GLOBAL
ELECTRONICS
COUNCIL

Sustainability for a Connected Future

STATE OF SUSTAINABILITY RESEARCH

SUSTAINABLE USE OF RESOURCES

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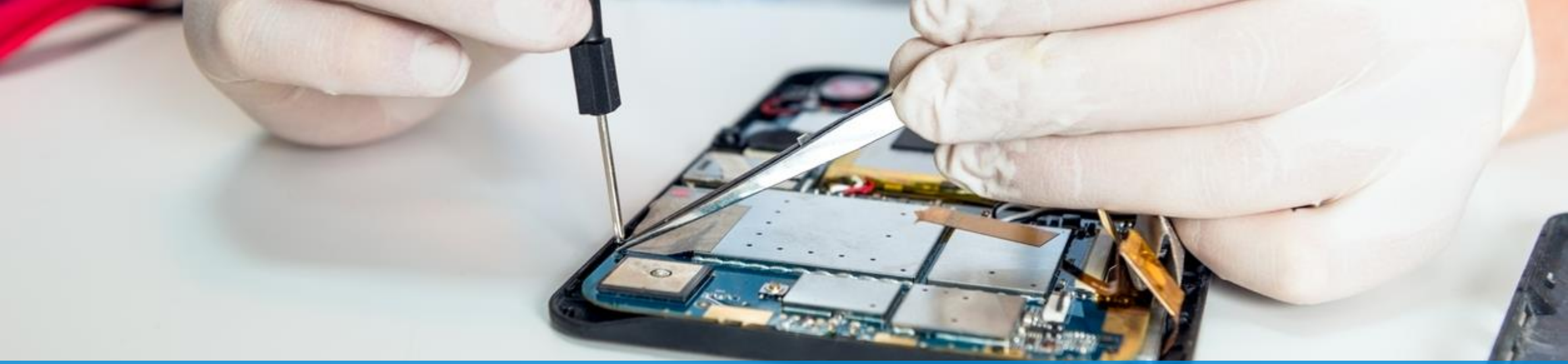
Contents



State of Sustainability Research: Sustainable Use of Resources

The development and release of State of Sustainability Research is the first step in the GEC criteria development process. This State of Sustainability Research provides a scientific, evidence-based foundation for EPEAT criteria. GEC welcomes stakeholder review of this report and submission of comments, including confirmation that the report identifies priority impacts and mitigation strategies, identification of additional life cycle analyses or data on sustainability impacts, and suggestions for other mitigation strategies and best practices leading to demonstrable impact reductions.

About GEC

The Global Electronics Council (GEC) is a non-profit that leverages large-scale purchasing power, both public and private sector, as a demand driver for more sustainable technology. By deciding to buy sustainable technology, institutional purchasers can "move the needle" toward a more sustainable world. GEC also helps manufacturers understand the sustainability impacts of their technology, commit to address those impacts, and act to change operational, supply chain, and procurement behaviors.

GEC is the manager of the ecolabel EPEAT®, used by more purchasers of electronics than any other ecolabel worldwide. EPEAT is a comprehensive voluntary sustainability ecolabel that helps purchasers across sectors -- from financial, healthcare and education institutions to state, provincial and national governments -- identify more sustainable electronic products that have superior environmental and social performance. EPEAT establishes criteria that address priority sustainability impacts throughout the life cycle of the product.

EPEAT Sustainability Impact Priorities

GEC organizes its analysis of sustainability impacts, and the criteria it proposes to reduce these impacts, into the following four priority impact areas of importance to large-scale purchasers of electronic products:

- Climate Change Mitigation
- Sustainable Use of Resources
- Reduction of Chemicals of Concern
- Corporate Environmental, Social, and Governance (ESG) Performance

In this State of Sustainability Research, we identify priority contributors for sustainable use of resources across the life cycle of Information and Communications Technology (ICT) products and mitigation strategies to reduce these impacts. This Research serves as the evidenced-based scientific foundation for EPEAT criteria development.

Sustainable Use of Resources: An Imperative for Circularity

The World Economic Forum reported that in 2019, over 92 billion tons of materials were extracted and processed, producing about half of global CO2 emissions [1]. The unsustainable use of resources has triggered raw material scarcities, contributed to climate change, and caused widespread environmental degradation with implications for and negative impacts on human health and our environment [2].

Sustainable use of resources to enable a circular economy is a priority for government policy, institutional purchasers, and manufacturers world-wide. Institutional purchasers, both public and private sector, are interested in procuring products and services that further sustainable production and consumption. The business sector is similarly invested in meeting customer demand for sustainable products and enabling resilient supply chains. Policy drivers range from the EU's Green Deal and Circular Economy Action Plan, the UN's Circular & Fair ICT Pact (CFIT) and U.S. Executive Order 14017 [3] and associated White House Report on America's Supply Chains [4] to enacted and proposed right to repair legislation across the world.

The power of public procurement to move markets is tremendous, accounting for an average of 12% of gross domestic product (GDP) in OECD countries and up to 30% of GDP in many developing countries [5]; a key enabler for achieving UN Sustainable Development Goal 12 for Sustainable Consumption and Production.

Figures

Tables

Acronyms

ABS – Acrylonitrile Butadiene Styrene

BFR – Brominated Flame Retardants

CDP – Carbon Disclosure Project

CED - Cumulative Energy Demand

CEP – Circular Electronics Partnership

CPU – Central Processing Unit

CRT – Cathode Ray Tube

EEE – Electrical and Electronic Equipment

EPA – Environmental Protection Agency

EPS – External Power Supply

ESG – Environment, Social, and Governance

EU – European Union

FPD – Flat Panel Display

FTC – Federal Trade Commission

GDP – Gross Domestic Product

GEC – Global Electronics Council

GHG – Greenhouse Gas

GPP – Green Public Procurement

GPS – Global Positioning System

GWP – Global Warming Potential

HDD – Hard Disk Drive

HDPE – High Density Polyethylene

HIPS – High Impact Polystyrene

IEC – International Electrotechnical Commission

ICs – Integrated Circuits

ICT – information and Communications Technology

IDC – International Data Corporation

iNEMI – International Electronics Manufacturing Initiative

IPM – Interior Permanent Magnet

ITU – International Telecommunications Union

JRC – Joint Research Commission

LCA – Life Cycle Assessment

LCD – Liquid Crystal Display

LED – Light Emitting Diode

MTCO2eq– Metric Tons of Carbon Dioxide Equivalent

MLCC – Multilayer Ceramic Capacitors

NIST – National Institute of Standards and Technology

OEMs – Original Equipment Manufacturer

PA – Polyamide

PC – Polycarbonate

PCB – Printed Circuit Board

PCR – Post-Consumer Recycled

PIR – Post-Industrial Recycled

PET – Poly Ethyl Terephthalate

PMMA – Poly Methyl Methacrylate

REE – Rare Earth Elements

SDG – Sustainable Development Goal

SSD – Solid State Drive

USB – Universal Serial Bus

VCMA – Voice Coil Magnet Assembly

WEEE – Waste Electrical and Electronic Equipment

WFN – Water Footprint Network

Sustainability Impacts of Resource Use and Mitigation Strategies for the ICT Sector

1. Introduction

Globally, electronic waste (e-waste) is the fastest growing waste stream [6]. In 2019 alone, countries around the world generated 53.6 million metric tons of e-waste, with projections to reach 74.7 million metric tons by 2030 [6]. The United Nations attributes this growth in e-waste to technological innovation and product proliferation, along with shorter life cycles and fewer repair options [6].

E-waste is a valuable source of raw materials, such as gold, silver, cobalt, and lithium. In addition to these valuable materials, e-waste contains toxic materials, such as heavy metals and flame retardants. Lack of collection and proper recycling of e-waste leads to loss of valuable resources and can also result in leaching of toxic materials into the environment, posing risks to ecosystems and human health. At the same time, the growing consumption of ICT devices increases demand for limited natural resources. The extraction and processing of raw materials, particularly metals, can lead to ecosystem damage and exposure of toxics to workers and local populations, as well as increased energy consumption and greenhouse gas emissions.

A circular economy is paramount for the electronics industry to become more sustainable and resilient. Circularity seeks to keep products in use for as long as possible, emphasizing durability, repairability, reuse, and the importance of recycling. When core materials are more easily recovered and reintroduced as raw material feedstock in the supply chain for electronics or other sectors, it enables conservation of limited resources, alleviation of adverse climate change impacts, and protection of workers and communities from potential health hazards associated with raw material extraction and processing as well as waste generation and handling.

Section 2 of this research identifies priority sustainability impacts with respect to materials selection and use, product design, end-of-life management, water management, and product packaging for electronic products. Section 3 provides potential mitigation strategies for each of the aforementioned sustainability impacts. Sections 4 and 5 provide resources and best practices for standardization and a summary of recommended criteria for the EPEAT ecolabel, respectively.

2. Sustainability impacts

This section identifies the most significant environmental impacts associated with the production and consumption of ICT devices — from raw material extraction and processing to end of life — with a focus on material resources (see Figure 1).

Additional GEC State of Sustainability Research provides in-depth examinations of related and critically important sustainability impacts. For instance, Climate Change Mitigation looks at the major contributors to greenhouse gas (GHG) emissions in the ICT product lifecycle, associated largely with the use of energy resources.[1] GEC's State of Sustainability Research for Corporate Environment, Social and Governance (ESG) Performance addresses responsible sourcing in the ICT supply chain, including "conflict" minerals[2] and the impact of material extraction and processing on workers and communities.[3] GEC's State of Sustainability Research for Chemicals of Concern considers toxics associated with sourcing materials, product use and e-waste.

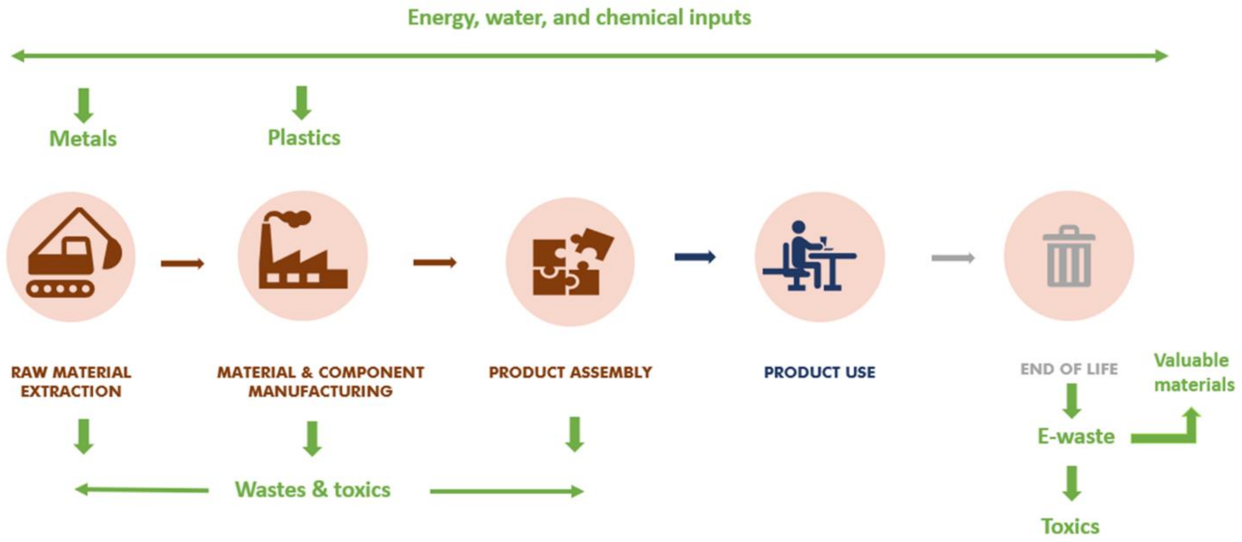


Figure 1. Material impacts across the life cycle of the electronics value chain

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[1] Available at https://globalelectronicscouncil.org/climate-change/

[2] Under U.S. and European Union laws, "conflict minerals" are currently the minerals columbite-tantalite (coltan), cassiterite, wolframite, and their commonly extracted derivatives, respectively – tin, tantalum, and tungsten – which along with gold are referred to as "3TG."

[3] Forthcoming in 2023

2.1 Shorter product lifetimes and premature obsolescence

Shorter product lifetimes are an important contributor to the growing e-waste stream, and a root cause of the sustainability impacts of electronic products. Consumers replace their still functioning electronics with newer models when instead they could repair products to restore functionality is part of the problem. Along with this consumer demand or increased consumption, shorter product lifetimes and premature obsolescence also directly contribute to the rise in demand for the extraction and processing of materials.

A report from the European Environmental Agency on electronic product obsolescence analyzed existing research on actual, designed, and desired lifetimes of several products.[4] For televisions, the designed lifetime – the lifetime intended by the manufacturer when designing the product – was 25 years, but the user replaced it in under 10 years (see Table 1). For smartphones, the designed lifetime was more consistent with the actual lifetime. However, in this case, users expressed interest in the device lasting at least 2 years longer than the actual lifetime. Research indicated similar results for notebook computers and printers, as for smartphones [7].

Product	Desired lifetime	Actual lifetime	Designed lifetime
Smartphone	5.2	2.5	2
Television	11	7.3	25
Notebook computer	7	4.2	Not Available
Printer	7.5	4	Not Available

Table 1. Comparison of lifetimes for smartphones and televisions (in years). Source:[7]

Why do users discard products prematurely? For smartphones, a 2020 EU survey identified the following reasons: the old device broke (37%), the performance of the device had significantly

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[4] In this study, "actual lifetime" was the time from product sale until it was discarded or replaced; "designed lifetime" was the length of time that the manufacturer intended for the product to function; and "desired lifetime" was the average time that the customer wanted the product to last.

deteriorated (30%); and applications or software stopped working (19%) [8]. This same survey found that 64% of respondents would like to keep their device for 5 years.

A German study investigated the trends for replacing a notebook computer after first use in calendar years 2004, 2007 and 2012/2013 (see Figure 2). They found that the percentage of notebook computer replacements due to defective parts or malfunction increased over time, whereas the percentage replacement of still-functioning notebooks with a better one (i.e., consumer desire for more functionality) decreased [9].

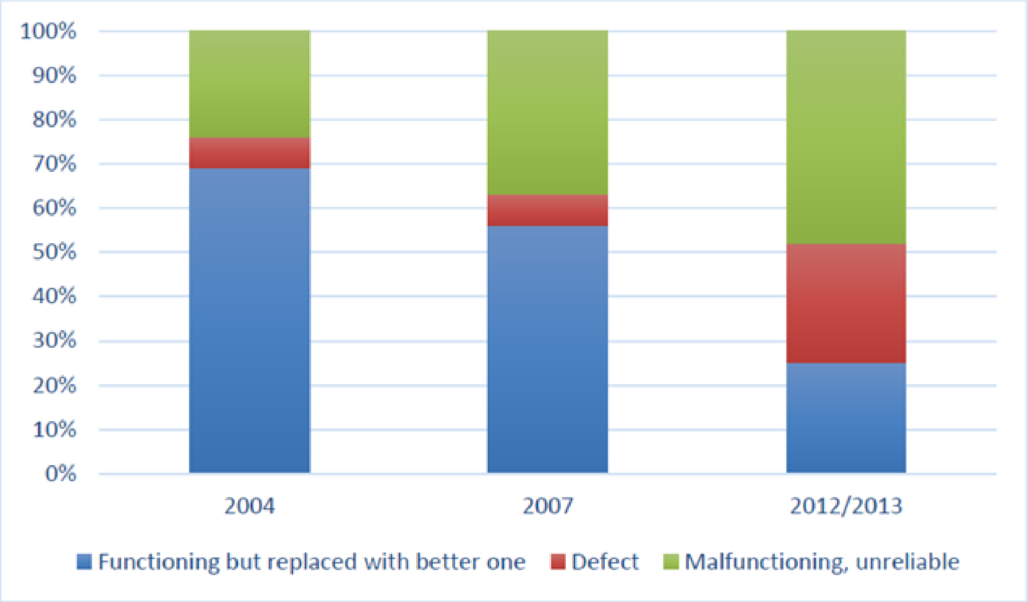


Figure 2. Reasons for replacing a notebook after first use. Source: [9]

These examples illustrate the potential to increase the lifetimes of these products – by design or by the user – through design for product durability and repairability, and ultimately reduce the sustainability impact of materials and e-waste as discussed below.

2.2 Materials in ICT products

Present day electronics contain a wide variety of raw materials, including metals, plastics, and chemicals. A smartphone alone contains more than 60 elements, representing more than half of the elements on the periodic table [10]. Metals and plastics are the largest, by mass constituents of ICT products. They are essential to provide the finish, form, and functionality that customers desire, however, their usage in ICT products result in associated environmental impacts. Table 2 summarizes the variety of materials found in ICT products and their applications. It should be noted that lead in CRT glass and mercury in backlighting in LCD monitors are now largely legacy uses.

Material classification	Materials	Application in electronics
Base metals	Copper (Cu)	PCB, alloys, wiring, connectors, transformers
	Iron, Steel (Ferrous (Fe))	Steel, casing, magnets,
	Zinc	Steel, Zn-Al-Cu alloy (94%), plating
	Nickel	Steel (8%), lithium-ion batteries
	Aluminum (Al)	Alloys, wiring, casing, heat sink
Hazardous metals	Lead	CRT funnel (14.7%), CRT neck (14.7%), solder (40%)
	Chromium	Steel (18%)
	Cadmium	Batteries, coatings, pigments, and electroplating
	Mercury	LCD screens and monitors
Hazardous and critical metal	Beryllium	Alloys with copper in connectors and battery contacts
Critical minerals	Bismuth	Solders, capacitor, heat sink
	Antimony	Flame retardant, CRT glass
	Tin	Solders, CRT, PCB
	Cobalt	Li-ion batteries
	Lithium	Coin cell batteries, Li-ion batteries

	Tantalum	Capacitors, capacitor wire
	Gallium	Integrated circuits (ICs)
	Germanium	Integrated circuits (ICs)
	Indium	LCDs, semiconductors
	Silicon	Connectors, semiconductors, SSDs
	Tellurium	Semiconductors
Precious metals	Gold	PCB, contacts, integrated circuits (ICs)
	Silver	PCB, brazing alloy (3%), lead-free solder (3%)
Precious and critical metal	Palladium	MLCC, PCB
Rare earth elements	Cerium	Integrated circuits
	Lanthanum	Lenses, batteries, alloys
	Dysprosium	Permanent magnets, HDD
	Neodymium	Permanent magnets, HDD
	Praseodymium	Permanent magnets, HDDs
	Terbium	Permanent magnets, HDDs
	Ytrrium	Florescent phosphorous, alloys, LCDs
Plastics	ABS, HIPS, PC-ABS, PC Epoxy etc.	Casings, PCBs, electronic components

Table 2. Classification of materials and their applications in electronics. Multiple sources [11]–[20] are used to compile the table.

Table 3 summarizes the average material composition of different ICT products. Metals are the greatest contributors towards the mass of most of these products, including notebook computers, TVs, monitors, desktop computers, smartphones, servers, and storage equipment. The exceptions are tablets and printers in which plastics are the greatest contributors towards the mass. Figure 3 illustrates percentage contribution of materials towards the total mass for select ICT products. Of note, the contribution of critical, precious, and rare earth elements (REE) is not shown in Table 3 and Figure 3, as their percentage contribution to mass is relatively small when compared to other metals. However, their presence is essential for electronics to function, and despite their small quantities have substantial sustainability impacts, as discussed below.

