of the products (in absolute terms), followed by a definition of the test methods and reporting standards would need to put in place. Alternatively, a mandatory usage of meter on specific products groups could be regulated to provide an objective information on the product lifetime throughout its use; it could count the number of hours of use (e.g. in TVs, smartphones, laptops etc.) or the cycles of use (e.g. for batteries in portable ICT).

Durability/Reliability score

Multi-parameter circularity aspects, such as durability or reliability, often require a complex assessment process, and can be expressed via different metrics. For instance, the reliability of an electronic device can be assessed by means of its resistance to accidental drops or high temperatures, its battery endurance or the lifetime of one of its components. As such, scoring of circularity aspects can offer a tool for assessing and communicating such multi-parameter and complex product characteristics.

According to European standard EN 45552, reliability refers to the functioning of a product before any limiting event, while the concept of durability is more inclusive of limiting events that may require maintenance and repair until a limiting state is reached.

For the development of a reliability or durability scores, a distinct methodological framework can be established on the basis of identification of relevant priority parts, parameters and a scoring system. In the case of durability, the consideration of reliability, reparability and upgradeability may need to be combined. Examples of such methods can be drawn from the ongoing French initiative for the introduction of a durability index[75] , as well as the work of JRC on reparability index[76].

Such scores can offer tools for product policy, either via setting a minimum score as requirement, or via linking the results to a classification system which can be used for communicating a durability or reliability class to consumers.

[75] ADEME, In Extenso Innovation Croissance (Benoît TINETTI, Marion JOVER, Chloé DEVAUZE, Mariane, IGHILAHRIZ), Fraunhofer IZM (Anton BERWALD), 2021. Preparatory study for the introduction of a durability index.

[76] European Commission, Joint Research Centre, Cordella, M., Sanfelix, J., Alfieri, F., Methods for the assessment of the reparability and upgradability of energy-related products : application to TVs : final report, Publications Office, 2019, https://data.europa.eu/doi/10.2760/501525

Software related durability and device performance impact

Availability of software security, corrective / functionality updates

The lifetime of software is crucial to the lifetime of electronics. This provision aims to avoid functional obsolescence, safety and incompatibility issues of the electronic device. The provision covers security, corrective and functionality updates for the firmware and operating system.

The availability of software updates entails availability of all elements that are necessary for the normal operation of the device after the installation of an update.

Setting horizontal minimum requirements on firmware / system software for all consumer electronics can increase durability by reducing software-related hardware obsolescence.

Availability and durability of cloud based services of the product

Many electronics make use of cloud based services to provide their function. Examples include products as security cameras, smart speakers. The end of support for these cloud based services can make the electronic device 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 at least 5 years after the last item was placed on the market model).

Decoupling of the electronic device from cloud services

An additional provision could ensure the possibility of turning off the external cloud service either through a built-in functionality or through appropriate software updates from the coupling and continue using the device independently. OEMs should ensure the availability of minimum “core functionalities” even without an activated network function; or the labelling on the product that it relies on an internet connection or external cloud services.

Software update impact on device performance

Another relevant provision is related to ensuring that software updates do not have a negative impact on device performance, unless there is explicit consent by the end-user for the negative impact prior to the update.

Repair, Reuse, Upgrade

Reparability Scoring Index / Label

A reparability score is the result of the following steps (Cordella et al. 2019; Spiliotopoulos et al. 2022):

- Identification of priority parts
- Identification of relevant parameters influencing reparability (existing for ErP/electronics)
- Scoring system and aggregation
-

Repair Info / maintenance instructions to independent operators/end-users

Examples of information are the following:

- a disassembly map or exploded view;
- wiring and connection diagrams, as required for failure analysis;
- electronic board diagrams, to the level of detail needed to replace parts
- list of necessary repair and test equipment;
- technical manual of instructions for repair;
- diagnostic fault and error information;
- component and diagnosis information
- instructions for software and firmware (including reset software);
- information on how to access data records of reported failure incidents stored on device;

- procedure for authorisation of part replacement, when remote notification or authorisation of serial numbers are necessary for the full functionality of a spare part and the device.
- how to access professional repair (internet webpages, addresses, contact details).

Furthermore, the process for registration of independent/professional repairers should be specified and harmonised: "the process for professional repairers to register for access to information; to accept such a request, the manufacturers, importers or authorised representatives may require the professional repairer to demonstrate that…"

Prevention of parts pairing practices

Part pairing practices can be potentially used by OEMs to restrict and control parts replacement (e.g. to prevent the use of third party / second hand spare parts or limit product functionalities). Based on this, it is suggested that parts paring practices should be generally avoided, unless strictly necessary for security issues that cannot be managed in a different way. In such cases, the the authorisation of part replacement, and all the elements that would be necessary for a normal operation of the device after a replacement of a part, should be accessible to the owners/user of the devices, to the professional repairers, refurbishers and remanufacturers established in the EU Member States

Spare part availability and delivery time

The following parameters are relevant for spare part availability:

- Duration: "manufacturers, importers or authorised representatives shall make available to [end-users/independent operators] at least the following spare parts, for a minimum period from [X] month after the date of placement on the market until [Y] years after the date of end of placement on the market: [parts]"
- Method of availability: "the list of spare parts concerned and the procedure for ordering them shall be publicly available on the free access website of the manufacturer, importer or authorised representative, from [X] month after placing the first unit of a model on the market and until the end of the period of availability of these spare parts.
- Delivery Time: "manufacturers, importers or authorised representatives shall ensure the delivery of the spare parts within [X] working days after having received the order."
- Maximum price of spare parts: "manufacturers, importers or authorised representatives shall indicate an expected maximum pre-tax price at least in Euro for spare parts"

Disassembly or related to Disassembly Depth, Tools, Fasteners, Working Environment and Skill Level

The following options are proposed (based on EN 45554:2020):

- General provision (when specification is non-applicable): "manufacturers shall ensure that joining, fastening or sealing techniques do not prevent the disassembly for repair or reuse purposes (of the following components)"
- Specification based on:
- Fasteners: "fasteners shall be [removable or reusable]"
- Tools: "the process for replacement shall be feasible with [no tool, a tool or set of tools that is supplied with the product or spare part, or basic tools, or with commercially available tools]"
- Disassembly depth: the process for disassembly of a part shall be feasible within a [X] number of steps.
- Working environment: "the process for replacement shall, as a minimum, be able to be carried out in a [workshop environment or use environment]"
- Skill level: "the process for replacement shall, as a minimum, be able to be carried out by [Expert or layman or generalist]."

Use of component and material coding standards

The following specification can apply:

- Labelling of every main component with title and QR code leading to a spare part availability provider: *https://frame.work/*
- Coloured wires

Use of standard components

Examples of provisions:

- Common battery within same product family
- Port harmonisation
- Use of shared solutions, fittings, and parts
- Use of standardized materials and recommended colors
- Use of standardized components to secure interchangeability. This could either occur within a brand level (e.g., lighting port used by various apple products), across multiple (two or more) brands (eg., use of USB c connector), or even within a brand proprietary

Reusability/Upgradability specific provisions

Reusability and Upgradeability are concepts closely related to Reparability, in the sense that all design-related reparability provisions aiming at ease of disassembly are acting in a synergic manner to increase reusability and upgradeability. Nevertheless, there are still some types of provisions that are more distinctly specific to reusability and upgradeability:

- Modular design (the product is built from individually distinct functional units), transformability; detachable elements; adjustable sizing, customizing surfaces,
- functionality for secure data deletion and reset the device to its factory settings

The requirement on a functionality for secure data deletion can be implemented by means of technical solutions such as, but not limited to: 1) a functionality implemented in firmware, typically in the Basic Input/Output System (BIOS), 2) 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 3) in software installable in the supported operating systems provided with the product.

Secure data deletion in ICT devices can be also achieved by a 'secure deletion of the encryption key', that means the effective erasure of the encryption key 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.

Remanufacturing / Refurbishment

Ability to be identified of products/parts

One of the key steps of remanufacturing/refurbishment processes is the product inspection and the determination of the condition its parts and the functionality. In this way it is possible to determine which parts need reprocessing e.g. repair, reworked, replaced or upgraded and which parts might need special care. In the product identification it is also important to identify the original legal requirements applying to the product by giving information on the applicable legislation at the time the product was placed on the market.

Example of provisions are based on typical criteria that influence the ease of identification of the product and its parts according to the standard EN45553:2020:

- Access for diagnostics (e.g. embedded or external diagnostic tools to verify condition);

- Information on how to determine its functionality (also relevant in the preparation for reuse context, see also the CENELEC standard EN 50614:2020)[77];;
- Information on the status of the functionality (e.g. if the different functions of the product 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 product 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

As described in the EN45553, the ability to locate access points and fasteners describe the ability to localize key elements for disassembling and assembling the product. To facilitate the location of access points typical design criteria can include:

- Indication of where access points are located (e.g. by marking or making clear where and how to connect the diagnosis 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

As for the EN45553, this aspect describes the ability of a product design to give operators physical access to its parts. In a refurbishing / remanufacturing process is important to have access to the parts that need to be disassembled, repaired, reworked, replaced or upgraded. Moreover is important to have access to the location where the functionality can be checked. Typical criteria that influence accessibility to support disassembly are:

- Access to parts during disassembly;
- Modularity of the device parts; and
- Access to fasteners, e.g. joints, gripping points and breaking points.

In order to facilitate remanufacturing, it can also 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).

