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SERIES L: ENVIRONMENT AND ICTS, CLIMATE CHANGE, E-WASTE, ENERGY EFFICIENCY; CONSTRUCTION, INSTALLATION AND PROTECTION OF CABLES AND OTHER ELEMENTS OF OUTSIDE PLANT

The potential impact of selling services instead of equipment on waste creation and the environment – Effects on global information and communication technology

Recommendation ITU-T L.1024

ITU-T

ITU-T L-SERIES RECOMMENDATIONS

ENVIRONMENT AND ICTS, CLIMATE CHANGE, E-WASTE, ENERGY EFFICIENCY; CONSTRUCTION, INSTALLATION AND PROTECTION OF CABLES AND OTHER ELEMENTS OF OUTSIDE PLANT

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Recommendation ITU-T L.1024

The potential impact of selling services instead of equipment on waste creation and the environment – Effects on global information and communication technology

Summary

Recommendation ITU-T L.1024 utilizes information compiled from stakeholders that provides insights into cases in the information and communication technology (ICT) ecosystem, in which ICT goods are sold as services or subscriptions rather than products. Currently, these cases are not clearly understood from an environmental point of view.

Current estimates are that billions of new ICT goods – smartphones and others – are sold annually and sales are expected to be higher in 2025 than in 2020.

Business models based on servitization which would – most effectively – improve the circularity of these ICT goods are not well understood, e.g., prolonging the lifetime or increasing the e-waste collection rate.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T L.1024	2021-01-06	5	11.1002/1000/14564

Keywords

Business model, circular economy, environmental footprint, refurbishment, remanufacturing, repair, reuse, servitization.

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

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The potential impact of selling services instead of equipment on waste creation and the environment – Effects on global information and communication technology

1 Scope

This Recommendation contains analyses and predictions of the real or potential environmental consequences of a transfer to selling services instead of equipment for the global information and communication technology (ICT) industry.

It is plausible that some economic realities will drive some parts of the ICT ecosystem to be sold as services instead of goods. There are several studies looking at parts of the ecosystem and specific service transformations. However, there is few studies focusing on what this likely trend will mean for overall environmental impact.

The Recommendation considers possible conflicts and solutions regarding the opportunities and problems arising from a potential global service transformation of ICT.

The Recommendation contains a guide to cases where a service transformation makes sense or not from an environmental point of view.

This Recommendation takes into account previous and ongoing appropriate ITU deliverables on life cycle assessment (LCA) and circular economy, e.g., [b-ITU-T L.Suppl.28], [ITU-T L.1015], [ITU-T L.1020], [ITU-T L.1021], [ITU-T L.1022] and [ITU-T L.1023].

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T L.1015] Recommendation ITU-T L.1015 (2019), *Criteria for evaluation of the environmental impact of mobile phones.*

[ITU-T L.1020] Recommendation ITU-T L.1020 (2018), *Circular economy: Guide for operators and suppliers on approaches to migrate towards circular ICT goods and networks.*

[ITU-T L.1021] Recommendation ITU-T L.1021 (2018), *Extended producer responsibility – Guidelines for sustainable e-waste management*.

[ITU-T L.1022] Recommendation ITU-T L.1022 (2019), *Circular economy: Definitions and concepts for material efficiency for information and communication technology*.

[ITU-T L.1023] Recommendation ITU-T L.1023 (2020), *Assessment method for circular scoring*.

[ITU-T L.1410] Recommendation ITU-T L.1410 (2014), *Methodology for environmental life cycle assessments of information and communication technology goods, networks and services*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 global warming potential (GWP) [ITU-T L.1410]: Ratio of the warming of the atmosphere caused by one greenhouse gas to that caused by a similar mass of carbon dioxide. GWP is calculated over a specific time frame generally 100 years.

NOTE – See also [b-ITU-T L.Suppl.32].

3.1.2 preparing for reuse [b-Ardente]: Checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused.

3.1.3 reconditioning; refurbishing [b-Ardente]: Return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components.

3.1.4 remanufacturing [b-Ardente]: Return a used product [or component] to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product.

3.1.5 repurposing [b-Ardente]: Utilize a product or its components in a role that it was not originally designed to perform.

3.1.6 reuse [b-EN 45554]: Process by which a product or its parts, having reached the end of their first use, are used for the same purpose for which they were conceived.

3.1.7 second-hand product [b-Ardente]: Tangible movable property that is suitable for further use as it is or after repair.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 abiotic resource depletion potential (ADP): From a functional point of view, is the decrease of availability of the total reserve of potential functions of resources. From the intrinsic value of naturally occurring minerals point of view, is the decrease of the unique natural configurations of elements in resources in the environment. Abiotic refers to natural resources (including energy resources) such as iron ore, crude oil which are regarded as non-living.