	Mass in percentage									
Product category	Al	Cu	Fe	Plastic	Battery	PCB	Flat panel glass	Other glass	Other metals	Others
Desktop computer	8.7	3.9	52.2	20.9		9.9	1	1.2	0.9	1.2
Laptops	15.4	1.8	11.5	28.3	14	12.4	8.2	0	5.8	2.4
LCD monitors	6.2	5.3	35.8	28.4		6.2	17.9	0	0	0.2
LCD TV	2.5	0.9	42.6	28.1		5.8	12.9	0	4.7	2.5
LED monitors/LED TV	13.6	0.02	27.9	39.8		4.1	14.2	0	0	0.3
Printer	0.2	0.6	30	60.8		3.1	0.1	3.8	0	1.4
Smart phone	9.4	1.2	6.3	23.2	22.6	14	8.9	7.9	2.5	4.1
Tablet	9.3	0.4	4.1	19.5	22.8	6.6	14.8	21.8	0	0.6
Rack server			61.6			27.9				10.6
Blade server	11.0	4.0	69.0			17.0				
Storage media mix (HDDs, SSDs)	76.0		14.0	0.1		10.0				

Table 3. High-level average material composition (in %) of ICT products. Sources: [21] - Notebook computer, LCD TVs, LED TVs/monitor, LCD monitors, Desktop computers, smartphone, tablets. Printers , [22] – Rack server, [23] – Blade server and storage media mix

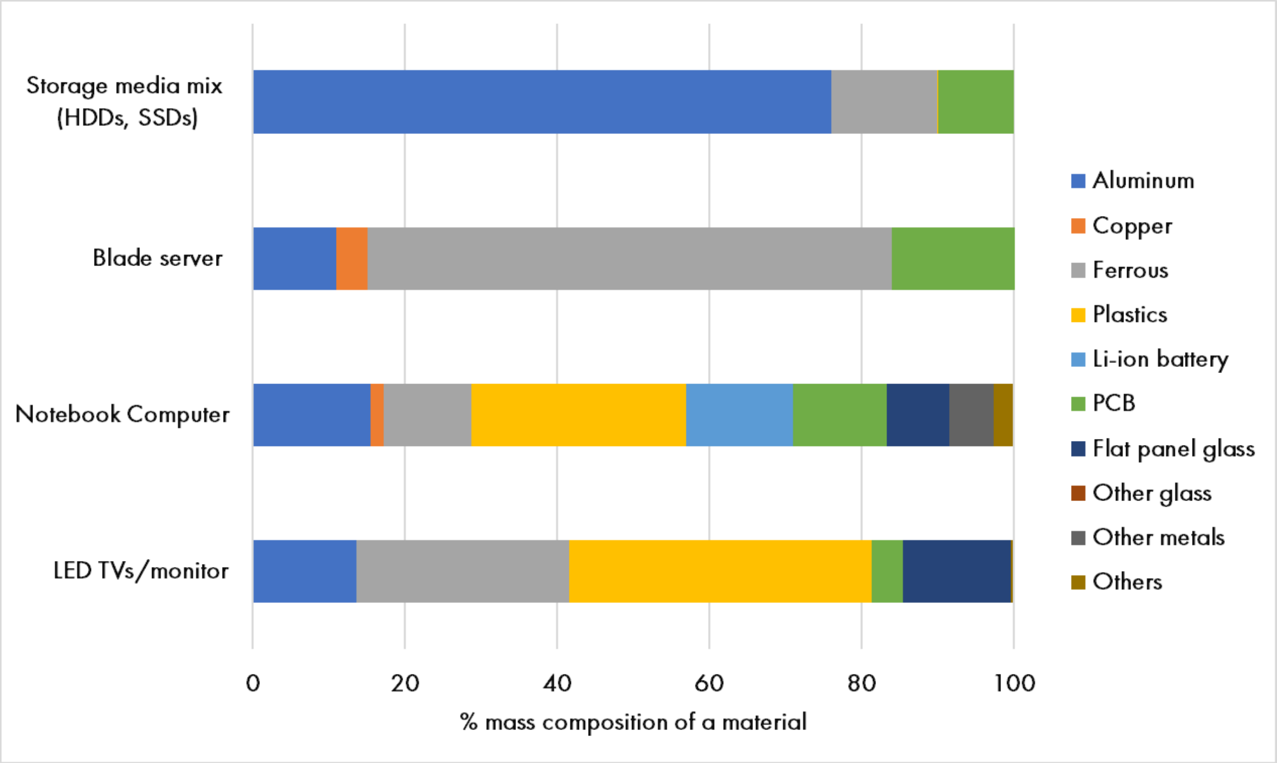


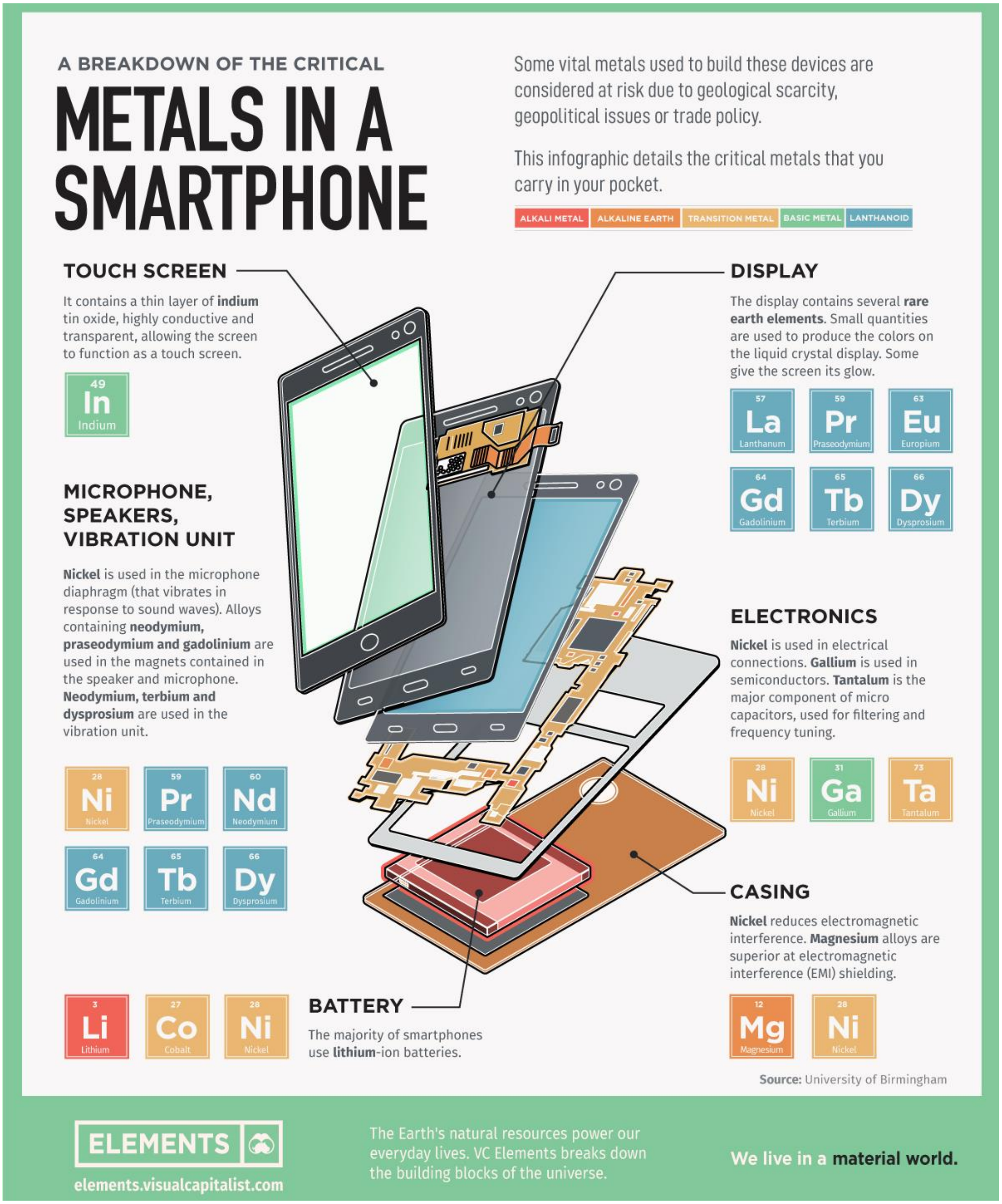
Figure 3. Percentage contribution of materials towards the total mass of ICT products. Sources: [21] - Notebook computer, LED TVs/monitor, [23]– blade server and storage media mix.

2.3 Sustainability impacts of metals

Extraction and processing of metals depends on massive amounts of materials, water, and electricity, leading to a range of adverse environmental impacts, including climate change, water scarcity, adverse land use and habitat loss and resource depletion [24]. Metal mining, processing and refining processes if not managed properly release toxic chemicals into the environment, polluting air, water, and soil systems [25]. For example, gold mining is associated with the release of highly toxic chemicals, including cyanide and mercury, which pose substantial risks to public health and the environment [26].

There is also growing concern about future availability and supply of new materials for ICT devices given ever increasing demand, especially for critical raw materials. Countries define critical raw materials differently around the world, but in general, define them as minerals that are economically and strategically important to a given country or region. The U.S. Department of the Interior published its official list of 35 minerals considered critical to U.S. national security and the economy in May 2018 [27]. The EU’s latest list, published in 2020, includes 30 critical raw materials [28]. These critical raw materials and processing capacity are concentrated in particular countries causing supply chain dependence risk; and due to their unique properties, there is a lack of viable substitutes. Rare earth elements, a subset of critical raw materials, include 15 elements ranging in atomic number from 57 (lanthanum) to 71 (lutetium). REEs are difficult to mine as its unusual to find them in concentrations high enough to warrant the cost of extraction. Critical raw materials used across electrical and electronic equipment are identified in Table 2.

Figure 4 shows the critical metals found specifically in a smartphone and explains the highly specialized function each metal serves in the application.



A BREAKDOWN OF THE CRITICAL

METALS IN A SMARTPHONE

Some vital metals used to build these devices are considered at risk due to geological scarcity, geopolitical issues or trade policy.

This infographic details the critical metals that you carry in your pocket.

ALKALI METAL | ALKALINE EARTH | TRANSITION METAL | BASIC METAL | LANTHANOID

TOUCH SCREEN

It contains a thin layer of **indium** tin oxide, highly conductive and transparent, allowing the screen to function as a touch screen.

MICROPHONE, SPEAKERS, VIBRATION UNIT

Nickel is used in the microphone diaphragm (that vibrates in response to sound waves). Alloys containing **neodymium, praseodymium and gadolinium** are used in the magnets contained in the speaker and microphone. **Neodymium, terbium and dysprosium** are used in the vibration unit.

BATTERY

The majority of smartphones use **lithium**-ion batteries.

DISPLAY

The display contains several **rare earth elements**. Small quantities are used to produce the colors on the liquid crystal display. Some give the screen its glow.

ELECTRONICS

Nickel is used in electrical connections. **Gallium** is used in semiconductors. **Tantalum** is the major component of micro capacitors, used for filtering and frequency tuning.

CASING

Nickel reduces electromagnetic interference. **Magnesium** alloys are superior at electromagnetic interference (EMI) shielding.

Source: University of Birmingham

The Earth's natural resources power our everyday lives. VC Elements breaks down the building blocks of the universe.

We live in a **material world.**

Figure 4. Visualizing the critical metals in a smartphone. Source: [29]

For relative comparison purposes, Table 4 identifies the content of precious and critical metals in various electronic devices and components. Supporting raw material data is provided in Appendix A.

Products	Number of critical raw materials	Number of precious metals
LCD notebooks	14	4
LED notebooks	13	4
LCD TVs	10	3
LED TVs	8	3
LCD Monitors	10	3
LED Monitors	7	3
Cell Phones	2	3
Smartphones	8	4
PV Panels	2	0
HDDs	4	3
SSDs	1	3
Tablets	14	3

Table 4. Relative comparison of the number of critical and precious raw materials found in select electronic products and components. Source: [30]. See Appendix A, Table 1 for raw data.

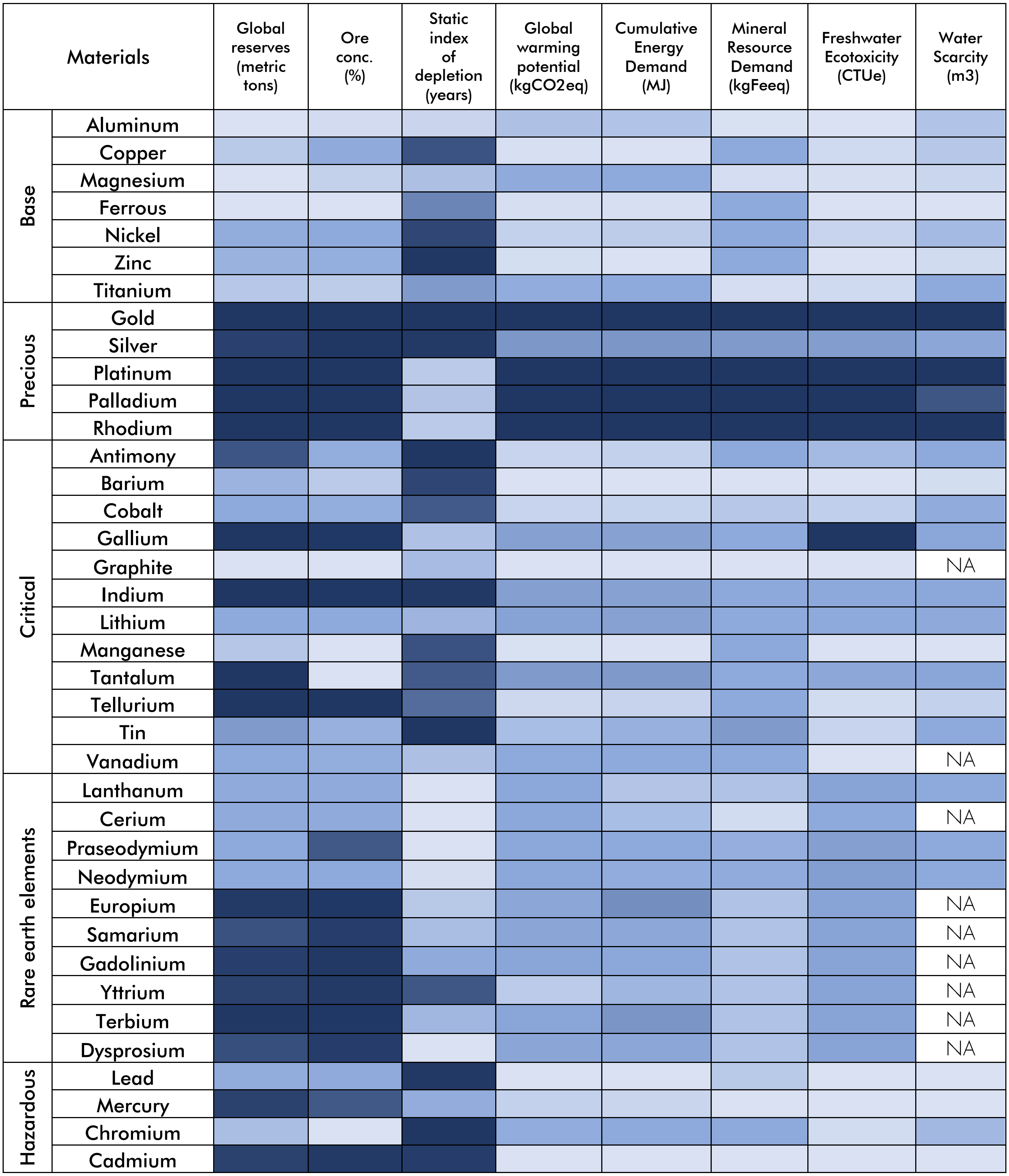
Further, the COVID-19 pandemic revealed that supply chains that provide crucial raw materials for manufacturing electronics are increasingly vulnerable to social, geopolitical, and technical disruptions. These vulnerabilities are likely to escalate in the future, due to global health crises, natural disasters, and global political instability, all of which will be magnified by climate change impacts [31].

Material criticality has been a topic of interest in both academia [31], [32] and industry [33], [34] in recent years. These studies have applied a multi-criteria framework to identify vulnerabilities, or material hotspots using metrics that capture environmental, supply chain, and socio-political risks. The findings of these studies are consistent when it comes to identifying the materials that are prone to highest risk. Here, we present the findings of a recent study.

Althaf and Babbitt (2021) investigated the sustainability impacts resulting from the extraction and production of nearly 40 metals and minerals that provide critical functionality to electronic products [31]. Figure 5 summarizes the hotspots for key environmental impact and supply-demand metrics used in this study to capture material hotspots, presented as a heat map. The results highlight that precious metals, such as gold, platinum, rhodium, and palladium, have the greatest supply chain and resource depletion risks. These supply chain vulnerabilities are driven by many factors including relatively low reserves and ore concentration, and high reliance on production as a byproduct from other metal extraction processes [35]. Precious metals also have significant environmental impacts on a per kilogram basis, including global warming potential, energy, and mineral resource demand. Because precious metals are present in low concentrations in ores, they require greater energy, water, and resources to extract and refine. Base metals such as iron, aluminum, and copper, are not at risk for scarcity or availability, as compared to precious and critical metals but still require energy and water resources to extract.

In addition to precious metals, critical metals such as indium, tantalum, tellurium, gallium, and REEs are also observed as hotspots when considering availability, ore concentration, and depletion metrics. Though these elements are present in electronics in very small concentrations, their risk contribution is high enough to cause disruptions through the product supply chain [31]. Notably, cobalt and nickel, of importance for battery production are observed as hotspots when considering depletion metrics. Despite abundant availability in nature, cobalt and nickel are depleting faster than other metals, due to demand from multiple sectors, such as electric vehicles and energy storage applications. Furthermore, most cobalt is sourced from the Democratic Republic of the Congo (DRC), which is prone to socio-political disruptions that may further restrict the supply of cobalt. Another battery material, cadmium, is also observed to be depleting faster, on a relative comparison basis, through its available reserves, again attributed to increased demand for these materials across different industry sectors.

In addition, per analysis by the U.S. EPA, REE mining and processing activities can create numerous risks to human health and the environment, the severity of which varies by mine plant operation. The contaminants of concern depend on the REE mineral ore, toxicity of the contaminants from waste rock, ore stockpiles, and process waste streams as well as the specific characteristics of the mining process and waste handling methods. And the mobility of contaminants depends on the characteristics of the geologic, hydrologic and hydrogeologic environments [36].



Materials		Global reserves (metric tons)	Ore conc. (%)	Static index of depletion (years)	Global warming potential (kgCO2eq)	Cumulative Energy Demand (MJ)	Mineral Resource Demand (kgFeeq)	Freshwater Ecotoxicity (CTUe)	Water Scarcity (m3)
Base	Aluminum								
	Copper								
	Magnesium								
	Ferrous								
	Nickel								
	Zinc								
	Titanium								
Precious	Gold								
	Silver								
	Platinum								
	Palladium								
	Rhodium								
Critical	Antimony								
	Barium								
	Cobalt								
	Gallium								
	Graphite								NA
	Indium								
	Lithium								
	Manganese								
	Tantalum								
	Tellurium								
	Tin								
	Vanadium								NA
Rare earth elements	Lanthanum								
	Cerium								NA
	Praseodymium								
	Neodymium								
	Europium								NA
	Samarium								NA
	Gadolinium								NA
	Yttrium								NA
	Terbium								NA
	Dysprosium								NA
Hazardous	Lead								
	Mercury								
	Chromium								
	Cadmium								

Figure 5. Heat map showing vulnerabilities for metals of concern based on selected environmental and supply-demand metrics. The gradation of color from light to dark represents increasing risk. Source: [31]. Water scarcity values are taken from [37].

Note: The color scale is based on a relative percentile range (90th, 50th and 10th). For environmental impacts (which are based on a relative comparison of GWP, CED, mineral resource demand, water scarcity footprint and freshwater ecotoxicity), darker color indicates that metals are in 90th percentile range and are at the greatest risk. For supply metrics (which are based on global reserves, ore concentration and a static index of depletion), darker color indicates that metals are in 10th percentile range and are at the greatest risk with respect to resource depletion. Raw data is included in Appendix A, Table 2. "NA" represents that data was not available.

