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Green Future Networks

Network Equipment Eco-Design and End to End Service Footprint

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Network Equipment Eco-Design and End to End Service Footprint

by NGMN Alliance

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Abstract

The main goal of the present White Paper is to give an overview of the existent procedures and visions for eco-design of Information & Communication Technologies (ICT) network equipment. In order to introduce network equipment eco-design principles, this White Paper investigates the strategy to reduce the environmental footprint and then presents the basis of circularity. It presents a method called Life Cycle Assessment (LCA), which allows to assess the network equipment environmental footprint with an accurate level of precision and completeness. A view on the materials footprint and the role of critical raw materials as part of product's eco-design is given considering the associated supply risks. Other important topics dealt in this White Paper are network equipment re-manufacturing and refurbish benefits as well as innovation in packaging inspired in eco-design principles. To finalize, the status of work on the development of a methodology to measure the end-to-end services footprint is presented.

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1 Executive Summary

This White Paper is one of four NGMN's Green Future Network Phase 1 project deliverables. The main goal of the present White Paper is to give an overview of the existent procedures and visions for eco-design of Information & Communication Technologies (ICT) network equipment. To illustrate those procedures, the document presents an analysis for base stations, Home Network Equipment and servers. The other three papers focus on sustainability challenges and initiatives in mobile networks, network energy efficiency, and metering.

Assessment of ICT equipment, and especially the ones required to set up the future networks, are complex. Thus, assessing their environmental footprint requires dedicated methods in order to achieve an accurate level of precision and completeness. The Life Cycle Assessment (LCA) methodology, which is based on the ISO 14044 standard, has been developed to answer this question, and standardization bodies such as the ITU-T have developed dedicated recommendations for ICT, like L.1410 which provides best practices to carry through life cycle assessment. With the help of this recommendation, the overall quality of life cycle assessments carried out by the ICT sector can be improved. This will, on one hand, help manufacturers have a better understanding of the environmental footprint of their equipment portfolio, and on the other hand, at an operator or end user level help perform studies at service level with consistent data. Thus, these players can provide transparent communication to their customers on the subject.

In order to introduce network equipment eco-design principles, this White Paper first investigates in Section 2 the strategy to reduce the environmental footprint and then presents the basis of circularity, in the context of ICT, which deals with length of use, second life, reuse of parts and recycling. Generally speaking, circularity of products is becoming increasingly important and more precisely, the concept of circular economy for the telco ecosystem appears as a very vast area, where important optimizations can still be achieved. This implies a hierarchy in the way equipment is treated in order to reduce its impact on the environment and to minimize the use of materials. The latest leads to the principles and approaches with which the hardware of the equipment should be designed, taking into account longevity, reparability and upgradability. Furthermore, to succeed in the implementation of real circular economy in the ICT, different sectors need to work together with global optimization goals as strategy.

The White Paper presents the methodology to be used first in order to assess the environmental footprint of network equipment by using the Life Cycle Assessment (LCA) in Section 3. This shows which phases of the life cycle have the highest contribution to the different environmental indicators and should help identifying different key contributors. Second, it explains how to use this LCA to guide the eco-design process in order to reduce the environmental footprint of network equipment. This is performed by highlighting key points which have a high contribution to the different environmental footprint indicators and identifying the different aspects to prioritize. An example of LCA impact on radio base station and components is presented, as well as how to use the product circularity method.

In addition, a focus on materials of interest for the sector is presented. A view on the materials footprint and the role of critical raw materials as part of product's eco-design is given considering the associated supply risks, showing that active communication and actions by every player in both upstream and downstream of the product value chain is required to achieve circularity of these materials. It also shows that an LCA should be aware of which materials are covered by the chosen method and how the reserves are calculated.

Then, this White Paper focusses on the methods used to determine re-manufacturing and refurbish benefits for base stations, enterprise servers and Home Network Equipment. A general view on the procedures for integrating eco-design into the product development process is presented.

Despite the fact that network equipment packaging could be considered irrelevant when compared with other equipment environmental impacts, ICT companies are looking for solutions to reduce this source of pollution and waste. With this aim, this White Paper presents an innovation inspired in eco-design and applied to packaging called Lean/Smart Packaging. A glimpse into the current existing eco-rating, eco-labels and eco-information in the ICT sector is included, with the aim of presenting examples for inspiration in order to get a standardized information for network equipment.

To finalize, Section 4 presents the status of works on the development of a methodology to measure the end to end services footprint. The target would be to evaluate how much energy is used to provide access to a certain service, taking into account the service's full life cycle, including devices. According to the different studies, this area still requires some research and innovation.

NGMN aligns its partners regarding environmental impact, critical materials usage, and environmental footprint. Working towards improving sustainability, this White Paper concludes with the following main recommendations and findings:

- NGMN encourages vendors, operators, research institutions and other ecosystem players to participate in standardization efforts on the equipment environmental footprint reduction to share knowledge, develop and adopt common approaches.
- In order to reduce the environmental impact, NGMN strongly recommends that operators include requirements related to circular economy and environmental footprint assessment in their purchase process requirements.
- It is further strongly recommended that vendors expand their activities regarding circular-economy and environmental footprint assessment in their system definitions, specifications and products' designs, taking into account eco-design principles, critical materials usage, refurbishing and re-manufacturing.
- NGMN sees a strong need for the industry to increase the efforts in developing common methodologies to bring solutions to the complex question of assessing services environmental footprint. This might be realized for example through collaborative partnerships between actors with different expertise.
- NGMN is currently defining its phase two of Green Future Networks activities and will take important open industry topics including these recommendations into consideration.

2 ENVIRONMENTAL CHALLENGES OVERVIEW FROM A CIRCULARITY PERSPECTIVE

2.1 Introduction

Production of ICT network infrastructure equipment causes unneglectable Greenhouse Gas (GHG) emissions and also consumes a large amount of resources. These include, but are not limited to, various metals and plastics. Scarce or problematic materials are also used, such as Critical Raw Materials (CRM), conflict minerals and rare earth elements. When made from primary sources (i.e. materials derived from mined ores or crude oil used for plastics), these materials are referred to as primary materials and the supply chain starts from the mine and the oil wells which both have to be considered as part of the life cycle impact of the product. The impact of materials is thus beyond the immediate use of resources and energy and also needs to consider a wider range of impacts. In particular, as mine and oil production is associated with land use and pollution, they both are associated with impact on the landscape, biodiversity and natural habitats. This implies two things, origin of materials becomes important as standards for protecting these differ a lot. Likewise, using secondary materials (i.e. recycled materials) instead of primary materials in products helps addressing those and is an important eco-design action alongside designing products for recyclability. Moreover, using recycled materials is also associated with lower GHG emissions, this effect could be substantial for materials relying on energy intensive processes such as aluminium.

In order to close the loop and work towards full circularity, equipment need to use recycled materials and be recycled at end of life, and move towards phasing out primary materials. Looking at the use of materials, two main material fractions need to be considered; metals and plastics. While the recovery and reuse of some metals such as aluminium, copper, steel, etc. is already relatively well established, the use of recycled plastic still needs to be expanded.

Besides the environmental problems associated with mining, primary raw materials are a finite supply source. Dwindling deposits and increasing demand have driven up prices and this trend will continue even more strongly in the future unless a growing portion of demand is satisfied by secondary raw materials, ecology and economy go hand in hand.

Turning to the other aspect of circularity, equipment should have a recyclability rate as close to 100% as possible. At the end-of-life, the actual recycling and recovery rates (collection plus recycling/recovery of total produced equipment) are, in many regions legally regulated, such as the directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) [1]. However, the recycling rates therein just constitute a conservative minimum and although this is a multifaceted challenge, the ambition of designers should be to ensure products prepared for high recyclability. Again, this is something that has an impact on hardware design approaches. Materials and components need to be selected and combined also with recyclability in mind. Laminated or composite materials should be avoided, as separation into their constituents takes additional efforts and resources. Consideration needs also be given to materials that are just present in single digit milligram or even sub-milligram amounts. Typical examples for those materials are Gold, Indium, Tellurium and rare earth elements as these are hard to recover. In addition, their deposits in the earth's crust are small and diluted which causes high mining impacts when primary materials are used. Distribution between countries is also uneven and several materials concentrates in very few countries which exposes supply chain to political dependencies, which renders a reduced use of such materials even more critical. Wherever possible, such materials should be replaced by more common materials reducing supply related risks. Besides metal and the raw material mentioned earlier, plastic continues to be largely used and recycling aspects for this material should also be taken into account.

At end of life, preferably after a second life, recycling of materials is the main objective, and this recycling needs to be economically feasible in order to happen. This is again a multifaceted challenge where increased interest in recycled materials and internalizing environmental costs helps to set relevant price levels. However, in any case, equipment needs to be designed for disassembly and separation into the different recycling fractions in a way that simplifies both automatic and manual processes. Here, the same considerations apply as for reparability. Hardware architecture may even be conscious of recycling fractions, that is, consider whether components may be grouped into sub-assemblies in a way that a certain sub-assembly contains only materials of the same recycling fraction. In any case the overall impact throughout the life cycle should be a guiding star to optimize the design and different impacts need to be considered together, such as use of energy, recyclability, use of recycled materials.

2.2 Environmental Footprint Reduction Strategy

Circularity of products and material flow is becoming increasingly important. The concept of circular economy, which is closely related to materials efficiency, has become very popular and needs to be further implemented. This concept includes a multitude of aspects associated with prolonging the lifetime of products and increasing the circularity of subsequent steps, including aspects such as durability, repair, reuse, upgradability, remanufacturing, recyclability, use of recycled materials and use of critical raw materials. In Europe, assessment of these aspects has been addressed by a set of standards developed jointly by CEN, CENELEC [2] and ETSI [3]. These are horizontal standards but lay out the different aspects associated with circularity.

As outlined in Section 3, the relative importance of different parts of the life cycle varies between equipment categories. Typically, products associated with networks and data centre tend to have a longer life span and operate 24/7, which makes the majority of GHG emissions and several other impacts associated with their usage, if world average conditions are considered. However, for end-user equipment with short life span and for networks and data centre operating on a low-carbon electricity grid, a substantial portion of the lifetime GHG emissions and other impacts are allotted to the production phase. Nevertheless, if indicators such as abiotic resources depletion is considered even for these long life span and 24/7 equipment, the manufacturing phase will be the most important to consider. This implies a hierarchy of how to deal with this equipment to reduce their environmental impact and minimize the use of material:

1. Length of use: The longer the equipment is used, the better the GHG emissions during production are spread over the lifetime. Therefore, certain design aspects need to be considered. See Section 3.5 for a method to assess criteria related to product durability. Note that for products where the use stage impact dominates, phasing out of products before their technical lifetime ends may be a preferred strategy. To understand which strategy to apply when for such products, a more detailed analysis is required as highlighted in Section 3.8.3.
2. Second life: If products are phased out before their technical life ends, a subsequent secondary use needs to be facilitated. In principle the same design considerations apply as for the primary use. See Section 3.8 for examples on repair/remanufacturing. However, to enable this to happen it is important to have a user interface that helps to preserve and erase personal data in a safe and simple process, and to support portability of content.
3. Reuse of parts: If 1 and 2 are exhausted, because e.g. the equipment is worn out and/or beyond economic repair, identification and reuse of any usable part is a preferred option. See Section 3.8 for examples on repair/remanufacturing.
4. Recycling: When 1 to 3 are exhausted (potentially after several iterations), material recycling as close as possible to 100% needs to be possible. See Section 3.5 for a global method on setting up circularity scoring.

2.3 Important Circular Aspects to Consider

This envisioned hierarchy of utilization leads to the principles and approaches with which the hardware of the equipment should be designed. This is also reflecting the materials efficiency aspects as outlined in Section 2.2.

Longevity

Extending the lifetime means that the equipment should maintain its function over the extended lifespan. From the design perspective that means that circuitry and mechanical parts are designed with this in mind. Likewise, components need to be also selected with life expectancy in mind. Typically, this is already the case for network equipment with high reliability requirements and long life spans associated with more substantial investments, while consumer devices designed for a fast moving mass market have a longer way to go. Mean Time between Failures (MTBF) is the expected time between inherent failures of a system during normal operation. MTBF calculations are sometimes used as a tool to predict the life expectancy of equipment, so that design choices can be controlled and adjusted if necessary. There are norms that allow a standardized calculation which include [4], SN29500 of Siemens AG [5], Reliability Prediction Procedure for Electronic Equipment SR-332 of Telcordia Technologies [6] and Reliability prediction of electronic equipment Mil-HDBK-217 of the US military [7]. Even with a predicted sufficient life expectancy, deficiencies in assembly and bad component batches from pre-suppliers can still limit the factual life expectancy. As a consequence, manufacturing should be accompanied by adequate quality assurance to prevent this from happening.

Reparability

To further extend the operational life of equipment, it needs to be designed with reparability in mind. For network products operating in a business-to-business context, modularity at subsystem (e.g. different board configurations) or at function level (e.g. radio technology in a base band unit), and repair processes are already common place and part of basic product design. The borderline between continued use and disposal is determined by the availability of repair solutions and the repair cost. Particularly, the wage of repair technicians drives cost and hence the arrangement of parts and sub-assemblies should minimize the time and effort needed for disassembly and assembly. This in turn is dependent on the design approach:

- Accessibility of parts and sub-assemblies: These should not be mutually obstructive. Any solution where access to a certain defective component requires previous dismounting of several other parts or sub-assemblies not affected by the defect is to be avoided. Conversely, all parts or sub-assemblies should be accessible in such a way that they can be replaced directly without affecting other working components or sub-assemblies.

- Use of fasteners: The connection of mechanical parts should be by screws of ideally a uniform size and that of electrical components by plugs and sockets. Conversely, soldering joints require extra equipment in the workshop and take more time. Particularly bad is the use of gluing joints. Opening those usually takes severally minutes of heating and may damage other components, making worse the defect by attempting to repair it.

Another important aspect is the availability of spare parts as repairs are only feasible as long as spare parts are available. The availability period for spare parts should be planned in such a way that at least the expected life expectancy following longevity principles is covered. The ITU L.1023 Recommendation [8] includes all these aspects of circular product design and will be covered more in details in Section 3.9.

Upgradability/Modularity

Technology advances quite rapidly. New standards, such as 5G, may need to be incorporated or additional bands to be covered for a given site. The equipment should be flexible enough to allow simple upgrading. Otherwise, the equipment becomes prematurely obsolete and needs to be disposed long before the end of its life expectancy.

For antennas one could think about modularity at band level. Thus, when a new generation of radio mobile architecture is deployed only a portion of the antenna has to be replaced or added. Also, such solutions exist for some network equipment. Looking at the network infrastructure, usually certain types of equipment, in particular site equipment, do not undergo technological advances, such as housing and power supply, and can continue to be used despite rapid progress in network technology. A common way to handle upgradability (and also expandability) of network equipment is to use modular approaches where elements that are subject to technological change or expansion of capacity come as plug-in modules. This may include additional signal processing functions, radio functions and antennas. A common approach is to host modules in standardized racks that supply functions such as power supply, heating and cooling with likewise standardized interfaces. A further option is to provide expandable, upgradable functions as self-contained modules with built-in power supply, heating or cooling. As always, the full life cycle impact need to be considered to understand which approach gives the lowest total impact on a network level. In either case, this modular thinking solves two aspects: enabling technological advances with just additional modules saves a lot of resources and enables the part of the equipment not subject to technological changes to be used until the end of its life expectancy. Even when a module reaches end-of-life or becomes obsolete, disposing it creates much less electronic scrap than disposing a whole base station. This also demonstrates how economy and ecology may go hand in hand. Network infrastructure is the biggest investment item for network operators. Whenever a new technology or new band coverage is required, it will be cheaper to purchase new plug-in modules instead of complete base stations.