NOTE – Paraphrased from [b-van Oers]. See also [b-ITU-T L.Suppl.32].

3.2.2 computational use value: A rating of the usefulness of a computing device for specific computing tasks

3.2.3 cumulative energy demand (CED): A measure of primary energy demand from renewable and non-renewable resources or similar that can be used as representative of primary energy consumption.

NOTE – See [ITU-T L.1410].

3.2.4 energy proportional computing: Energy proportionality is a measure of the relationship between power consumed in a computer system, and the rate at which useful work is done (its utilization, which is one measure of performance). If the overall power consumption is proportional to the computer's utilization, then the machine is said to be energy proportional.

NOTE – Based on [b-Barroso].

3.2.5 recycling use value: A rating of the value of a computing device based on raw material value considering the cost of recycling it.

3.2.6 re-use rate: Degree to which an information and communication technology (ICT) good or its component parts are reused for the same purpose.

3.2.7 servitization: The process of creating value by adding services to products. In more detail 'the offering in terms of "goods or services" through "goods and services" to the marketing of bundles of "goods + services + support + knowledge + self-service".

NOTE – See [b-Kowalkowski].

3.2.8 use value: A rating of the usefulness of a good for a useful purpose, in comparison to the exchange value by which the commodity compares an item to other objects on the market.

NOTE – Based on [b-Franquesa 2018].

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

ADP	Abiotic resource Depletion Potential
CED	Cumulative Energy Demand
ED	Energy Depletion
GWP	Global Warming Potential
GWP100	Global Warming Potential at 100 years
HDD	Hard Disc Drive
ICT	Information and Communication Technology
LCA	Life Cycle Assessment
ONT	Optical Network Terminal
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PSU	Power Supply Unit
RAM	Random Access Memory
RMD	Raw Material Depletion
SSD	Solid-State Disc
SMART	Self-Monitoring, Analysis, and Reporting Technology
STB	Set-Top Box
WD	Water Depletion
xDSL	any type of Digital Subscriber Line

5 Conventions

None.

6 Business models

Previous methods include [b-Tasaki] and [b-Goldey].

[b-Tasaki] proposes a method in which replacement conditions of products are compared with iso-environmental-load lines to determine the appropriateness of replacement.

A theoretical limit of 50% environmental impact reduction for one remanufacturing cycle for ICT infrastructure goods has been proposed [b-Goldey].

6.1 Desktop computing as a service per hour via different business models

Electronic devices such as desktops, laptops or mobile phones are said to be reused when they have already been manufactured, are used and maintained in good use for a few years by an organization, and then are discarded by the initially envisaged use and user. While most are still operational, they are disposed of or recycled unless they are repaired, remanufactured, refurbished or redistributed to other users. These devices are collected by a second-hand agent or sent to a remanufacturer for processing, sale or rent, and redistributed to other users. The reuse process ends when, after a few years, the device or a component returns to the disposal state, which means its useful value then, even if improvements were made, no longer allows its reuse. That process should end in recycling, a process that transforms computational use value into raw material use value [b-Franquesa 2018]. The eReuse initiative works with social enterprises in Spain that collect and refurbish desktop and laptop devices donated by public and private organizations (numbering over 10 000 in the last 5 years). These computing devices are sold for a price that reflects the cost of refurbishment and carry a guarantee for a 1-2 year period. In the case of a fault, devices are replaced instead of repaired *in situ*. Several recipient organizations like schools prefer to pay a yearly fee or sign a contract for a number of computing units with an agreed performance level (computing as a service). They receive some additional computer units to ensure quick replacement of any that are faulty.

The eReuse field study reported in [b-Franquesa 2019] collects data (public dataset from October 2013 to May 2019) about desktop and laptop devices beyond their first usage (reuse) [b-Franquesa 2020]. In reuse, nearly all devices are refurbished with reused components, except new batteries and hard disc drives (HDDs), when they raise signals of failures (by self-monitoring, analysis, and reporting technology; SMART). The dataset shows durability per manufacturer (90th percentile among devices from the same manufacturer) of the total usage period, up to 46 477 h (5.3 years) and a maximum of 65 332 h (7.5 years), consistent with [b-Ardente]. The concept of energy proportional computing (see clause 3.2.4) is significant for the use stage of servers, although it may have been neglected in the LCA in [b-Ardente], but is less important for personal computers. [b-Franquesa 2019] and the corresponding public dataset [b-Franquesa 2020] found that reuse can contribute to approximately a duplication of lifespan in personal computers, especially in a servitized model with network data storage, where faulty computers can be easily replaced by *in-situ* spares.