2.4 Environmental impacts of plastics

Plastics are polymers derived primarily from fossil fuels, including crude oil, natural gas, and coal. The plastics production process can release hazardous substances into the air and water, such as acetone, styrene, benzene, and volatile organic compounds, which can be harmful to both the environment and human health. Workers are also at risk of exposure to chemical spills and chemical fires.

Electronics include a wide range of plastics. Plastics are present in ICT casing components, circuit boards, and electronic components, for example. Figure 6 illustrates average WEEE plastics composition in Europe for flat panel displays (monitors, TVs, notebook computers, and tablets) and small ICT products (smartphones, desktop computers, GPS equipment, printers, routers, and fax machines) [38]. This data originates from a study that collected more than 800 data points from a wide variety of sources, including published literature, WEEE recyclers, WEEE plastic recyclers, and take-back schemes. As illustrated in the Figure 6, high impact polystyrene (HIPS), polycarbonate – acrylonitrile butadiene styrene (PC-ABS), acrylonitrile butadiene styrene (ABS) and epoxy are the greatest contributors towards the total mass of plastics in flat panel displays (FPD) and small ICT equipment. Plastics containing brominated flame retardants (BFR) represent a significant portion for small ICT equipment (29%), while BFR containing plastic use in FPDs represent only 9% of the total plastics fraction.

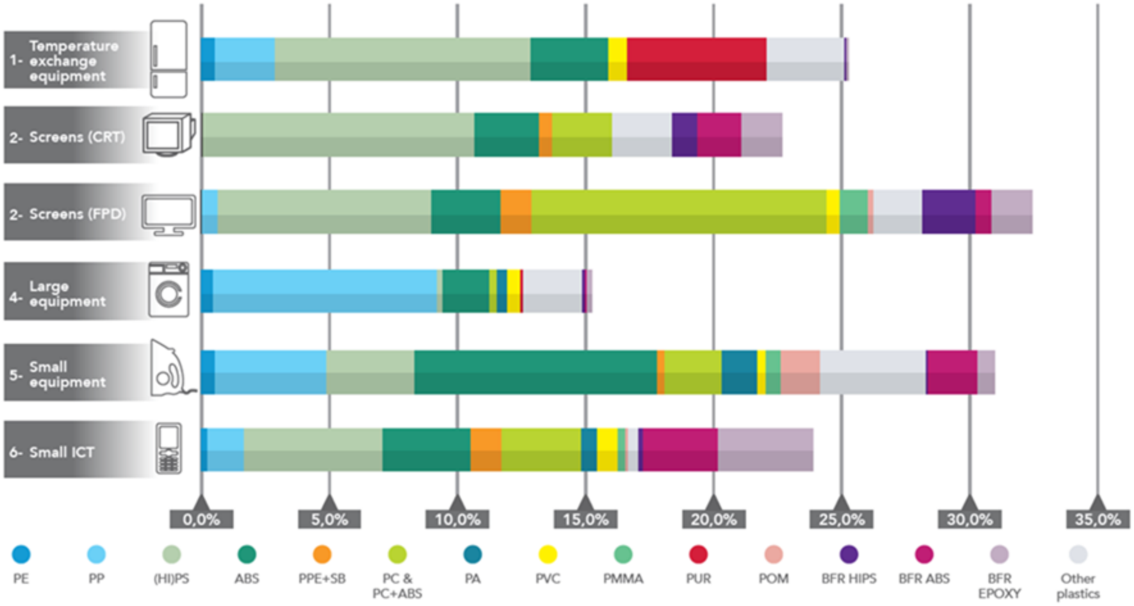
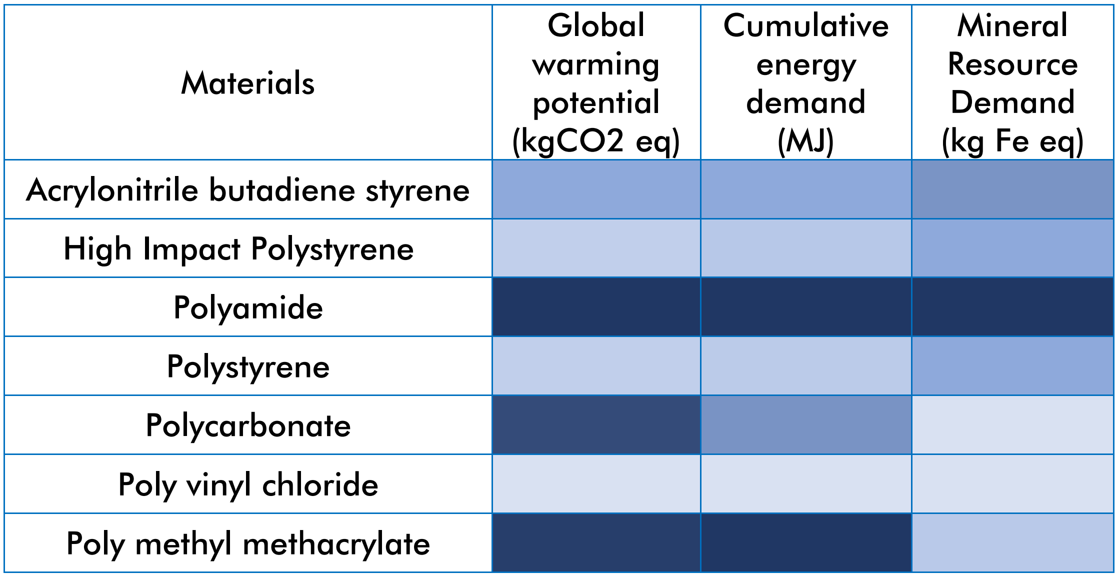


Figure 6. Plastics composition per category of electronics. Source: [38]

Data on environmental impacts of producing polymers (per kg of material) shows that on a relative comparison basis, polyamide (PA), polycarbonate (PC), and poly methyl methacrylate (PMMA) have the highest carbon footprint (see Figure 7) [39]. Polyamide is also observed as a hotspot for the mineral resource demand metric compared to the other assessed polymers.

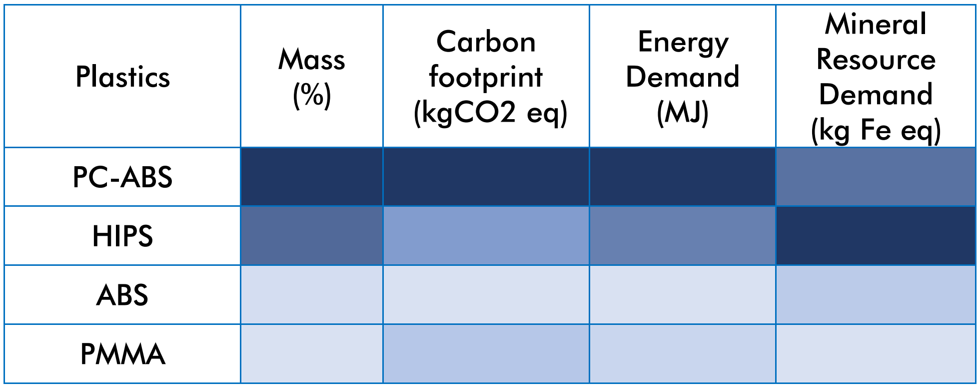


Materials	Global warming potential (kgCO2 eq)	Cumulative energy demand (MJ)	Mineral Resource Demand (kg Fe eq)
Acrylonitrile butadiene styrene			
High Impact Polystyrene			
Polyamide			
Polystyrene			
Polycarbonate			
Poly vinyl chloride			
Poly methyl methacrylate			

Figure 7. Heat map showing plastics of concern for selected environmental metrics. Source: [39]

Note: the color scale is based on percentile range (90th, 50th and 10th. Polymers in 90th percentile range are shown in the darkest color, which indicates the greatest impact for each environmental metric as a relative comparison basis. Raw data is included in Appendix A. Table 3.

At a product level, material hotspots are dependent on both the amount of plastic and the magnitude of impact of the plastic. Figure 8 shows mass percentage composition and environmental impacts scaled to mass composition of plastics in FPDs. For carbon footprint and energy demand impacts, the relative magnitude of hotspots is PC-ABS, followed by HIPS, PMMA, and lastly ABS. PMMA, despite being present in smaller amounts in FPDs when compared to ABS, has a slightly greater impact than ABS for carbon footprint and energy demand mainly because of the magnitude of impact is greater on a per kilogram basis. For mineral resource demand, HIPS has the greatest impact, followed by PC-ABS, ABS, and PMMA.



Plastics	Mass (%)	Carbon footprint (kgCO2 eq)	Energy Demand (MJ)	Mineral Resource Demand (kg Fe eq)
PC-ABS				
HIPS				
ABS				
PMMA				

Figure 8. Material hotspots trends for FPDs. Estimated using data from [38], [39]

Note: the darker colors indicate a value of higher magnitude. Raw data in Appendix A, Table 4.

The carbon footprint hotspots for small ICT product categories follows a similar trend. Due to its higher magnitude of impact on a per kilogram basis, PC-ABS has the greatest carbon footprint, followed by HIPS and ABS. For mineral resource demand, the order of hotspots observed is HIPS, followed by PC-ABS, then ABS.

The key takeaway from this research for product design is that the type of plastic, not just the mass of plastic, can drive impact, which requires case-by-case analysis.

2.4.1 Biobased plastics

Interest in the ability of biobased plastics to serve as a renewably sourced replacement for fossil-fuel based materials has continued to increase. “Bioplastics” include durable and non-degradable (neat or partial blends) made from a biological source or plastics that are biodegradable [40]. “Biodegradable bioplastics” can include biological-based biodegradable plastics, but also include biodegradable petrochemical plastics, such as polybutylene adipate terephthalate (PBAT) and polybutylene succinate (PBS) [41]. The U.S EPA conducted a screening level life cycle assessment to understand the implications of using a baseline fossil-fuel based PC-ABS polymer in a notebook computer enclosure compared to alternate materials, including biobased materials such as Polylactic acid (PLA) and bamboo, as well as aluminum [42]. Findings of this study showed that for global warming potential, PLA had less impact as compared to other alternative materials. However, for other impact categories, including eutrophication, ecotoxicity, and carcinogenic impacts, PLA had the highest impact, as compared to other alternatives. This implies that trade-offs exist and the need for a holistic approach when considering alternative material uses is needed to avoid burden shifting and regrettable substitutions. Also, methodological limitations exist as there is no standardized LCA approach to account most notably for representation of land use changes and biogenic carbon. For example, Byron et al. recommend that LCA practitioners consistently apply biogenic carbon storage credits only to long-term carbon sinks and account for indirect land-use change arising from feedstock cultivation [43]. This implies that actual global warming potential impact caused by bioplastics may be underestimated. Further, increased use of bioplastics will lead to increased use of land and water and can have a negative effect on biodiversity. The EPA study also highlights that lack of infrastructure to separate bioplastics from other plastics can contaminate the plastic waste stream from electronics. Considering these factors, there is a need for further research and quality data to understand if bioplastics are a potential substitute for fossil-fuel based plastics.

2.5 End-of-life impacts

Electronic waste (e-waste) is the fastest growing waste stream on the planet, with millions of devices discarded every year. Countries around the world generated nearly 53.6 million metric tons of e-waste in 2019 [6]. The Global e-Waste Monitor estimated that the rate of formal collection and recycling for e-waste in 2019 was only 17.4% (i.e., 9.3 million metric tons), indicating that recycling activities are not keeping pace with the global growth of e-waste [6].[5] The fate of the rest of global e-waste (i.e., 44.3 million metric tons) is uncertain, with its whereabouts and associated environmental impact varying across different regions [6]. The illicit transboundary movement of used electrical and electronic equipment (UEEE) and e-waste, however, is a well-documented concern. As reported by the United Nations Global E-Waste Monitor (2017), a study conducted by the Basel Action Network (BAN) placed GPS trackers in obsolete equipment in the EU and U.S. [44]. BAN found that 34% of the 205 trackers crossed international borders, with 93% of those exported ending up in developing countries in Asia. In a separate study, conducted in 2015/2016 in Nigeria, 71,000 tonnes of UEEE and e-waste were imported annually via two main ports in Lagos. More than 77% of the UEEE and e-waste originated from ports in EU member states, followed by the U.S. and China at ~ 7.33% each. Basic functionality tests showed that on average 19% of UEEE devices were non-functional [45]. Table 5 summarizes generation, collection, and recycling rates of e-waste by region in 2019. The data shows that Europe is leading the world, collecting, and recycling 42.5% of their total generated e-waste, followed by Asia (11.7%), the Americas (9.4%), Oceania (8.8%), and Africa at the lowest rate of (0.9%). The collection and recycling rate for North America alone is 15%. While developed or high-income countries, such as the U.S. and EU, are equipped to collect and process e-waste, as the data on collection and recycling rates illustrate, there is room for improvement. In middle- and low-income countries, infrastructure is not yet fully developed, or, in some cases, is entirely absent. As a result, most of these regions manage e-waste informally, often under uncontrolled conditions, and hence with the potential to cause the severe aforementioned environment and human health impacts [6].

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[5] In this study, the United Nation uses the terms "electrical and electronic waste" and "e-waste" interchangeably.

Region	Generated Amount (million metric tons)	Generation (kg per capita)	Collection and recycling rate (%)
Europe	12	16.2	42.5
Americas	13.1	13.3	9.4
Asia	24.9	5.6	11.7
Africa	2.9	2.5	0.9
Oceania	0.7	16.1	8.8

Table 5. E-waste statistics of different regions. Source: [6]

E-waste contains valuable materials and recovery of these materials can help to conserve resources, reduce environmental impacts, and build resilient supply chains. For instance, urban mining of gold from discarded electronics reduces carbon dioxide emissions by 80% per unit of gold compared with mining from virgin sources [46]. The Global E-Waste Monitor reported that nearly $57 billion USD worth of raw materials, primarily iron, copper and gold was present in e-waste generated globally in 2019 [6]. Table 6 summarizes select metals, and quantities present in total Waste Electrical and Electronic Equipment (WEEE) generated globally in 2019.

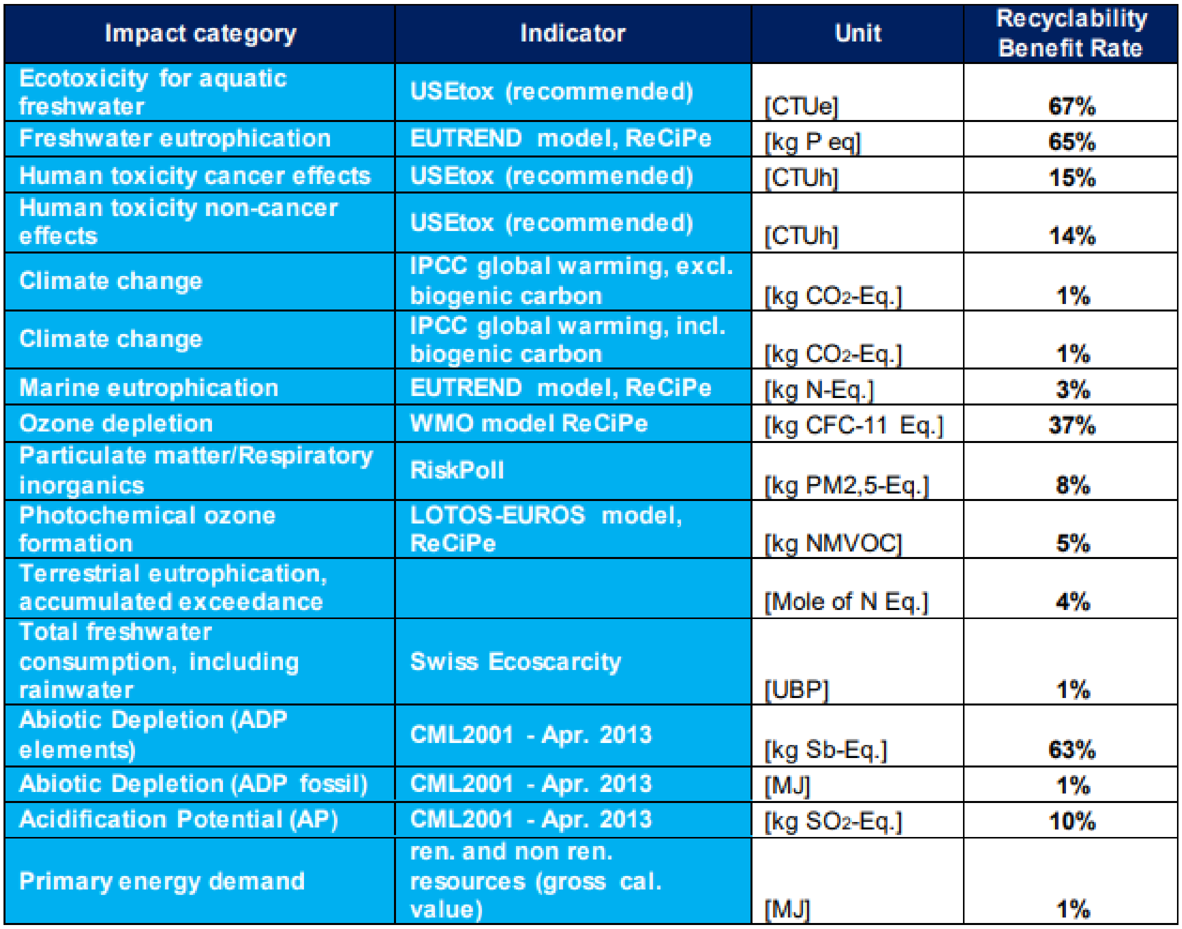
Material	Quantities present in WEEE (2019) (in kilo metric tons; approximated) (Global)
Iron (Fe)	20,500
Copper (Cu)	1,800
Cobalt (Co)	13
Silver (Ag)	1.2
Gold (Au)	0.2

Table 6. Select material contents of WEEE and quantities. Source: [6]

In addition to valuable materials shown in Table 6, e-waste also contains hazardous or toxic materials, including mercury, lead, halogenated flame retardants, plasticizers, and UV stabilizers [47]. Improper management of e-waste can potentially lead to the release of these toxic materials and byproducts into the environment, impacting both ecosystems and human health. Lithium-ion batteries in the e-waste stream, when mishandled or improperly discarded, can ignite fires that threaten worker safety, create air pollution, and decrease the efficiency of recycling by driving up cost and disrupting operations [48]. The burning of e-waste in informal settings to extract the valuable metals found in electronics, notably in developing and underdeveloped countries, releases fine particles and harmful byproducts known to cause brain, heart, liver, kidney, skeletal system, nervous, and reproductive system damage into the environment [47]. Dumping of e-waste illegally in non-hazardous waste landfills, can allow both heavy metals and flame retardants to seep from the e-waste into the soil. From the contaminated soil, metals from e-waste, such as mercury, lithium, lead, and barium can leach into ground water resources polluting drinking water [49].

The environmental impacts of the use of and end-of-life management of plastics is of growing societal concern. Mismanaged plastics that are released into the environment can persist for more than 100 years, leaching microplastics and chemical additives into our food and water, which can then be ingested by humans and animals [50], [51]. Additionally, uncontrolled burning of plastic containing halogenated flame retardants can release highly toxic dioxins and furans, which are persistent organic pollutants that can accumulate in the environment and food chain [50]. Therefore, separating and recycling of plastics is essential at end of life. However, the diversity of plastics and the lack of information on types of plastics and flame retardants used in electronics reduces the economic viability of recycling plastics from e-waste. Lack of separation of e-waste by different polymer types and FRs means loss of potentially recyclable plastics in the current market. If polymers containing FRs undergo recycling, legacy or banned flame retardants may inadvertently circulate back into the product stream.