Many functionalities are provided by software, thus upgradability not only means upgradability of hardware but also upgradability of software. This has several aspects. One is the length of the software update period which should support the life expectancy of the whole equipment assembly. Another aspect is that new modules need to come with standardized software interfaces that allow simple plug and play solutions for their integration into the equipment. The specification of these interfaces needs to remain stable for a sufficient period of time to allow downward compatibility.

3 ASSESSING AND REDUCING THE ENVIRONMENTAL FOOTPRINT OF NETWORK EQUIPMENT

3.1 The Business Model Effect on Environmental Impacts

The choice of business model influences the eco-design process and plays a major role towards an efficient use of resources. An important distinction is whether products are sold or leased to the end-user. Generally leasing setups are assumed to provide more incentives for keeping products in use during longer time intervals, improve reparability, etc. One example of a leasing setup is the Home Network Equipment which is rented by operators to the end-users in several countries. If the user ends the subscription, has a failure on the device or wants to change the type of subscription, the equipment is recovered by the operator. The device then enters a refurbishment process that aims to ensure that the product has been tested and verified to function properly, is free of defects and can be re-rented to another subscriber. Typically, this involves the following steps:

- Fault detection: Check if the product is functional (e.g. if a firmware reset/update is required). If a fault is found at electronic level, the device is sent for repair.
- If the product is functional, its aesthetics condition is checked to replace any damaged part. The idea is to have good enough looking product to be able to reuse or to resell it.

- Provision of replacement product: The user is provided a replacement product.

The environmental benefits of the product-service-system business model (i.e., in which the product is only provided to the customer to support a service) were for instance demonstrated for Home Network Equipment [9]. This study compares a business as-usual model (equipment are sold to the customers) to a business model including refurbishment. In the second one even if the equipment has to be recovered from the customer, transported to a refurbishment plant and some parts have to be swapped (mostly casing parts, the main electronic board is almost reused every time) as there is no need to manufacture a new product for each customer, the environmental benefits are quickly achieved. Figure 1 shows the potential environmental footprint reduction for two environmental indicators. It has to be noted that several key factors, such as the mechanical design of the equipment or the location of the refurbishment (and thus distance to ship the equipment) will affect the result.

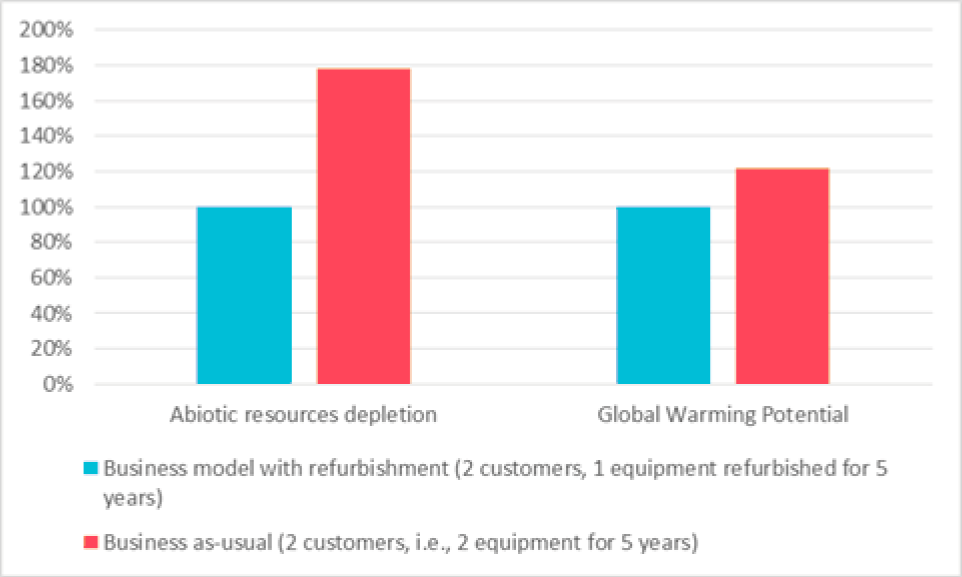


Figure 1. Environmental footprint comparison between both business models (adopted from [9])

3.2 Life Cycle Assessment, Standardized Way to Estimate Environmental Impact

The eco-design principles focus on reducing the environmental footprint of an equipment, network or service entire life cycle and should consider several impact indicators (e.g. global warming potential, toxicity or abiotic resources depletion). A basis for understanding the environmental impact hotspots and how to address them is to assess the overall impact of a product and its distribution. Thus, a first step is to develop a baseline assessment using Life Cycle Assessment (LCA). LCA is standardised by the International Organization for Standardization (ISO) standards (ISO 14040 [10] and 14044) [11] for any type of goods. For the

ICT domain the ETSI ES 203 199 [13] and the ITU-T L.1410 [14] bring supplementing requirements specific to ICT equipment, networks and services in order to improve the quality of the assessment, for example by guiding the practitioner on which parts (e.g. integrated circuits and their semiconductor chips) and processes (e.g. mining, Integrated Circuits manufacturing and operation of equipment) have to be considered and how to report the results consistently and with sufficient transparency. The LCA is designed to show which phase of the life cycle (manufacturing, transport, use or end-of-life) has the highest contribution to the different environmental indicators. It will also help identify key contributors such as:

- a certain material or industrial process used in the manufacturing phase,
- a high power consumption in standby mode in the use phase,
- airplanes (if applicable) are used to ship the equipment,
- an improper delay to recycle the equipment.
- Etc.

Typical data sources include representative primary data from suppliers (e.g. manufacturers), assemblers, transporters, end-users and recyclers, combined with secondary data where primary data is lacking. With the LCA as a basis, environmental impacts and their distribution can be estimated and priority action to address hotspots can be identified.

It is observed that all LCA results are indicative as they are based on models and assumptions, not measurements, and results are only valid under the assumptions of the study and cannot be used to make generalized conclusions about the carbon footprint and environmental footprint of equipment. For this reason, results differ with product generation, configuration, country of operation, production region, etc.

As extensive LCA, eco-design and circular economy scoring effort have been carried out on base stations and Home Network Equipment. They will serve as a connecting thread between the different sub-sections of this White Paper. Additionally, other equipment, such as Radio Frequency (RF) cables & connectors or servers will also be covered.

3.3 Using LCAs to Guide Eco-design Processes

The Home Network Equipment LCA presented in this section was performed by an operator with the following functional unit "to provide an xDSL access to a household in France for 5 years". The study was done for one Home Network Equipment with its accessories, packaging as well as the spare parts required for the refurbishment process.

The main considered hypotheses were:

- Equipment assembled in China with parts purchases globally
- Transported by container ship to France
- Rent to customers for usage in France
- Recovered by the operator for refurbishment at the end of the customer's subscription
- End-of-life considered with the French WEEE stream

This LCA's results highlight four key points which have a high contribution to the different environmental footprint indicators:

- total energy consumption during use phase,
- total area of semiconductor in the integrated circuits (see Figure 2),
- total area and complexity (i.e. number of copper layers) of the printed circuit board (see Figure 2),
- the weight and type of plastic used for the enclosure parts (see Figure 2).

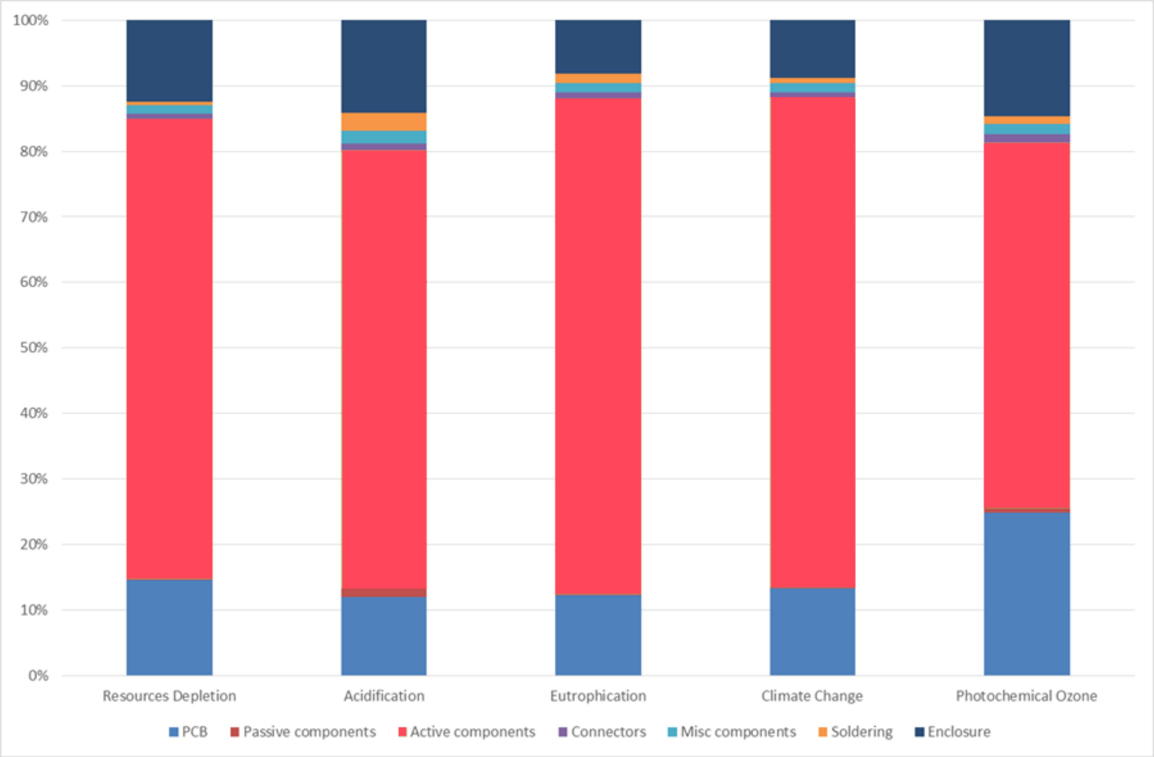


Figure 2. Relative LCA results for Raw Materials Acquisition and Production of Home Network Equipment

The relative importance of life cycle stages differ a lot depending on type of equipment. In particular, total primary energy and electricity consumption may represent a vast majority or a limited minority (smartphone) of overall greenhouse gas emissions (e.g. electricity mix, battery powered or powered from the main grid, lifetime, etc.). However, looking specifically beyond the use stage on other life cycle stages, LCAs of numerous types of ICT infrastructure equipment - from the smaller desktop corded Liquid Crystal Display (LCD) business office phone to the larger base band units - indicates the importance of semiconductors and printed circuit boards as main contributors to the embodied emissions of products.

In order to reduce the environmental footprint, the eco-design process will have to identify the different aspects to prioritize. Based on typical findings from LCAs several key questions apply:

- Adaptability of energy usage: Is it possible to include advanced sleep modes, so the equipment can switch off features which are not in use?
- Minimization of circuit area: Are integrated circuits with the same functionalities available with smaller dimensions (e.g. 7 nm instead of current 16 or 28 nm)? This could help reducing the total semiconductor area, as well as the power consumption.
- Minimization of total board area: Can the product be designed so that the overall copper area is minimized?
- Modularization: Can the function be modularized in a way that allows for separate replacement and activation of different parts?
- Minimization of materials usage: Would it be possible to design a smaller device and thus reduce the amount of material required for the casing?

For Printed Circuit Board Assemblies (PCBAs), using new design technologies, e.g. embedding technologies for heterogeneous integration of active and passive components & reversible interconnection technology, certain parts can be reused as complete modules (e.g. power modules and embedded component packaging).

Beyond such considerations, designing for circularity adds product value in the design stage, while use-oriented services help maintain product value in the use stage, and reuse/refurbishment/recycling retain product value after the first use stage.

To illustrate how design for circularity comes into play, one study on smartphones indicates that – from the perspective of environmental impacts - design for remanufacturing is often the best for the PCBA, design for reuse is best for screens and frames, and design for recycling most benign for the battery and cover [15].

Thus, in addition to the above “one life cycle” focused aspects, additional life cycles and associated cycles of refurbishment will bring additional design requirements. Indeed, in order to achieve an efficient refurbishment process the device should be designed according to some “Design-for-Refurbishment” principles. Concretely, gluing electronics to casting parts should be avoided. From the Home Network example, the Wi-Fi antennas should never be glued on the casing parts as it would make the separation of the electronic card for the casing difficult (e.g. the micro-coaxial cables used with Wi-Fi antennas could be ripped off or the micro-coaxial connectors on the electronic card damaged). Sometimes some of the Design for Refurbishment requirements might be conflicting with the one listed in the first instance (i.e. less materials mass "design for material efficiency"). For instance, in order to maximize the capability to refurbish, repair and upgrade the equipment, it might be preferable to use screws to fasten the enclosure parts together instead of snap-fits. The extra grams of steel may have an additional environmental footprint, but if it ensures that the enclosure can be opened and closed dozens of times without breaking, it is worth it (if in accordance with the LCA calculation). This shows the importance of a total environmental optimization of the design rather than looking at individual design parameters one-by-one.

3.4 LCA and Components Eco-design

RF Connectors and cables represent only a minor contribution to the overall LCA score of cell site equipment. Nevertheless, it is recommended that each supplier of network equipment seeks to improve the LCA score (Global Warming Potential 100 (GWP100), abiotic depletion potential and others).

In terms of the RF connectors needed to attach RF signal transmission lines to antennas and to radio units or amplifiers or passive network devices (filters, combiners, splitters etc.), one key to LCA score improvement is downsizing. Connector manufacturers have developed and standardized several series of small size RF connectors (such as for instance 4.3-10, 2.2-5, and Nex10 (standardization in progress)), each complying with the demanding Passive Intermodulation (PIM) requirements of mobile networks, whereas the power rating scales with the size.

Thus, in order to minimize material consumption, resources depletion and climate impact (i.e., to optimize LCA scores) it is recommended to make use of the smallest connector type which meets the power rating requirement in the addressed application scenario.

Figure 3. shows the result of a simplified LCA carried out on the manufacturing footprint of the 4.3-10, 2.2-5 and Nex10 RF connectors using the latest Product Environmental Footprint method (EF 3.0) [12]. Figure 3 clearly shows that the connectors which use less material (i.e. 2.2-5 and NEX10) and thus come along with lower mass have a much lower environmental impact. Note that these calculations were done based on the full bill of materials of each connector

design, but make use of a simplified calculation approach regarding the manufacturing process and the plating and should be further improved.