The life cycle environmental impacts of a desktop computer can be roughly estimated by creating an environmental intensity per mass for a server [b-Ardente] and multiplying by 5 kg desktops [b-Franquesa 2019]) and assuming that the power consumption of a desktop is one-third of the server- The results for desktops are shown in Table 1.

Table 1 – Summary of approximate life cycle environmental impacts of a desktop without refurbishment

Environmental impact category	Manufacturing	Use	End-of-life
GWP, kg CO_2e	154	1 025	−11
ADP, kg Sb-e	0.02	0.000 18	−0.013
CED, MJ	2 288	23 834	−125
CO_2e: carbon dioxide equivalent; Sb-e; antimony equivalent			

If the scenario is translated to a computing as a service or servitized model, environmental impacts per device and per hour (of availability and possible usage of a computing device) can be examined and compared. If Table 1 represents the impact of the first usage cycle of a new computer, Table 2 represents the expected potential effect of reuse after refurbishment in comparison to the use of two new devices (as in clause 6.2). Reuse roughly results in doubling of usage hours by a new user, usually with lighter computing requirements, but the same manufacturing and end-of-life impacts. There is an assumption in the comparison of a 20% improvement in power consumption in the case of a second new device, and the small impact of local refurbishment and local repair is not accounted for.

Table 2 – Summary of idealized impacts from reuse, 5 year baseline usage ($I_1$5): one device with reuse for twice the lifespan ($I_1$10) compared to two devices without reuse ($I_2$10) for a period of 2 × 5 years

Environmental impact	One device		Two devices	Impact improvement (%)	
	One use, 5 years $I_1 5$ = M + U + E	Use + reuse: 10 years $I_1 10$ = M + 2U + E	5 + 5 years $I_2 10$ = 2(M + U + E)	One to two users ($I_1 5 - I_1 10$)/$I_1 5$	Two to one devices ($I_2 10 - I_1 10$)/$I_1 10$
GWP, kg CO_2e (total)	1 168	2 193	2 336		7
ADP, kg Sb-e (total)	0.007 18	0.007 36	0.014 36		95
CED, MJ (total)	25 997	49 831	46 794.6		−6
GWP, g CO_2e/h	26.7	25.0	26.7	6	7
ADP, mg Sb-e/h	0.2	0.1	0.2	49	95
CED, KJ/h	593.5	568.8	534.2	4	−6

The impact of use is highly dependent on electricity production (CO_2 emissions), but the increasing use of renewable and local sources tends to reduce this contribution over time (in the two device scenario, Table 2 assumes a reduction to 80% of energy consumption for the second). Transparency is crucial for LCA calculations.

6.2 Practical approach showing SEEQ business model

A first approach compares the environmental footprints of the two following scenarios.

– Baseline scenario: one product is sold to each successive customer, denoted not refurbished and highlighted in red in Figure 1. This scenario requires the manufacture of two devices (denoted M1 and M2 in Figure 1), their distribution to customers (denoted D1 and D2 in Figure 1), as well as their end-of-life treatment (denoted E1 and E2 in Figure 1). Both pieces of equipment are used by customers involving environmental impacts denoted U1 and U2 in Figure 1.

– Refurbishment scenario: the products are rented to customers, recovered to be refurbished and then shipped to other customers. In Figure 1, this scenario is denoted refurbished and highlighted in green. This scenario involves the manufacture of the first device (denoted M1 in Figure 1), its distribution and use by the first customer (denoted D1 and U1 in Figure 1**Error! Reference source not found.**). The device is then recovered to replace some parts in order to reach a condition that is as-good-as-new (operation denoted R1 in Figure 1). The device is then shipped to a second customer who will use it (denoted D2 and U2, respectively, in Figure 1). Finally the device is sent for end-of-life treatment (denoted E1 in Figure 1).

In Figure 1, the lifespan is considered to be 5 years for both scenarios. This duration has to be adapted depending on the type of equipment (shorter for small electronic devices, longer for large network equipment for example).