With respect to environmental benefits of recycling, Peiro et al. (2015) estimated that for an enterprise server, benefits ranges from 1% to 67% depending on the impact category assessed, as illustrated in Figure 9 [52]. Benefits exceeded 60% for ecotoxicity of aquatic freshwater, freshwater eutrophication, and abiotic depletion of elements (see Figure 9).



Impact category	Indicator	Unit	Recyclability Benefit Rate
Ecotoxicity for aquatic freshwater	USEtox (recommended)	[CTUe]	67%
Freshwater eutrophication	EUTREND model, ReCiPe	[kg P eq]	65%
Human toxicity cancer effects	USEtox (recommended)	[CTUh]	15%
Human toxicity non-cancer effects	USEtox (recommended)	[CTUh]	14%
Climate change	IPCC global warming, excl. biogenic carbon	[kg CO_2-Eq.]	1%
Climate change	IPCC global warming, incl. biogenic carbon	[kg CO_2-Eq.]	1%
Marine eutrophication	EUTREND model, ReCiPe	[kg N-Eq.]	3%
Ozone depletion	WMO model ReCiPe	[kg CFC-11 Eq.]	37%
Particulate matter/Respiratory inorganics	RiskPoll	[kg PM2,5-Eq.]	8%
Photochemical ozone formation	LOTOS-EUROS model, ReCiPe	[kg NMVOC]	5%
Terrestrial eutrophication, accumulated exceedance		[Mole of N Eq.]	4%
Total freshwater consumption, including rainwater	Swiss Ecoscarcity	[UBP]	1%
Abiotic Depletion (ADP elements)	CML2001 - Apr. 2013	[kg Sb-Eq.]	63%
Abiotic Depletion (ADP fossil)	CML2001 - Apr. 2013	[MJ]	1%
Acidification Potential (AP)	CML2001 - Apr. 2013	[kg SO_2-Eq.]	10%
Primary energy demand	ren. and non ren. resources (gross cal. value)	[MJ]	1%

Figure 9. Recyclability benefit rate for enterprise servers for the combination of manual and automatic recycling treatment. Source: [52]

[CTUe] = Comparative Toxic Units (ecotoxicity), [kg P eq] = kilograms of phosphorous equivalent, [CTUh] = Comparative Toxic Units (health) , [kg CO2Eq] = kilogram of carbon dioxide equivalent, [kg N-Eq] = kilograms of nitrogen equivalent, [CFC-11 Eq.] = chlorofluorocarbon equivalent, [kg PM2.5-Eq.] = kilogram of particulate matter equivalent, [kg NMVOC] = kilogram of Non Methane Volatile Organic Compounds, [Mole of N Eq.] = mole of nitrogen equivalent, [UBP] = Ecological impact point for eco-scarcity, [kg Sb-Eq.] = kilograms of antimony equivalent, [MJ] = megajoule or 1 Million Joules; [kg SO2-Eq.] = kilogram of sulfur dioxide equivalent.

2.6 Water consumption and scarcity

Water scarcity and pollution is a rising global concern. Water is an essential input across the life cycle of electronic products. Mining and processing of materials used for the production of electronics consume significant amounts of water [25]. Manufacturing and assembly of components that are subsequently incorporated into a final assembled product consumes water [53]. Further, water is also required for production of energy, which is an essential input in the electronic product life cycle [54]. Additionally, activities across the life cycle of electronics release wastewater, containing toxic pollutants that can leach into ground and surface water resources.

The majority of material and component manufacturing for the electronics sector takes place in already water stressed areas, putting further pressure on scarce water resources [37]. For example, China, which supplies the majority of materials and components, is experiencing severe water stress [55]. Water scarcity and pollution impacts are further intensified by climate change, increasing agricultural activities, growing population and social geopolitical considerations [56]–[58]. These external factors can often lead to resistance to mining or manufacturing projects from local communities and potential supply chain disruption [59]. Consequently, the contributions to water pollution and scarcity of all activities in the electronics life cycle must be understood in order to design and implement effective mitigation strategies.

2.7 Product packaging

Electronics packaging is also a source of raw material consumption and waste. While the majority of publicly available LCAs include packaging in their stated scope, they do not necessarily report the specific contribution of packaging relative to other full life cycle impacts. Factors including packaging design, packaging weight, product to packaging ratio, and material selection influence the packaging contribution of full product life cycle impacts. Additional factors include whether the packaging is primary packaging for the electronic device, secondary packaging or tertiary transport or shipping packaging.

3. Strategies for sustainable use of resources

In alignment with the aforementioned sustainability impacts, this section identifies multiple strategies for sustainable use of resources and their potential to realize reduction in greenhouse gas emissions, resource depletion, and other environmental impacts, based on available case examples. Figure 10 illustrates these strategies within a product lifecycle framework.

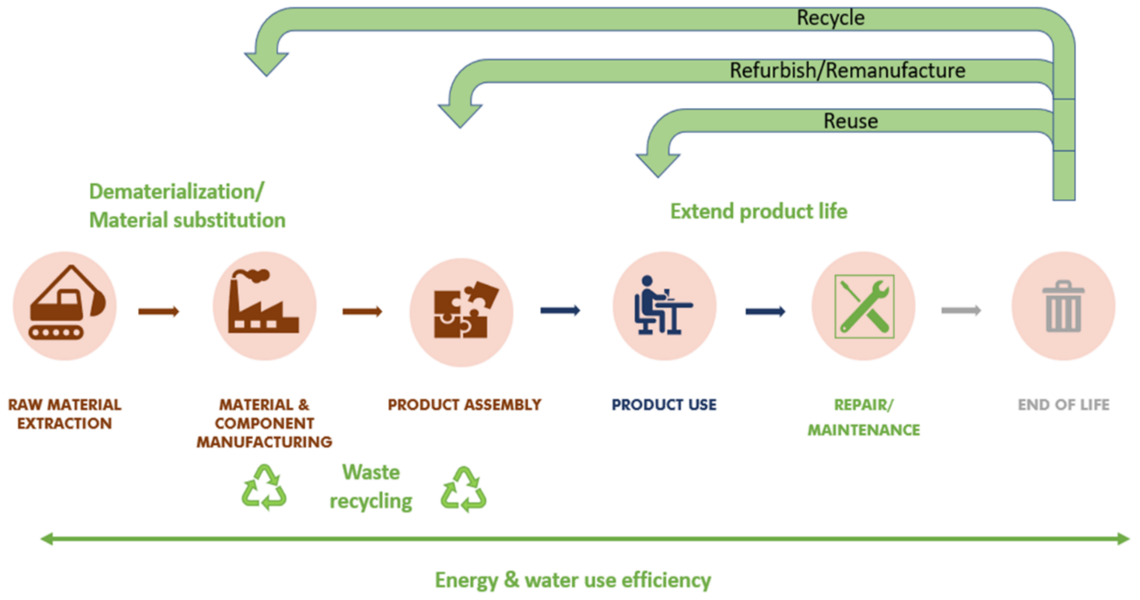


Figure 10. Strategies for sustainable use of resources. Source: Global Electronics Council

3.1 Dematerialization and material substitution

Product design solutions such as reducing the intensity of materials (dematerialization) in a product have the potential to reduce the consumption of new materials, and associated life cycle environmental impacts. The electronics industry has undergone dematerialization over the last decade, as evidenced by the transformation from bulky and heavier products to lightweight compact devices [60]. Reducing product weight and dimensions also reduces transportation emissions. Replacing a high impact material with a lower impact material can also reduce environmental impacts, as illustrated earlier with the selection of plastic type or with the substitution of recycled content materials for virgin materials as discussed below.

3.2 Use of recycled content material

Procurement of materials from secondary sources, whether it is from closed loop electronics recycling or open loop commodity markets, reduces environmental impacts and helps drive a circular economy. For example, substituting recycled for virgin metals can decrease embodied GHG emissions in mobile phones by an estimated 50% [61]. Table 7 illustrates that postconsumer recycled resins have lower environmental impacts than corresponding virgin resins across multiple impacts, with a few exceptions, although impact can vary by resin type [62].

	Savings in impact when compared to virgin resins		
Environmental metrics	Recycled PET	Recycled HDPE	Recycled PP
Total Energy	79%	88%	88%
Water consumption	-4%	59%	46%
Solid waste	58%	-1%	23%
Global warming potential	67%	71%	71%
Acidification	70%	47%	58%
Eutrophication	46%	-2%	43%
Smog	75%	37%	50%

Table 7. Percentage savings across various environmental impacts when recycled resins are compared to virgin resins. Source: [62]

Digital Europe [63] documented several examples of impact reduction resulting from the use of recycled content in the ICT sector, including:

- Dell estimated that carbon emissions from closed loop recycling of ABS is 11% lower than virgin ABS.
- Trucost determined that the environmental benefits (including ecotoxicity, fossil fuel depletion, CO2 emission and human health impacts) of using closed loop ABS are 44% better as compared to virgin ABS.

- HP reports that closed loop plastics RPET when compared to virgin plastics has 33% less carbon emissions than virgin resin, consumes 54% less fossil fuels, and 75% less water.
- Sony estimates that its own brand of recycled plastics called SORPLAS™ (Sustainable Oriented Recycled Plastic) generates 80% less CO2 equivalent emissions than the manufacturing processes used for conventional virgin plastics.

The EU's Ecodesign study on smartphones, mobile phones and tablets summarizes recycled content usage claims made by brands for different materials -- including plastics, metals, and rare earth elements – illustrating the range of opportunities to use recycled content in ICT [8] (see Table 8). The percentage listed is the fraction by weight of the material sourced from recycled content, either post-industrial or post-consumer content (PCR), in the component part noted in the application column.

Brand	Material	Percentage of recycled content: post-industrial (PIR) or post-consumer (PCR)	Application
Apple	Rare earth elements (Neodymium, dysprosium)	100%, unknown if PIR or PCR	Taptic engine, loudspeakers, all magnets
Apple	Tin	100% PCR	Solder on main logic boards
Apple	Aluminum	100%, unknown if PIR or PCR	Aluminum enclosures
Fairphone	Tungsten	50%, unknown if PIR or PCR	Vibration motor
Apple	Plastics	35%, unknown if PIR or PCR	Multiple components of iPhone 11 Pro Max
Apple	Plastics	35% PCR	iPhone XR speaker enclosure
Google	Plastics	47% PCR	Plastic mechanical parts of Google Pixel 4a

Samsung	Plastics	20%, unknown if PIR or PCR	Power supply Galaxy Note 9
Samsung	Plastics	60%, unknown if PIR or PCR	Earphone
Fairphone	Plastics	40%, unknown if PIR or PCR	Plastic parts of Fairphone 3+
Fairphone	Polycarbonate	50% PCR	Back covers and modules Fairphone 2
HP	PC/ABS, PET, ABS	Exact percentage and whether PIR or PCR not known	Mechanical components of HP Elite Dragonfly
HP	Magnesium	Unknown	Mechanical components of HP Elite Dragonfly

Table 8. Brands claims on recycled content used in products. Source: [8]

Dell Technologies partnered with their supply chain to utilize waste carbon fiber from the aerospace industry, binding it with polycarbonate resin to produce a lighter, stronger plastic enclosure for notebooks computers.

Manufacturers have demonstrated that recycled content plastic can be used in wide variety of components in ICT products and have made progress in using PCR plastic; however, adoption of this best practices is not universal as illustrated with the following analyses of the EPEAT Registry.

- As shown in Table 9, all computer and display product types contain some percentage of PCR or biobased plastic content. (Note that while biobased plastic content is an option, PCR content is the prevalent material.) The optional EPEAT criterion for PCR plastic or biobased content awards points for products that meet 2 minimum content thresholds, which are defined for each product type. Table 9 lists the thresholds along with the percent of products meeting each threshold. Monitors and integrated desktops meet the highest threshold requirements of 50% and 40%, respectively. Interestingly, for all product types more products claim the higher content threshold than the lower threshold, indicating that the established thresholds are technically feasible. Of the 35 manufacturers participating in the Computer and Display product category, 17 manufacturers (49%) use post-consumer recycled/biobased content in products.

				% of products meeting postconsumer recycled/biobased content thresholds						
	Total number of unique EPEAT registered products	Total number of unique products eligible for criterion 4.2.1.2	Total number of eligible products meeting criterion	3%	5%	10%	15%	35%	40%	50%
Desktop	322	271	145	-	-	23%	-	31%	-	-
Integrated Desktop Computer	84	84	48	-	-	-	10%	-	48%	-
Monitors	729	727	383	-	-	-	22%	-	-	31%
Notebook	847	777	298	-	12%	26%	-	-	-	-
Tablet/Slate	93	51	16	2%	29%	-	-	-	-	-
Thin Client	22	19	11	-	-	26%	-	32%	-	-
Workstation	52	49	40	-	-	33%	-	49%	-	-

Table 9. Postconsumer recycled/biobased content for computers and displays on the EPEAT Registry

Note: The table presents EPEAT Registry data for criterion 4.2.1.2, Higher post-consumer recycled plastic, ITE-derived PCR plastics or biobased plastic content as of November 2021. Total number of eligible products excludes those products for which a manufacturer denoted a criterion not applicable.

The EPEAT Registry also documents the use of PCR plastics sourced from discarded IT equipment. As illustrated in Table 10, desktops, integrated desktops, monitors, and workstations source 10% or more by weight PCR plastics from IT equipment.

	Total number of unique EPEAT registered products	Total number of unique products eligible for criterion 4.2.1.3	Total number of eligible products meeting criterion	% of eligible products meeting criterion
Desktop	322	265	67	25%
Integrated Desktop Computer	84	82	26	32%
Monitors	729	727	268	37%
Notebook	847	795	4	1%
Signage Display	56	55	0	0%
Tablet/Slate	93	66	0	0%
Thin Client	22	19	0	0%
Workstation	52	49	23	47%

Table 10. ITE-derived recycled content for computers and displays on the EPEAT Registry (Criterion 4.2.1.3)

For imaging equipment, as outlined in Table 11, 31% of registered products registered, including printers, multifunction devices and scanners, meet the criterion for 5 – 10% PCR content. Thirteen of the 15 companies (87%) registering products have at least one product that meets this requirement.

	Total number of unique EPEAT registered products	Total number of unique products eligible for criterion 4.2.1.3	Total number of eligible products meeting criterion	% of products meeting 5%-10% recycled content threshold
Products	1444	1442	453	31%
Number of Manufacturers	15	15	13	13

Table 11. Postconsumer recycled content for imaging equipment on the EPEAT Registry

Note: There are 1444 uniquely registered products globally from 15 manufacturers on the EPEAT Registry as of November 2021. 4.2.1.3, Minimum 5% to 10% postconsumer recycled plastic. Total number of eligible products excludes those imaging equipment products for which a manufacturer denoted the criterion not applicable.

Some products incorporate even higher PCR content. Seven percent of imaging equipment registered for use globally, marketed by 5 manufacturers, have at least 25% PCR content. Devices with 25% PCR include multi-function devices and printers.

- For mobile phones, as illustrated in Table 12, 24% of products registered meet the criterion for PCR and biobased content, over 25%. Three of 4 manufacturers offer products with PCR and biobased content.

				% of products meeting recycled content/biobased thresholds			
	Total number of unique EPEAT registered products	Total number of unique products eligible for criterion 8.1.2	Total number of eligible products meeting criterion	>1%-5%	>5-10%	>10-25%	>25%
Products	41	41	23	0%	12%	20%	24%
Number of Manufacturers	4	4	3	0	3	2	3

Table 12. Postconsumer recycled/biobased content for mobile phones

Note: The table presents analysis of EPEAT Registry data for mobile phone criterion 8.1.2, Total combined post-consumer recycled content plastic and biobased plastic content in mobile phones. Total number of eligible products excludes those products for which a manufacturer denoted a criterion not applicable.

- For servers, as illustrated in Table 13, two products from one manufacturer have documented levels of PCR plastic content. The Registry does not differentiate if the product claims are at the 10% or 25% PCR threshold level, nor if they are from WEEE-derived plastic. It should also be noted that servers typically contain higher metal than plastic material content, as illustrated by the fact that that as of November 2021, manufacturers designated required server criterion 7.1.2 for external enclosures to contain a minimum of 10% PCR plastic not applicable for 100 out of 103 products on the Registry.

	Total number of unique EPEAT registered products	Total number of unique products eligible for criterion 7.1.3	Total number of eligible products meeting criterion	% of products meeting ≥10%, ≥25% threshold
Products	103	103	2	2%
Number of Manufacturers	5	5	1	1

Table 13. Recycled content claims for server equipment

Note: There are 103 uniquely registered products globally from 5 manufacturers on the EPEAT registry as of November 2021. This table presents analysis of EPEAT Registry data for server criterion 7.1.3, Optional - Post-consumer recycled plastic content.

3.2.1 Comparing materials strategies for a notebook computer

Which materials are preferable from an environmental impact perspective – metal versus plastic or virgin versus recycled material? GEC analyzed carbon footprint data, obtained from Althaf and Babbitt (2021) and Althaf et al. (2019), to provide an answer to this question on a per kilogram of material basis for the casing of a notebook computer. Material composition data on notebook computers with alternative materials was obtained from Madaka et al. (2022). The benefits of two scenarios were estimated – (1) replacing virgin aluminum in a notebook casing with plastic (ABS was assumed) and (2) replacing virgin aluminum in a notebook casing with 100% recycled aluminum. As shown in Figure 11, on average, 32% of savings in GHG emissions occur by using recycled aluminum or plastics instead of virgin aluminum in the casing. Madaka et al. (2022) conducted a similar kind of analysis from a water scarcity footprint perspective and observed a similar trend.

Figure 11 also shows the top 5 metal contributors to the material footprint of a notebook computer, in addition to the casing material. Notable is the relative contribution of aluminum, precious metals (gold, palladium), battery materials (lithium) and iron to the footprint regardless of the casing material used. This analysis highlights that the contribution from the use of aluminum in remaining components (i.e., components other than the external casing) is still significant. More research is required to understand if aluminum in other components such as internal casings and hard disk drives can be substituted with recycled aluminum or a different material type to further reduce the material footprint. In the case of precious metals, while the mass of these materials is relatively low, their contribution is still significant due to the high per kilogram environmental impact of these materials, as discussed in section 2.3. Lithium is notable as a critical mineral and iron's listing is attributed to large usage of steel on a mass basis.

While we examined carbon and water footprint impacts in this study, there are other material selection environmental impact considerations, including tradeoffs between aluminum and plastics such as the presence of additives in plastics (e.g., flame retardants, UV stabilizers, plasticizers) and the recognition that plastics from electronics are not necessarily as easily recycled as aluminum. Durability considerations were not within the scope of this study.