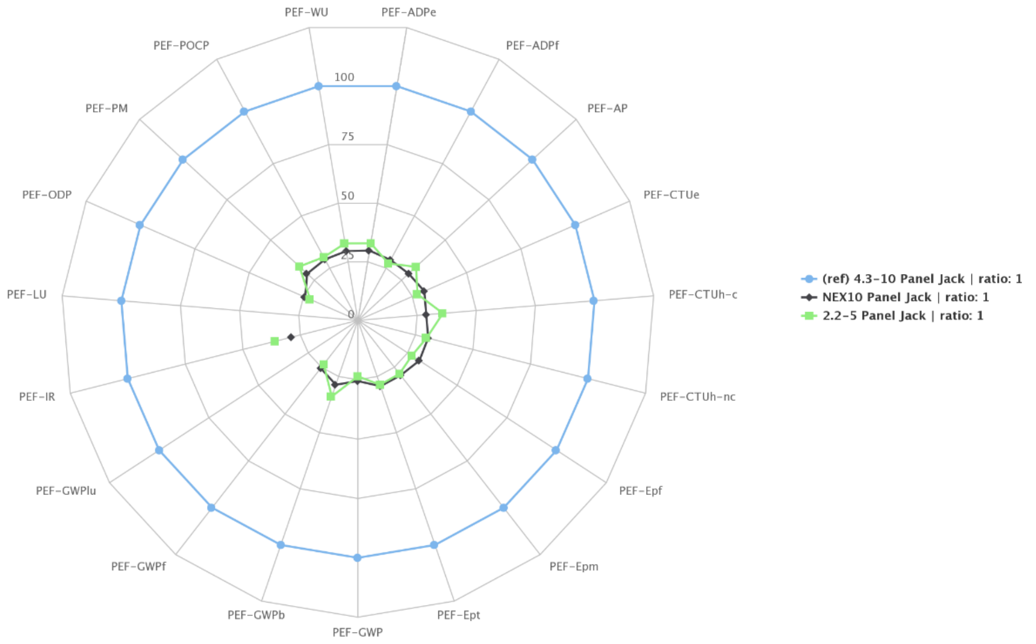


Figure 3. Preliminary comparative environmental footprint results for the 4.3-10, 2.2-5, and Nex10 RF connectors (panel jacks for UT 141)

Jumper cables, which connect the radio unit (or the Tower Mounted Amplifier (TMA)) and the antenna, bridge a distance of typically 0.5m to 6m. The attenuation along a jumper cable scales with its length and depends on the diameter of the cable: a bigger diameter comes along with lower RF losses per unit length. For instance, at 2 GHz the attenuation of a ¼" vs. a ½" jumper cable is in the range of 28dB vs. 16dB, respectively, per 100m.

Thus, on one hand with a bigger jumper diameter lower RF power levels are sufficient in order to obtain a predefined radiated power at the antenna and this results in lower power consumption over the time of operation. On the other hand, a smaller jumper diameter reduces the material consumption.

The usual criterion for the choice of the jumper cable diameter assumes a maximum of 1dB of attenuation along the whole jumper length and for cost-saving reasons the smallest available jumper cable diameter is chosen which ensure that this level of attenuation is not exceeded.

In the light of eco-design aspects we recommend a full LCA as a basis for the choice of the appropriate jumper cable size, taking into account the material consumption, resources depletion and climate impact of manufacturing, which increases with size (diameter), and also taking into account the power loss by attenuation along the length, which decreases with size (diameter), with the latter depending on the operating time (product life cycle).

3.5 The Life Cycle Impact of a Radio Base Station for Cellular Mobile Communication

Few published LCA studies of radio base stations exist. However, specifically for the carbon footprint, results are available for operation of networks and embodied emissions separately, which gives some indications of the environmental impact of base stations.

Figure 4 gives an overview over the carbon footprint of the ICT sector with red bars depicting embodied emissions and blue ones representing the use stage [16]. The figure indicates the balance between embodied and use stage emissions when applying a world average emission factor for electricity and assuming a lifetime of 10 years for base stations. As depicted, the majority of network emissions is associated with the operation.

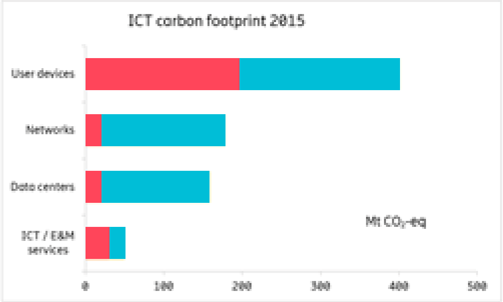


Figure 4. Distribution of the carbon footprint of the ICT sector

Looking at individual products, Figure 5 shows the results presented at an ETSI workshop [17] representing preliminary results for a Macro indoor base station configured for 40 W RF power per sector (2 TX, 20 W/antenna), 3 sectors/site and 10 MHz bandwidth, with energy consumption assumed to be according to [18], RF load 20% with 10% added for site cooling, and typical site equipment included. Moreover, this estimation was performed assuming world average electricity mix for the use stage, including also the energy supply chain and distribution losses, as well as full recycling.

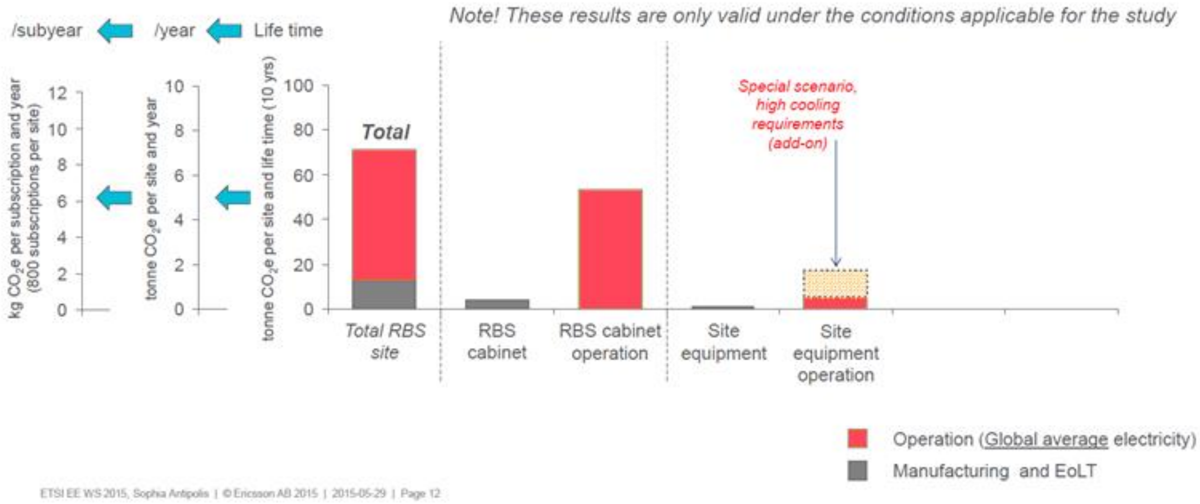


Figure 5. Example of LCA results for a Macro base station and site

The embodied emissions of the same base station (but not the same configuration) has been covered in [19], which uses a base station from the same product generation and family as a reference and pilot (the main purpose of the reference is the development of a tool for simplified estimations of embodied emissions).

The results below represent one indoor base station with 6 radio units, 1 digital unit, 3 power supply units and 1 power distribution unit. Product characteristics are as shown in Table 1.

Table 1. Hardware characteristics of a typical base station module used by Parameterized Embodied Emissions Calculator (PEEC) [19]

	Indoor cabinet	**Radio Unit**	**Digital Unit**	**Remote Radio Unit**	**Power supply Unit**	**Power Distribution Unit**
Electronics (kg)		1,54	1,41	1,85	Black-box module	Black-box module
PCB area (m^2)		0,17	0,16	0,20		
Average PCB layers		11	11	11		
IC die area (cm^2)		25	41	25		
Standard components (kg)		0,6	0,7	0,8		
Electromechanical components (kg)*	2,61**					

Die-casted aluminium	1,72	4,2	1,45	16,0		
Other mechanics	78,48	1,6	0,03	7		
Cables	5,4					
Power supply components						
Battery						
Total mass	88,21	7,34	2,89	24,85	2,3	2,4

* In this example this category includes only fans. Connectors are counted as standard electronic components and cable assemblies as cable sets

** Corresponds to 3 radial fans

*** Power units on the printed board were counted as standard electronic components

Using the tool in [19], the corresponding embodied emissions were found to be 4,4 ton of CO$_2$e, distributed in accordance with Table 2.

Table 2. Example of embodied emissions of a representative configuration of a macro indoor base station as calculated by Parameterized Embodied Emissions Calculator (PEEC) with the data described above.

			Greenhouse gas emissions (kg CO$_2$eq)				
Modules	**Qty**	**Mass in product (kg)**	**Raw material**	**Production**	**Transport**	**Ericsson support**	**TOTAL**
Indoor cabinet	1	88,21	389	209	233	245	1175
Radio unit	6	44,04	1080	1086	392	123	2681
Digital unit	1	2,89	91	163	37	8	2681
Power supply unit	3	6,9	211	12	2		225
Power distribution unit	1	2,4	18	6	1		24
TOTAL		144,44	1789	1576	664	376	4405

Consequently, as described in [19], among the embodied emissions, the raw material acquisition stage is the major contributor (41%), closely followed by the production stage (36%) then transport (15%) and support operations (9%). Putting the embodied emissions into context, these are generally estimated to represent only 10 to 15% of the use phase emissions for a radio base station (assuming 10 years of use and a global electricity mix). For markets with a low carbon electricity mix, the relative importance of the embodied emissions increases while overall emissions decrease.

For the use stage, more generic indications can be made based on the study of radio networks [20], building on a large set of primary operator data from the members of ETNO, combined with secondary data for additional operators in other regions, estimating the global average impact per operator to be 27 kWh/subscription and 14 kg CO_2e/subscriber.

3.6 Application of the Product Circularity Method

When analysing a product circularity there are many parameters to consider and it might be a bit overwhelming to cope with all of them, or even try to sort them to focus on the most crucial ones. Here the question of eco-design will overlap with the concept of Circular Economy [21][20]. On this topic, the members of the ITU-T SG5 Q7 developed a method [8] to assess the circularity score of an ICT equipment, by combining results carried out at Request For Proposal (RFP) level on network equipment sourcing and available material in the CEN/CENELEC documents on material efficiency (EN 4555X series). The ITU method [8] is based on a set of 21 criteria, such as “Use of pre- or post-consumer recycled plastics” or “Fasteners, connectors and tools used to disassemble parts […]” which are assessed according to two metrics:

- The Margin of Improvement (MI), i.e. a comparison between the studied product design and an optimal one (in the sense of circular economy) for the given criteria. Each of the 21 criteria includes four levels of performance, according to already existing standards (e.g. for the criteria on “Fasteners, connectors and tools” the classification from Class A for reusable fasteners to Class C for neither removable nor reusable described in the CEN/CENELEC EN 45554 [22]).
- The Relevance (R), i.e. it defines how important a given criteria is regarding the type of product and its business model (e.g. the product is sold or the product is part of a product-service-system).

This method can be used by the manufacturers in the design process, as well as by the operators in equipment acquisition process to obtain information from the manufacturers regarding the improvements on circular economy they have implemented.

For the assessment of the Relevance (R) values, the type of equipment (i.e. a Home Network Equipment), its business model (e.g. equipment rented out to customers and recovered to be refurbished, sometimes several times during its lifespan), the results of LCAs on this type of equipment and the economic aspects (e.g. total cost of ownership) have been taken into account. For instance, all Home Network Equipment will be refurbished several times during its lifecycle, thus it is critical to be able to disassemble them quickly. Thus R equals 4 (most relevant) for the criterion 3RUe4 regarding disassembly depth, as shown in Table 4.

In contrast, as the customer only rents the equipment and has to return it at the end of its subscription, the availability of spare parts to customers is not really relevant. All the repair and refurbishment operations are carried out by the equipment manufacturer or third party companies. Thus, R equals 1 (least relevant) for the criterion 3RUm2 regarding spare parts distribution, as shown in Table 4. Regarding the scoring for MI it is done according to the performance levels defined in the Table 3 of the recommendation [8]. However, for some of them the performance levels have to be defined at equipment type level, as the levels are very different from one equipment type to another. For instance, the table below shows the four levels of MI for the criterion 3RUe4 regarding disassembly depth.

Table 3 Guidance for identification of MI level for the Disassembly depth criterion

3RUe4: Disassembly depth	Number of steps necessary to reach priority parts	MI = 1 – All the priority parts for repair operations are accessible after one or two disassembly steps
		MI = 2 – All the priority parts for repair operations are accessible after three or four disassembly steps
		MI = 3 – All the priority parts for repair operations are accessible after five or six disassembly steps
		MI = 4 – All the priority parts for repair operations are accessible after more than six disassembly steps

For the Home Network Equipment studied in this example the priority part for repair operation are the printed circuit board assembly and the display. In order to be able to reach it, four operations have to be carried out:

1. remove the screws which fasten the top enclosure to the bottom enclosure,
2. remove the top enclosure,
3. detach the display from the top enclosure,
4. remove the printed circuit board assembly which is fastened with two snap-fits (i.e. clips) on the bottom enclosure.

According to the table above this performance level is equal to MI equal 2. All the other criteria are assessed following the same method (the Figure 2 shows this intermediate result).

Table 4 R and MI scores for the studied Home Network Equipment

Circular Design Guidelines Group (CDGG)	Criteria	Relevance (R)	Margin of improvement (MI)
Product durability	PD1: Software and data support	4	1
	PD2: Scratch resistance	4	2
	PD3: Maintenance support	2	2
	PD4: Robustness	3	2
	PD6: Data security	2	2
Ability to recycle, repair, reuse, upgrade - equipment level	3RUe1: Fasteners and connectors	3	1
	3RUe2: Diagnostic support	4	3
	3RUe3: Material recycling compatibility	3	1
	3RUe4: Disassembly depth	4	3
	3RUe5: Recycled/renewable plastics	2	1
	3RUe6: Material identification	2	3
	3RUe7: Hazardous substances	3	2
	3RUe8: Critical raw materials	2	4
	3RUe9: Packaging recycling	2	2
Ability to recycle, repair, reuse, upgrade - manufacturer level	3RUm1: Service offered by manufacturer	4	1
	3RUm2: Spare parts distribution	1	2
	3RUm3: Spare parts availability	4	1
	3RUm4: Disassembly information	1	3
	3RUm5: Collection and recycling programmes	2	2
	3RUm6: Environmental footprint assessment knowledge publicly available	3	3

Note that the criterion PD5: Battery is not mentioned in this table. Indeed, as the equipment does not feature any battery, this criterion is irrelevant (R equals 0).

The score of each criterion is then calculated according to its R and MI results. This is done thanks to the recommendation "Score matrix with values for MI and R combinations" [8]. For instance, for the criterion 3RUe4 regarding disassembly depth according to the assessment carried out previously the results are R equals 4 (most relevant) and MI equals 3. According to Figure 1 in [8] this combination of R and MI gives a score of 80.

The same process is applied to identify the scores of the other criteria, according to their R and MI. The results of these calculations are displayed in the Table 5.