Ability to be disassembled/ assembled

The ability to be disassembled/assembled describes the ability of a device to be separated into its parts and the ability of its parts to be assembled. Similarly to repair, relevant parameters can include parameters like disassembly depth, tools, fasteners, working environment and skill level. The EN45553 suggests additional criteria that influence the ability of a product to be disassembled and assembled like:

- 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
- Asymmetry/symmetry of parts (e.g. to ensure correct assembly)

[77] EN 50614:2020. Requirements for the preparing for re-use of waste electrical and electronic equipment

- 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 remanufacturing process

As described in the EN45553, the ability to be wear and damage resistant during the remanufacturing process steps describes the ability of a product and/or its parts to withstand all treatment necessary during the remanufacturing steps without being damaged.

Proposed criteria that influence wear and damage resistance to avoid premature deterioration due to the remanufacturing process are:

- 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

Ability to easily separate the product into different materials

An example of requirements linked to this provision includes the avoidance of connections that enclose a material permanently (as inserts into plastic).

Methods such as: moulding inserts into plastic, rivets, staples, press-fit, bolts, bolt and nut, brazing, welding and clinching make harder to separate the different materials. These processes mentioned are typical for tightly enclosing one material into another and are therefore recommended to be avoided to facilitate recycling (PolyCE, 2021)

Choice of materials and restrictions on substances

Virgin polymer materials are often engineered for very specific and demanding applications to meet a complex set of requirements or properties. To fulfil these, a large variety of different thermoplastics such as Styrenics (PS, HIPS, ABS, SAN), Polyolefins (HDPE, LDPE, PP), and different engineering thermoplastics (PC, POM, PUR, PA) are being used in consumer electronics. A broad variety of additives (both organic & inorganic) are often added before processing. They are used to change material properties such as colour, melting point, flammability, density, or to meet legal, design or cost purposes. In some circumstances different materials are moulded together. These design practices make more challenging the separation and recovery of the polymers. Whenever it is possible, these design practices should be avoided in order to increase the recyclability of plastic components (PolyCE, 2021).

Examples of requirements linked to this provision include:

- Avoid the use of coatings on plastics such as painting, lacquering, since it can result in changed density of the plastic.
- Do not use plating, galvanizing, vacuum-metallization as coating on plastics, since it can result in density change of the plastic.
- Avoid moulding different material types together by 2K or xK processes (different plastic materials injected into the same mould, or over-moulding, or in mould labelling) such as moulding a thermoplastic elastomer onto PP.
- Minimise the use of unnecessary additives in plastic component as they reduce the purity of the plastic streams.
- Avoidance of hazardous substances that cause material streams not to meet the requirements to be recycled and reused in new products in the future.

- Avoidance of design choices hindering recycling

Access to product data relevant for the recycling (including CRM)

Examples of relevant requirements include:

- marking of parts and materials, use of component and material coding standards for the identification of components and materials, indicative weight range of different materials, including Critical Raw Materials (CRM) and environmentally relevant materials; access to information, hardware and software needed for the recycling process.
- making available in the form of manuals or by means of electronic media (e.g. CD-ROM, online services) information relevant for treatment facilities as for art 15 (1) of the Directive 2012/19/EU
- making available to recyclers, on a free-access website[78], the dismantling information needed to access any of the products components referred to in point 1 of Annex VII of Directive 2012/19/EU. This dismantling information shall include the sequence of dismantling steps, tools or technologies needed to access the targeted components.

Currently only two ecodesign implementing measures adopted have addressed CRM recyclability, introducing information requirements on their presence in the product. One of these regulations refers to servers and data storage products[79], and focuses on Cobalt (in batteries) and (Neodymium) in Hard Disk Drives.

Recyclability information

Examples of requirements linked to this provision include:

- include a sentence or a pictogram in relation to product disposal[80]
- provide guidance to consumer about product dismantling (if necessary before the recycling)
- provide information on the recyclability of the product
- Marking of plastic components (e.g. type of polymer)

Recyclability score

The recyclability-related provisions listed above can serve as parameters for the development of an overall recyclability index/score. This would allow manufacturers to form their design-for-recyclability strategies. Similarly to the reparability score, the recyclability score can comprise of standardised methodological steps:

- Identification of priority materials
- Identification of relevant parameters influencing recyclability
- Scoring system and aggregation

[78] the "Information for Recyclers" (I4R) platform (https://i4r-platform.eu/) was developed to share information with recyclers of WEEE and in order to comply with the requirement

[79] Regulation on ecodesign requirements for servers and data storage products (EU 2019/424). Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1553786820621&uri=CELEX%3A32019R0424

[80] Currently, mandatory marking of EEE indicating separate collection consists of the crossed-out wheeled bin - see Annex IX of the WEEE Directive

Summary of the material efficiency measures

Table 50: Prioritisation of material efficiency provisions for the different product grouping identified; Rated prioritisation: (+lower, ++medium, +++higher)

	Hardware durability and reliability				Software Related Durability				Reparability, upgradability and reusability								Remanufacturing and refurbishing					Recyclability				
	Resistance to stresses/ageing mechanisms	Battery endurance in cycles	Minimum / Expected Lifetime	Durability/Reliability score	Availability of software functionality / security / corrective updates	Availability and durability of cloud based services of the product	Decoupling of the electronic device from cloud services	Software update impact on device performance	Introduction of a Reparability Scoring Index / Label	Availability of repair/upgrade info	Prevention of parts pairing	Spare parts availability and delivery time	Disassembly / Depth, Tools, Fasteners, Working Environment, Skill Level	Use of component and material coding standards	Standardisation of certain relevant spare parts	Reusability/Upgradability specific provisions	Improve the ability to be identified of products/parts	Ability to locate access points and fasteners	Accessibility of parts	Ability to be disassembled/ assembled	Wear and damage resistance during the remanufacturing process steps	Ability to easily separate the product into different materials	Choice of materials and restrictions on substances	Access to product data relevant for the recycling	Recyclability information	Recyclability Score
Electronic displays	++	N.A.	++	++	+++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	+ +	++
Audio/video devices	++	++	++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	+ +	++
Audio Equipment	+++	+++	+++	+++	+	+++	+++	+++	+	+	+	+	++	+	++	++	+	+	+	+	+	++	++	++	+ +	++
Personal ICT Equipment	+++	+++	++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	+ +	++
Accessories and peripherals	+++	+++	+++	+++	+	+	+		+	+	+	+	+	+	++	+++	+	+	+	+	+	++	++	++	+ +	+
Wearable ICT Devices	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	+	++	+	+	+	+	+	+	++	++	++	+ +	+
Imaging Equipment	++	N.A.	++	++	++	++	++	+++	++	++	++	++	++	+++	+++	+	+++	+++	+++	+++	+++	++	++	++	+ +	+
Home / Office Network Equipment	++	N.A.	++	++	+	+	+	+	+	+	+	+	++	+	+	+++	+++	+++	+++	+++	+++	++	++	++	+ +	+

** Some provisions on reparability and recyclability for electronic displays are already included in Regulation (EU) 2019/2021*

Considering the wide range of relevant provisions across a number of products under the consumer electronics family, a qualitative assessment can lead to the identification of priorities. Such assessment is presented in Table 50 above, making the use of a three-scale ranking system for priority (+lower, ++medium, +++higher). Since the assessment is only qualitative, the ranking should be understood as an assessment of which provisions can be prioritised for each product category, rather than a comparison between the product groups listed (in other words, Table 50 should be read horizontally rather than vertically). The qualitative assessment was done based on principles described below.

As the majority of impacts associated with ICT products (especially consumer electronics) stems from material extraction and manufacturing, reliability and durability are very relevant aspects for this product family. The appropriateness of opting for a reliability, reparability and/or durability could be examined at product group level. For instance, for product groups which demonstrate variable failure rates for different parts, the development of both a reliability and reparability index can offer complementary information on the circularity of a product. By contrast, less complex product groups as audio equipment, wearable devices, accessories and peripherals (e.g. a charging cable) may benefit more from a reliability provision than repair.

Hardware durability and reliability is a relevant aspect also for mobile personal ICT devices (e.g. smartphones and tablets) that are more exposed to use and/or environmental stresses, battery aging, accidents.

Software related durability measures are high relevant for 1) ICT devices whose correct functioning and security level are high dependent from the update level of the firmware and operation system (e.g. personal ICT devices) and 2) for devices whose main functionalities are linked to cloud based applications, as it could be the case for some security cameras, loudspeakers, smartwatches

Whenever a product family is composed of some frequent failing parts/components and for which some distinct parameters influencing **reparability** can be identified, then a product can be proposed as relevant for reparability. This can be the cases of mobile and wearable ICT devices as smartphones, tablets, smartwatches whose display component is highly exposed to drops/shocks.

Reparability strategies tends to be more effective for devices with a longer expected lifetime and higher purchase price (or in general with cost of repair that can be kept low compared to the purchase of new devices). For this reason priority is rated higher for electronic displays, audio/video devices, and personal ICT equipment. Use of standard components as EPS, batteries, SSD modules, RAM modules among others, can benefit the reparability of different families of ICT devices, including imaging equipment.

Modular design is an important features for accessories as External Power Supplies (where the DC cable can be detachable) and in general for personal ICT equipment as computers (e.g. upgradable RAM and SSD) and it considered beneficial also for the upgradability/reusability of reliable equipment as home/office network equipment.

Similarly to repair, measures aiming to facilitate **remanufacturing and refurbishment** are more relevant for devices with a longer expected lifetime and higher purchase price. Moreover, a special consideration is need for printer cartridges for their nature of consumables and the importance of reducing the electric and electronic waste production associated to their use.

Recyclability measures are considered more product group neutral, due to the similarities of ICT product groups in terms of material composition. Regarding the specific proposal of a recyclability index, due to the complexity of development of such indices, it is proposed that not all products in scope are covered at the same time.