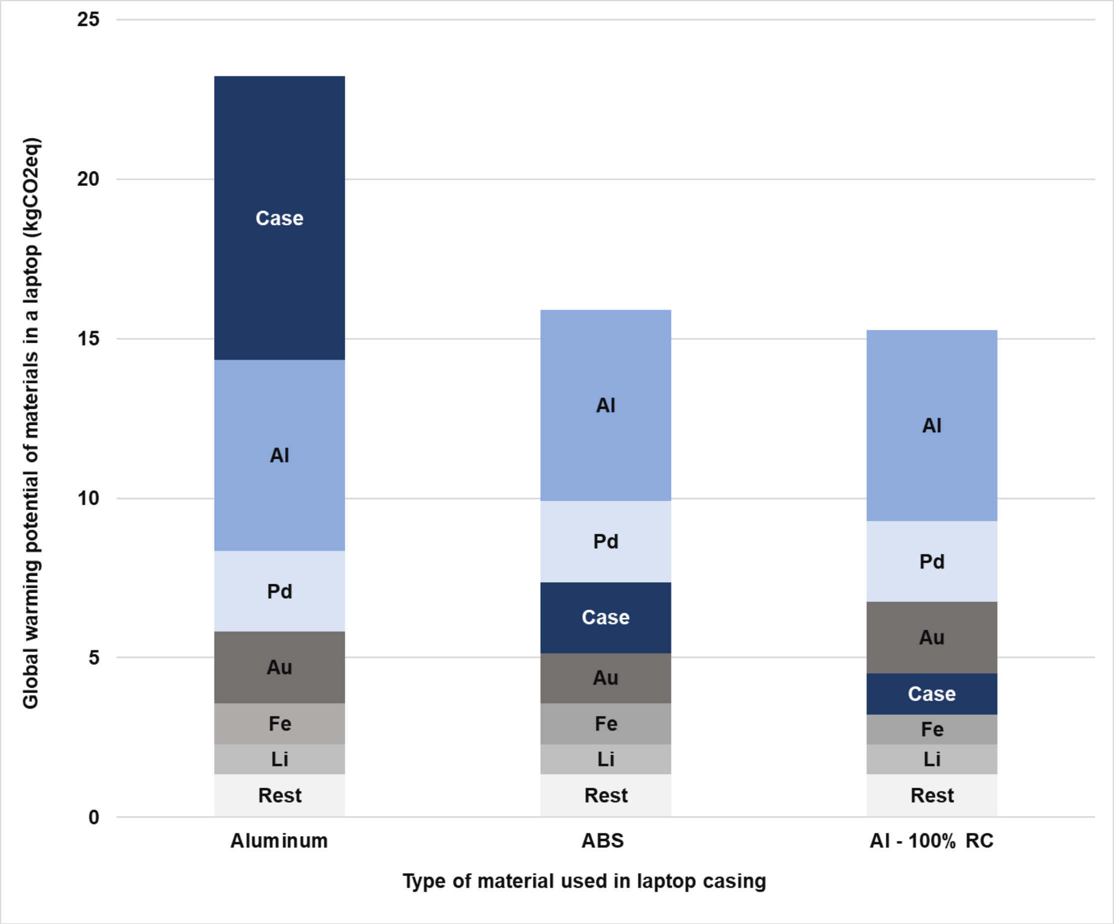


Figure 11. Comparing carbon footprint of notebook computers (or laptops) using different casing materials: plastics, aluminum, recycled aluminum.

Note: This analysis includes casing materials, but only metals for all other components. The plastics contribution from use in components other than the external casing is excluded here due to lack of available data on different types of plastics used.

3.2.2 Reuse and recycling of critical and rare earth elements

Using recycled critical minerals and rare earth elements reduces negative environmental impacts associated with raw material extraction and processing. Incentivizing recovery and reuse of critical and rare earth elements can also spur research and development and infrastructure investment for the responsible collection and processing of e-waste. For example, recycling neodymium in magnets from computer hard drives uses 60% less energy than virgin material mining [64]. Dell partnered with Seagate and Teleplan to create a new closed loop recycling process for rare earth magnets. While the initial pilot used 25,000 recycled magnets in hard disk drives for Dell notebook computers, the process now feeds into a wide range of products, benefitting all of Seagate's customers [65].

The International Electronics Manufacturing Initiative (iNEMI) estimated greenhouse gas emission savings, as compared to shredding, for different value recovery pathways for hard disk drive (HDDs), as shown in Figure 12 [66]. Collected HDDs came from consumer electronics (e.g., desktops) as well as datacenter enterprise products. The recovery pathways investigated were: 1) one time direct reuse of HDDs for the same function (i.e., data storage); 2) reusing voice coil magnet assemblies (VCMA) from old HDDs in new HDDs; and 3) recovery of magnets from shredded old HDDs through magnet-to-magnet recycling processes that result in new magnets used in new HDDs. Out of the pathways investigated, direct reuse of HDDs for the same function (i.e., data storage) had the greatest environmental benefits by avoiding 5.5 kg CO2 eq. of global warming impact per HDD lifecycle, followed by reusing VCMA in new HDDs that avoids nearly 2 kgCO2 eq. of global warming emissions. Recycling of magnets avoids 0.7 kgCO2eq. of emissions.

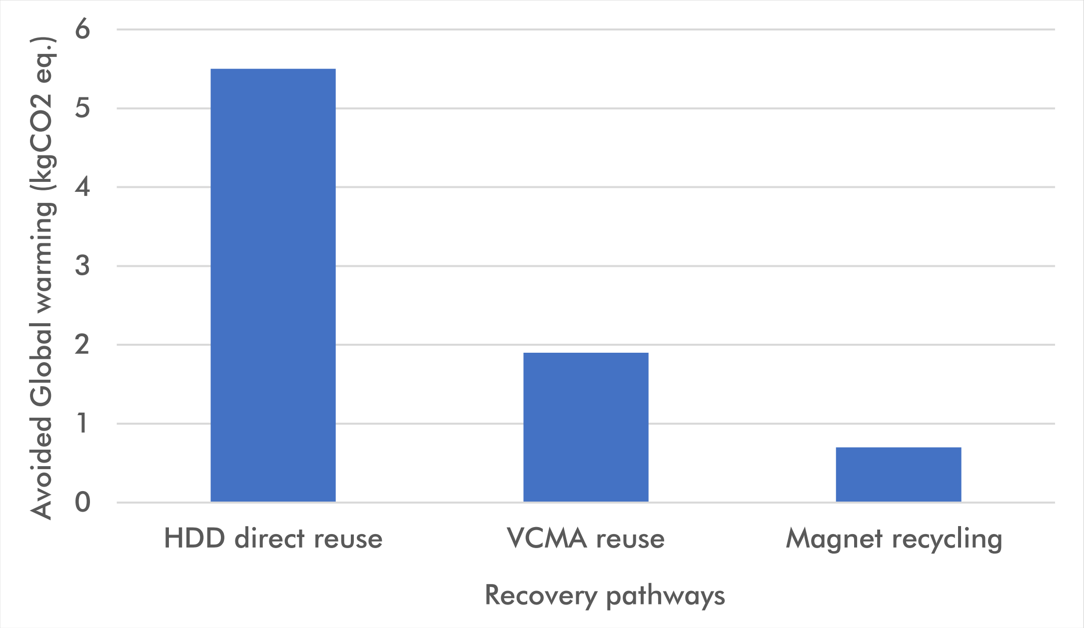


Figure 12. Environmental benefits of value recovery per HDD life cycle, as compared to shredding. Source: [66]

3.3 Product longevity

Increasing product lifetimes is essential to improve the overall sustainability of electronics products. This is achievable through circular business models – including repair, reuse, remanufacturing, and recycling, which is increasingly supported by public policy and manufacturer commitments.

3.3.1 Circularity value proposition

A study by Bacher et al. (2020), illustrates how the value of electronics can be retained in a more circular electronics production and consumption system with repair and reuse yielding the highest value, followed by remanufacturing and recycling [7]. In contrast, in a traditional linear economy, electronics lose value with short lifetimes and failure to recover valuable materials. In Figure 13, the vertical y-axis represents increasing value. The horizontal x-axis represents a baseline value for lifetime of a product. Obsolescence, which leads to waste, is below the line, while repair/reuse, remanufacture and recycling, which all extend the life of a product, are above the line.

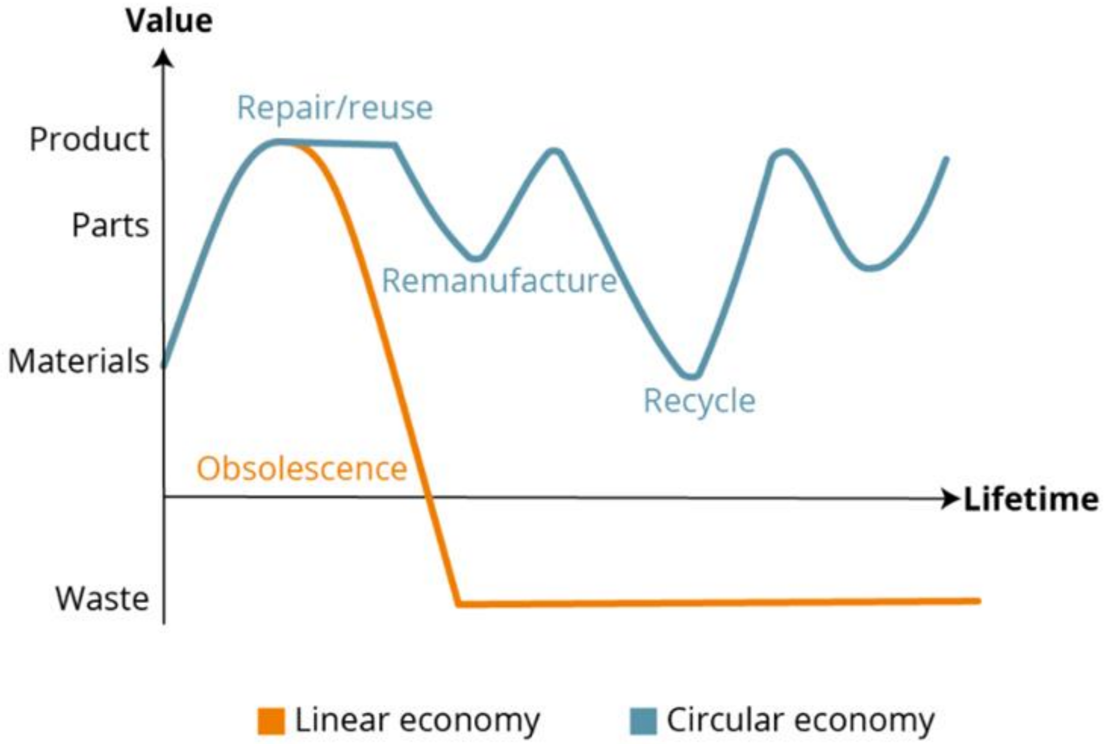


Figure 13. Illustrative indication of the value of materials overtime for a circular vs linear economy for electronics. Source: [7]

A growing body of research demonstrates that circularity initiatives including remanufacturing and reuse that extend the product life, as well as recycling, can reduce GHG emissions significantly.

Smartphones

- A study by Cordella et al. (2021) documented the avoided carbon emissions resulting from several product life extension strategies. It found that a 23 to 30% reduction of life cycle carbon emissions results from replacing a smartphone in 3 or 4 years instead of every 2 years (the average time for which a smartphone is typically used). Carbon emission savings range between 29% to 44% by extending smartphone life to 3 and 4 years, respectively, through battery replacement. Similarly, a 23% to 40% savings can be achieved by extending smartphone life to 3 or 4 years through display replacement. Alternatively, replacing a new smartphone with a remanufactured smartphone realizes 48% of carbon savings and reusing a device for an additional 2.25 years, purchased by resale, realizes the greatest savings in carbon footprint (79%) [67]. This study did not consider additional potential environmental benefits associated with recycling of replaced components, such as batteries.

- Another study compared reductions in global warming emissions (CO2 equivalents) for various smartphone recycling, remanufacturing, and reuse scenarios to a base scenario of 100% recycling [68]. As illustrated in Figure 14 , increasing the percentage of product reuse and remanufacturing, compared to recycling, reduced GHG emissions from 8% to 87%. The base "100% recycling" scenario involved recovery of all precious metals present in a smartphone but incineration or landfill of other materials. The remanufacturing scenario involved disassembly, cleaning, testing, repair, and reassembly operations for the mobile phone, as well as reuse of the charger and the battery. The reuse scenario assumed that the mobile phone, battery, and charger are used for four years instead of two years. The scenario of 95% reuse and 5% remanufacturing resulted in the greatest reduction (87%) in carbon equivalent global warming emissions**.**

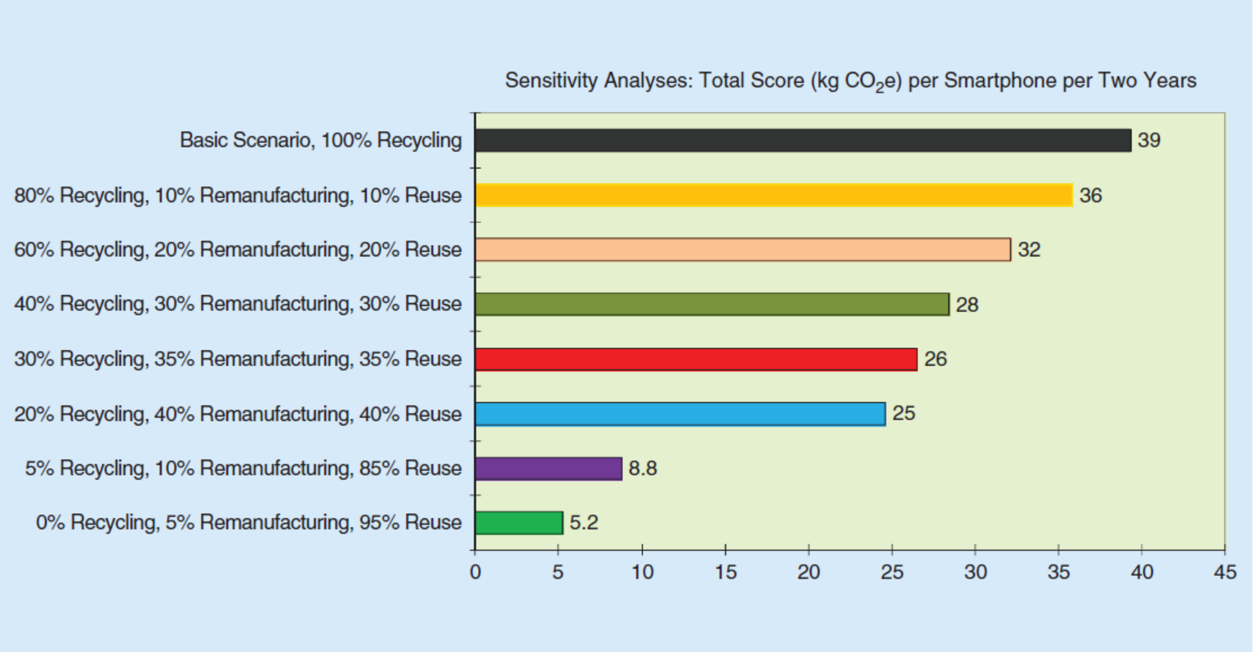


Figure 14. The effect of the end-of-life treatment scenario on total life cycle CO2e emissions in a smartphone life cycle. Source: [68]

Notebook Computers

- A study comparing the life cycle impacts of using a second-hand notebook computer obtained from a commercial reuse operation and a new device found environmental savings ranging from 39% to 50%, depending on the impact. As illustrated in Figure 15, there was a 40% reduction in GHG emissions attributed to using a second-hand notebook compared to a new notebook [69].

- Similarly, extending the lifetime of a notebook computer used in a professional setting (or enterprise) from 3 to 5 years can potentially reduce organizational GHG emissions by 37% [70].

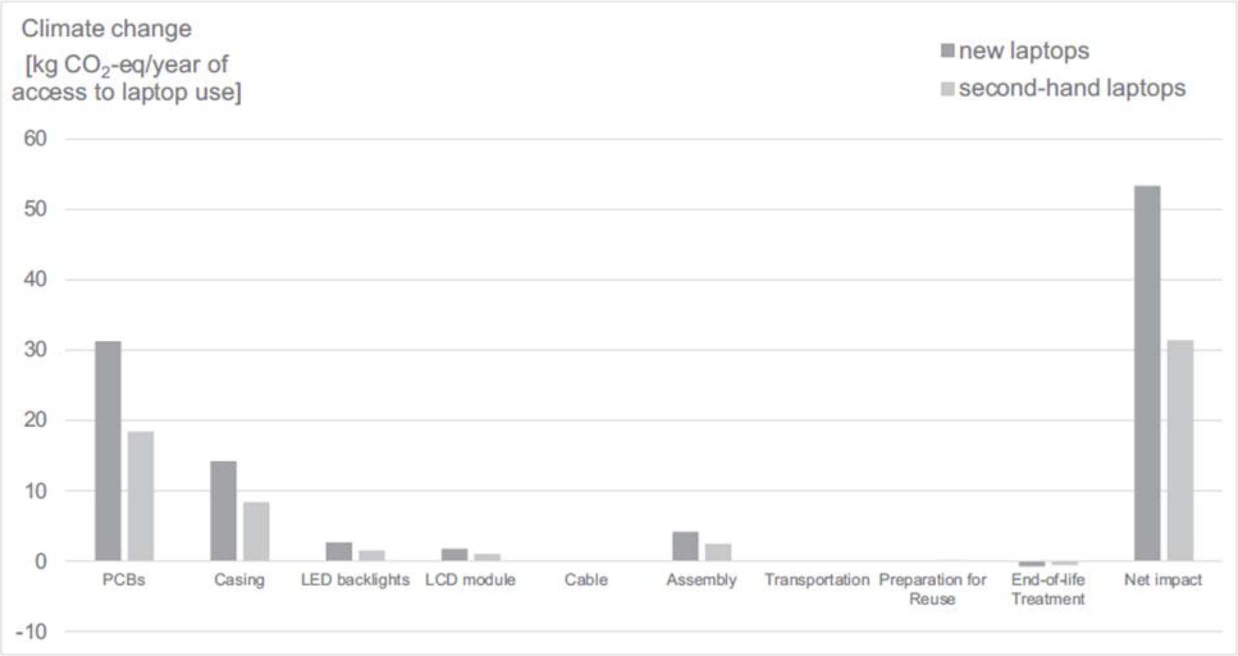


Figure 15. Comparison of life cycle climate change impact between a new notebook computer (laptop) and a second-hand (or reused) device. Source: [69]

Servers

A 2015 EU Joint Research Commission (JRC) technical report on enterprise servers [52] concluded that a server with refurbished or reused components (HDDs, memory cards, CPUs, and main boards) has environmental benefits comparable to a new server that is 22% more energy efficient, with respect to global warming potential (GWP). A server that reuses only HDDs and memory cards has environmental benefits (GWP) comparable to a new server that is 7% more energy efficient.

Circular business models

Enterprise and institutional markets provide opportunities for manufacturers to partner with purchasers to establish fleet management business models to scale return, reuse, and recycling. Alternatives to the traditional product sales model such as leasing and product-as-a-service where a manufacturer or vendor retains ownership of the product also provide an incentive for reuse and remanufacture of products. For example, HP Inc.'s Managed Print Services is a "product-as-a-service" business model. It replaces the linear business model where customers purchase goods and replace them frequently, with a circular model utilizing ongoing contractual, subscription-based service relationships. HP found that this product-as-a-service model extended product life, optimized usage, avoided manufacturing, and reduced material and transportation impacts, yielding resource efficiency improvements of 13%, decreased ecosystem impacts of 12%, and reduced paper wastes by 25% as compared to traditional printing solutions. The service is also certified as CarbonNeutral® in accordance with the CarbonNeutral Protocol [71].

3.3.2 Durability and repairability

Product durability is generally viewed as a product's ability to perform its intended function at a desired performance level over a given period of time [72]. Recognizing the criticality to circularity, governments around the world are seeking to stimulate durability by setting clear mandatory requirements for product lifetimes, including product lifetime labeling. The EU Green Public Procurement (GPP) criteria for computers, monitors, tablets, and smartphones address durability and product lifetime extension with technical specifications on manufacturer warranties, provision of service agreements, availability of spare parts, secure data deletion, and rechargeable battery longevity. For mobile equipment, including notebook computers, tablets, and smartphones, the EU GPP criteria further specify durability testing such as impact resistance drop testing and temperature stress tests [73].

Product longevity necessitates not only durable and reliable product design but also the ability to easily and cost effectively repair products. A 2018 technical report by the EU JRC [9] summarized the results of an IDC 2016 [74] study on failure rates of notebook computers reported by 800 organizations in the U.S. Results showed that the average annual failure rate for notebooks is 18% (average percent of total company's notebooks requiring repair of some kind during a year). They also observed that the non-cumulative rate of failure increases each year a device is in use ranging from 11% failing the first year to more than 20% failing by year five. By the end of year five, they observed that 61% of notebooks had a failure that required repair.