Table 5. Circularity score for the studied Home Network Equipment

Circular Design Guidelines Group (CDGG)	Circularity score	Criteria
Product Durability	100	PD1: Software and data support
	80	PD2: Scratch resistance
	60	PD3: Maintenance support
	70	PD4: Robustness
	60	PD6: Data security
Ability to Recycle, Repair, Reuse, Upgrade - equipment level	90	3RUe1: Fasteners and connectors
	15	3RUe2: Diagnostic support
	90	3RUe3: Material recycling compatibility
	80	3RUe4: Disassembly depth
	75	3RUe5: Recycled/renewable plastics
	60	3RUe6: Material identification
	70	3RUe7: Hazardous substances
	20	3RUe8: Critical raw materials
	60	3RUe9: Packaging recycling
Ability to recycle, repair, reuse, upgrade - manufacturer level	100	3RUm1: Service offered by manufacturer
	50	3RUm2: Spare parts distribution
	100	3RUm3: Spare parts availability
	40	3RUm4: Disassembly information
	60	3RUm5: Collection and recycling programmes
	30	3RUm6: Environmental footprint assessment knowledge publicly available

The next step is to calculate the score at group level. These scores are obtained by calculating the average of the score for the criteria contained in the group. For instance, the product durability group contains six criteria, but only five are relevant for the studied equipment. Thus, the score for product durability is equal to: $\frac{100+80+60+70+60}{5} = 74$

From these group level scores, the Circularity Score can then be calculated by adding the scores for the other two groups i.e. 62 and 63, then, the Circularity Score is equal to: $\frac{74+62+63}{3} = 66$

3.7 Materials of Interest

3.7.1 Materials Footprint – Understanding Impact of Materials from 4 Perspectives

The term carbon footprint is commonly understood as the life cycle carbon equivalent emissions related to for instance a product. In comparison, the concept material footprints is more multifaceted and a number of different perspectives need to be explored from the product life cycle – including use of materials, and the GHG emissions, resource depletion and toxicity aspects associated with the use of materials. The associated materials footprints are closely related to the concept of circular economy and points to the importance of using, re-using and recycling all the materials of a value chain in an optimized way.

What does these footprints look like globally from the perspective of ICT? A research report [23] attempted a top-down approach to derive the materials footprint of the ICT and the closely related Entertainment & Media (E&M) sector across i) amount of materials used; ii) carbon footprint of the materials focusing on Raw Materials Acquisition and End of Life Treatment stages; iii) material resource depletion; and iv) toxicity of materials.

Before looking at these footprints it is important to zoom out and look at the overall use of materials globally. The world has experienced a fast increase in material demand from around 1995. This is largely related to the accelerated economic development taking place in China in the 90's and in other developing countries since 1995. In spite of increasing recycling rates, the share of recycled metals in production is decreasing. The main reason for this is the fast increase in material and metal demand. Since the metals recycled today emerge from much lower production volumes, even a full recycling of these metals would not meet today's demands.

It is also important to understand the importance of recycling. Without high recycling rates a material resource will be consumed relatively fast (i.e. within decades/centuries) and can thus provide less value to society overall, even if product lifetimes are extended by reuse, and product use is made more efficient by sharing. So where are we today? The figure below illustrates, for the period 1985-2015, per material, the estimated global recycling rates, and the global share of recycled materials as percentage of total annual materials usage.

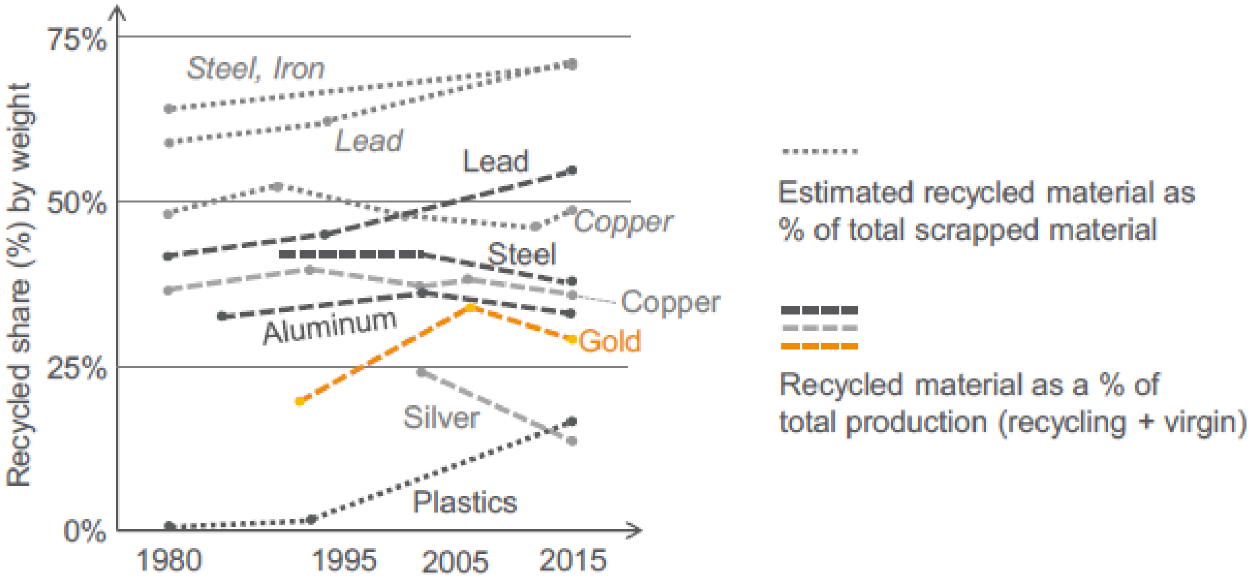


Figure 6. Global recycling rates and share of recycled materials in total materials production for some metals and for plastics. The lines are linear interpolations to show the trend and do not represent the detailed development between the stated years [23].

Material footprint by mass, or shares of mass

The study looked specifically at materials of relevance for the ICT and E&M sectors. For these selected materials the so-called total mass material footprint – hence the total mass of materials used for one year – corresponded to 14 million tons annually compared to the total usages of these materials equaling an overall annual use of 2.6 Gt. This was about 0.5% of the global use of these materials. Electrical and electronic equipment (EEE) in general used about 4% of the same materials. As data is only available for EEE the study needed to derive ICT and E&Ms share of EEEs material usage to arrive at this share.

Looking at the overall share of material is however not sufficient - for some rare metals the share is significantly higher. For instance, ICT and E&M usage represent over 80% of the overall usage of indium, gallium and germanium looking at mass.

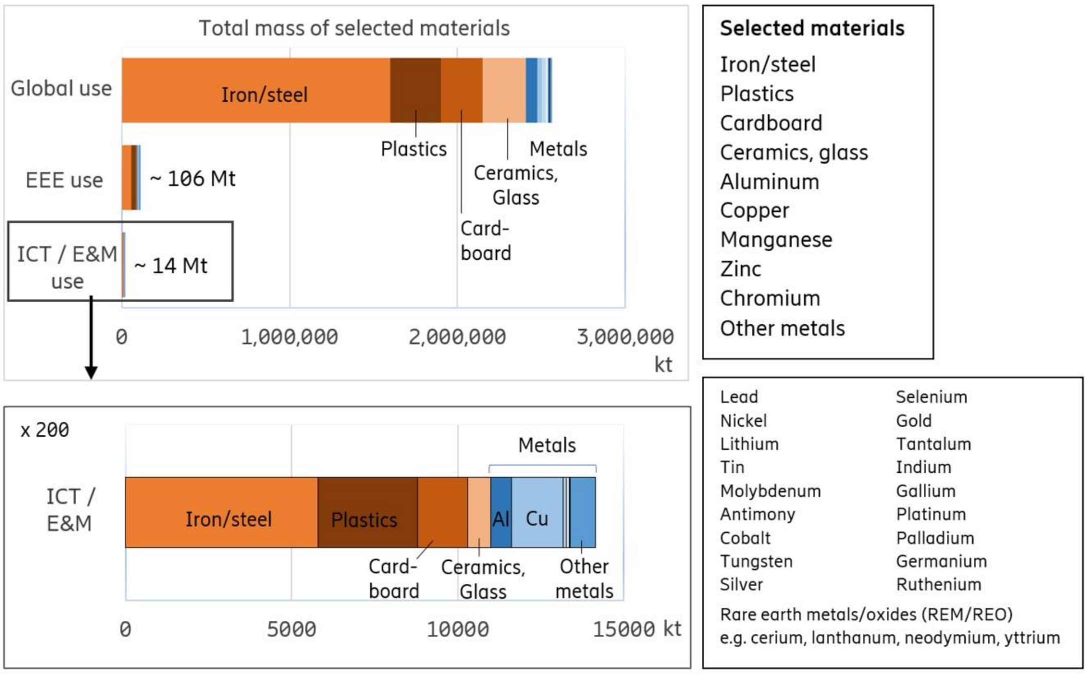


Figure 7. The annual global use of selected materials and the amount used by the EEE sector and the ICT and E&M sectors [23]

Material carbon footprint

The so-called material carbon footprint refers to the GHG emissions related to raw material acquisition.

The material carbon footprint of the ICT and E&M sectors was estimated to be about 0.9% of the carbon footprint for the selected materials using a world average recycling scenario for the ICT and E&M sector. That corresponds to about 0.1% of the overall global carbon footprint (including land use).

Material resource depletion footprint

Resource depletion is when resources are being consumed faster than they can recover. Some raw material resources, especially metals, have become scarcer over the years. Some of these metals are essential for ICT and E&M products, and more generally for EEE. For this reason, the material resource depletion or the Abiotic Depletion Potential (ADP) also is of interest.

In contrast to GHG emissions where a wide consent exists on how to translate usage to impact, there are parallel methods in use to estimate resource depletion which gives great differences in the results, so the uncertainty is high. Using the three most commonly adopted methodologies, ICT and E&M's share of resource depletion was estimated to be 13% (ADP Ultimate Reserve, the most commonly adapted method in LCA's), 31% (ADP Reserve) and 48% (ADP Reserve base) respectively without considering any recycling. Including the current world average recycling rates further decreased the Ultimate Reserve method, the lowest depletion estimate, from 13% to 7%.

Recycling is key to minimize resource depletion in general. Resource depletion would approach 0% if all materials could be recycled properly. For material resource depletion related to ICT and E&M, the key metals are gold and copper and the other metals mentioned in relation to toxicity, but also antimony, indium and geranium.

Material toxicity footprint

This represents the material footprint with regards to the human and ecosystem toxicity potential for the raw materials acquisition and end of life treatment for all products of the studied sectors produced in one year. The material toxicity footprint for the ICT and E&M sectors was estimated to represent about 3% of the impacts related to the global use of the selected materials (including also cement).

Copper followed by gold were the key contributors to the human and ecosystem toxicity potentials. Other materials of special interest were zinc, lead and silver. The uncertainties are very high for toxicity potentials due to uncertainty of impact assessment methods which could not sufficiently consider local conditions and distribution effects, but the results indicate that the ICT and E&M sectors play a much larger role than the total materials usage by mass indicates.

If full recycling could be obtained the toxicity potentials could become nearly zero, but without any recycling the potentials could become nearly twice as high as estimated here.

Combining results

Looking jointly at the four footprints, the difference in results shows the importance of considering all of them, and to look at different materials individually. Looking at just average share of materials is not sufficient to understand ICT´s impact related to materials. Based on the toxicity and resource depletion aspects, gold and copper are found to be the two of the key metals used by the ICT and E&M sectors. Other materials of special interest are zinc, lead and silver (often mined together) from both a toxicity and resource depletion potential perspective, and, from a resource depletion potential perspective antimony, indium, and germanium.

Taken together with the life cycle contribution from materials to climate change and to the exposure of eco-systems and human beings to toxic substances, there are several well-founded reasons for all sectors including ICT to monitor their materials usage and their environmental impacts related to materials. To decrease the impact from materials, it is important to increase reuse and sharing to prolong the lifetime of the products made from the materials. However, the most important measure is to recycle metals, especially rare ones such as gold and copper. In a circular economy the recycling rates need to approach 100% to conserve materials for use by future generations.

3.7.2 Critical Raw Materials as Part of Product's Eco-design

The design of products is influenced by raw materials used for the manufacturing. Some of those raw materials are considered to be critical. According to the definition of the European Union, so-called Critical Raw Materials (CRMs) are of high economic importance to the European economy, however, are also associated with supply risks. Supply risks do have various reasons [24] [25].

- Scarcity Risk: Constraint physical availability
- Geopolitical Risk: Quantity risk due to political and governance activities
- Demand Risk: Volatility of demand
- Environmental Risk: Environmental damage from extraction and processing, human health implications
- Supply Chain Risk: Factors influencing material procurement
- Market Risk: Market viability of products relying on CRMs
- Social Risk: Social implications on local communities, society and workers

Among those factors influencing the risk, scarcity risk and environmental risk need to be especially considered for the eco-design. Scarcity risks can be identified by looking at the depletion time of reserves as well as fractions of companion metals and environmental implications derive from impact of metals due to their toxicity, energy and water, as well as emissions from the processing [26]. For the eco-design of products it is thus crucial to identify on whether materials used will also be available in the future, as well as which negative implications on the environment might appear by using a specific metal.

CRMs are not globally defined, but rather depend on the perspective. Therefore, its definition might differ per organization and the region it belongs to. The European Union however defined the following raw materials as CRMs.

Table 6 CRMs defined by the European Union (2020)

Antimony	Hafnium	Phosphorous
Baryte	Heavy Rare Earth Element (HREE)*	Scandium
Beryllium	Light Rare Earth Element (LREE) **	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	Bauxite
Fluorspar	Niobium	Lithium
Gallium	Platinum Group Metals	Titanium
Germanium	Phosphate Rock	Strontium

* HREEs: Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium
** LREEs: Cerium, lanthanum, neodymium, praseodymium and samarium

To identify risks associated with the business of telecom service providers, a company-level or product-level criticality assessment can be conducted to find out which CRMs bring a higher risk of supply disruptions. For such an assessment firsthand the core equipment for the service and raw materials contained in each equipment need to be identified. A way to collect the data is through a bill of material transparency. Often, a lack of transparencies on the contained raw materials hinders the process. Therefore, awareness should be raised on the topic and collaborations among supply chain partners should be encouraged for the CRMs identification. Once the criticality of each CRM is assessed, various strategies can be implemented to mitigate associated risks.

Improving the 'circular use' of CRMs is gaining attention as one of the major mitigation strategies, which is also stated as part of the EU Action Plan for CRMs [27]. The concept 'circularity' is built upon Circular Economy (CE) principles which in brief can be described in the 3R framework of 'reduce, reuse, and recycle.' The framework can be further expanded in detail to the 9R framework of 'refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover' [28]. The principles come with a hierarchy where reduction is prioritized over reuse, and reuse preferred to recycle.

While various circular strategies can be considered to mitigate the risks associated with CRMs, each strategy comes with its own challenges. Substitution and improving material efficiency can be ways of reducing CRMs contained in the equipment from the designing process.

However, firms might face difficulty substituting certain materials as it might not bring the same performance or require high cost in transforming existing production facilities. Furthermore, in the case of upcoming technologies, the substitution comes with constraints as specific physical properties for the functioning of devices need to be met.