Other material efficiency aspects analysed but not proposed

Recycled content

A potential measure could be to set minimum content of post-consumer recycled material (e.g. plastic) expressed either as a fraction of the total material input (in %) or in absolute numbers (kg per unit, million tonnes Mt in aggregates)

Although such a measure could be a way to stimulate recycled plastic demand in production, the proposal was discarded for the following reasons:

- Relevance: the life cycle environmental impacts of ICT products are mainly associated with the manufacturing of electronics (e.g. PCB and ICs) and with the extraction and processing of precious metals used in these components and the environmental benefits are relatively smaller compared to other measures.
- Comparability: The use of this criterion is not appropriate to compare the environmental performance of products using plastic with products using alternative materials for casing (e.g. aluminium / magnesium alloy).
- Possible trade-offs: The increase in recycled content (w/w%) could, in some cases, come with some trade-offs, such as an increase in the use of plastic to ensure the same performance. The mere measurement of the recycled content cannot consider this trade-off.

In addition there are some concerns about Market Surveillance of such a requirement; the new standard EN 45557:2020 has introduces horizontal principles for the calculation and verification of recycled content (w/w%) in energy-related products and some voluntary certification schemes have been developed for the recycled content certification (e.g. UL ECVP 2809 (3rd edition), SCS Services Recycled Content Standard V7.070), the market surveillance of the supply chain for ICT remain very challenging.

18.3 Other policy recommendations

#4 Minimum Guarantee for B2B ICT sales

Currently, minimum liability conditions for goods according to Directive (EU) 2019/771, and digital content and digital services according to Directive (EU) 2019/770, are applicable only in the business-to-consumer sector. In the context of public procurement, such conditions exist as criteria in already established voluntary GPP guidance documents, which could be enforced mandatorily (see proposal #13 below).

However, sales of ICT products in a business-to-business context are currently not covered by European legislation. It is suggested to explore the establishment of such minimum guarantee for products such as consumer electronics sold in B2B transactions.

#5 Quality labelling and certification for refurbishing and second-hand markets

Quality label for refurbished products

As pointed out by the EU Parliament Study “A Longer Lifetime for Products - Benefits for Consumers and Companies”[81], a common quality labelling for refurbished products could facilitate incorporating product lifetime into purchasing decisions for second-hand products, while tackling the challenge of providing honest information to consumers without overloading them.

The information provided on a label for refurbished products should be clear and reliable in order to generate consumer confidence on the use of products for a longer time. The label could be based on self-declaration but some form of market surveillance could be foreseen.

This could be done by adopting an EU common labelling system about the quality of refurbished ICT goods.

Market places for second-hand / refurbished ICT devices are already providing information to consumers but they could use slightly different grading systems or the same class/grade can have slightly different meanings. The grade systems for consumer ICT mainly focus on cosmetic and technical conditions of the device. In the table below examples of grading systems applied by different marketplaces.

Table 51: Examples of grading systems for refurbished products

RefurbMe[82]	**BackMarket[83]**	**Gazelle[84]**

[81] https://www.europarl.europa.eu/RegData/etudes/STUD/2016/579000/IPOL_STU(2016)579000_EN.pdf
[82] https://www.refurb.me/blog/what-are-refurbished-grades-a-b-c
[83] https://help.backmarket.com/hc/en-us/articles/360026656634-What-to-expect-from-each-product-grade
[84] https://buy.gazelle.com/collections/clearance/products/ipad-7-32gb-wifi

Excellent (Grade A) Devices are like new.	**Excellent** Appearance: Like new. The body may have very light micro-scratches, invisible at a distance of 8 inches (a bit longer than a standard-sized pencil) or more. For items with screens, the screen will have no scratches. Technical Condition: Excellent. Durability scores are high, and chances of encountering technical issues are very low.	**Excellent** The screen and body of these devices are in excellent condition.
Good (Grade B) Devices are in working condition but have light cosmetic issues.	**Good** Appearance: Light signs of wear. The body may have light micro-scratches, invisible at a distance of 20 inches (about an arm's length) or more. For items with screens, the screen will have no scratches. Technical Condition: Very Good. Durability scores are above average, and chances of encountering technical issues are low.	**Good** Very good condition, although with light aesthetic blemishes. The functionality is the same.
Fair (Grade C) Devices have light but visible scratches on the body.	**Fair** Appearance: Signs of wear. The body may have a few visible scratches and dents that don't affect performance. For devices with screens, they may have light scratches that are slightly visible when the device is on. Technical Condition: Good. Durability scores are average and still correspond with the quality levels required by our quality charter.	**Fair** A good condition with visible wear and tear.

Quality Code of Conduct or Certification for ICT refurbishers and second-hand marketplaces

An additional proposal would include the voluntary commitment to observe a European standard for quality in refurbishment and placing of second-hand ICT devices on the market. It would boost consumer trust in purchasing second hand ICT, encourage an increase in the quality of ICT refurbishment and reduce market barriers for refurbished products. The standards would be applicable to refurbishers or directly to second hand products marketplaces (and indirectly to the refurbishers and traders operating under the marketplace).

It would cover key aspects of the refurbishment process services, which are important factors for consumer decisions on buying second hand, e.g. quality control during the refurbshment process, clear length and coverage of the commercial guarantee, transparent and clear communication of the status of the refursbished devices. The commitment would set a standardised minimum level of quality on each aspect. This will increase consumer confidence, as they could trust that providers with this label address consumer concerns about refurbishment carried out in an effective manner.

Existing standards at national level can be of inspiration for a EU proposal. As example is the British Standard BS 8887-240:2011[85] which specifies requirements for the process of reconditioning, i.e. returning a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components.

This proposal could be implemented by:

1) a negotiated industry code of conduct, agreed by representative business associations at EU level. Consumer organisations and civil society representatives would be involved in the development process. The Commission could facilitate negotiations and help to provide publicity. The code would be open to all the operators across the EU (including independent refurbishers and marketplace platforms). To ensure visibility and consumer recognition, a standardised label would be made available to all subscribers. Enforcement of the code would be monitored by the stakeholders that negotiated the code.

2) an EU standardisation process. Once a EU standard is available a quality management standard for refurbishing and marketing second hand ICT devices could be certified by accredited Certification Bodies for the audit and certification of management systems.

#6 Take Back and preparation for Reuse

According to Milios (2021) in the electronics sector there is a need for developing take-back systems exclusively for re-use, either on the side of existing systems of recycling or by completely substituting the existing systems.

The higher effectiveness of a more targeted collection has been demostrated on the field by Coughlan and Fitzpatrick (2020): trialling the preparation for reuse of consumer ICT WEEE in Ireland, targeted collections demonstrate significantly higher reuse rates than from the current collection system.

Johnson et al. (2015) also provided recommendations around removing barriers to accessing suitable equipment which included the establishment of special collections of WEEE for material suitable for preparation for reuse and also to enable approved preparation for reuse of WEEE organisations to receive WEEE from the general public specifically targeting items with potential for preparation for reuse.

According to Milos (2021), having collection systems running in parallel would unavoidably create tensions regarding the collected volumes of materials for either re-use or recycling. A viable option could be to establish integrated systems of collection for re-use and recycling, managing products and materials in a cascading manner.

The “Study on options for return schemes of mobile phones, tablets and other small electrical and electronic equipment in the EU” (Ramboll et al. 2022) identify and conceptualise policy measures for action at the EU level to incentivise the return and take-back of small used and waste EEE. Among other actions identified, this study suggests make use of door-to-door and postal services to ease the return of used and waste EEE, the development of dedicated drop-off points database for small EEE and targets for re-use at national level.

Products that have sufficient value and function could be re-used while those who are under a threshold value could be redirected to recycling.

Related to the development of appropriate channels for sourcing used equipment, another intervention required by the electronics sector is the enhanced communication through establishment of on-line platforms. Either government-sponsored or industry-managed, on-line platforms have the potential to diminish transaction costs and enable easier sourcing of used equipment between interested parties. This policy intervention also implies a wider mobilisation of actors, from public authorities to companies and civil society participation, accelerating policy transition processes.

#7 Sustainable Sourcing

The EU Regulation (EU) 2017/821 has introduced a 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 regulation requires EU companies in the supply chain to ensure they import these minerals and metals from responsible and conflict-free sources only. On first of January 2021 this new regulation came into full force

[85] BS 8887-240:2011 Design for manufacture, assembly, disassembly and end-of-life processing (MADE) Reconditioning

across the EU. It is important to highlight that this regulation is quite limited in scope as do not apply to final product manufacturers, including ICT device manufacturers, as only EU mineral importers are obliged to perform a due diligence.

The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas ('OECD Due Diligence Guidance') is the main reference (OECD, 2016) for the implementation of the due diligence obligations. With the exception of this specific legislative initiative on 3TG minerals, multinational companies in the ICT field have been encouraged to take responsibility for their supply chains only a voluntary basis, despite human right violations in their mineral supply chain are evident as reported by academic research, NGOs and from the studies reported in this report.

The EU Non-financial Reporting Directive (NFRD) Directive 2014/95/EU has introduced information requirements. Large companies from 2018 onwards are requested to publish information on the policies they implement in relation to environmental protection, social responsibility and treatment of employees, respect for human rights, anti-corruption and bribery, and diversity on company boards, including on due diligence procedures throughout the supply chain with a view to addressing existing and potential negative effects. The NFRD does not impose a legal obligation on EU companies to undertake human rights due diligence; however if they do, they are required to provide information on it. It also requires them to give the reasons why they do not undertake it, if that is the case. The Directive 2014/95/EU is currently under revision.[86]

In this context the European Commission has undertaken some preliminary steps, including publishing a study[87] and conducting public consultations[88], towards a possible legislative initiative on mandatory due diligence. In particular, in 2022, the European Commission, proposed a *Directive on sustainable corporate governance* that would have a cross sectoral scope and broad range of sustainability impacts covered including human rights and environmental due diligence[89].