Figure 16 shows the most commonly damaged components in notebook computers identified in the IDC 2016 survey. The screen is the component that is most often damaged, followed by the keyboard, data-storage drive (HDD or SSD), and battery. The study also looked at the ways users damage company-owned devices and observed that simply dropping the device while carrying it was a major reason for damage. Spilling liquid on the device and devices falling off desks were also prevalent causes of damaged notebook computers (see Figure 17).

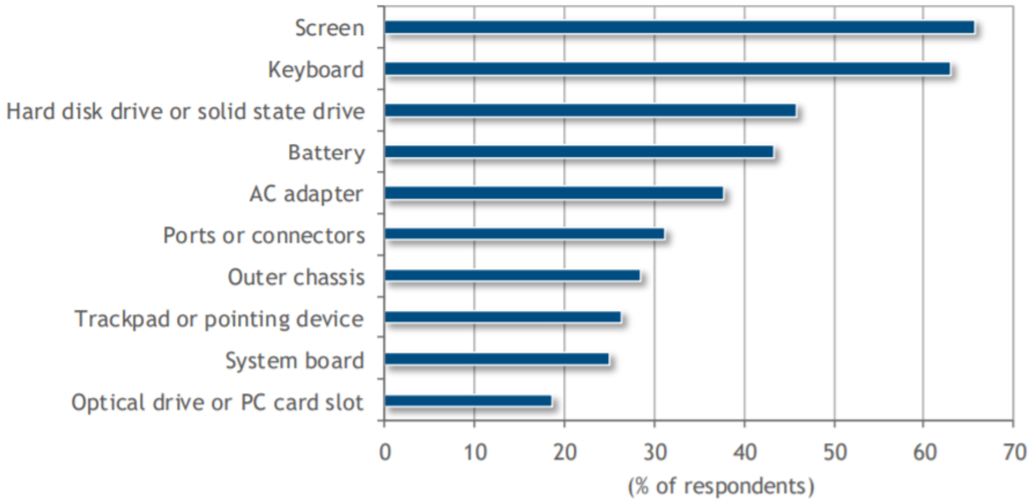


Figure 16. Most frequently damaged components in a notebook as reported in JRC report. Source: [74]

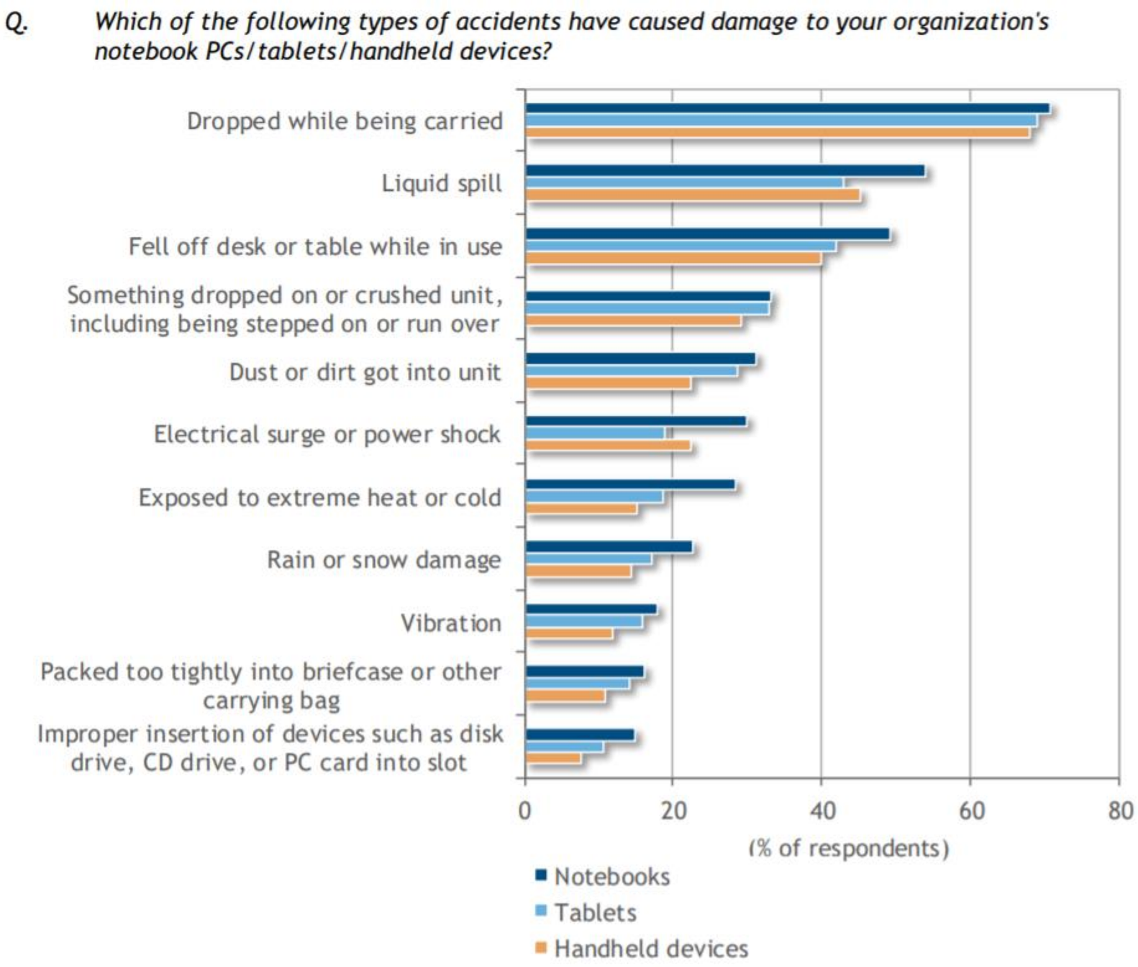


Figure 17. Mechanisms through which damage occurs to a notebook device identified in IDC study and reported by JRC technical report. Source: [74]

The EU's Ecodesign study for smartphones, mobile phones, and tablets [8] reported findings of a study on the primary components with higher failure rates as well as the associated failure mechanism in these devices (see Table 14). Similar to notebook computers, the screen is the most frequently damaged component in smartphones, followed by the back cover, battery, and connectors. Screen and back cover damage is mainly due to simple accidental drops of a device by a user and other mechanical stresses (e.g., shocks and vibrations). The main causes of failure for batteries were aging, use under stress, and breakage of the power/EPS connector [8].

Part	Most prevalent failures over life of product	Failure mechanism
Screen (Glass cover, touch screen layer, display)	Screen cracked, scratched, splintered Blank screen, broken/dead pixels (spots, stripes or similar), no background light	Accidental drops or other mechanical stresses (shocks, vibrations)
Back cover	Breakage	Accidental drops or other mechanical stresses (shocks, vibrations)
Battery	Loss of performance in terms of duration of battery cycles Battery not charging	Aging of the battery due to quality issues or use under stress conditions or regular long-term use EPS / battery connection failure
Connectors	Overheating Disconnected connector assemblies	Mechanical stress, particle ingress
Operating System	Malfunctioning/loss of security and performance (e.g., device not switching on, error codes, apps crashed)	OS and/or security updates not provided by the manufacturer
Whole Product	Short circuits disconnection of main parts (including buttons and connectors)	Stress conditions (e.g., exposure dust and water, shocks, vibration)

Table 14. The primary failure components for smartphones, mobile phones and tablets. Source: adapted from [8]

3.3.3 Rechargeable battery durability

Short rechargeable battery life is one reason for premature obsolescence of mobile ICT devices, including notebook computers, tablets, and smart phones. Hence, extending the life of batteries can in turn extend the useful life of these mobile devices [75]. The EU GPP criteria for computers, displays, tablets, and smartphones outline best practices for mobile device batteries include verification testing to confirm rechargeable battery performance and electrical performance, as well as use of diagnostic software to enable users to monitor the "state of health", "state of charge" and "full charge cycles" The EU GPP criteria also specifies pre-installed battery management system with intelligent charging software that identifies a user's typical charging patterns, only fully charging when needed by the user, and thereby extending the life of the battery.

3.3.4 Challenges for repairability

Though successful repair of higher failure rate components can extend the lifespan of electronic devices and bring benefits to both the environment and consumers, a number of critical obstacles persist. Several studies indicated that barriers for repairability are the high cost of repair, difficult device disassembly, insufficient availability of spare parts, and lack of repair manuals. Some studies on specific products include:

- As reported in a 2021 EU JRC technical study, smartphone users in several European countries, including Belgium, Spain, Italy, and Portugal, cited economics (cost of repair, value of device compared to repair costs) as the top reason for not repairing the device (65% of respondents), followed by repair of the device was not possible (18% of respondents) [8].

- The JRC also reported findings of another study conducted by YouGov in the UK that investigated the reasons for buying a new device versus repairing a device that stops working. More than 50% of respondents stated that repair costs and the age of the broken device as major reasons, followed by the general inconvenience associated with repair of a device (27%) [8].

  A U.S. based survey of the consumer electronics repair industry studied common electronic products and components in the marketplace and the reasons for unsuccessful repair of these devices [76]. The primary causes identified to be applicable across product categories included unavailability and cost of spare parts, and complicated repair process. Lack of availability of tools required for repair was also identified as a significant contributing factor for storage devices (SSD, HDD, USB), modems and PCs (see Figure 18).

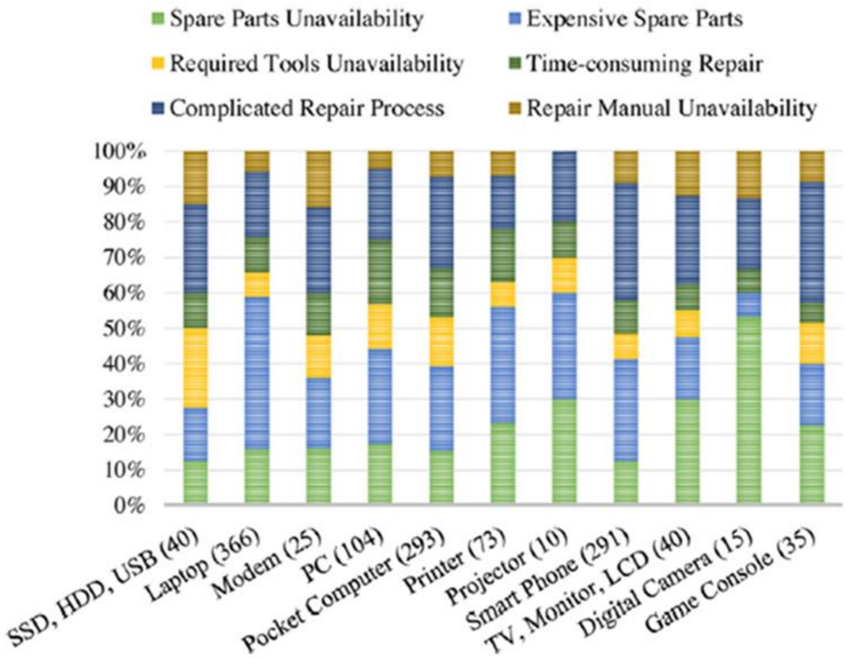


Figure 18. The most common products that repair businesses could not repair together with the reasons (U.S. based survey). Source: [76]

Note: numbers in parentheses are the number of observations.

3.3.5 Repair, reuse, and recycling scoring

Recent initiatives aim to increase the repairability of electronic products with the development of assessment tools and scoring systems. These tools provide evaluation metrics and an incentive for product designers to improve repairability of products along multiple dimensions, including, for example, ease of disassembly, upgradeability, spare parts availability, and documentation. The French Repairability Index, effective January 2021, mandates product labelling that informs purchasers about the repairability of products. As illustrated in Figure 19, manufacturers must display a color-coded label that scores products on a scale of 0 to 10 for the following 5 aspects:

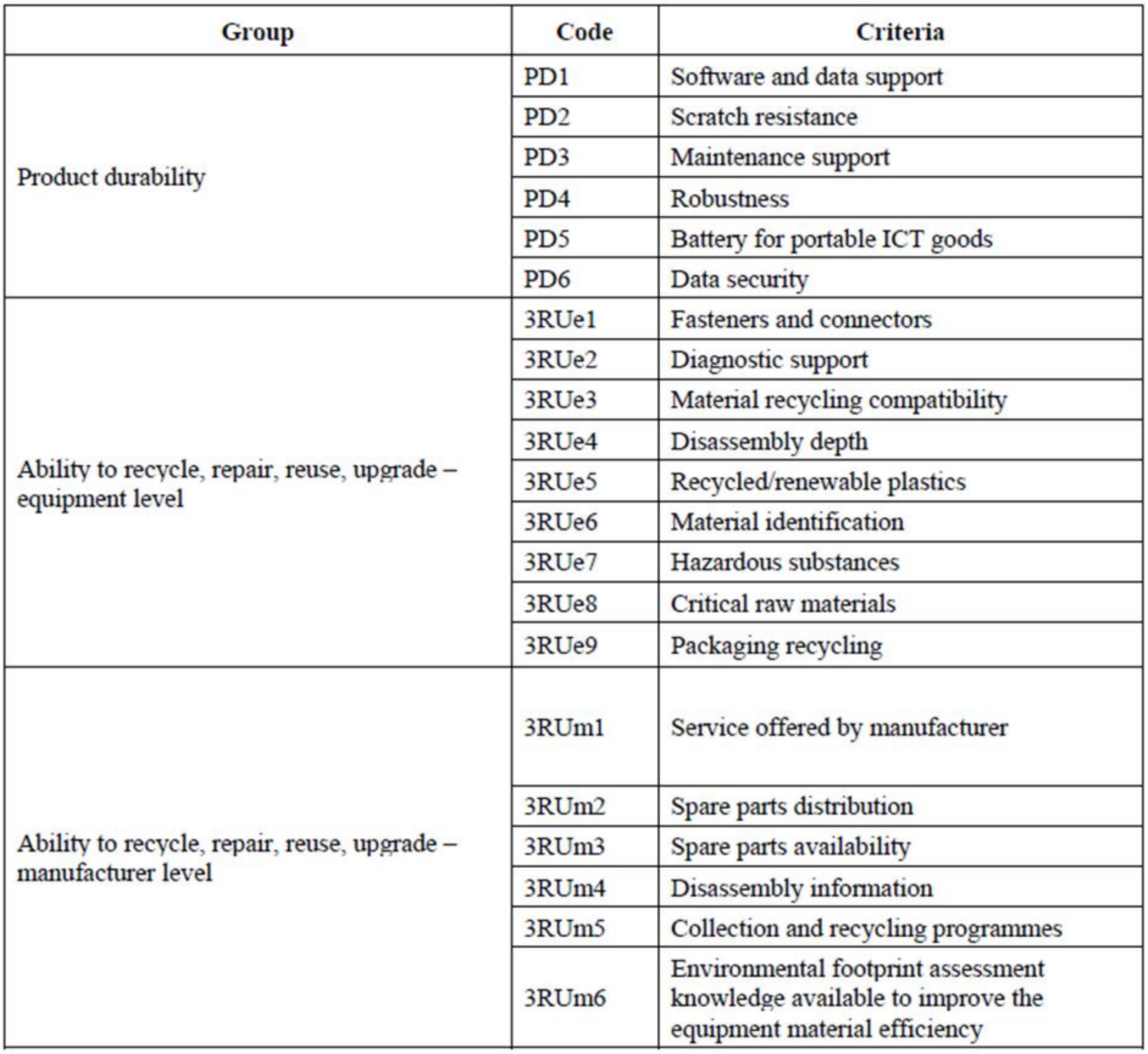
- Documentation: the score is based on the commitment of the manufacturer to make available, for free and for a specified number of years, technical documentation to repair organizations and consumers that facilitate product repair.

- Ease of disassembly: the score is based on the ease of disassembly of the product, the types of tools necessary for disassembly, and the types of fasteners used in the product.
- Spare parts availability: the score is based on the commitment of the manufacturer to make spare parts available and the delivery time.
- Spare parts price: the score is based on the ratio between the price of spare parts and the price of the product.
- Specific criteria: the score is based on criteria specific to the product category (e.g., software updates) [77].

At present the French repairability index applies to five product categories: smartphones, laptops, TVs, washing machines, and lawn mowers. In 2024, the French Ministry of Environment intends to release a durability index rating that covers reliability and robustness, in addition to repairability [78].

Figure 19. Example Repairability Index scores. Source:[78]

The International Telecommunications Union (ITU) assessment matrix for circular scoring (ITU-T L.1023) provides a comprehensive evaluation tool with criteria that address three issues: product durability; the ability to recycle, repair, reuse, and upgrade products; and manufacturer information and services that facilitate repair, reuse, and recycling of products. Table 15 summarizes the criteria covered in each of these three areas.



Group	Code	Criteria
Product durability	PD1	Software and data support
	PD2	Scratch resistance
	PD3	Maintenance support
	PD4	Robustness
	PD5	Battery for portable ICT goods
	PD6	Data security
Ability to recycle, repair, reuse, upgrade – equipment level	3RUe1	Fasteners and connectors
	3RUe2	Diagnostic support
	3RUe3	Material recycling compatibility
	3RUe4	Disassembly depth
	3RUe5	Recycled/renewable plastics
	3RUe6	Material identification
	3RUe7	Hazardous substances
	3RUe8	Critical raw materials
	3RUe9	Packaging recycling
Ability to recycle, repair, reuse, upgrade – manufacturer level	3RUm1	Service offered by manufacturer
	3RUm2	Spare parts distribution
	3RUm3	Spare parts availability
	3RUm4	Disassembly information
	3RUm5	Collection and recycling programmes
	3RUm6	Environmental footprint assessment knowledge available to improve the equipment material efficiency

Table 15. ITU assessment matrix for circular scoring for ICT (Source: ITU)

3.3.6 Design for repair, reuse, and recycling

Robust product designs with reliable components can reduce the failure rate of components, thus extending product lifetime. When the product or its components fail, the ability to repair and refurbish the product is essential to keeping it in service, either with the initial user or a second user. At the end of its service life, the product design should facilitate recycling.

Design features that can facilitate repair, reuse, and recycling include:

- Easy removal of external enclosures or casings to access components for repair or to separate for recycling.
- The ability to easily access and replace components that are most likely to fail or be damaged.
- Use of universal connectors to prevent premature disposal of incompatible technology.
- Easy identification and removal of hazardous materials and components such as lithium-ion batteries. Batteries that are glued to internal casing components are difficult to remove.
- Minimizing the use of substances of concern in materials and products to enable circular material cycles (see the European Commission's 2020 Chemicals Strategy for Sustainability (CSS) and GEC's State of Sustainability Research on Chemicals of Concern for additional details).
- For plastics, use a single plastic type in parts, avoid molded-in metal inserts, and use plastic markings that identify resin type and additives (e.g., ISO 11469).
- Use reversable joining methods instead of bonding with non-removable adhesives, soldering, brazing, or welding. Minimizing non-reversible adhesives or similar bonds, especially over whole surfaces and for dissimilar materials, can facilitate disassembly and material liberation. However, in some cases, such bonds can facilitate recycling, such as when strategically placed welds (non-reversible design) provide a better path of preferential breakage and liberation during shredding, compared with using bolts (reversible design).
- Consider intuitive disassembly processes and easy to understand visual cues without labels (e.g., colors, symbols, notches, etches, or moldings).
- Use surface coatings compatible with material recycling.

When applying these general design principles to facilitate repair, reuse, and recycling, manufacturers must also consider trade-offs between functionality, longevity or durability, reliability, cost (which is necessary for market acceptance) and recyclability [79].

3.3.7 Modular design

Adoption of a modular design can facilitate maintenance, repair, and reuse of electronic products. For instance, a 2015 EU JRC technical report on servers [52] reported that modular design enabled the reuse of components. Figure 20 shows the most frequently reused parts (hard disk drives and memory cards), followed by processors.