The reuse of equipment helps to extend the materials' value in the chain for a maximum possible period. However, design and circular business strategies should be accompanied to achieve this aim. The equipment and its components need to be designed suited for repair, refurbishment and remanufacturing. At the same time, the downstream of equipment need to be set up by relevant stakeholders to encourage reuse and recycling. Extended Producer Responsibility (EPR) can be an example of this, where the ownership of equipment stays with the producer; thus, equipment is collected and properly reused or recycled at the end of its lifetime. Efforts to adjust regulations on cross-border movements of WEEE to support the reuse of equipment and component need to follow.

When equipment runs out of its market value, CRMs can be recovered via recycling. However, the recycling of CRMs comes with strong limitations, as many CRMs get lost in the recycling process [29] and often their recycling rate remains below 1% [30]. Advanced technologies for CRMs recycling have been in development, even though their commercialization faces challenges due to low CRMs concentrations and lack of economic [32]. The recycled CRMs work as a gateway to the use of secondary materials. Notwithstanding, this needs to be implemented with a comprehensive analysis, as for example the environmental impact of shipping the secondary materials to another continent for component manufacturing can offset the advantages of using recycled materials.

The designing process is crucial for CRMs circularity, as it enables a better adoption of all three CE principles and relevant strategies and determines to which extent the circularity can be achieved in each stage of the product lifetime. For this reason, it is significant that manufacturers design equipment with conditions for CRMs circularity in mind. Not only the information on contained CRMs should be able to be identified and shared transparently across the value chain, but also efforts need to be made among product architects and contract manufacturers to design equipment for the 'reduce, reuse, and recycle' of CRMs. Considering that a significant volume of CRMs is often situated on the printed circuit board, which is highly challenging to disassemble for CRMs reuse or recycle, a further effort to develop circular circuits remain significant.

In a telco environment, the circularity of CRMs cannot be achieved by the effort of one player alone. Active communication and actions by every player in both upstream and downstream of the product value chain is required. A service provider will need a strategic choice of downstream processors and can encourage communication along the value chain. Communication between downstream processors and suppliers will bring insight into what needs to be considered specifically for circular strategies at each stage of the product lifetime.

CRMs are also directly linked to the question of method used in LCA to evaluate impacts such as abiotic resources depletion or raw material depletion. When the LCA analyst selects a method he must be aware of which materials are covered by the method, how the reserves are calculated (e.g. reserve base or reserves available in the entire earth crust up to 10-15 kilometres depth), etc. The number of different parameters makes this choice complex, as it is underlined in [31].

3.7.3 Polymers Circularity in Eco-design

Plastic is typically not used as a pure polymer but as a formulation of polymer plus additives which tailor the plastic to its specific application. In the present processes the additives remain in the post-consumer plastic and are in most cases not a perfect fit anymore for the new application. Therefore, designers need to make certain compromises in the appearance and mechanical properties of the parts.

In order to overcome this restriction, circularity needs to be thought on a molecular level. This leads to the following strategies:

1. Chemcycling, where waste plastic is chemically taken apart into monomers which are then used for the synthesis of new polymers. This allows the same freedom in formulation as with plastic from fossil sources but is yet 100% post-consumer.
2. Use of CO_2 either as a starting material for polymer synthesis or indirect use to create monomers or their precursors.
3. Use of biopolymers: Plant material, created by photosynthesis from CO_2 and H_2O, is used to derive monomers. The polymers are biodegradable and decompose to CO_2 and H_2O again when not needed anymore. This loop somehow follows the example of nature with its yearly cycle of leafage.

More details can be found in [34]. The circularity of structural parts made from plastic needs to be thought in the future on a wider scale to give hardware designers more options and to improve the presently low quota of material reuse of waste plastic.

3.7.4 Regulated Substances in Electronics

Circulation of materials is not sufficient to reduce environmental impact of materials but need to be combined with restricting materials usage to those that are non-hazardous and sustainable [35]. Again, also in this topic the whole supply chain needs to be considered as far upstream as the extraction or production of materials. Mining operations, especially excavation, ore and waste rock transportation, blasting, ore processing, and tailing treatments, are the main impacts produced during the exploitation phase and are involved in climate change, particulate matter formation, and land destruction [36]. Analogous considerations can be made for the process chain of crude oil. On the other end of the lifecycle, harmful substances hamper recycling. Looking downstream, components with hazardous substances need to be handled with care during disassembly, separated and treated in special processes to avoid release into the environment. Electronic waste management remains an important issue, especially in specific regions, that needs to be solved.

In order to control all of these risks, the use of hazardous substances should be avoided. The legislator is partially addressing this. Namely, for such equipment the Reduction of Hazardous Substances (RoHS) directive [37] and its amendment [37][38] is of main relevance. RoHS limits Pb, Hg, Cr(VI), Polybrominated Biphenyls (PBB) and Polybrominated Diphenyl Ethers (PBDE) to 1000ppm each while Cd is limited to 100ppm. [37] limits four of the Phthalates. Further on, parts of the EU Regulation covering Registration, Evaluation and Authorisation of Chemicals (REACH) is applicable with substance restrictions and as well as information requirements [38]. 211 Substance of Very High Concerns (SVHCs) [39] are subject for information requirements in the value chain if they exceed 0.1% in any component, as well as submitting an entry into the Substances of Concern In articles as such or in complex objects (Products) (SCIP) database [40] at the European Chemical Agency (ECHA) [41].

These legal regulations do not cover all hazardous substances that may be contained in equipment. Therefore, it should be the ambition of hardware designers to go beyond and to limit voluntarily more harmful substances. Halogenated hydrocarbons beside PBB and PBDE are still used as flame retardants. Nevertheless, the concerns around bio-persistence apply also to these substances. It is recommendable to make the equipment halogen-free according to [42]. Likewise, it seems arbitrary that RoHS amendment [38] just limits Butyl Benzyl Phthalate

(BBP), Di(2-ethylhexyl) Phthalate (DEHP), Dibutyl Phthalate (DBP) and Diisobutyl Phthalate (DIBP) out of a much larger substance class whose members are all likely to have the same effect on the endocrine system as those four Phthalates regulated by 2015/863. For instance, in the 2005/84/EC [43] six phthalates were prohibited in the type of toy defined by this directive (art. 1): Di-Iso Nonyl Phthalate (DINP), Di(2-Ethylhexyl) Phthalate (DEHP), Dibutyl Phthalate (DBP or DNBP), Di-Iso-Decyl Phthalate (DIDP), Di-N-Octyl Phthalate (DNOP) and Butyl Benzyl Phthalate (BBP). There are several studies [44] dealing with endocrine disruptive chemicals where Phthalates are considered as a whole substance class to have endocrine disruptive properties. Even one of the studies blames exposure to that substance class to be responsible for an increase of diabetes and obesity. Hence, it is also recommendable to extend the limitation voluntarily to the whole substance class. Arsenic, Antimony and Beryllium are harmful in all of its compounds and are used in network and server equipment and these substances should be limited. Gallium Arsenide may need to be exempted as an indispensable semiconductor material, at least where not replaceable by Gallium Nitride. Limits may be 1000ppm (=0.1%) which is typically the borderline between contamination and intentional addition.

Even these additional voluntary limitations do not cover all harmful substances that may be present in ICT equipment. Components today are mainly selected by their technical specification and price. In order to avoid hazardous substances or at least minimize their amounts and hazards, a new process needs to be installed supplementing conventional component selection. The chemical composition of candidate components needs to be reviewed, whether any constituent has health (chapter 3) or environmental (chapter 4) hazard statements, according to the Globally Harmonized System (GHS) for the Classification and Labelling of Chemicals [47]. As GHS applies to chemicals, this consideration needs to be applied to the chemicals that go into the components. The component's chemical composition is typically available in the Full Material Declaration Sheets which can thus be used to make a corresponding assessment. Again, here a meaningful threshold to not chase minor contamination is to have a maximum concentration of 1000ppm (0.1%) per component. There are different routes to proceed following the outcome of such assessment:

1. No constituent with a chapter 3 or 4 hazard statement: the component is compliant and can be taken over into the bill of material.
2. At least one constituent with chapter 3 or 4 hazard statement: the market needs to be checked for alternative components with different chemical compositions, resulting in the following:
   a. No alternative component available: Harmful substance needs to be temporarily accepted as currently irreplaceable. The raw material industry needs to be

requested to develop an alternative substance fulfilling the same physical function but being less harmful.

b. Alternative component without a constituent with a chapter 3 or 4 hazard statement: the component is okay and can be taken over into the bill of material.
c. Alternative component with a constituent with a chapter 3 or 4 hazard statement: a least risk approach is required where the constituents are evaluated by the amounts of harmful substances contained and the severity of their hazard statements. The component with the least risk needs to be taken over into the bill of material.

The open access Hazard Statements Indicator (HSI) method is also relevant for evaluating which material combination is the least toxic and hazardous [48].

3.8 Methods Used to Determine Re-manufacturing and Refurbish Benefits

ITU-T has published a Recommendation L.1024 which explores how much carbon emissions could be avoided if certain ICT goods are reused a second time [49]. L.1024 also contains an analytical method which is useful for determining the environmental benefit of remanufacturing.

3.8.1 Base station Remanufacturing Trade-offs

Here the analytical approach is applied to a wireless base station. Table 7 shows an LCA result for the base station [50].

Table 7 Summary of approximate life cycle environmental impacts of larger base station without refurbishment

Environmental impact category	Manufacturing	Use	End-of-life
GWP100, kg CO_2 equivalent (CO_2e)	2887	≈60000 . NOTE: All base stations have different use stage impacts.	135
ADP, g antimony equivalents (Sb-e)	14000	≈4. NOTE: All base stations have different use stage impacts.	Not available.

For base stations it is not evident to which degree different sub-parts are re-used, so for the sensitivity calculation it is assumed that all sub-parts are re-used, as presented in Table 8.

Table 8 Hypotheses for Reused parts of base station and reuse rates

Sub-part	kg CO2e, GWP100/piece	g Sb-e, ADP/piece	Re-use rate (%)
Pre-equipped Cabinet including shelves	247	Not available	100
Filter Unit	525		100
Amplifier Unit	649		100
Digital Shelf Unit containing different Circuit Packs -- standard Surface Mount (SM) and Through-Hole (TH) components	1438		100
Cabling	33		100

The following equations (1) and (2) show the environmental benefits of remanufacturing base stations for GWP100 and ADP, respectively.

$$\partial_{GWP,base\ station} = 1 + \frac{(\Delta P_{GWP} - PRE_{GWP})}{U_{A,GWP}} = 1 + \frac{((2887) - 0.5\% \times (2887))}{60000} = 1.05 \qquad (1)$$

$$\partial_{ADP,base\ station} = 1 + \frac{(\Delta P_{ADP} - PRE_{ADP})}{U_{A,GWP}} = 1 + \frac{((14000) - 0.5\% \times (14000))}{4} = 4.48 \qquad (2)$$

The higher the value of ∂, the higher the environmental benefit of refurbish/remanufacturing. As shown by equation (1), refurbishment is not CO_2 beneficial when the energy consumption of the refurbished base station is more than 5% higher than the energy consumption of a new base station. It would be even lower if not all sub-parts are reused, and for those base stations which have high relative remanufacturing eco-costs (here assumed 0.5% of the embodied footprint). Base stations which have higher relative use stage impacts would also cause lower environmental benefit of remanufacturing.

For the equation 2 the calculation follows the same logic. The 4.48 means that refurbishment is not beneficial when the energy consumption of the refurbished base station is more than 348% higher than the energy consumption of a new base station.

3.8.2 Enterprise Server Remanufacturing Trade-offs

Here the analytical approach is applied to a server. Table 9 shows an LCA result for the server [51].

Table 9. Summary of approximate environmental impacts of the life cycle of an enterprise server without remanufacturing

Environmental impact category	Manufacturing	Use (4 years)	End-of-life
GWP100, kg CO2e	858.3	3077.2	-58.9
ADP, kg Sb-e	0.11	0.001	-0.07
Cumulative Energy Demand (CED) (MJoules)	12724	71500	-696

Scores like those in Table 9 can also be obtained by using the LCA standard L.1410 [14]. The re-use rates in Table 10 are used to identify which sub-parts to include in the calculation.

Table 10. Hypotheses for Reused parts of server and reuse rates.

Sub-part	Mass (g)	kg CO2e, GWP100/piece	kg Sb-e, ADP/piece	Re-use rate (%)
Hard Disc Drive	1750	83	0.01	47.7
Memory cards	135	140	0.013	40.1
CPUs	54	200	0.028	5.2
Power supply	3426	340	0.0043	5.0
Mainboard	1662	210	0.029	2.7
Raid card	5.2	0.37	0.000023	2.1
Chassis	13454	99	0.0047	1.4
Expansion card	349	50	0.0078	0.7

The following equations (3) and (4) show the environmental benefits of remanufacturing servers.

$$\partial_{GWP,server} = 1 + \frac{(\Delta P_{GWP} - PRE_{GWP})}{U_{A,GWP}} = 1 + \frac{((83+140) - 0.5\% \times (83+140))}{3077.2} = 1.07 \qquad (3)$$

$$\partial_{ADP,server} = 1 + \frac{(\Delta P_{ADP} - PRE_{ADP})}{U_{A,GWP}} = 1 + \frac{((0.01+0.013) - 0.5\% \times (0.01+0.013))}{0.001} = 23.9 \qquad (4)$$

One interpretation of Equation (3) (environmental benefit score 1.07) is that remanufacturing is not CO_2e beneficial when the energy consumption of the remanufactured server is more than 7% higher than the energy consumption of a new server.

In the Equation (4) the 23.9 means that refurbishment is not beneficial when the energy consumption of the refurbished server is more than 2290% higher than the energy consumption of a new server.

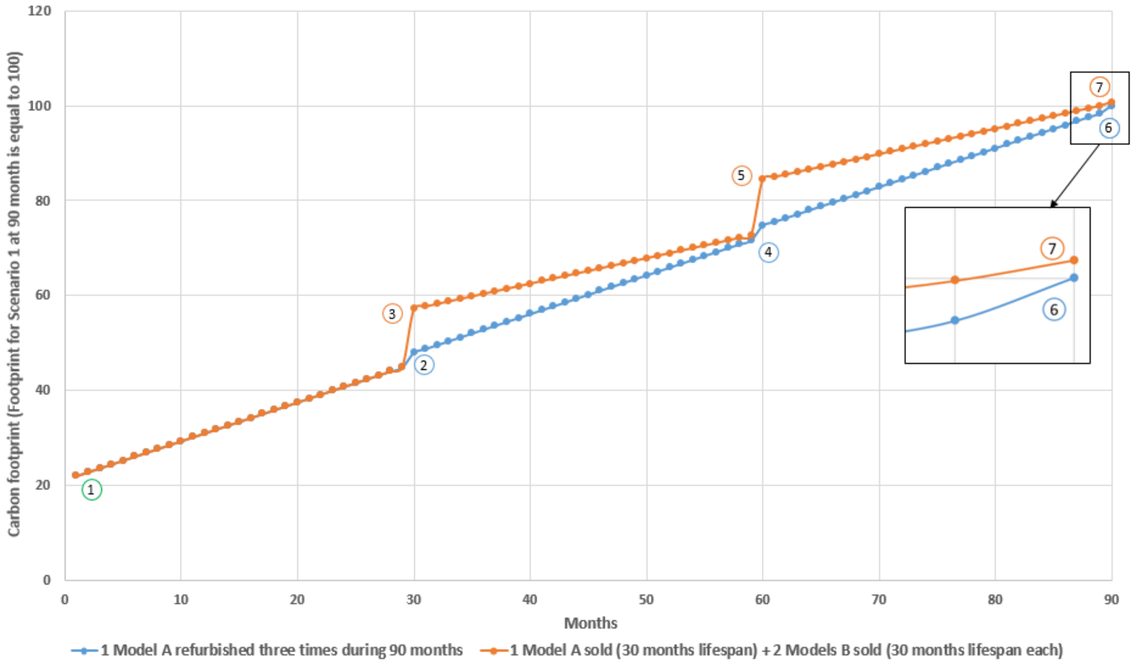
3.8.3 Home Network Equipment Refurbishment Trade-offs

The recent ITU-T recommendation L.1024 [49] also features a methodology which enables consideration of benefits from remanufacturing, as well as the potential effects of energy efficiency improvement between different generations of equipment.