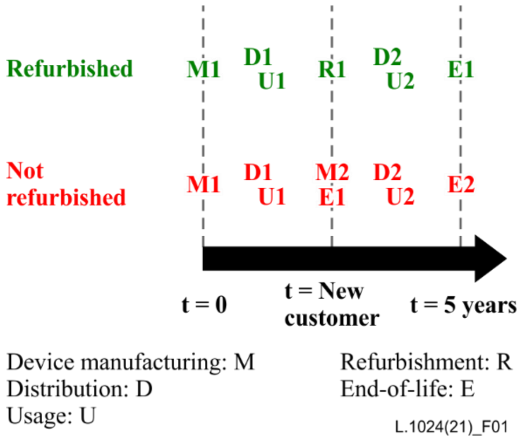

Figure 1 – Different steps to be considered in a comparison between a scenario including refurbishment and a baseline scenario without refurbishment [b-Vaija]

For the refurbishment scenario, it is important to have a good understanding of the reverse logistics supply chain in order to assess correctly the environmental footprint of the different steps. Figure 2 shows details of the different operations that can be involved. The first part of the figure (highlighted in orange) describes the different pathways to recover equipment from the customer. The second part (highlighted in blue) aids comprehension of the first sorting steps, which separate the different grades of product received by the sorting centre (from old product no longer required to be returned to the market to no-fault-found products). The third part (highlighted in green) shows the different parties that can be involved: a third party company operating a refurbishment centre for mechanical part swaps; and a manufacturer for repair requiring, for example, operations on a printed circuit board assembly (PCBA) board. The last part (highlighted in pink) concerns packaging and shipping. System operation also requires input of spare parts (highlighted in yellow) and handling the end-of-life of old equipment and defective parts (highlighted in grey).

The following factors will also be crucial to the calculation of the environmental footprint of the refurbishment scenario.

– Recovery rate of equipment from the first customer. Every time a device is not recovered for refurbishment, it means a new one will have to be manufactured.

– Sorting centre location. If equipment has to be shipped over long distances, it will have detrimental effects on the environmental footprint.

– Percentages of no-fault-found equipment and that with a certain type of failure. Depending on the type of failure, the equipment can be categorized as reparable or beyond repair due to the cost of the operation. A device that cannot be repaired will have to be replaced by a new one.

– Percentage of replacement for different parts. External parts that are prone to wear or visible can have a very high replacement rate (e.g., highly glossy top housing plastics parts on consumer electronic equipment). Failure to consider refurbishment of a device during the initial design phases can lead to a 100% replacement rate for some parts.

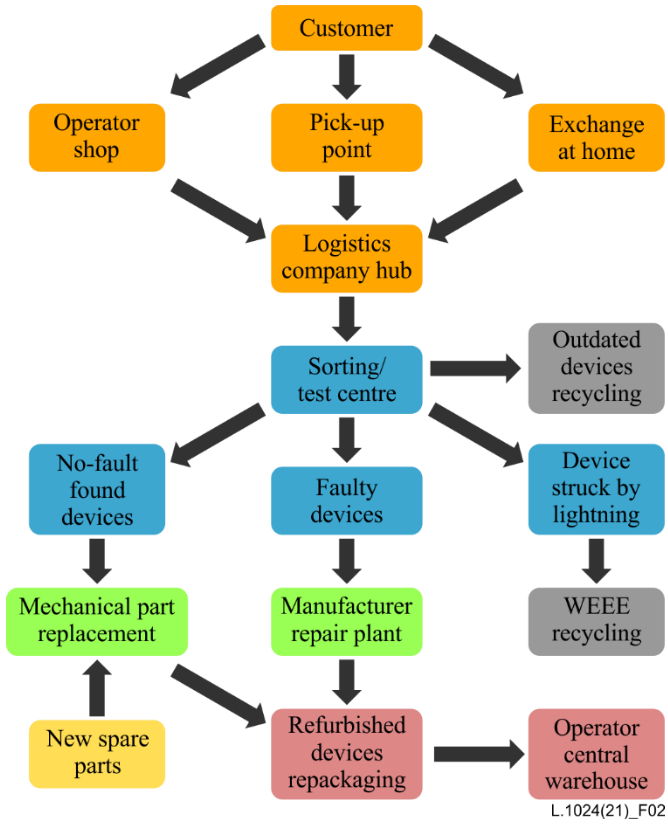

Figure 2 – Details of the refurbishment reverse logistics supply chain (adapted from [b-Vaija])

The environmental impact results for both systems can then be calculated with LCA methods, as described in [ITU L.1410]. Figure 3 shows an example for both the scenarios described in Figure 1.