Regarding initiatives relevant for the ICT sector, the European Commission recently proposed a new Battery Regulation with mandatory sustainability requirements which include supply chain due diligence for minerals used in batteries[90]. According to the Commission Communication there is a fair degree of consensus among stakeholders for a mandatory due diligence. According to the proposal a mandatory supply chain due diligence is considered more effective than a voluntary in addressing the social and environmental risks related to raw material extraction, processing and trading of certain raw materials for battery manufacturing purposes.

It is proposed that mandatory due diligence is established for ICT product manufacturers. This could be explored in the context of an expansion of scope of the aforementioned EU Regulation (EU) 2017/821 to cover not only materials that are directly imported in the EU market, but also when those materials are present in imported ICT products placed in the EU market. Alternatively, it could be explored whether the aforementioned newly-proposed *Directive on sustainable corporate governance* could serve this purpose.

Summary of other device level recommendations

Table 52: Importance of system level policies for the different product grouping identified; Rate importance/priority: + , ++, +++

	Device level			
	B2B Guarantees	Refurbish Quality Label	Take Back & prep Reuse	Sustainable Sourcing

[86] https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/non-financial-reporting_en#review
[87] https://op.europa.eu/en/publication-detail/-/publication/8ba0a8fd-4c83-11ea-b8b7-01aa75ed71a1/language-en
[88] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12548-Sustainable-corporate-governance
[89] Proposal for a Directive on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0071
[90] COM(2020) 798 final

Electronic displays	+++	+++	+++	++
Audio Video devices	+++	+	++	++
Audio Equipment	+++	+	++	++
Personal ICT Equip.	+++	+++	+++	++
Accessories	+	+	+	++
Wearable Devices	+++	+	+	++
Imaging Equipment	+++	+++	+++	++
Home / Office Network Equipment	++	++	++	++
DC devices	++	+++	+++	++
Telecom / network	N/A	++	++	++

Similarly to the approach in Table 50, Table 52 presents a qualitative assessment of the recommendations of section 18.3 identifying priorities for each product group, but not a comparison among product groups.

18.4 System level

#8 Video streaming default settings

As demonstrated by the survey carried out in the framework of this study (IPSOS 2022), video streaming default settings are used by the majority of respondents. This is also confirmed by further evidence in Suski et al. (2020). Therefore, a requirement to set the resolution to minimum resolution settings by default alone has the potential to bring about energy savings as demonstrated by studies (Medlener et al (2022).

Video can be streamed by the hardware device using various platforms, such video sharing and social media platforms or SVOD/TVOD platforms, or dedicated applications which can be installed by user or pre-installed by the OEM before placing on the market. As such, a requirement to use minimum resolution can be addressed at device level within the ecodesign framework, or at platform/application level via another regulatory instrument.

Additionally it is suggested that, to enable users to use less data traffic, video streaming services should automatically detect the size of the display of the viewing device and reduce the amount of data to the necessary level. The standard resolution of video content should basically be aligned with the size of the display of the end devices (Köhn et al., 2020).

#9 Consumer information on environmental impact of settings and data usage

Another requirement relevant provision is related to providing information to consumers about potential change in energy use when settings are changed by them. Regulation (EU) 2019/2021 on ecodesign requirements for electronic displays already contains a requirement that such warning message is displayed:

“If the user selects a configuration other than the normal configuration and this configuration results in a higher power demand than the normal configuration, a warning message about the likely increase in energy use shall appear and confirmation of the action shall be explicitly requested”.

“If the user selects a setting other than those that are part of the normal configuration and this setting results in a higher energy consumption than the normal configuration, a warning message about the likely increase in energy consumption shall appear and confirmation of the action explicitly requested”.

“A change by the user in a single parameter in any setting shall not trigger any change in any other energy-relevant parameter, unless unavoidable. In such a case a warning message shall appear about the change of other parameters and the confirmation of the change shall be explicitly requested”.

Another source of “passive” data usage is ‘unintentional’ or ‘background’ data demand (Hazas et al 2016). High levels of communication between apps and the cloud have been found associated with automated updates or performing backup of application data and digital photos to the cloud (Hazas et al 2016). Similarly to the case of changes in settings, such operations could also be accompanied by messages to device users warning about background data usage and allowing them to opt for performing them manually rather than automatically.

The abovementioned provisions would be relevant to all ICT products that have the ability to stream and display video. Those include computers, game consoles, smartphones and tablets.

#10 Energy Efficiency and Carbon Footprint Labelling of Telecommunication Network Services

The systemic nature of digital services and the challenge to account for their environmental impacts and attribute them to different parts of the system has been described in Tasks 3 and 4. Nevertheless, consumers making purchasing decisions for digital services (e.g. telecommunication services) respond to simple and understandable information, which can be aggregated to a single metric, score or class. Life Cycle Assessment approaches can be pursued in order to assess a range of environmental impacts, and identify the most relevant one(s) to communicate. For instance, the ITU standard L.1410[91] outlines an LCA-based methodology for ICT, which encompasses the distinction between ICT goods, ICT network, and ICT services.

According to the Commission Study on Greening Cloud Computing and Electronic Communications Services and Networks Towards Climate Neutrality by 2050 (Idea et al. 2022), two possible approaches to communicate the environmental footprint of electronic communications networks and services could be applied:

Reporting at company level

Reporting at level of subscription service

Many electronic communications network providers already report at company and disclose how much energy they consume in total as a company, what is their share of renewable energies and the GHG emissions related to their services. For this purpose companies refer mainly to the Global Reporting Initiative (GRI), Greenhouse Gas Protocol (GHGP) or the results of energy management according to ISO 14001 or ISO 50001 as suitable methods of accounting. Key metrics used in reporting are:

Annual energy consumption of the company [MWh/a]

Share of renewable energies in annual energy consumption [%]

Annual GHG emissions of the company [tonnes CO2-eq/a]

However reporting at level of company is not the most suitable option to enable greener end user subscription decisions. It can be argued that reporting at the level of subscription can better guide consumers. In order to access the internet there are several technical access options, each of which require different amounts of energy (e.g. mobile vs fixed access network, different generations). Moreover, different operators could be able to reach different level of energy efficiency of their system and different use of renewables. The customers of this service decide which provider to contract and which access technology to use.

The same Commission Study (Idea et al. 2022) suggests that, in order to reduce the complexity of calculating the energy consumption of data transmission, information could therefore (at first) only be provided on the energy consumption of the access network. This would already make it possible to distinguish between different access options (e.g. broadband cable or fibre optics) and different providers.

By using reference units, key figures can be presented in such a way that they are intuitively understood by end-users. A suitable "functional unit", which in the case of a “subscriber” could be an average user or a user with a defined data volume and online times (see Figure 89). In order to realise an appealing presentation of these numerical values for consumers, the respective watt values (power consumption of the service per subscriber) or other efficiency values (e.g. energy intensity or carbon footprint of data transmission) could be put into a colour scale, comparable to the well-known EU energy label.

[91] L.1410 : Methodology for environmental life cycle assessments of information and communication technology goods, networks and services. Available at: https://www.itu.int/rec/T-REC-L.1410

Energy efficiency colour scale	E.g. Power consumption of the service per subscriber	E.g. Energy intensity of data transmission	E.g. Carbon footprint of data transmission
	< 1 Watt	< 1 Wh/GByte	< 1 g CO_2-eq/GByte
	< 2 Watt	< 2 Wh/GByte	< 2 g CO_2-eq/GByte
	< 4 Watt	< 4 Wh/GByte	< 4 g CO_2-eq/GByte
	< 8 Watt	< 8 Wh/GByte	< 8 g CO_2-eq/GByte
	< 16 Watt	< 16 Wh/GByte	< 16 g CO_2-eq/GByte
	< 32 Watt	< 32 Wh/GByte	< 32 g CO_2-eq/GByte
	≥ 32Watt	≥ 32 Wh/GByte	≥ 32 g CO_2-eq/GByte

Figure 89: Example for energy efficiency label for access network. Source: Commission Study on Greening Cloud Computing and Electronic Communications Services and Networks Towards Climate Neutrality by 2050 (IDEA, Oeko Institute, Visionary Analytics, 2022).

#11 Application software products: material and energy efficiency

The preparatory study of the Ecodesign Working Plan 2022-2024[92] recommends that, to exploit the savings potential as far as possible, future legislative implementation is pursued by:

A) Setting horizontal minimum requirements on firmware / system software for all ErPs to increase durability by reducing software-related hardware obsolescence.

B) Including and further specifying requirements on software updates horizontally or as pre-requisite in all Ecodesign and Energy Labelling regulations to reduce the risk of deteriorating energy/ resource efficiency of products after updates.

C) Conducting a feasibility study on the possibility to set energy and resource efficiency measures on application software.

While approach A) has been already applied for other aspects (i.e. stand-by efficiency) and approach B) is being addressed by Ecodesign and Energy labelling regulations, initiatives under C) is not yet applied in the Ecodesign / Energy Labelling context.

Firstly, a future feasibility study on "application software" should clarify whether, to what extent and under which circumstances application software can be regulated under the current (and future) Ecodesign legal framework.