Figure 8 shows the comparison between two different business models for the Home Network Equipment studied in the Section 3. The first business model, highlighted in blue, involves the refurbishment of an older generation of equipment (noted model A). This model is not very energy efficient and as such the slope of the line is pretty steep. However, as this equipment is refurbished, there is no need to manufacture several devices during the 90 months lifespan. A small increase of the environmental footprint can be noticed during the refurbishment steps (noted with 2 and 4). This is related to the transport of the equipment to the refurbishment centre, the spare parts required to achieve an "as-good-as-new" quality level functionally and aesthetically wise, as well as the energy and ancillary materials required to operate the refurbishment centre.

The second business model, highlighted in orange, starts with the same old model A of equipment. But after 30 months of operation this device is replaced by a more energy efficient equipment, noted model B (step 3). After an additional 30 months this equipment is also sent to the end-of-life stream and replaced by a new one (step 5). As model B's energy efficiency is better the slope of the orange line is less steep. However, each time a new equipment is manufactured the carbon footprint increases drastically.

After 90 months of lifespan for these equipment (and according to the hypothesis which were set up) the carbon footprint of the business model featuring refurbishment is very close to the one based on selling equipment (respectively steps 6 and 7 in Figure 8), with a marginally lower impact for the first model.



① For both scenarios: manufacturing and shipping of one Model A Home Network equipment (HNE)
② For Scenario 1: refurbishment of Model A HNE
③ For Scenario 2: end of life of Model A HNE + manufacturing and shipping of first Model B HNE
④ For Scenario 1: refurbishment of Model A HNE
⑤ For Scenario 2: end of life of first Model B HNE + manufacturing and shipping of second Model B HNE
⑥ For Scenario 1: end of life of Model A HNE
⑦ For Scenario 2: end of life of second Model B HNE

Figure 8. Carbon footprint comparison of two different business models for Home Network Equipment

This method allows to obtain very precise results regarding different business models and for different environmental indicators (the results showed in Figure 8 can also be calculated for an indicator as Abiotic Resources Depletion). However, it requires to have in hand all the data on the life cycles (e.g. environmental footprint of the manufacturing, how many spare parts are required, what is the energy consumption of the different models, etc.).

The results in Figure 8 show that refurbishment is not a silver bullet that will always allow to reduce the environmental impacts. For a given type of equipment the energy efficiency improvement between two generations of products, as well as the potential new features, have to be assessed, especially for equipment powered 24/7. The mechanical design of the equipment (e.g. can it be disassembled quickly and without breaking any part) and the durability of the different sub-assemblies (e.g. resistance to wear for the casing parts) will also have a significant influence on the final result. Thus, for an equipment that was not designed according to “Design-for-refurbishment” requirements it will be more challenging to achieve benefits by applying this business model as it might lead to quasi systematic swaps for different parts.

3.9 Procedures for Integrating Eco-design into the Product Development Process

Manufacturers have developed frameworks in which LCA, circularity and eco-design with eco-metrics (such as recycled content and packaging materials mass and volume) can be integrated [52]] in the design process, as presented in Figure 9.

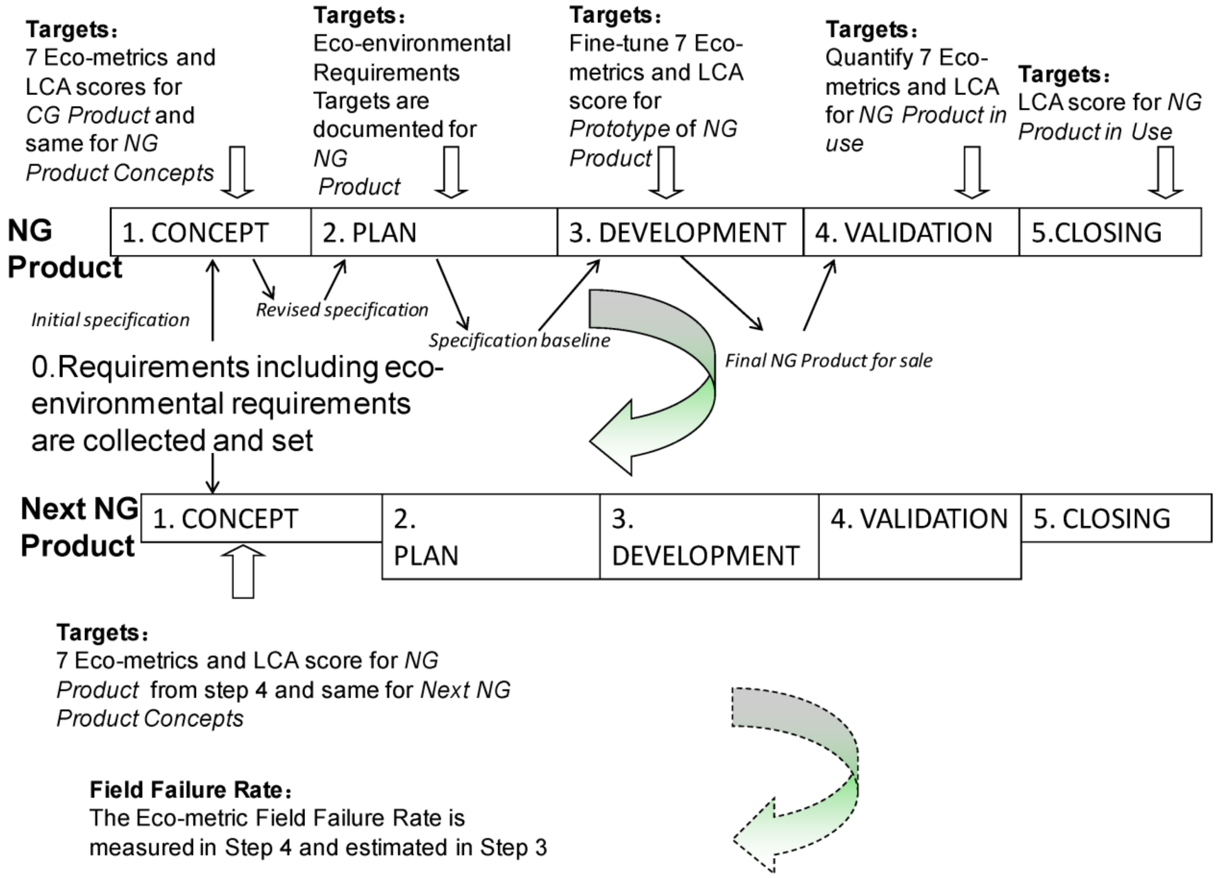


Figure 9. Steps of typical product development and the actions and targets for eco-design.

In the Collection Stage (0) the inputs are e.g. roadmaps for energy efficiency and LCA scores of similar products as the Current Generation Product (CGP). Based on the features obtained from customer surveys and analyses of voluntary trends, several technical/functional/performance requirement targets, and some environmental requirement targets are set. e.g.:

- Reduce the overall power usage compared to CGP
- Introduce recycled content materials

The output from the Collection Stage (0) is the initial specification.

In the Concept Stage (1) the most promising concepts and optional solutions are listed and drafted based on technical/functional/performance requirements and green requirements. The green requirement targets can be set based on findings in the customer surveys documented in the initial specification. Moreover, for the CGP, in use by the customer, the seven or more eco-metrics i.e. 1. energy efficiency, 2. packaging materials mass and volume, 3. hazardous substances, 4. precious metals, 5. total mass, 6. recyclability/recoverability/reuse-ability/disassemble-ability, 7. lifetime reliability and final LCA score (GWP100, ADP, single scores etc.) are obtained. For Next Generation Product (NGP) concepts the same eco-metrics are defined and preliminary LCA scores are obtained for each concept proposed by designers.

For CGP the final LCA score and measured Field Failure Rate (FFR) value are possible to obtain as CGP is a final product used in the market. All eco-metrics are estimated and the preliminary LCA scores are calculated for the different NGP concepts. The output from Concept Stage (1) is the revised specification.

In the Plan Stage (2) the design is planned. Moreover, the green requirement targets in design are documented in the report from Plan Stage. For example, for the Base Station example given in Section 3.5.1 the targets of the Plan Stage could be:

- fine-tune and improve three of seven or more eco-metrics
- uses recycled metals for the Pre-equipped Cabinet including shelves
- has >10% lower packaging material mass than CGP
- has at least 3% better power efficiency than CGP
- has better absolute LCA score than CGP

The output from Plan Stage (2) is the specification baseline for NGP. Revised specifications are developed into a specification baseline to be fine-tuned during the subsequent Development Stage (3). In the Development Stage (3) the system architecture and the detailed design for NGP are formed. The detailed NGP design is based on the specification baseline for a NGP concept. Prototypes are created and then fine-tuned repeatedly to meet the technical/functional/performance and green requirements. The designers find ways of fine-tuning the applicable eco-metrics further for the NGP Prototypes resulting in Final NGP. The new fine-tuned values of the eco-metrics and the LCA score for the Final NGP design are quantified and calculated, respectively, and put into the report from Development Stage (3). The Final NGP is manufactured and sold.

The requirements from Plan Stage (2) are checked to validate how the eco-metrics and the LCA score were investigated for NGP. It is also checked if the requirements from Plan Stage (2) are fulfilled. The Development Stage (3) is followed by the Customer Validation (4) process.

The Customer Validation Stage (4) validates data from the use phase of NGP. Here the final values of the eco-metrics and the LCA score for the final NGP design are quantified and calculated, respectively, and put into the report from Customer Validation (4). Here the FFR values are based on actual failure samples of NGP returned by customers. The eco-metrics values from Customer Validation Stage (4) will be used as benchmark for the next NGP.

In the Closing Stage (5) another LCA score is calculated based on additional data from the life cycle of NGP and the design project for NGP is closed. The LCA score from this the Closing Stage (5) is usually very close to the previous from Customer Validation (4). Design stages 0 to 5 (Figure 9) are then repeated for next NGP e.g. starting with collecting new customer requirements (from e.g. roadmaps and LCAs).

3.10 Packaging Innovation by Eco-design

A wide variety of products which need packaging exist in large ICT companies. At present, Traditional Packaging (TP) technologies consume pointlessly high amounts of resources that generate excessive pollution and waste. So called Lean/Smart Packaging (LSP) concepts could help reduce such emission, resource, and waste footprints. Regarding circular eco-design of packaging, LSP has been proposed [53]. LSP concepts are compared to TP concepts by a simplified LCA. Regarding assessment of total environmental burden, the recent trend is to use numerous weighting indicators instead of one or two mid-point indicators. Hence, one primary energy indicator Cumulative Energy Demand (CED) and three “eco-cost” weighting methods - Environmental Priority Strategies (EPS), Life cycle Impact Assessment Method based on Endpoint modelling (LIME) and International Life Cycle Data network (ILCD) - are included.

The LSP is made possible from six design strategies: reduce, return, reuse, material recycle, recover (energy) and degrade. This is coherent with packaging eco-metric improvement within eco-design processes (See Section 3.6).

The scope is as shown in Figure 10 and the studied product system is Raw Material Acquisition and Distribution. The cut-off are the assembly and end-of-life of the packaging materials. The assembly of the ICT infrastructure good (Electric and Electronic Equipment, EEE) is out of scope.

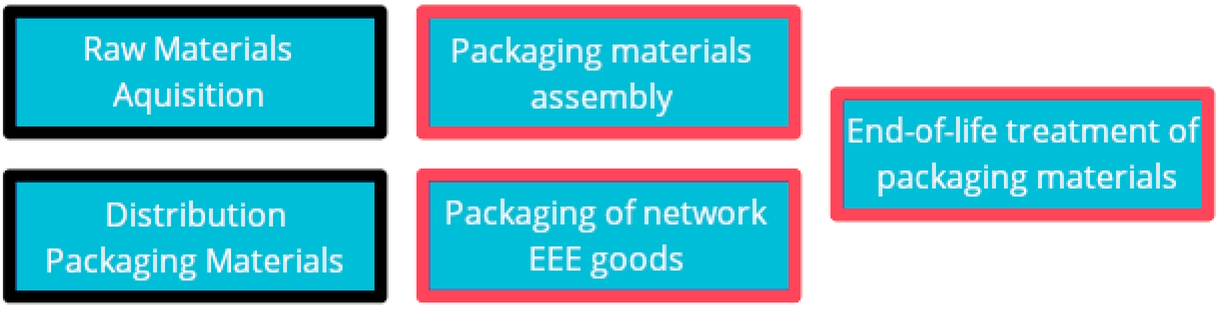


Figure 10. The scope and studied product system for packaging concepts comparative LCA study by ICT manufacturer (Anders Andrae, Huawei).

As shown in Figure 11 to Figure 14; lower masses, smaller volumes and green packaging concepts (LSP) can at first sight clearly reduce the environmental footprint compared to TP. The first example shown in Figure 11 refers to the development and application of plastic-steel light pallets, instead of plywood pallets. Plastic pallets are known replacements to wood ones but plastic-steel pallets have not yet been evaluated. The functional unit (f.u.) is "one pallet transported 10000 km by ship."