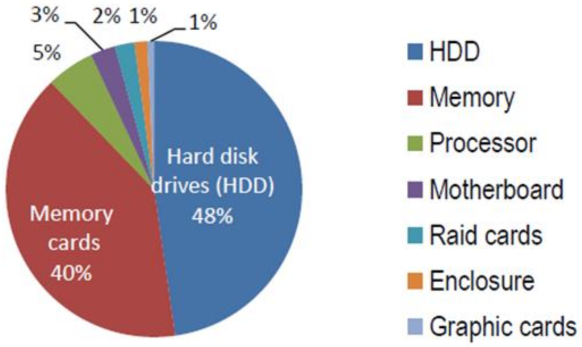


Figure 20. Frequently reused parts in servers. Source: [52]

Modular design, however, can increase the initial upstream embodied carbon (or production impacts). This is mainly because modular designs require more board-to-board connectors and additional module housing, and hence come with a higher printed circuit board footprint when compared to a non-modular design. Keeping the product in service longer, however, can offset the production impacts. Additionally, modular design can make it easier to recover components in the electronics that contain critical and rare earth elements.

Fairphone estimated that a modular design for a smartphone (Fairphone 3) resulted in 0.744 kg CO2 eq of additional greenhouse gas emissions, which accounted for 2.3% of all production impacts [80]. While it increased production impacts, Fairphone observed that modularity enabled repair of a device, increasing product life span, and thus reducing overall global warming potential.

Further, Fairphone assessed two repair scenarios (A and B) where phones are assumed to be used for 5 years and repaired once during their lifetime. In scenario A, Fairphone assumed that faulty modules are replaced by new ones by taking advantage of modular design. In scenario B, Fairphone assumed that part of the faulty module is actually repaired at board-level, allowing for replacement of specific components. As illustrated in Figure 21, global warming potential impact per year of use drops significantly with longer lifetime (nearly 36%), largely due to decrease in the production phase. The difference in benefits between repair scenario A and scenario B is negligible when compared on a per year of use basis [80].

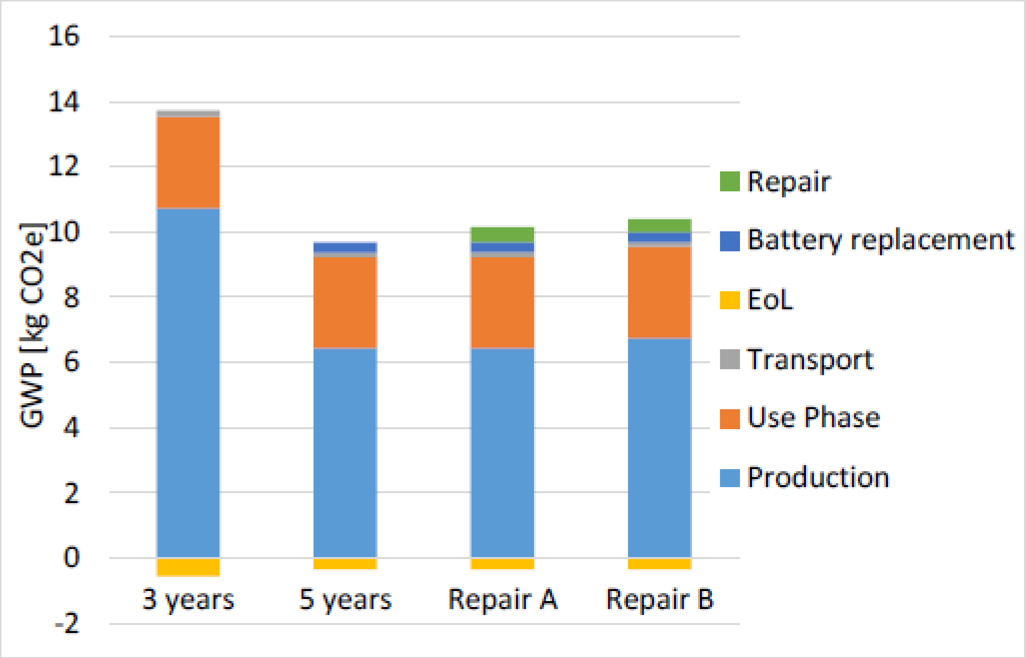


Figure 21. Comparison of GWP per year of use for baseline (3 years) and extension of smartphone life to 5 years by repair. Source: [80]

3.3.8 Additional practices to enable product longevity

In addition to product design, manufacturers can support product repair and facilitate product longevity by:

- Providing maintenance and repair information to product users and professional/independent repairers.
- Ensuring spare parts are available beyond the end of production of the product; see Appendix B for recommended spare parts for different ICT product types.
- Offering data transfer and data deletion options to facilitate reuse; for example, see Secure Data Deletion section below.
- Providing software updates to help reduce functional obsolescence.
- Providing warranties for refurbished products.
- Monitoring trends in product generation lifetimes to understand impacts and inform product lifetime extension strategies.

- Increasing consumer awareness of the availability of product maintenance and repair options, including efforts to make access to repair convenient and affordable.

Further, business practices that enable manufacturers to retain responsibility for and control over their product assets, such as leasing models, can incentivize durability, recovery, and closed loop strategies. (See, for example, the discussion of HP Inc.'s Managed Print Services in Section 3.31)

3.3.9 Secure data deletion to enable reuse

To facilitate circularity via reuse of devices, users must have reasonable assurance that their data may not be easily retrieved and reconstructed.

Without secure data deletion, privacy and security concerns can hinder return and subsequent reuse. Use of unified standards for device sanitization is a recommended mitigation strategy [81]. Best practices include NIST SP 800-88 R1 [82] and ISO/IEC 27040:2015. The NIST standard defines a data risk management framework to assist organizations and system owners in sanitization of many media, including HDDs and SSDs. The ISO/IEC standard, in addition, provides guidance for erasing data on HDDs, SSDs, and other media types. It also provides references to other international standards that address existing practices and techniques applicable to storage security. Unfortunately, data sanitization standards alone have not been sufficient to enable reuse. Organizations that depend on NIST's cybersecurity standards to protect sensitive data from unauthorized access often do not trust NIST's secure deletion standards to sanitize storage media and require the storage media to be physically destroyed. Afterwards, metals may be recycled or landfilled. While steel, copper and aluminum in HDDs, for example, are generally recovered, rare earth elements are typically not recovered [83]. A study by Walzberg et al illustrated how user attitude, which is affected by trust, is a barrier to reuse [83].

Audit and certification of secure data deletion processes and technology by third-party forensic experts is a potential mitigation strategy. While this process is already in use by some recyclers, it could also be leveraged by manufacturers and information technology asset disposition (ITAD) companies. The third-party results could then be provided to end-user consumers, including institutional purchasers.

3.4 Interoperability to reduce waste

In September 2021, the European Commission reported that 38% of EU consumers have experienced problems at least once, of not being able to charge their mobile devices since they did not have access to a charger compatible with their device. In addition, disposed of and unused chargers pile up to an estimated 11,000 tonnes of e-waste every year in the EU [84].

Interoperability of key components, such as charging ports, and technology has the potential to reduce a product's environmental footprint with respect to production and disposal impacts. In addition to a harmonized charging port design, the European Commission is proposing harmonized requirements for fast charging technology, unbundling the sale of a charger from the sale of the electronic device and improved information to consumers.

3.5 End-of-life management

Recovery and processing of e-waste is often hindered by complex designs, lack of information on tools and instructions to disassemble products, minimal collection rates, and lack of infrastructure to manage e-waste properly. Establishing or enhancing programs that collect used products and divert products, components, and materials to secondary markets, making information and tools available to facilitate end-of-life processing, and ensuring that facilities that handle e-waste meet sustainability standards and international guidelines on transboundary movement of used and end-of-life electronics under the auspicious of the United Nations Basel Convention can help build circular pathways and ensure proper management of e-waste. Environmentally responsible recycling and complex repair operations are also not always available locally, necessitating the need to build capacity or create efficient reverse logistics.

The World Economic Forum found that to facilitate trade along circular electronics value chains (2020) steps must be taken to reduce the complexities of product classifications, and related factors associated with costs of reverse logistics. For used electronics, reverse logistics were 31% more expensive than outbound shipments of new products. For end-of-life electronics deemed hazardous, costs were 190% more costly as compared to new outbound electronic products [85]. The WEF calls for the Basel Convention to engage with the trade community to encourage country-level implementation that simplifies and digitizes procedures, examines classification decisions and other aspects to meet the environmental tenants of the Basel Convention and facilitate circular trade.

3.5.1 Increasing collection of ICT products

As discussed earlier, e-waste collection is not keeping up with the volume of products placed on the market. In addition, there is regional variation in the percentage of products collected. Collection rates are highest in the European Union, where there are regulatory producer responsibility (or take-back) mandates for equipment collection and recycling.

The Circular Electronics Partnership (CEP) Roadmap cites the need to improve the manufacturer take-back rate of used electronics from consumers and large buyers (i.e., businesses and government) as essential for attaining 100% responsible "repurposing" of sold electronic products. Repurposing includes the reuse of products through repair, refurbishment, and remanufacturing, harvesting of parts/components for reuse, and recycling of materials when reuse is not possible. The CEP Roadmap cites several barriers to collection including the lack of a formal take-back infrastructure in developing and emerging markets, and notes that interventions in these markets, where collection and e-waste processing is dominated by the informal sector, could yield the greatest economic, environmental, and social benefits [86]. Consumer education and awareness are also needed to improve take-back rates in both developed and developing markets.

Innovations in collection and responsible processing of used electronics including circular finance business models, such as waste compensation, are discussed in the next section.

3.5.2 Building recycling infrastructure in low & middle-income countries

Developing economies are particularly vulnerable to the impacts of e-waste due to inadequate infrastructure for the collection and processing of equipment, and the reliance on the informal sector which often lacks appropriate practices for the safe and environmentally responsible processing of e-waste. Strategies for building and strengthening the existing infrastructure include implementation of extended producer responsibility (EPR) and other take-back policy frameworks but also market drivers to incentivize increased collection and responsible processing such as formation of producer or manufacturer collective schemes, investment in local and regional infrastructure, and partnership with the informal sector. Per a Solving the e-Waste Problem (SteP) 2020 report [87], "partnerships or alliances between the formal and informal sector is of utmost importance in order to promote integrated solutions among different actors, provide social, financial, and health benefits as well as to guarantee a sustainable management of waste material throughout the value chain."

To achieve its circular economy goals, the Netherlands included a "waste compensation" requirement in its public tender for IT equipment, where every new product purchased will fund the recovery and recycling of an equivalent amount of e-waste in a country that lacks a safe recycling infrastructure (Netherlands Public Tender Guide) & NL Platform) [88], [89] . The Netherlands is partnering with Closing the Loop, an organization that collects e-waste in countries where electronic waste collection is not formalized – mostly in Africa, on behalf of its customers, who pay a fee, thereby compensating for their IT device purchases, making them waste neutral [88]. Another waste compensation example, described as a "one for one concept", includes Samsung's partnership where every purchase of a new Samsung Galaxy S10E model is "offset" by recycling one discarded phone from Ghana, Cameroon, Uganda or Nigeria [90].

3.5.3 Increasing reuse of ICT

This State of Sustainability Research demonstrated the sustainability benefits of extending the life of products. Product design for repair, refurbishment, and remanufacturing is one strategy but is only effective if at the end of service life products are evaluated and processed for reuse. Tracking the ultimate fate of equipment and components is critical for ensuring responsible deployment of functional UEEE and for evaluating progress towards circular IT, through the application of the waste management hierarchy that gives preference to reuse before recycling.

Extending the life of products also necessitates the development of secondary reuse markets as users replace products that no longer meet their technology needs, yet still have value to other users, with or without repair and refurbishment. While manufacturers and purchasers can identify reuse markets, particularly local markets, partnering with organizations that specialize in repair and reuse markets may facilitate the development and access to reuse markets.

Further, to facilitate the cost-effective and safe repair and refurbishment of products, access to information, tools, and spare parts is critically important.

3.5.4 Recovery and recycling of critical minerals and rare earth elements

Per a UNEP status report, end-of-life recycling rates for REEs, defined as the "percentage of a metal in discards that is actually recycled", is less than 1 percent [91]. Recovery barriers include economics, technology, and societal or consumer awareness. In addition to manufacturer programs to increase collection of end-of-life electronic products and design for recycling practices to enable disassembly and pre-processing, market and policy incentives are needed to further recycling process innovation, end markets, and economies of scale.

As part of a value recovery study for hard disk drives (HDDs), iNEMI identified the following barriers to maximizing value recovery:

- Secure data deletion concerns (lack of reliable assurances for data wiping) leading to users demanding physical destruction, eliminating disassembly and reuse options;
- Economically viable collection;
- Dismantling costs; and
- Lack of standardization of parts or quality standards for reuse.

This led to five separate demonstration projects for recovery and reuse of REEs from HDDs, only one of which is currently commercially available, Urban Mining's m2m®(Magnet to Magnet®) recycling process where used HDDs are processed into new sintered magnets with similar magnetic properties [92]. Further research is needed to make extraction easier and hence economically viable.

3.5.5 Responsible end-of-life processing

E-waste contains hazardous materials that require proper handling to prevent worker exposure to toxics and environmental contamination. Standards for the responsible handling of e-waste are available and continually evolving, and include, for example Responsible Recycling ("R2") for Electronics Recyclers standard, the e-Stewards Standard for Responsible Recycling and Reuse of Electronic Equipment, and EN 50625.

3.5.6 Zero waste manufacturing

Zero waste manufacturing is a concept to support transitions to a circular economy by developing manufacturing technologies and systems to eliminate waste through source reduction, reuse and recycling [93]. The Zero Waste International Alliance defines zero waste as “the conservation of all resources by means of responsible production, consumption, reuse, and recovery of products, packaging and materials without burning and with no discharges to land, water, or air that threaten the environment or human health” [94]. In the electronics supply chain, leading brands are collaborating with their supply chains towards zero waste manufacturing goals. Third-party resources and certification tools include UL 2799 Environmental Claim Validation Procedure for Zero Waste to Landfill [95] and the U.S. Green Building Council’s TRUE – Total Resource Use & Efficiency zero waste program [96].

3.6 Water inventory for manufacturing facilities

The first step for any organization to tackle water related impacts is to understand how much water they are using and where the usage occurs. Consequently, to understand physical and economical water scarcity risks and take appropriate action to mitigate such risks, an organization should develop a complete water inventory, inclusive of the following:

- Volume of total withdrawals by region, basin, and source (e.g., surface water, groundwater, sea water, municipal water, wastewater from another organization, rainwater collected onsite, delivered water);
- Volume and percentage of water recycled and reused; and
- Volume, destination, and quality of discharges.

In addition to volumetric water withdrawal and discharge, understanding the water stressors of the region in which these activities occur enables organizations to apply impact assessment methods. Impact assessments can enable better project, product, process and even facility location decisions, as well as programmatic changes to reduce adverse impacts of freshwater use [97]. For instance, Intel initially developed a water use inventory for their operations to identify the facilities with greatest water use. They later executed a water stress assessment as a supplement to their water use inventory. In the new analysis, Intel found that previously identified sites for greatest water consumption did not necessarily correlate with highest water scarcity impact, as many of these facilities are in low water stressed regions. For instance, as illustrated in Figure 22, while facilities in Oregon and Ireland consume the largest volumes of water, they do not have the largest impact on water scarcity when accounting for geographic water stress as part of a comprehensive water sustainability impact assessment [97].

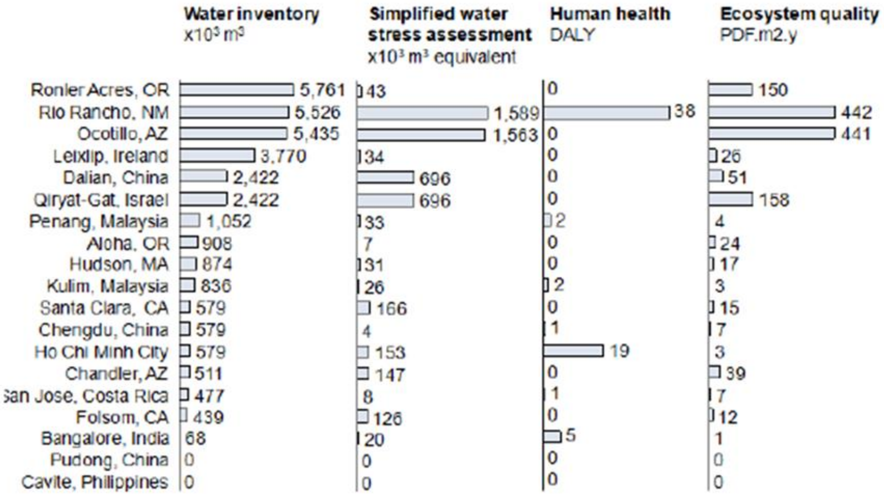


Figure 22. Comparison of water inventory, water stress assessment, and impacts on human health and ecosystem quality for Intel's operations. Source: [97] DALY = Disability Adjusted Life Year (health indicator); PDF.m2y = Potential Disappeared Fraction of species over a certain area over a certain time

The Global Water Footprint Standard by Water Footprint Network (WFN) and ISO 14046 provide principles, requirements, and guidelines for conducting a water footprint assessment of products, processes, or organizations by applying life cycle assessment principles. These standards also provide guidelines on reporting the water footprint analysis. Several analytical tools are available to identify regions subject to water stress, such as the WRI Aqueduct Global Water Risk Mapping Tool, WFN Water Footprint Assessment Tool, GEMI Local Water Tool, and the WWF-DEG Water Risk Filter, and CDP water watch tool.

Recognizing the importance of water to sustainability, increasingly companies include water inventory data in corporate sustainability reports. Global reporting initiative (GRI) standard 303 provides guidance on reporting on water withdrawal, water discharge, and water consumption as well as how an organization can disclose interactions with water as a shared resource and manage impacts related to water discharges. CDP also provides a platform for companies to disclose their water risks and actions taken by the companies to address these risks with the goal of transparency.

3.7 Product packaging strategies

Common to all products, packaging exemplifies the options for and trade-offs between the diverse strategies for the sustainable use of resources. Material efficiency strategies, including dematerialization, design for disassembly and use of recycled and renewable content, can reduce the negative environmental impacts associated with the production and use of packaging. In addition to these elements, package design to optimize recovery and availability of end markets are essential considerations to enable circularity. Below are some considerations to take into account when considering strategies for the sustainable use of resources in achieving sustainability goals.

3.7.1 Product packaging dematerialization

Eliminating unnecessary materials to reduce packaging weight can result in reductions of environmental impacts. The product-to-packaging ratio is the proportion of the weight of all packaging materials to the weight of the product, considered on a per use basis. Techniques to improve the product-to-package ratio include eliminating unnecessary void space or volume, bulk packaging[6], and reducing packaging weight, which also potentially results in increased transportation efficiency. For example, in reducing their carton size for their ThinkPad series, Lenovo notes a 0.4 percent reduction to their individual packaging equates to an 18% increase in pallet density, resulting in a 6.7 percent efficiency improvement in transportation CO2 emissions [98]. Samsung designed S10 smartphone packaging by eliminating all plastics except for the screen protector and minimizing remaining paper and molded pulp, resulting in a 16% packaging weight reduction when compared to the S9 model. Samsung estimated a global warming potential savings of 1,181 MTCO2 eq in 2019 for all of their S10 sales as a result of this packaging dematerialization [99]. HP used virgin sourced fiber for their fluting and liner in their packaging leading to 29% reduction in the amount of packaging materials, and as a result, reduced transportation emissions due to lower packaging weight [100]. This virgin sourced fiber is lighter than recycled content fiber, hence leading to a decrease in carbon dioxide emissions of 5,000 metric tons.

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[6] Bulk packaging is defined as a single primary package used to ship more than one product.