According to the Directive 2009/125/EU, 'Energy-related product', (a 'product'), means any good that has an impact on energy consumption during use which is placed on the market and/or put into service, and includes parts intended to be incorporated into energy-related products covered by this Directive which are placed on the market and/or put into service as individual parts for end-users and of which the environmental performance can be assessed independently.

One of the key legal aspects to clarify is whether a software can be considered "a good" (and a product) or not. A recent CJEU case[93] ruled that, in the first place, as regards the term 'goods', according to the Court's case-law, that term is to be understood as meaning products which can be valued in money and which are capable, as such, of forming the subject of commercial transactions. It follows that that term, as a result of its general definition, can cover computer software since computer software has a commercial value and is capable of forming the subject of a commercial transaction. Based on that the sentence ruled that, software

[92] Preparatory study for the Ecodesign and Energy Labelling Working Plan 2020-2024 - TASK 4 COMPLEMENTARY ANALYSES AND RECOMMENDATIONS FOR THE ECODESIGN AND ENERGY LABELLING WORKING PLAN 2020-2024 – FINAL. Available at: https://www.ecodesignworkingplan20-24.eu/documents

[93] https://curia.europa.eu/juris/document/document.jsf?docid=246082&doclang=EN

is a "good" regardless of the medium on which it is supplied. Consequently, computer software supplied to customers by granting a perpetual licence does constitute a "sale of goods".

Other sectorial legislation has already addressed the physical vs digital product scope issues. An example comes from the Medical Device Regulation (MDR)[94] where “software that are devices in themselves” are recognised as independent products submitted, under specific conditions, to requirements, including the bearing of the CE marking and the Unique Device Identification (UDI) provided on a readable accessible screen.

Moreover, the UDI placement criterion can be of inspiration for the placement of relevant information as the CE Marking or other information requirements.

The MDR requires that, where the software is delivered on a physical medium, e.g. CD or DVD, each packaging level shall bear the relevant information in a human readable form. Moreover the relevant information shall be provided on a readily accessible screen for the user in an easily-readable plain-text format, such as an ‘about’ file, or included on the start-up screen. Software lacking a user interface such as middleware for image conversion, shall be capable of transmitting this information through an application programming interface (API);

On the other hand, the Commission proposal (COM(2022) 142 final) establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC explicitly refers to physical goods in the proposed definition : ‘product’ means any physical good that is placed on the market or put into service.

In addition, further research and methodological developments might be necessary. A study by Gröger et al. (2018)[95] developed a possible method for carrying out measurements software energy consumption and the associated hardware utilisation. In parallel, the Blue Angel Basic Award Criteria[96] addresses software energy efficiency, but so far only covers application software with a user interface. Further, research is also needed with regard to usage statistics to define standardised usage scenarios for each software category.

In terms of requirements, energy and resource efficiency measures on “application software” could be implemented in the form of minimum requirements, information requirements, and / or mandatory labelling. The Ecodesing and Energy Labelling preparatory study suggests:

- Minimum Ecodesign requirements on energy and resource efficiency of application software, e.g. energy demand, CPU cycles, hardware utilization, support for the energy management system, etc.).
- Energy Labelling requirements to display the energy and resource efficiency of application software products to end consumers.

Further information requirements, e.g. instructions on efficient use of the application software, support for the energy management system.

Other potential aspects relevant for minimum mandatory requirements, could cover aspects like:

- Minimum continuity of the application software product (ideally it should be comparable with the expected lifetime of the hardware)

Information requirements could cover aspects that allow the optimisation of the application software / hardware system like:

- Information on system requirements (processor performance)
- Information on local working memory required (MByte)
- Information on local permanent storage required (MByte)

[94] Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC (Text with EEA relevance.)

[95] 15 Gröger, J.; Köhler, A.; Naumann, S.; Filler, A.; Guldner, A.; Kern, E.; Hilty, L. M.; Maksimov, Y. V. (2018): Entwicklung und Anwendung von Bewertungsgrundlagen für ressourceneffiziente Software unter Berücksichtigung bestehender Methodik (UBA TEXTE, 105/2018). Umweltbundesamt (ed.), 2018. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-12-12_texte_105-2018_ressourceneffiziente-software_0.pdf

[96] https://www.blauer-engel.de/en/productworld/resources-and-energy-efficient-software-products

- Requirements for other software (operating system, middleware and auxiliary applications: software stack) (e.g. Windows 7, .NET Framework and browser version XY)
- The required external services that are not available on the reference system (e.g. cloud services, storage services, API usage, …)
- The required additional hardware (e.g. graphics card, peripheral devices such as a camera connected via USB).

Information on backward compatibility. Software application with longer backward compatibility can reduce the risk of technology obsolescence for hardware

A labelling system of application software could be used by consumers to evaluate the material and energy efficiency performance of the application software. From the material efficiency perspective it could include aspects that contribute to extend the lifetime of the hardware are:

- system requirements (processor performance)
- working memory required (MByte)
- Minimum local permanent storage required (MByte)
- Requirements for other software (operating system, middleware and auxiliary applications: software stack) (e.g. Windows 7, .NET Framework and browser version XY)
- The required external services that are not available on the reference system (e.g. cloud services, storage services, API usage, …)
- The required additional hardware (e.g. graphics card, peripheral devices such as a camera connected via USB).
- % of hardware utilisation in idle and active mode (standard usage scenario)
- Interoperability
- Continuity of the software product
- Backward compatibility
- Uninstallability
- Modularity
- Offline capabilities

Energy Efficiency:

- Energy consumption in idle and active mode (standard usage scenario)
- Support for the energy management system

Energy and resource efficiency measures on "application software" in the form of minimum requirements, information requirements, and / or mandatory labelling could be potentially implemented to a large variety of software products, including software used for crypto-currency mining, gaming, smart cities, IoT, autonomous vehicles, public services.

Ecodesing and energy labelling requirements could complement those of the supply of digital services and digital content (in which application software is included) established by the Directive (EU) 2019/770. This Directive introduces general conformity requirements on digital content or digital service, which shall:

(a) be fit for the purposes for which digital content or digital services of the same type would normally be used, taking into account, where applicable, any existing Union and national law, technical standards or, in the absence of such technical standards, applicable sector-specific industry codes of conduct;

(b) be of the quantity and possess the qualities and performance features, including in relation to functionality, compatibility, accessibility, continuity and security, normal for digital content or digital services of the same type and which the consumer may reasonably expect, given the nature of the digital content or digital service ….

(c) where applicable, be supplied along with any accessories and instructions which the consumer may reasonably expect to receive; and

(d) comply with any trial version or preview of the digital content or digital service, made available by the trader before the conclusion of the contract.

According to the same Directive 2019/770, the trader shall ensure that the consumer is informed of and supplied with updates, including security updates that are necessary to keep the digital content or digital service in conformity, for the period of time:

(a) during which the digital content or digital service is to be supplied under the contract, where the contract provides for a continuous supply over a period of time; or

(b) that the consumer may reasonably expect, given the type and purpose of the digital content or digital service and taking into account the circumstances and nature of the contract, where the contract provides for a single act of supply or a series of individual acts of supply.

#12 Mandatory Green Public Procurement

EU Green Public Procurement (GPP) criteria aim at facilitating public authorities' purchase of products, services and works with reduced environmental impacts. Even though GPP criteria for Data Centres, Server Rooms and Cloud Services are already in place (European Commission, 2020) and can contribute to meeting climate and circularity objectives, their application remains voluntary, thus a lack of knowledge and wider implementation at Member State level restrains the GPP framework from reaching its full potential (Montevecchi et al, 2020; Bilsen et al, 2022). A mandatory application of the criteria may lead to positive impacts (Bilsen et al, 2022). A mandatory reference to GPP is included here in the proposal for Recast of Energy Efficiency Directive[97].

One particularly relevant aspect within the EU GPP framework would be extending the minimum duration of guarantee (liability for lack of conformity) to the public procurement. Currently, minimum liability conditions for goods according to Directive (EU) 2019/771, and digital content and digital services according to Directive (EU) 2019/770, are applicable only in the business-to-consumer sector.

According to these directives the seller (or the trader) shall be liable to the consumer for any lack of conformity which exists at the time when the goods/digital services were delivered and which becomes apparent within two years of that time.

No mandatory minimum liability is foreseen in business to business contracts, including for the procurement of goods and services provided under public procurement contract. Minimum level of guarantee could be implemented by making some of the voluntary EU GPP Criteria, already developed under the EU GPP Framework, mandatory for all the products.

It would be recommended to make mandatory the "core level" criteria – which are designed to allow for easy application of GPP, focusing on a product's environmental performance and aimed at keeping administrative costs for companies to a minimum.

As example, the EU GPP Criteria for computers, monitors, tablets and smartphones (SWD(2021) 57 final) include minimum manufacturer criteria for new and refurbished devices (see table below).

Table 53: Existing voluntary criteria for Computers, Monitors, Tablets and Smartphones

Core criteria on manufacturer's warranty of Computers, Monitors, Tablets and Smartphones
TS3: Manufacturer's warranty Applicable to all categories of devices except refurbished/remanufactured devices The tenderer must provide products covered by X years [*minimum 2, to be defined*] of the manufacturer's warranty. Verification:

[97] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0558

The tenderer must provide written evidence of the manufacturer's warranty. Equipment holding a Type I Ecolabel fulfilling the specified requirements will be deemed to comply.
TS24: Refurbished/remanufactured product warranty Applicable to the procurement of refurbished/remanufactured products. The tenderer must provide products covered by X years [*at least 1 year*] warranty. Verification The tenderer must provide written evidence of the warranty

#13 Financial instruments

Certain business models, such as the offering of unlimited data plans and a fixed price regardless of the data use level, enables data use and subsequently energy use.