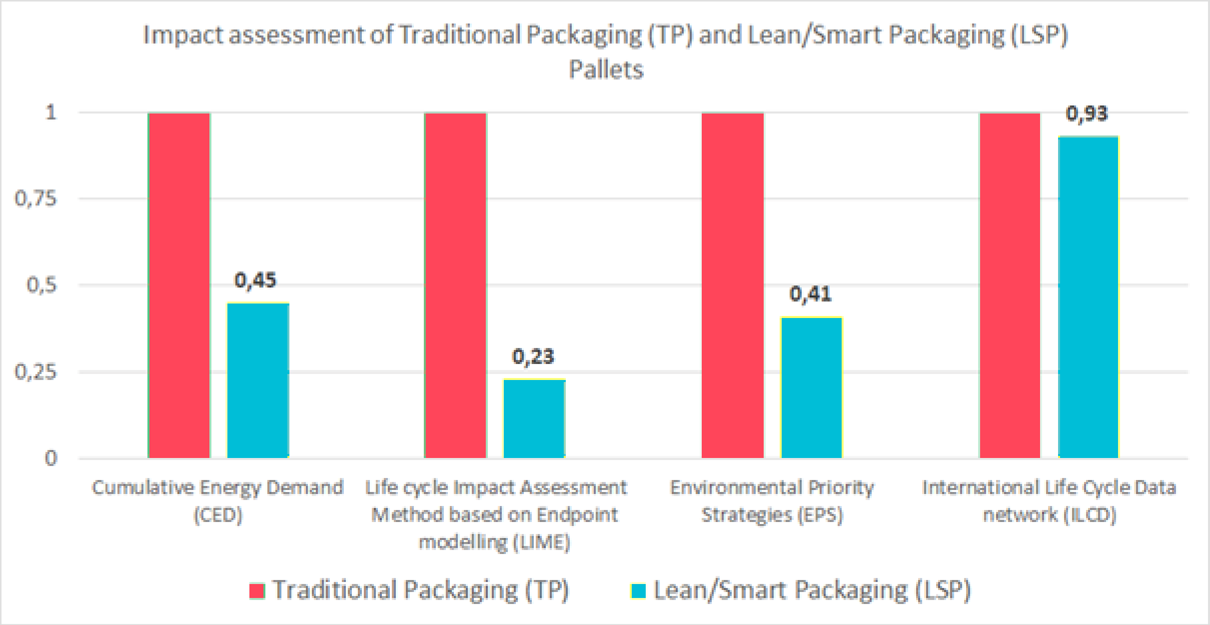


Figure 11. Relative environmental footprint score of pallet concepts used by ICT manufacturer

The second example in Figure 12 refers to development and application of cover boards as a way to reduce weight and wood consumption. Thinner paper boards can here replace wood ones. The f.u. is "one cover board transported 10000 km by ship."

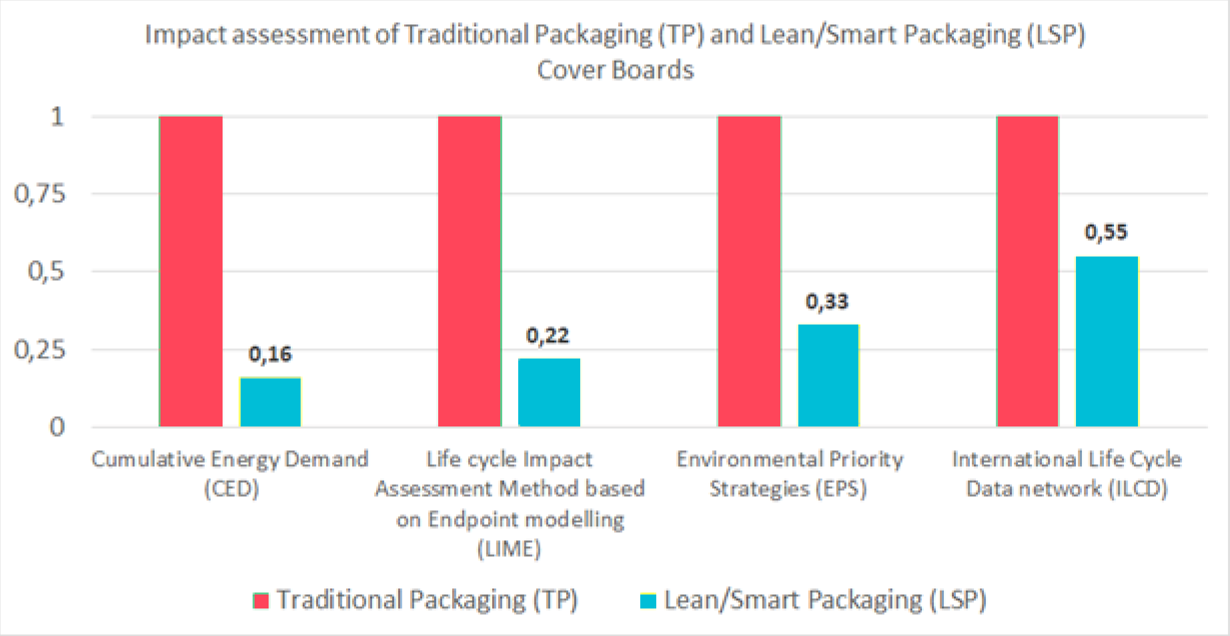


Figure 12. Relative environmental footprint score of cover board concepts used by ICT manufacturer

The third example in Figure 13 refers to the development of new gap filling methods done to reduce the packaging volume and reduce waste. The f.u. is “packaging material for one EEE module transported 10000 km by ship.” EEE module production - and EEE mass effect on ship transport - are excluded.

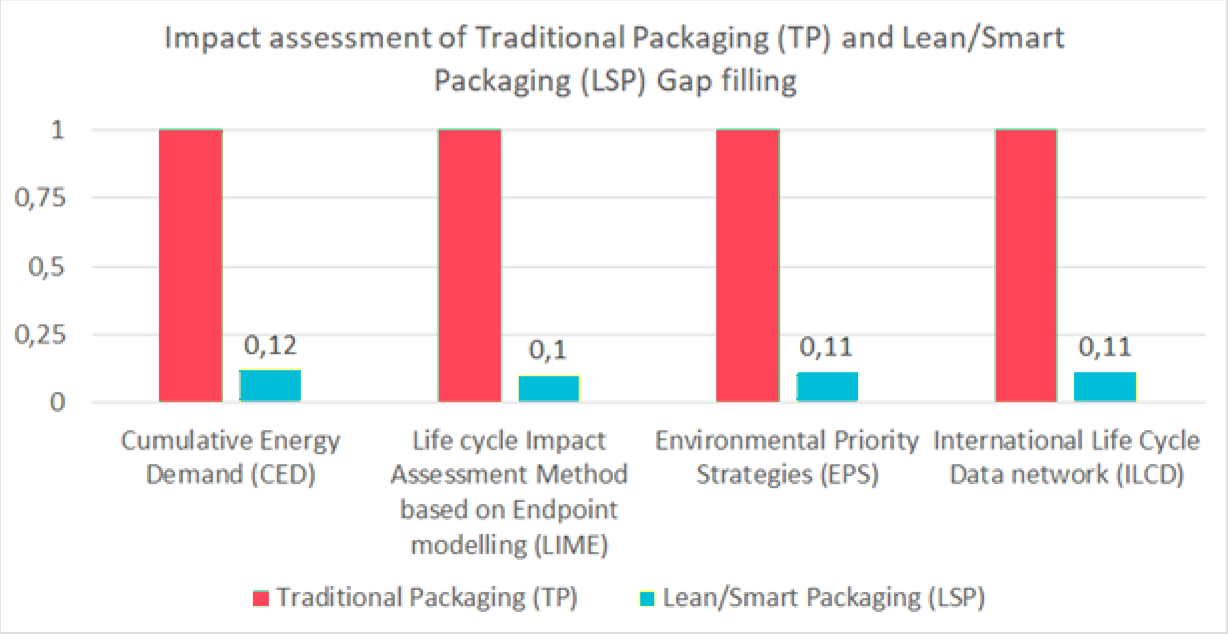


Figure 13. Relative environmental footprint score of gap filling concepts used by ICT manufacturer

The last example in Figure 14 refers to the development of a complete packaging solution which is done to reduce the overall weight and volume. Predominantly, as a result of this innovation more EEE goods can be stacked per pallet. However, this packing rate effect is not yet included as far its effect on the overall environmental footprint. The f.u. is "one complete package for one EEE good transported 10000 km by ship."

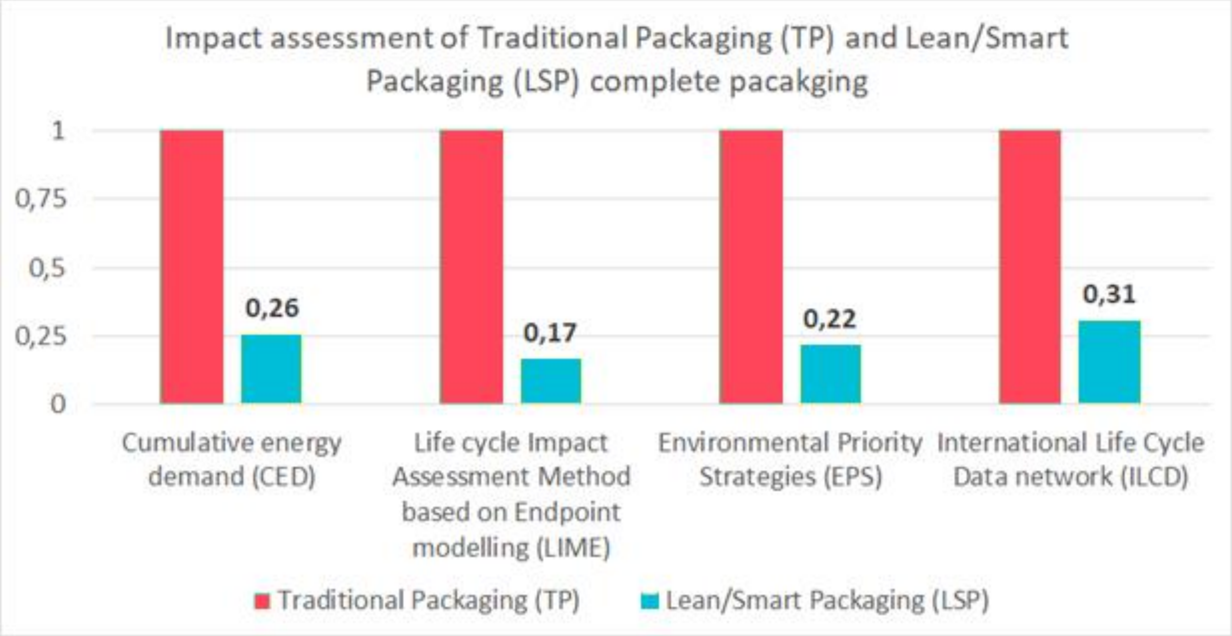


Figure 14. Relative environmental footprint score of complete packaging concepts used by ICT manufacturer

The next step is to increase the circularity further of the packaging and switch from end-of-life treatment to end-of first use.

3.11 Eco-rating, Eco-labels, Eco-information

Telecommunication companies use ecolabels to communicate the environmental performance of ICT network infrastructure products. So far, servers are the most commonly addressed product group and in fact no eco-label criteria have yet been developed for radio equipment. LCA and other tools are used to better inform customers of the environmental impacts of the products they purchase and the LCAs are used to guide the eco-labels and Environmental Product Declaration (EPD) such as the PEP ecopassport [54].

EPD for telecom include: power, signalling and telecom systems [55], PV inverters [56], and Zigbee Routers [57]. However, these EPDs are not common and recent. The energy label created under the EU's Energy Labelling Directive [58] is also used to inform customers about the energy performance of e.g. enterprise servers and data storage products. Please notice that the currently existing ecolabels for telecommunication equipment concern mainly servers. Some of the most electricity using equipment in the ICT networks, i.e. radio equipment, have yet to determine an energy efficiency label or certificates.

Existing ecolabels created in different parts of the world specifically for servers are:

- TCO Certified is a globally recognised sustainability certification for IT products in offices and data centres. TCO Certified is developing new criteria for servers [59].
- Electronic Product Environmental Assessment Tool (EPEAT) is a global ecolabel for the IT Sector developed by the Green Electronics Council. EPEAT has published criteria for servers [[60].
- China Environmental Products Labelling program. Some manufacturers have embedded eco-design for e.g. rack servers, blade servers, multi-node servers, integrated storage servers, and distributed storage servers to minimize negative impacts and conserve energy resources. They thereby received the China Environmental Product Label.
- Thayer Certification Centre (TLC) [61] has a certification scheme for green products. The certification focuses on energy conservation and also measures indicators spanning environmental protection, EMC, safety specifications, production processes, packaging, and recycling. Some manufacturers' Uninterruptible Power Supply (UPS) products have received this certification for Green Product Certification.

3.11.1 European Green Deal and Circular Economic Action Plan 2.0 - Digital Product Passports with Sustainability Information for all Products?

It is important to highlight that the Directorate General for Communications Networks, Content and Technology (DG Connect) is in the process of creating a digital EU product passport system and a common European "Dataspace for Smart Circular Applications" (EDSCA). Both are part of the Circular Economy Action Plan. EU Product passports are expected to include information about recycled content, critical materials, hazardous materials and carbon footprint [62], [63].

Open Architecture Framework Electronic exchange systems will be the enabler for digital EU product passports of each individual product placed on the market.

4 END TO END SERVICES FOOTPRINT

There is an increasing demand, both internally in companies and externally from regulation bodies or B2B customers, for a thorough measurement of the environmental impact of services, taking into account the services' full life cycle, including the devices. This section will show the latest methodological advances in this field, including the links to eco-design.

What is an end-to-end services footprint?

The main objective of end-to-end services footprint may be to answer how much energy is used to provide a certain access service.

Several challenges exist that render this kind of assessment complicated for the operators:

- Eco-design of the ICT infrastructure equipment and network will lead to a reduced environmental footprint of the services delivered. But how can individual service footprints be estimated?
- Over The Top (OTT) services content pass through the networks without any restriction, operators have no control of the quality of the content (for instance resolution and HDR support for a video) and therefore on the impact it will have on the network's performance and their energy consumption.
- The share of the costs of non-requested content (e.g. advertisements) is not clear.
- How to quantify and control the content quality, as a function of the environmental impact, is not evident.

In order to answer such questions, knowledge about the network constituents and their actual energy consumption in the use stage are necessary. Network operators have that knowledge and the ICT good manufacturers have the best knowledge of the upstream manufacturing footprint, mainly via LCAs performed of network elements.

End-to-end services typically span across the end-to-end network, from end user application, to device, access, transport, edge/core and back end service platform & application. Different services have different profiles. In 5G, three categories of services have been defined: eMBB, uRRLC and mMTC [64]. Each of this service has different KPIs in terms of latency, density, throughput/bandwidth, etc. One of the key measurable impact of an end-to-end service is energy consumption and the associated KPI energy efficiency.

To measure end-to-end service energy consumption different approaches can be adopted. Either a top-down approach, which considers the overall operator energy consumption and then estimates for each end-to-end service in the portfolio, what is the ratio of each service, either based on data volume or number of subscribers. Or a bottom-up approach, trying to measure and consolidate the underlying physical infrastructure consumption, the ratio used by the virtual infrastructure for a given service and the consumption of this virtual network and then decompose per end-to-end service flowing through this virtual infrastructure. But then this end-to-end service energy consumption can be calculated for all the subscribers of that service, or per subscriber, or even more granular per application of given subscriber using that service. The driver to choose one option or the other can typically be to meet regulation, i.e. French regulation (see below for more details), or to meet customer engagements, i.e. a network slice with a given energy efficiency, or more generally speaking to measure the energy consumption and efficiency for given volumes or applications in order to improve and best adapt underlying resources. However today no standard is available to measure end-to-end service, or network service, or network slice energy consumption.