3.7.2 Use of recycled content

Use of recycled content in packaging can yield sustainability benefits such as fewer natural resources and lower GHGs associated with packaging production. Whether associated with reductions in use of fossil fuels or tree stocks that remain in the forests, there will be less waste sent to landfills, and less land and marine pollution, especially in the case of plastics. In their Recycled Content (ReCon) Tool, U.S. EPA estimates that virgin production of one ton of corrugated cardboard, a material commonly used in boxes for electronics packaging, has a GHG emission factor of 0.83 MTCO2 eq and a savings of 2.38 MTCO2 eq for 100% recycled content, attributed to reductions in manufacturing and transportation energy as well as credit for not depleting forest carbon stocks [101].[7]

It is recognized, however, that product protection and material usage goals must be carefully balanced. Wood-based recycled content packaging may contain shorter fibers as compared to virgin material. Shorter fibers can lead to using more material to produce the level of durability needed to prevent product breakage during shipping. Additionally, it is noted that it may be necessary to combine recycled content with some amount of sustainably sourced virgin fiber content to achieve necessary strength performance for product protection.

3.7.3 Use of renewable content

One approach for the sustainable use of resources utilized in packaging, which is not yet widely adopted for electronics, is sourcing materials from rapidly renewable content. Renewable content refers to the use of resources replenishable by natural processes, such as materials made from plants, agricultural waste, or animal feedstocks [102]. Examples include pulp and paper fibers made from various feedstocks such as eucalyptus, hemp, flax, bagasse, arundo donax, wheat straw, kenaf, and bamboo [103] and bioplastics made from feedstocks such as corn starch, sugarcane, and a variety of other sources like potatoes, algae, mycelium (mushroom “roots”), and food waste [104].

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[7] When paper and wood products are recycled or source reduced, less timber is harvested. Given this, trees remain in forest, storing carbon dioxide absorbed from the atmosphere. EPA’s Waste Reduction Model (WARM) credits this absorption of atmospheric greenhouse gases from the reduced timber harvesting resulting from recycling.

Renewable content can reduce the need to exploit finite resources and, given the intake of carbon dioxide during plant growth, also has the potential for lower human health and environmental impacts than petrochemical alternatives [105]. While electronics are already typically sold in folding cartons and corrugated boxes, companies are adopting innovative renewable materials in their packaging. However, life cycle tradeoffs should be carefully evaluated when using renewable content instead of conventional materials to meet sustainability goals. For example, when compared to traditional polymer-based composites, a renewably sourced hybrid poly butylene succinate (PBS) composite reduces impacts of cumulative energy demand by 40%, global warming potential by 35% and eco-toxicity by 45%, but comes at a cost of increased acidification and eutrophication by 14% and 76%, respectively [106].

While a majority of studies indicate that wood-based products are associated with lower CO2eq fossil fuel process-based emissions as compared to non-wood products, as previously stated, studies often fail to fully address land use and carbon storage impacts. As observed in GEC's State of Sustainability Research on wearable electronic devices[8], fiber-based materials may be denser than plastics, resulting in mass increases that can potentially increase a product's GHG profile during the transportation phase. Leskinen et al. (2018) consider existing studies insufficient for supporting policy decisions based on material substitution alone, instead recommending that material efficiency and minimizing waste be integral considerations of a mitigation strategy [107]. More research is needed to understand material usage type trade-offs and to quantify the environmental impacts. In all cases, when it is necessary to supplement recycled content with virgin content, third-party verification of sustainable forestry practices is recommended.

3.7.4 Recyclable and reusable packaging: theoretical versus actual benefits

As with electronics, designing packaging for end-of-life recycling is essential to optimize the sustainability attributes of the package-product system. However, packaging made with materials that are technically possible to recycle may end up in a landfill if the infrastructure to support recycling is not well developed. For instance, Cornell (2007) notes that technology exists to recycle polypropylene and polyvinyl chloride, but facilities would not obtain the 10,000,000 pounds minimum needed per year to sustain itself [108]. Since the intentions of using a "recyclable" material does not always match the realities of what happens to it at end-of-life, countries provide guidance on the official use of the term. For example, in the U.S., as per the Federal Trade

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[8] Available at https://globalelectronicscouncil.org/hwwedsosr_combined/

Commission (FTC) “A package should be marketed as recyclable only when it can be collected, separated, or otherwise recovered from the waste stream through an established recycling program for reuse or use in manufacturing or assembling another item.” Similarly, in Canada, “Recyclable packaging is the one that can be diverted from the waste stream through available processes and programmes and can be collected, processed and returned to use in the form of raw materials or products.” In both the U.S. and Canada, it is not enough to confirm that there are municipal or industry collection systems where the product is sold in order to make a claim of "recyclable" — there must also be facilities to process the collected materials and reuse them as an input to another product that can be marketed and used.

4. Standardization

Table 16 summarizes relevant standards and voluntary programs that can provide a foundation for definitions, best practice, and benchmarks for sustainable use of resources.

Focus	Standard
LCA standards	ISO 14040, Environmental management – Life cycle assessment – Principles and framework
	ISO 14044, Environmental management – Life cycle assessment – Requirements and guidelines
	ISO/TS 14067, Carbon footprint of products – Requirements and guidelines for quantification and communication
Environmental claims standard	ISO 14021, Environmental labels, and declarations–Self-declared environmental claims (Type II environmental labelling)
Repairability	EN 45554:2020, General methods for the assessment of the ability to repair, reuse and upgrade energy-related products
	Repairability index calculation instructions for electrical and electronic equipment
	ITU. L.1023: Assessment method for circular scoring
	IEEE Std 1874, IEEE Standard for Documentation Schema for Repair and Assembly of Electronic Devices
Plastics marking	ISO 11469:2016, Plastics — Generic identification and marking of plastics products
	ISO 1043 - Plastics - Symbols and Abbreviated Terms Package
Recycled and reused content	GreenBlue Recycled Material Standard
	EN 45557:2020 General method for assessing the proportion of recycled content in ErP
	EN 45556:2019 General method for assessing the proportion of reused components in ErP
	UL Standard 2809, Environmental claim validation procedure for recycled content
	ISO 14021, Environmental labels and declarations, definitions for recycled content, pre-consumer and post-consumer material
Rare earth elements	ISO 22444-1:2020 - Rare earth — Vocabulary — Part 1: Minerals, oxides and other compounds
	ISO 22444-2:2020 - Rare earth — Vocabulary — Part 2: Metals and their alloys

	ISO 22450:2020 - Recycling of rare earth elements — Requirements for providing information on industrial waste and end-of-life products
	ISO/TS 22451:2021 - Recycling of rare earth elements — Methods for the measurement of rare earth elements in industrial waste and end-of-life products
	ISO 22453:2021 - Exchange of information on rare earth elements in industrial wastes and end-of-life cycled products
	ISO 22927:2021 - Rare earth — Packaging and labelling
	CLC/TR 45550:2020 Terms and Definitions related to material efficiency
Renewable wood-fiber content sourcing	Forest Stewardship Council (FSC), Program for the Endorsement of Forest Certification (PEFC)
Product design assessment	EN 45552:2020 General method for the assessment of the durability of ErP
	EN 45553:2020 General method for the assessment of the ability to remanufacture ErP
	EN 45555:2019 General methods for assessing the recyclability and recoverability of ErP
	EN 45558:2019 General method to declare the use of critical raw materials in ErP
	EN 45559:2019 Methods for providing information relating to material efficiency aspects of energy related products
Durability	IEC 60068-2 Environmental testing package
Battery and battery safety standards	IEC 61960-3:2017 Secondary lithium cells and batteries for portable applications
	JIS C8714 (Safety Tests for Portable Lithium-Ion Secondary Cells and Batteries for use in Portable Electronic Applications)
	ANSI/NEMA C18 - Safety Standards for Primary, Secondary and Lithium Batteries
	UL 1642 - Standard for Safety for Lithium Batteries
Data deletion	NIST SP 800-53, Security and Privacy Controls for Information Systems and Organizations
	ISO/IEC 27040:2015, Information technology — Security techniques — Storage security
End-of-life	The Sustainable electronics reuse and recycling (R2) standard

	The e-Stewards® Standard for Ethical and Responsible Reuse, Recycling, and Disposition of Electronic Equipment and Information Technology Version 4.0©
	EN 50625 - Collection, logistics & treatment requirements for WEEE
	IEC 62635 'Guidelines for End-of-life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment'
Manufacturing waste	UL 2799 Environmental Claim Validation Procedure for Zero Waste to Landfill
	U.S. Green Building Council's Total Resource Use & Efficiency zero waste program
Water	GRI 303: Water and Effluents, 2018
	ISO 14046, Environmental management — Water footprint — Principles, requirements and guidelines
	Global Water Footprint Standard by Water Footprint Network

Table 16. Summary of relevant standards for the sustainable use of resources

5. Summary of recommended criteria

This State of Sustainability Research for Sustainable Use of Resources serves as the evidenced-based scientific foundation for criteria development for the EPEAT ecolabel. Table 17 provides a summary of strategies to reduce the impact of material and resource use, along with available best practices to assist in implementation.

Topic	Mitigation Strategy	Best Practices/ Resources	Criterion Focus
Material resources	Replacing high impact material(s) with lower impact material(s) (not including use of recycled content), and Using less material (dematerialization)	Life cycle analysis using ISO 14067, ISO 14040, ISO 14044	Product
	Use of recycled content in product	UL Standard 2809, EN 45557	Product
	Reuse and recycling of critical and rare earth metals		Product
Product lifetime	Design and support of longer life product		Product
	Longer life rechargeable battery;	IEC 61960-3:2017	Product
	Availability of spare parts	EU GPP	Product
	Evaluation of product repairability	French repairability index, ITU.L.1023	Product
	Provision of information and services to support product repair		Product, Downstream value chain

	Durability testing for mobile equipment (notebooks, tablets, smartphones)	EU GPP criteria for computers, displays, tablets, and smartphones	Product
	Secure deletion of data	NIST 800-88, ISO/IEC 27040	Product
Packaging	Design for efficient material use, increase use of recycled content; increase use of responsibility sourced renewable content; increase reuse of packaging		Package
End-of-Life	Provision of information to recyclers to facilitate safe handling, reuse and recycling of end-of-life equipment and recycling		Product, Downstream value chain
	Product recovery for refurbishment, reuse, and recycling		Product
	Building recycling infrastructure in low and middle-income countries		Downstream value chain
	Increasing reuse of equipment and components	ISO/IEC and EN standards	Product, Value chain
	Recovery and recycling of critical minerals and rare earth elements		Product, Value chain
	Responsible recycling of end-of-life equipment	e-Stewards, R2, EN 50625	Downstream value chain
Waste	Zero waste manufacturing	UL 2799, USGBC TRUE	Upstream value chain
Water use and scarcity	Reduce water withdrawal and consumption, particularly in high water stress areas	GRI -303 standard, WFN Global water footprint standard, ISO 14046	Upstream value chain

Table 17. Summary of strategies to reduce impacts of materials and e-waste

Appendix A. Material content raw data

Appendix A, Table 1. Critical and precious material content raw data by product type; for Table 4

Product Type	LCD notebooks	LED notebooks	LCD TVs	LED TVs	LCD Monitors	LED Monitors	Smart-phones	HDDs	SSDs	Tablets
Materials	g/unit									
Aluminum					242	130	2.9	441	441	
Antimony	0.77	0.77	0.71	0.71			0.084			0.154
Arsenic	0.01	0.01								0.002
Barium	2.5	2.5			1					0.49
Beryllium							0.003			
Cadmium										
Cerium	<0.001	<0.001	0.005	<0.001	<0.001	<0.001				<0.001
Chromium	0.07	0.07								0.014
Cobalt	0.065	0.065					6.3			0.013
Copper	135	135	824	824			14	15	15	27
Dysprosium	0.06	0.06						0.06		0.012
Europium	<0.001	<0.001	0.008	<0.001	0.001	<0.001				<0.001
Ferrite										
Gadolinium	<0.001	<0.001	<0.001	0.002	<0.001	0.002				<0.001
Gallium		0.0016		0.005	0.003	0.003				
Glass			162	216	590	590	10.6			
Gold	0.22	0.22	0.11	0.11	0.2	0.2	0.038	0.005	0.005	0.044
Indium	0.04	0.04	0.003	0.003	0.079	0.082				0.008
Lanthanum	<0.001		0.007		<0.001					<0.001
Lead	5.3	5.3			16		0.6			1.1
Mercury	<0.001	<0.001			<0.001	0.004				<0.001
Molybdenum	0.04	0.04			0.633	0.633				0.008
Neodymium	2.1	2.1					0.05	1		0.427
Nickel	3.6	3.6					1.5			0.722
Palladium	0.04	0.04	0.044	0.044	0.04	0.04	0.015	0.003	0.003	0.008
Plastics			612	573	1780	1780	60	44	44	
Platinum	0.004	0.004					0.004			
Praseodymium	0.274	0.274	<0.001		<0.001		0.01	0.145		0.055
Selenium										
Silicon										
Silver	0.25	0.25	0.45	0.45	0.52	0.52	0.244	0.031	0.031	0.05
Steel/Iron					2530	2530	8	62	62	
Tantalum	1.7	1.7								
Tellurium										
Terbium	<0.001		0.002		<0.001					<0.001
Tin			18	18	24	24	1			

Titanium					0.633	0.633				
Tungsten					0.633	0.633				
Vanadium										
Yttrium	0.002	0.002	0.11	0.005	0.016	<0.001				<0.001
Zinc	0.004	0.004					1			<0.001

Appendix A, Table 2. Heat map raw data for metals of concern showing vulnerabilities for metals of concern based on selected environmental and supply-demand metrics, for Figure 5.

Materials		Global reserves (metric tons)	Ore conc. (%)	Static index of depletion (years)	Global warming potential (kgCO2eq)	Water scarcity (m3)	Cumulative Energy Demand (MJ)	Mineral Resource Demand (kgFeeq)	Freshwater Ecotoxicity (CTUe)
Base	Aluminum	3E+10	0.5	469	20	3.67	222	0.4	0.01
	Copper	8.7E+08	0.03	44	4.1	3.28	61	53	0.04
	Magnesium	8.5E+09	0.4	304	32	1.90	401	0.6	0.02
	Ferrous	1.7E+11	0.55	89	4.6	0.53	69	14	0.01
	Nickel	89000000	0.01	33	12	4.52	177	45	0.06
	Zinc	2.5E+08	0.06	19	5.1	1.39	62	4	0.01
	Titanium	8.2E+08	0.35	108	31	8.36	437	0.6	0.04
Precious	Gold	50000	0.000003	15	17083	5042.7	256403	81312	71
	Silver	560000	0.00005	21	360	71.5	5492	1424	2
	Platinum	69000	0.00001	383	29145	6469.9	368365	140481	90
	Palladium	69000	0.00001	329	6117	1803.7	84645	32322	16
	Rhodium	69000	0.00001	383	26849	7518.1	344844	130323	80
Critical	Antimony	1500000	0.05	9	10	6.09	149	4	0.16
	Barium	3E+08	0.33	32	0.3	1.26	5	0.01	0.001
	Cobalt	7000000	0.05	50	10	5.98	137	2	0.08
	Gallium	100000	0.0001	313	195	74.71	2738	10	16
	Graphite	3E+09	0.75	273	2	NA	55	0.03	0
	Indium	15000	0.0001	20	223	62.34	2715	118	0.45
	Lithium	17000000	0.01	221	168	26.66	2514	5	0.28
	Manganese	8.1E+08	0.55	43	3.6	0.83	62	179	0.01
	Tantalum	90000	0.69	50	305	95.73	4749	46	0.5
	Tellurium	31000	0.00001	66	8	2.39	135	28	0.03
	Tin	4700000	0.08	15	22	9.53	327	1486	0.06
	Vanadium	22000000	0.05	301	33	NA	516	14	0.01
Rare earth elements	Lanthanum	32400000	0.02	599	75	9.47	215	2.3	1.1
	Cerium	60000000	0.03	758	76	NA	252	0.7	0.3
	Praseodymium	6000000	0.003	606	73	14.85	376	3.6	1.7
	Neodymium	18000000	0.01	535	74	15.82	344	3.8	1.8
	Europium	240000	0.0001	364	103	NA	7750	2.3	1.1
	Samarium	1320000	0.0007	287	106	NA	1160	2.3	1.1

	Gadolinium	480000	0.0002	134	111	NA	914	2.3	1.1
	Yttrium	600000	0.0003	47	15	NA	295	2.3	1.1
	Terbium	120000	0.0001	234	108	NA	5820	2.3	1.1
	Dysprosium	1200000	0.0006	656	107	NA	1170	2.3	1.1
Hazardous	Lead	90000000	0.03	20	1.4	0.54	17	1.9	0.01
	Mercury	600000	0.003	150	12	0.84	126	0.1	0.01
	Chromium	5.7E+08	0.55	13	31	4.74	538	36	0.03
	Cadmium	600000	0.0003	24	1	0.65	17	0.2	0.002

Appendix A, Table 3. Heat map raw data for plastics of concern for selected environmental metrics, for Figure 7

Materials	**Carbon footprint (kgCO2 eq)**	**Energy Demand (MJ)**	**Mineral Resource Demand (kg Fe eq)**
Acrylonitrile butadiene styrene	4.6	100	0.018
High Impact Polystyrene	3.7	90	0.015
Polyamide	9.2	150	0.051
Polystyrene	3.7	89	0.015
Polycarbonate	8.1	110	0.0079
Poly vinyl chloride	2.6	70	0.008
Poly methyl methacrylate	8.6	150	0.011

Appendix A, Table 4. Heat map raw data for material hotspots trends for flat panel displays, for Figure 8

	Mass percent	Carbon footprint (kgCO2 eq)	Energy Demand (MJ)	Mineral Resource Demand (kg Fe eq)
Polycarbonate-Acrylonitrile butadiene styrene	36	2.916	39.6	0.003
High Impact Polystyrene	26	0.962	23.4	0.004
Acrylonitrile butadiene styrene	8	0.368	8	0.0014
Poly methyl methacrylate	7	0.602	10.5	0.001

Appendix B. Recommended spare parts availability

Appendix B, Table 1. Recommended spare parts availability

Product Category	Recommended Spare Parts	Reference
Computers (notebooks, desktops, All-in-ones, tablets)	Battery, display panel/assembly, LCD panel, HDD, SSD, ODD, RAM, PCB/system PCB/motherboard, fan/cooling radiator, external/internal PSU, power connector, charger, keyboard, ports and connectors	EU GPP for computers core[9] and comprehensive[10] (March 2021) French repairability index (July 2021)
Computer displays	Core requirement: Connectivity cables, power cables, external power supply unit Comprehensive requirement: Screen assembly, LED backlight, power and control circuit boards	EU GPP for computers (March 2021)
Mobile phones	Battery, display panel/assembly, front-facing camera, rear-facing camera, charger, connectors (including charging connector), PCB/mother board, buttons, microphone, speaker	EU GPP for computers core and comprehensive (March 2021) French repairability index (July 2021)
Servers	Batteries, storage, memory, processor (CPU), PCB, expansion cards/graphic cards, power supply unit (PSU), fans	EU GPP for data center equipment comprehensive (March 2020)
Imaging equipment	Core requirement: Spare parts listed below must be made available by manufacturers for at least 3 years from the date of purchase (where not considered a consumable): - Print heads - Laser unit - Fuser units - Drum units	EU GPP for imaging equipment (July 2020)

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[9] EU GPP Core 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.

[10] EU GPP Comprehensive criteria – which take into account more aspects or higher levels of environmental performance, for use by authorities that want to go further in supporting environmental goals and innovation.

	Comprehensive requirement: Spare parts listed below must be made available by manufacturers for a minimum of 5 years from the date of purchase (where not considered a consumable): - Storage devices - Scanning units - Print heads - Laser unit - Fuser units - Drum units - Transfer belts/kits - Maintenance kits - Paper feed components - Density sensors - Power and control circuit boards - Cartridge/container attachment components - External power supplies - Hinges	

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