Financial instruments such as pricing policies can provide a powerful policy tool by incentivising efficiency in data use and subsequently energy, in accordance with the polluter pays principle[98]. Examples can be drawn from other sectors with impactful consumption, such as water, where the EU Water Framework Directive (2000/60/EC) indicates that Member States shall ensure that *"water-pricing policies provide adequate incentives for users to use water resources efficiently, and thereby contribute to the environmental objectives of this Directive".*

Taxation can also play a role in lowering consumption. For example, reduced rates of electricity tax for Data Centres in some countries (e.g. Finland, Sweden, Norway or France) offer little incentive to save energy, and the Energy Taxation Directive currently under revision can have an impact in setting appropriate taxation minima (Banet et al, 2021).

Another policy that has been proposed is that of a "*transit fee*" which can be imposed on a certain unit of quantity of data traffic, which could address both environmental externalities and network congestion costs (Madlener et al, 2022).

Summary of the system level recommendations

Table 54: Importance of system level policies for the different product grouping identified; Rate importance/priority: +, ++, +++

	System level				
	Video default settings	**Telecom service Label**	**Application efficiency**	**Mandatory GPP**	**Financial**
Electronic displays	+++	N/A	++	+++	N/A
Audio Video devices	N/A	N/A	+	+	N/A
Audio Equipment	N/A	N/A	+	+	N/A
Personal ICT Equip.	+++	N/A	+++	+++	N/A
Accessories	N/A	N/A	N/A	++	N/A
Wearable Devices	++	N/A	+++	+	N/A
Imaging Equipment	N/A	N/A	N/A	+++	N/A
Home / Office Network Equipment	N/A	N/A	N/A	+++	N/A

[98] https://environment.ec.europa.eu/economy-and-finance/ensuring-polluters-pay_en

DC devices	N/A	N/A	N/A	+++	N/A
Telecom / network	N/A	+++	N/A	+++	+++
UPS	N/A	N/A	N/A	++	N/A

In terms of product coverage, requirements related to **minimum guarantee in a B2B context** are relevant for a wide range of product groups from consumer electronics to servers. A **quality label for refurbished products** would be most relevant for consumer electronics, while **take back schemes** specifically designed for preparation for reuse could initially target products with higher value, including smartphones, laptops and tablets in consumer sector or servers in the business to business sector.

Obligations related to **sustainable sourcing** would be linked to specific materials, including CRM, therefore affecting a wide range of ICT products.

A requirement to set low **video resolution settings as default** are relevant for all display and personal ICT equipment where streaming takes place, even though such requirement may be addressed to a streaming platform or app, rather than the device itself. Similarly, **consumer information on environmental impact of settings and data usage** would be most relevant for devices where consumer interaction takes place via a display, including displays themselves, personal ICT equipment and game consoles.

Labelling related to the **energy efficiency and Carbon Footprint for Telecommunication Network Services** would directly impact telecommunication providers, and indirectly devices for which such services are provided, such as personal ICT equipment. **Application software efficiency** would be relevant for a range of ICT devices, for which applications are used, again including personal ICT devices and displays.

Finally, **mandatory EU GPP criteria** could be set in the case of ICT products for which voluntary GPP criteria are already in place, including those related to the guarantee provision.

Figure 90 below provide a summary of the applicability of the policy recommendation by provision type and by ICT system level (device hardware – device software – application software – service / cloud). Table 55 provides a summary of the prioritization of the requirements / recommendations for the various ICT product groups in the scope of this analysis.

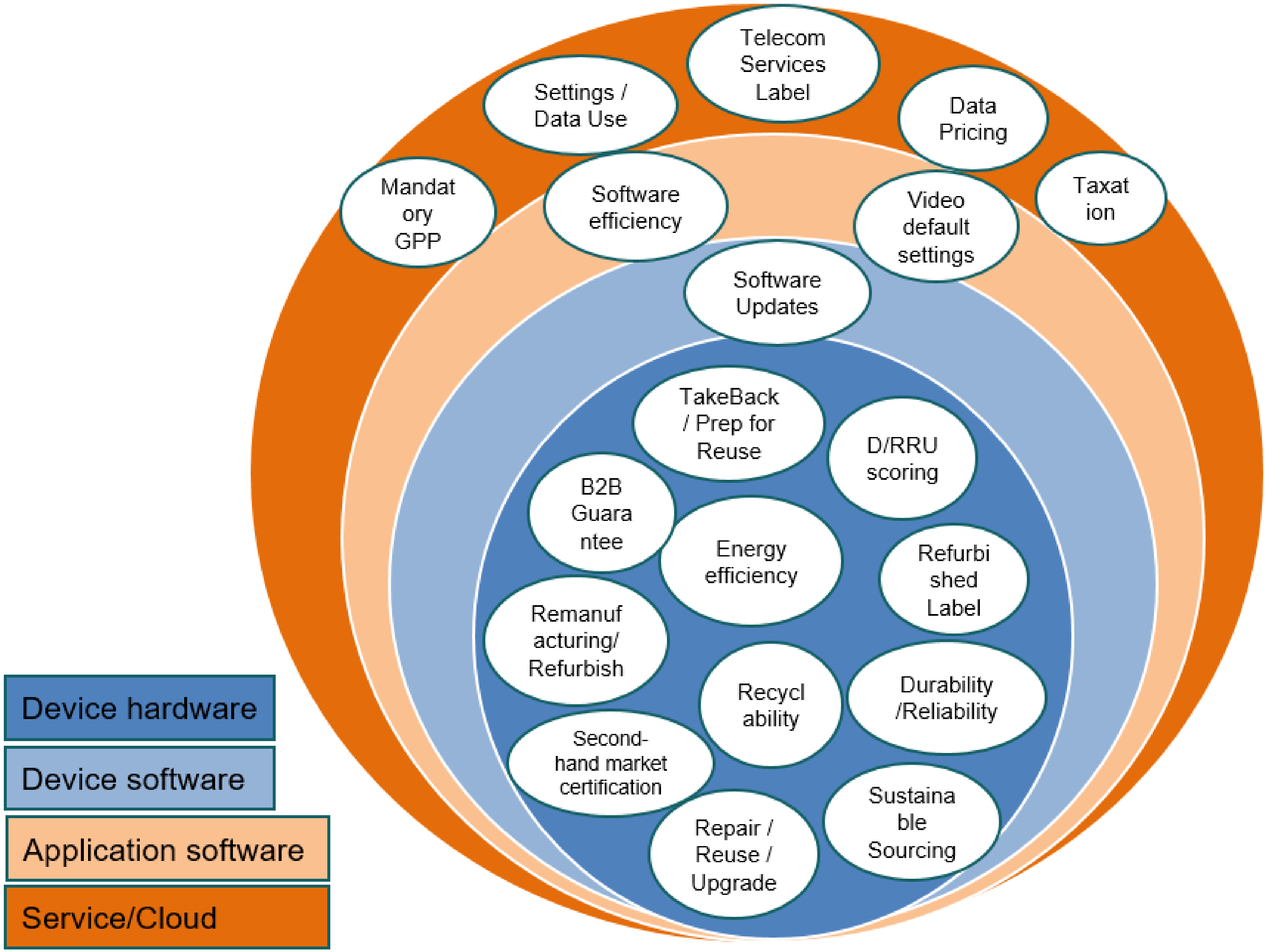


Figure 90: Policy recommendations by provision type and by ICT system level

On the basis of the approach followed in Table 50 and Table 52, Table 55 presents a summary of the qualitative assessment of all proposed recommendations identifying priorities for each product group, but not a comparison among product groups.

Table 55: Prioritization of requirements for the various ICT product groups; Priority score: +, ++, +++

	Device-based																															Service-Cloud based				
		Hardware durability and reliability					Software Related Durability			Reparability, upgradability and reusability								Remanufacturing & refurbishing					Recyclability					Other device based								
	Energy Efficiency	Resistance to stresses/ageing	Battery endurance in cycles	Minim/Expected Lifetime	Durability/Reliability score	Availability of software functionality / security / corrective updates	Availability and durability of cloud based services of the product	Decoupling of the electronic device from	Software update impact on device performance	Introduction of a Reparability Scoring Index	Availability of repair/upgrade info	Prevention of parts pairing	Spare parts availability and delivery time	Disassembly Depth, Tools, Fasteners, Work Env, Skill	Use of component and material coding standards	Standardisation of certain relevant spare parts	Reusability/Upgradability specific provisions	Improve the ability to identify products/parts	Ability to locate access points and fasteners	Accessibility of parts	Ability to be disassembled/ assembled	wear and damage resistance during remanufacturing process	Ability to easily separate into different materials	Choice of materials and restrictions on substances	Access to product data relevant for the recycling	Recyclability information	Recyclability Score	B2B Guarantees	Refurbish Quality Label	Take Back & prep Reuse	Sustainable Sourcing	Video default settings	Telecom service Label	Application efficiency	Mandatory GPP	Financial
Electronic displays	++	++	N.A.	++	++	+++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	+++	+++	+++	++	+++	N/A	++	+++	N/A
Audio/video devices	++	++	++	++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	+++	+	++	++	N/A	N/A	+	+	N/A
Audio Equip	+	+++	+++	+++	+++	+	+++	+++	+++	+	+	+	+	++	+	++	++	+	+	+	+	+	++	++	++	++	++	+++	+	++	++	N/A	N/A	+	+	N/A
Personal ICT Equip.	++	+++	+++	++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	+++	+++	+++	++	+++	N/A	+++	+++	N/A
Accessories	+	+++	+++	+++	+++	+	+	+		+	+	+	+	+	+	++	+++	+	+	+	+	+	++	++	++	++	++	+	+	+	++	N/A	N/A	N/A	++	N/A
Wearable ICT Devices	+	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	+	++	+	+	+	+	+	+	++	++	++	++	++	+++	+	+	++	++	N/A	+++	+	N/A
Imaging Equipment	+	++	N.A.	++	++	++	++	++	+++	++	++	++	++	++	+++	+++	+	+++	+++	+++	+++	+++	++	++	++	++	++	+++	+++	+++	++	N/A	N/A	N/A	+++	N/A
Home / Office Network Equipment	++	++	N.A.	++	++	+	+	+	+	+	+	+	+	++	+	+	+++	+++	+++	+++	+++	+++	++	++	++	++	++	++	++	++	++	N/A	N/A	N/A	+++	N/A
DC devices	+++	++	N.A.	++	++	+++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	++	+++	+++	++	N/A	N/A	N/A	+++	N/A