3GPP has introduced a number of energy management metrics and KPIs. Typically the 5G RAN produces power metrics defined in [65]. Similarly 3GPP SA5 Rel 17 has started to define KPIs such as network slice energy efficiency in [66], for the three different types of services, eMBB, mMTC and uRRLC. These calculations are either based on data volumes or end-to-end latency for instance. The energy consumption was out of the scope of this work.

A number of research papers have been published on topics related to calculation, or estimation of energy consumption for different aspects of the network, but none have really tackled the complexity of energy consumption of dynamic 5G services, on dynamic virtualized network topologies, multi-tenant, multi-party services, with potentially handover across heterogeneous access. This area still requires some research and innovation.

Other aspects could be considered as well, like the impact of a service on human behaviour and the associated impact on the environment. One example would be a navigation service that is proposing a path through highways because of better mobile coverage instead of the shortest path and induce a higher energy consumption of the end user’s car but these are more indirect footprint and out of the scope of this White Paper.

Existent works

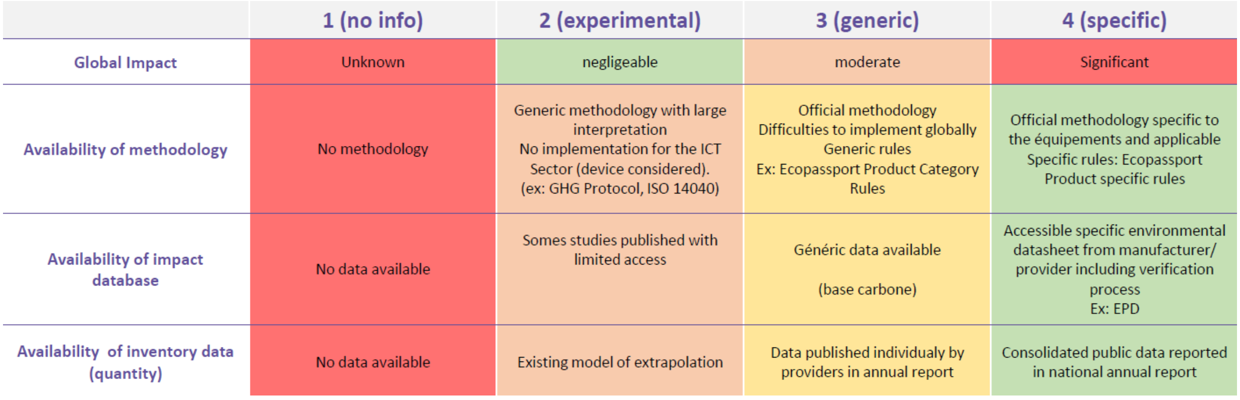
ETSI EE ES 203 199 [13]]/ITU L.1410 55 standards address services as well as products and networks and propose a starting point for such assessments. The development of this standard involved a wide range of participants including companies and authorities, and delegates from different regions. The joint ITU/ETSI standard considers the full life cycle. This standard should be the basis for any further standardization effort, e.g. detailed standardization of assessment of specific services.

Recently the ITU has also been developing a simplified method to assess the environmental footprint of networks. This work item, called L.Methodology_Arch was consented as L.1050 [67] during May 2021 ITU-T study group 5 workshop. This method does not target to assess the environmental footprint of the network with level of detail as high as a full LCA could provide, but rather to ideally capture at least 80% of the environmental footprint of the studied network. As such the recommendation features 3 lists of network equipment (one for FTTH network, another for mobile network and a third one for satellite networks) which should be considered in the assessment.

Researchers have also studied the environmental footprint of individual services thorough various methods [68][69][70][71]. Lately, the carbon footprint of services has created interest, in particular in France, where the new French law [[72] will oblige operators to "inform their subscribers of the quantity of data consumed in the context of providing access to the network and indicate the equivalent of the corresponding greenhouse gas emissions". The first version of the law will enter into application the 1st of January 2022 with a simplified calculation. This means that the different fixed networks (FTTx, xDSL, cable) will not be differentiated and the mobile networks will be all merged without considering the different radio technologies (2G, 3G, etc.). In 2023 and 2024 further development will take place including establishing inventories of network equipment (and their configurations) used by the different operators. This will help to fine-tune the environmental footprint at network level for the French operators and also to distinguish the environmental footprint of the different technologies.

Also, at French regulatory level the ARCEP (telecommunications regulation authority) and the ADEME (French environment agency) have launch a project to measure the environmental impact of digital technologies within their technical expert committee. Within this working party the consultants from NégaOctet project proposed a life cycle approach, including several environmental indicators (global warming, abiotic resources depletion, etc., to avoid pollution transfers to other impacts) and with a functional approach to allow comparison (environmental impacts assessed according to the performance of the product or the service). To be able to deal with services the perimeter will include end user devices, Internet of Things (IoT), network equipment as well as data centre and cloud.

As this task can be quite daunting, a first proposal was sent by NégaOctet to the members of the technical expert committee to identify for different categories of equipment what is their global environmental footprint (noted "global impact" in Figure 15), if methodologies and databases are available to assess this impact as well as the question of data availability regarding equipment inventories.

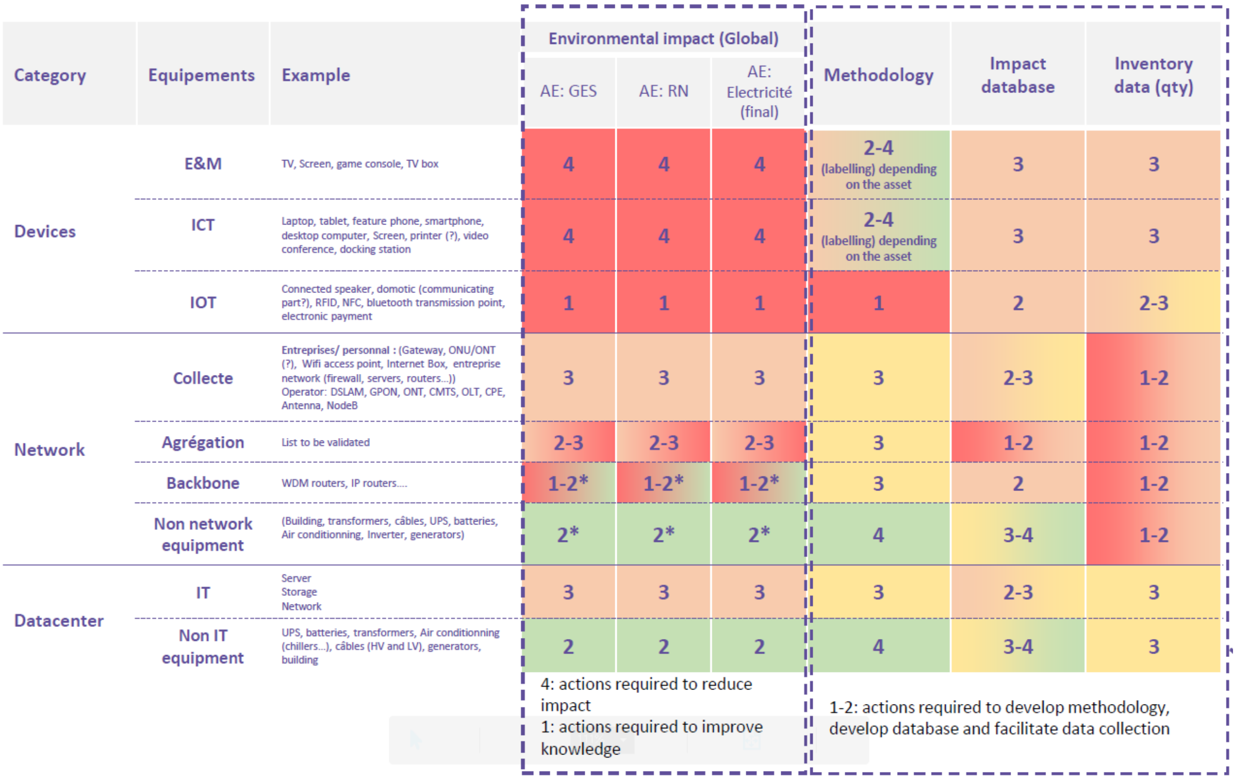


	1 (no info)	2 (experimental)	3 (generic)	4 (specific)
Global Impact	Unknown	negligeable	moderate	Significant
Availability of methodology	No methodology	Generic methodology with large interpretation No implementation for the ICT Sector (device considered). (ex: GHG Protocol, ISO 14040)	Official methodology Difficulties to implement globally Generic rules Ex: Ecopassport Product Category Rules	Official methodology specific to the équipements and applicable Specific rules: Ecopassport Product specific rules
Availability of impact database	No data available	Somes studies published with limited access	Généric data available (base carbone)	Accessible specific environmental datasheet from manufacturer/ provider including verification process Ex: EPD
Availability of inventory data (quantity)	No data available	Existing model of extrapolation	Data published individualy by providers in annual report	Consolidated public data reported in national annual report

Figure 15: Levels for global impact, availability of methodology, availability of impact database and availability of inventory data as defined in NégaOctet proposal (Source NégaOctet presentation).

For the different categories of equipment a proposal was also made by NégaOctet in order to identify which are the critical factors for each category. For instance, as shown in Figure 16 the environmental footprint is assessed according to three indicators: "AE:GES" for Global Warming Potential; "AE:RN" for abiotic resources depletion and "AE: Electricité (final)" for the electricity consumption.

This matrix, with the inputs of the different members of the technical expert committee, will be further refined to identify if the next steps should be focused on carrying out life cycle assessment for equipment with high impact and for which no data is currently available. Or if the overall issue is first to set up common methodologies to assess this environmental footprint.



Category	Equipements	Example	Environmental impact (Global) AE: GES	AE: RN	AE: Electricité (final)	Methodology	Impact database	Inventory data (qty)
Devices	E&M	TV, Screen, game console, TV box	4	4	4	2-4 (labelling) depending on the asset	3	3
	ICT	Laptop, tablet, feature phone, smartphone, desktop computer, Screen, printer (?), video conference, docking station	4	4	4	2-4 (labelling) depending on the asset	3	3
	IOT	Connected speaker, domotic (communicating part?), RFID, NFC, bluetooth transmission point, electronic payment	1	1	1	1	2	2-3
Network	Collecte	Entreprises/ personnal : (Gateway, ONU/ONT (?), Wifi access point, Internet Box, entreprise network (firewall, servers, routers…)) Operator: DSLAM, GPON, ONT, CMTS, OLT, CPE, Antenna, NodeB	3	3	3	3	2-3	1-2
	Agrégation	List to be validated	2-3	2-3	2-3	3	1-2	1-2
	Backbone	WDM routers, IP routers….	1-2*	1-2*	1-2*	3	2	1-2
	Non network equipment	(Building, transformers, câbles, UPS, batteries, Air conditionning, Inverter, generators)	2*	2*	2*	4	3-4	1-2
Datacenter	IT	Server Storage Network	3	3	3	3	2-3	3
	Non IT equipment	UPS, batteries, transformers, Air conditionning (chillers…), câbles (HV and LV), generators, building	2	2	2	4	3-4	3

4: actions required to reduce impact
1: actions required to improve knowledge

1-2: actions required to develop methodology, develop database and facilitate data collection

Figure 16: Matrix of equipment involved in digital sector environmental assessment, their global impact, the availability of methodology and databases to assess this impact and inventories (Source NégaOctet presentation).

5 CONCLUSION

In view of the achievements attained during last years, specially at ETSI and ITU-T organizations, and to continue advancing, vendors and operators are encouraged to participate in standardization efforts on the equipment environmental footprint reduction in order to share knowledge, develop and adopt common approaches.

Moreover, considering the presented LCA methodology used to assess the environmental footprint of network equipment and to guide the eco-design process in order to reduce the environmental footprint of network equipment, network providers and operators should integrate in the system definition, specification and purchase process requirements related to circular economy (for instance, according ITU-T L.1023) and environmental footprint assessment (using the LCA method, for instance with ITU-T L.1410).

Based on the view on the materials footprint and the role of critical raw materials as part of product's eco-design given, considering the associated supply risks, vendors should develop and increase awareness of the challenges related to GHG emissions or resources depletion (scare or critical materials) of network equipment. To this end, the technical skills on eco-design and life cycle assessment are to be expanded.

Also, methods used to determine re-manufacturing and refurbish benefits have been presented. Investigating new business models related to the circular economy paradigm appears as an interesting path, too. For instance, switching to Product-Service-System (PSS) could reduce the environmental footprint, or to include in hardware design strategies considerations about longevity, modularity and upgradability.

Finally, and in order to continue advancing in the network's environmental footprint reduction, NGMN suggests increasing the efforts to develop common methodologies to bring solutions to the complex question of assessing services environmental footprint, for example through collaborative partnerships between actors with different expertise.

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List of Acronyms

ADP	Abiotic Depletion Potential
BBP	Butyl Benzyl Phthalate
CDGG	Circular Design Guidelines Group
CE	Circular Economy
CED	Cumulative Energy Demand
CED	Cumulative Energy Demand
CGP	Current Generation Product
CO_2e	CO_2 equivalent
CRM	Critical Raw Materials
DBP	Dibutyl Phthalate
DEHP	Di(2-ethylhexyl) Phthalate
DIBP	Diisobutyl Phthalate
DIDP	Di-Iso-Decyl Phthalate
DINP	Di-Iso Nonyl Phthalate
DNOP	Di-N-Octyl Phthalate
ECHA	European Chemical Agency
EDSCA	European Dataspace for Smart Circular Applications
EEE	Electric and Electronic Equipment
E&M	Entertainment & Media
EPD	Environmental Product Declaration
EPEAT	Electronic Product Environmental Assessment Tool
EPR	Extended Producer Responsibility
EPS	Environmental Priority Strategies
FFR	Field Failure Rate
GHG	Greenhouse Gas
GHS	Globally Harmonized System
GWP	Global Warming Potential
HIS	Hazard Statements Indicator
HREE	Heavy Rare Earth Element
ICT	Information & Communication Technologies
ILCD	International Life Cycle Data network
ISO	International Organization for Standardization
IoT	Internet of Things
LCA	Life Cycle Assessment

LCD	Liquid Crystal Display
LIME	Life cycle Impact Assessment Method based on Endpoint modelling
LREE	Light Rare Earth Element
LSP	Lean/Smart Packaging
MTBF	Mean Time between Failures
NGP	Next Generation Product
OTT	Over The Top
PBB	Polybrominated Biphenyls
PBDE	Polybrominated Diphenyl Ethers
PCB	Printed Circuit Boards
PCBA	Printed Circuit Board Assemblies
PEEC	Parameterized Embodied Emissions Calculator
PIM	Passive Intermodulation
PSS	Product-Service-System
REACH	Registration, Evaluation and Authorisation of Chemicals
RF	Radio Frequency
RFP	Request For Proposal
RoHS	Reduction of Hazardous Substances
SB-e	g antimony equivalents
SCIP	Substances of Concern In Products
SM	Surface Mount
SVHC	Substance of Very High Concern
TH	Through-Hole
TMA	Tower Mounted Amplifier
TP	Traditional Packaging
UPS	Uninterruptible Power Supply
WEEE	Waste Electrical and Electronic Equipment