Telecom / network	++	++	++	++	++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	++	++	++	++	N/A	++	++	++	N/A	+++	N/A	+++	+++
UPS	++	+++	+++	+++	+++	+	+++	+++	+++	+	+	+	+	++	+	++	++	+	+	+	+	+	++	++	++	++	++	++				N/A	N/A	N/A	++	N/A

19 Conclusions

Addressing the environmental impacts of ICT products calls not only for a wider consideration of environmental aspects beyond energy efficiency, but also for a policy approach that spans beyond the boundary of individual products as hardware.

This study has demonstrated that the use of ICT has the potential to trigger wider effects, either by creating, enabling, and encouraging sustainable patterns of production and consumption (sustainability by ICT), or by stimulating ever increasing consumption (e.g. by induction effects).

First this study has confirmed that energy consumption associated with the manufacturing of ICT is highly relevant to the overall carbon footprint of ICT systems. That is the case especially for the manufacturing of integrated circuits, essential elements in components related to data processing, storage and connectivity.

Secondly, the focus has shifted towards the systemic energy consumption during the use phase of ICT, where the question is whether technological improvements leading to higher efficiencies are sufficient to compensate for the significant and ever-increasing data demand that is forecasted. Results from the literature are characterised by methodological differences and challenges of data availability, but forecasts range from consumption levels remaining stable in optimistic approaches, to significant increase in some others, should there not be further efficiency gains and overturning of current trends. High level of uncertainty is associated to the impact of new applications such as bitcoin mining, video streaming resolutions etc.

In this context, the main drivers of higher energy efficiency include the shift to larger and more efficient hyper-scale data centres, as well as technological improvements in terms of computation and network devices. On the other hand, exponential increases expected in terms of the number of devices, application software, connections and connected devices, subscriptions, streaming and, subsequently, data demand and IP traffic, may deem efficiency improvements insufficient to curb the consumption trajectory.

Finally, the positive effect of systemic optimisation expected by ICT systems needs to be taken into account, based on the expansion of IoT technologies and their application in a wide range of areas such as the integration of renewable energy sources, production management, transport, energy efficiency in home and offices.

In terms of material efficiency and related environmental impacts, ICT devices demonstrate commonalities with regards to the materials used and the 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 their environmental impacts and the depletion of critical materials they cause. Material use in the form of ICT accessories, consumables, and spare parts during the use phase, as well as end-of-life impacts, including improper recycling processes are also non-negligible. In addition to these first order effects, there are second order effects that result in material use. These effects are mostly related to obsolescence (more material use) and substitution (less material use). Beyond technical obsolescence, there are other types of obsolescence, such as those caused by software unavailability or incompatibility. The consequence is a shorter than desirable lifetime for several categories of ICT devices.

The understanding of the obsolescence mechanisms affecting ICT devices points to the development of appropriate design strategies for material efficiency and product lifetime extension. In terms of lifetime extension there are complementary strategies applicable such as reliability and reparability, but also upgradeability, modularity, reusability, and design for refurbishing / remanufacturing. Other material efficiency strategies that were examined are recyclability and the use of recycled material. Trade-offs between these design strategies are possible and need to be carefully addressed. Nevertheless, there are also opportunities for positive synergies between different material efficiency strategies.

This study finally resulted in a set of policy recommendations using a structure that starts with the device as tangible hardware with direct resource use and expands to software and telecommunication services that result in the use of more resources by a range of devices in an ICT system.

Existing EU product policy instruments can be used to improve material efficiency and the study provides some examples in that direction. However, a key challenge in this context is how product policy instruments, which often require lengthy regulatory processes for individual products and technologies, can be applied to fast moving technologies with a high turnover of new products entering the market.

The proposal for a new Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2022) published on 30 March 2022, builds on the existing Ecodesign Directive. This Ecodesign framework already allows for the setting of a wide range of requirements, including on material efficiency aspects described under policy recommendation #3. However, the new framework will also allow to set horizontal rules on certain aspects for groups of products that have sufficient common characteristics. The proposed ESPR also provides a basis for the setting of mandatory Green Public Procurement (GPP) criteria.

A distinction between products for which use phase energy consumption remains the most relevant aspect and those for which material extraction and manufacturing are critical is still meaningful. Therefore, a range of material efficiency provisions are proposed for consumer electronics using a horizontal approach. Such an approach would not only ensure harmonisation and systematisation of provisions addressing similar products, but also, it would potentially address the fast innovation cycles that characterise ICT products, by increasing the efficiency of regulatory processes.

The proposals mentioned above are paired with a number of measures that aim to facilitate the development of second-hand product and component use, such as refurbishing, remanufacturing and takeback schemes.

Beyond the device boundary, video streaming and the use of application software have been found to affect energy consumption to a significant degree. These could be addressed by means of minimum energy efficiency requirements (in the case of application software) as well as information requirements to raise consumer awareness on these impacts.

Lastly, wider systemic measures such as the labelling of telecommunication services, consumer information on data use and financial instruments could also contribute to curbing the induction effects of ICT systems by allowing consumers to make informed choices in the context of new business models and by fostering competition among providers on the basis of sustainability.

Annex I: Summary of comments from the stakeholders to the policy recommendations

Introduction

Environmental NGOs suggested that, considering that "As a Service" business models do not per se grant sustainability, policies should set contractual standards for products that are being marketed based on this business model. Elements should contain, option to buy the product at the end of the contract (extend the life cycle and not replacing with new), a clear price provided upfront, as well as reporting by the providers what has been done with products that have been returned: %repaired, %refurbished versus % being put to waste.

Device level: energy efficiency

Environmental NGOs support the inclusion of active mode requirements for products. However, they highlighted the relevance of using benchmarking tools representative as possible of actual use so that the figures are meaningful and representative. Environmental NGOs also suggested the implementation of power management and self-reporting requirements. Requiring default power management ensures that products enter lower energy consuming modes in the most effective way. The provision of live information to end users on the energy consumption of their products has not been addressed in current ecodesign regulations. Devices could inform users on how much energy they are using and how much they could save by changing certain settings and behaviours. For this type of technology to be efficient, checking conformity and accuracy of reported data versus declared would be needed.

Industry considers that the dynamic nature of game consoles creates extreme complexity for benchmarking gameplay efficiency and setting active gaming power caps. A stakeholder from the video game sector commented that their devices output is artistic, namely video games, and which cannot be consistently or meaningfully measured and compared in terms of quantifiable work output. The stakeholder also mentioned that the dynamic nature of consoles and PCs creates extreme complexity for benchmarking gameplay efficiency and setting active gaming power caps.

Device level: material efficiency

An organisation representing manufacturers argued that consumer electronics are not suited to single horizontal requirements on energy and material efficiency. They prefer vertical regulations in current and upcoming legislation (e.g. Ecodesign Directive and its upcoming revision (ESPR)), which better reflect the particularities of specific product groups. An industry representative highlighted possible trade-offs between damage resistance and reparability of devices by laypersons.

Suggestions were provided by Environmental NGOs to make more comprehensive the list of possible material efficiency provisions presented in Table 49. Among the provision suggested there are: software update impact on device performance, to prevent part pairing and additional provisions to facilitate remanufacturing and refurbishment.

On reparability, an industry organisation commented that one the options to build trust and influence the relationship between consumers and business, with the aim of extending the useful life of goods, is repairability by professionals. This means repairs by a manufacturer, seller, independent repairer or generalist. The same stakeholder believes that the professional repair by operators having skills, tools and knowledge is in general the recommended way to replace spare parts, since this guarantees the correct end-of-life handling of the parts intended to be replaced, with regards to the circular economy and EU Green Deal principles. Professional repairers can collect the replaced and damaged spare parts, i.e., batteries, and return them into recycling material flows, like back to the manufacturer. Whereas a layperson might not have access to a waste collector able to correctly sort the different materials. The adhesive and sealant industry recommends that electronics should be repaired by professionals to also ensure the continuity of the market of professional workers, as well as the quality of the replaced product. More trust is to be given to an electronic product repaired by a professional repairer. Professional repairers could establish prolongated or renewed warranty periods after repair, that would help to motivate and strengthen consumers rights and trust in repaired devices. Other industry representatives expressed deep concern by the absence of any reference concerning the need to protect consumer safety, product quality or IP rights when providing such information to end-users or independent repairers.

A manufacturer's representative commented on the proposal on standardising components. It is considered that would have a huge impact on the ability of manufacturers to innovate and further improve product designs, including areas such as reliability of devices. They considered that standardisation of components makes sense in case of components that have to be replaced multiple times during the lifetime of a product, such as for non-rechargeable AAA batteries. However, modern rechargeable (usually lithium based) batteries have such a high lifetime that replacement might only be necessary once or twice during the expected lifetime of a product. Mandating a given form factor for such batteries would make it difficult for manufacturers to maximise battery capacity within the limitations of a given product design and hence lead to batteries that would need to be replaced more often. Requiring standardised storage components (RAM & SSD) such as traditionally found in computers would disable manufacturers from integrating RAM together with the CPU into a "System on a Chip" (SOC). SOCs however have been found to be an important means to significantly improve performance (reduces need for upgrade), significantly reduce energy consumption as well as the environmental impact of manufacturing computers. The need to upgrade SSDs can equally be addressed by storing data in the cloud. Videogames industry representatives consider that pushing for the use of standardised components would stifle innovation in the sector.

On recyclability, an industry representative commented that naming specific materials as additives, multilayer packaging, and carbon black could result in a broad restriction. The same representative commented on the access to product data, asking to: ensure cybersecurity and confidentiality to protect confidential business information (CBI) and intellectual property; allow access to data on a need-to-know basis only and recommending that within the value chain only the direct seller or buyer should be provided access to information necessary for the final product passport ("one up, one down" principle); adhere to the data minimization principle (as much data as needed, as little data as possible); limit information requirements to the most relevant criteria and substances (of concern) in the final product; harmonize requirements with current and upcoming European legislations to guarantee consistency and to avoid double regulation; ensure that data collection, transparency and reporting requirements add value to and be relevant for the different players in the value chain – including the economic operators and consumers.

On the use of a recyclability score, the same industry representative commented that a recyclability score has (beside many other scores and ratings) probably little influence on the consumer's buying decision. Also, aggregated data cannot be used to help with information requirements that second-hand market or recycling companies may have. Therefore, they do not encourage using condensed data like a recyclability score. Nevertheless, if a recyclability score shall be included, the stakeholders ask that the scoring and norms applied shall be carefully selected by an expert panel, composed of several different stakeholders, including representatives of all relevant recycling technologies. and taking into account that state-of-the-art recycling technologies.

Even though recycled content is not proposed as measure, the same industry representative still mentions the norm EN 45557 is considered not yet mature enough to be used in a regulatory context.

On the benefits of refurbishing/reuse/remanufacturing, an industry representative commented that cannot be a general one size fits all recommendation, especially not for many types of ICT network infrastructure equipment, which show ever increasing energy efficiency. In such cases much more environmental impact will be induced overall due to more electricity consumption totally overshadowing the minor manufacturing impact "saved" by refurbish. Moreover, it was commented that the product attribute of EN 45553 "Accessibility of parts" may be less relevant to ICT network infrastructure goods that have limited access to some hardware parts for security reasons.

Device level: other policy recommendations

A stakeholder highlighted the possible links between lifetime/circularity issues and other policies, specifically the Cyber Resilience Act, as it could be extended to tackle some aspects of security that might improve product lifetimes. The same stakeholder supports the inclusion of minimum guarantee for B2B sales and the establishment of a quality label as suggested by the recommendation #5. Another stakeholder claimed that the B2B products and market needs attention as it represents the larger part of the ICT market, and professional buyers need guidance and protection as well. It is also suggested the inclusion of minimum energy/data efficiency performance standards for services, calculated on a per device/person basis, at least in the areas of crypto currency mining, smart cities, IoT, autonomous vehicles, public services. The same stakeholder highlighted that the ICT industry moves very quickly, so commitments are needed to develop faster and more proactive regulatory approaches for services. Also a shift toward 'digital sufficiency' is recommended to be addressed by the EU policy measures.

System level

According to a stakeholder, environmental impact was overlooked in the recently adopted Digital Services Act (DSA). Online platforms and service providers should be similarly regulated to account for their data, energy, and environmental impacts. The same stakeholder recommended to discuss potential rebound effects for the different policy proposals where relevant.

Another stakeholder highlighted a market situation where some OEM is implementing restriction and non-circular business practice, using lock-ins and bundled services in order to block reuse and independent repair. Among the criticalities mentioned there are firmware availability bundled into a service contract; time limited licences that can limit the lifetime; user/owner registration systems that can reduce reusability; lack of transparency.

On recommendation #8, according to an industry representative organisation, moving from high definition to standard definition affects the bitrate required to transmit video data but it was found to have only a very small impact on the overall energy consumption and carbon footprint of the network, since the main part of the energy is used to keep these networks up and running. In addition, it's likely that users will turn off these low-resolution settings anyway. According to a stakeholder from the videogames industry this proposed requirement would not necessarily be the most effective measure to reduce energy consumption, as players would most likely raise the resolution back to their liking. This would likely lead to the unintended consequences that players select a higher resolution than a default resolution pre-selected on the basis of the user's internet speed, as it is usually the case now.

Regarding recommendation #9, a stakeholder from the videogames sector disagreed with the suggestion that users should be able to opt out from automatic "passive data usage" (or "background data usage") some games rely on such practices (even some single player games). Moreover, the same stakeholder doubts that, as a general rule, decoupling a game from its access to the cloud would lead to a reduction in energy usage, as increased local capabilities on the user's end would very likely be required for the same game to run smoothly. Moreover, gameplay data that are sent automatically to the game developer, usually consist of a set of non-personal metadata which will allow the studio to improve the features and functionalities of its game(s) in next updates.

On recommendation #10 some stakeholders highlighted the complexity of setting a correct functional unit. According to an industry representative the transmission of data is decoupled from the overall energy performance and energy consumption of a network, and for this reason the KPIs for a footprint label should not include energy intensity per data transmitted. Moreover, the same stakeholder considers that basing KPIs on energy consumption per subscription would lead to lower intensity figures for larger network operators (with more subscribers) than for smaller operators (with fewer subscribers), considering that the network operators have the same surface and population coverage.

On recommendation #11 a stakeholder from an Environmental NGO declared its strong support toward measure #11 for horizontal requirements on firmware and software but recommend that the previously highlighted issues of updates that downgrade performance and rollback of updates are also explored in this context. Another stakeholder highlighted the relevance of software in obsolescence of ICT hardware and how the use restrictive practices on software can force upgrades through unilateral withdrawal of support. A list of priorities for software regulation are provided including energy labelling of software, mandatory settings reducing energy impacts, interoperability of software, long term security and vulnerability support (12 years) and no "lock-in" arrangements with licences. A stakeholder highlighted that service providers should provide information about their environmental impact with a carbon footprint per service unit (e.g. per hour, per year). By this, market transparency will be created, and cloud providers are motivated to offer particularly climate-friendly services. The reasoning is the same as for the data centres (introduction of a register) and for the telecom providers (footprint in the telecom- invoice), that is necessary to establish a market transparency in the first step to enable an ecological competition in the second step.

More specifically on video game software products, the industry association does not share the interpretation of the authors of the report that application software should be in scope of the current Ecodesign Directive based on the definition of "Energy-related product". In particular, the stakeholder believes that the environmental footprint of an application software, such as a video game, cannot be assessed independently of the device on which it is run.

On recommendation #12 a stakeholder from industry suggested that Mandatory GPP must be derived from mandatory Ecodesign & Energy Label, not from the voluntary EU Ecolabel, as the scope is totally different and based of different methodologies.

On recommendation #13 a stakeholder from industry commented that transmission of data is only a smaller part of the overall energy consumption, hence taxing the number of transferred bytes will have very little effect on the footprint of the networks. In addition, such tax on data transmission and consumption would be counterproductive and not in line with the digitalization ambitions of the EU, where digitalization and connectivity are a key for the low carbon transition. A data tax could also negatively impact European competitiveness and the possibility for SME's and rural societies to fully integrate the benefits of digitalization. Transmission networks are complex, but energy consumption and energy efficiency can be impacted in several ways, through deep sleep software solutions to modernization of equipment and removing older standards (such as 2G and 3G) and replace with energy efficient 4G and 5G standards. Potential regulation for energy efficiency should be focused at the network level and not on individual equipment or service levels (such as data transmission).

From other hand, a stakeholder provided examples of misaligned incentives. According to this stakeholder they include flat rates or generous data packages for music and video streaming. These tariffs can, for example, lead to users making video calls via messenger services instead of voice calls. The difference between the two is 300 MByte instead of 60 MByte per hour, resulting in 5 times the mobile data volume. If this data transmission takes place via UMTS networks, it results in a considerable CO2 footprint. More environmentally friendly than access via mobile networks is the use of WLAN networks. Environmentally conscious tariffs could therefore, for example, allow free telephoning via WLAN networks instead of flat rates for mobile telephony. Further disincentives are set in mobile phone contracts by offering new smartphones at bargain prices. The phones are paid for in a non-transparent way for the users via higher basic fees. The users are thus pushed to use a new smartphone every 1 to 2 years. The production of a smartphone requires many valuable raw materials, causes greenhouse gas emissions of around 100 kilograms and leads to further electronic waste. Instead, mobile phone contracts should motivate users to use their smartphones for as long as possible through low basic fees and nonsubsidised hardware, thus saving energy and resources.

Finally, an additional proposal from a stakeholder was provided in order to remove the blocks to the import of used devices and create an obstacle for the functioning of the Global Circular Economy. According to them, trademark owners have the right to block import from outside the EEA, as their consent is required. This is used to block grey import of goods and a tool to fight counterfeit products. Both especially focussed on new products put on the market. According to the stakeholder this practice can be a barrier for the circular economy as especially for enterprise IT, often larger quantities of the same products need to be sourced, used products are often kept as fall-back replacement on the shelf, for maintenance and repair, used spare-parts or components account for >70%.

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