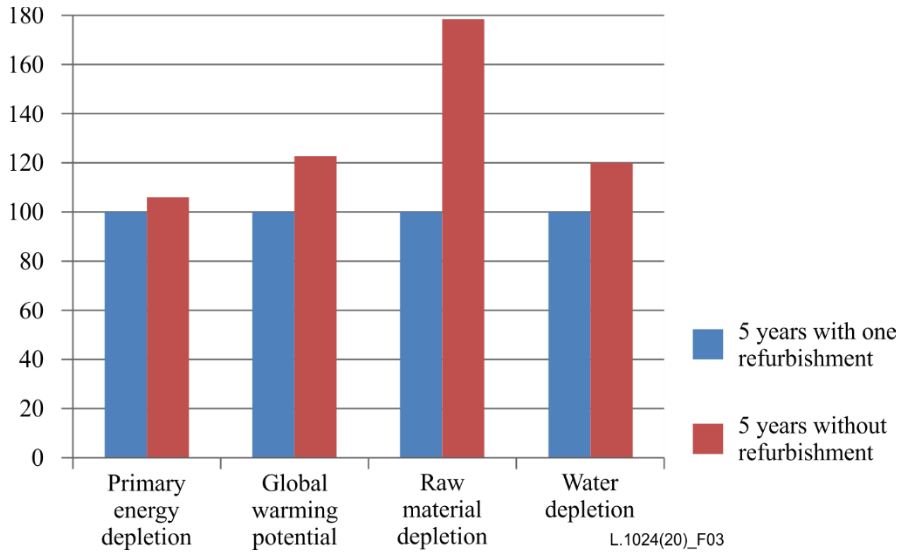

Figure 3 – Environmental footprint comparison between the baseline (equipment sold to customers) and refurbishment scenarios (equipment rented to customers) [b-Vaija]

Figure 3 shows that, in this example, the impact of all environmental indicators is lower for the refurbishment scenario. For primary energy depletion (ED), the difference is low (6.01%) in the usage phase, equal to U1 + U2 for both systems (as shown in Figure 1), which contributes 92.6% for this indicator. Scores for such indicators as global warming potential (GWP) and water depletion (WD) are mainly related to the usage phase (72.0% for GWP and 73.2% for WD), therefore refurbishment benefit is a little better than for ED.

As metals like silver, gold, tin or copper have relatively high characterization factors in the raw material depletion (RMD) method, the benefit of refurbishment is really visible for this indicator. Indeed, the refurbishment effort is mostly about mechanical parts replacement, while the motherboard is most often retained (electric defaults due to surges from lightning strikes on any type of digital subscriber line (xDSL) input or on the power line are examples of causes for motherboard replacement). Thus, the impact of the refurbishment step R1 is rather low for the RMD indicator, while the manufacture of a second device (M2) for the system without refurbishment requires gold for integrated circuit wire bonding, tin and silver for solder paste, copper for printed circuit board (PCB) conductive layers, etc.

The method used in clause 6.2 is similar to that in [b-Goldey].

6.2.1 Further explanation of calculation procedures

As the modelling includes energy efficiency improvement and energy consumption effects of additional functions, in the name of readability, the two following examples only focus on the carbon footprint calculation instead of the four indicators detailed in Figure 3.

a) First example considering energy consumption effects

In the first example (see Figure 4), the carbon footprint of the three following scenarios is compared.

– Scenario 1: a rather complex and energy hungry device (denoted model A) is manufactured (① in Figure 4) and rented to a first customer. After 30 months, the equipment is recovered by the telecommunication operator (the owner of the device) to carry out a refurbishment operation (③ in Figure 4). The equipment is then shipped to a second customer for 30 months of use. A second recovery and refurbishment step happens at the end of the life cycle (⑤ in Figure 4). The device is then shipped to the third and last customer for 30 months of use. At the end, i.e., 90 months after the introduction of the device, the equipment is sent to end-of-life treatment (⑦ in Figure 4). To summarize, scenario 1 requires: one complex device manufacturing and shipping operation; two recovery and refurbishment operations; two shipping operations from the refurbishment centre; and one end-of-life treatment operation.
– Scenario 2: the first 30 months of scenario 2 are the same as in scenario 1 (① in Figure 4). After 30 months, model A of the equipment is sent to end-of-life treatment instead of being refurbished. A more simple and energy efficient device (denoted model B in Figure 4) is manufactured and shipped to the second customer (② in Figure 4). After an additional 30 months, this model B device is also recovered, sent to refurbishment and shipped to a third customer (④ in Figure 4). At the end of the scenario (i.e., 90 months after the beginning) the equipment is sent to end-of-life treatment (⑥ in Figure 4). To summarize, scenario 2 requires: one complex device and one less complex device manufacturing and shipping operations; one recovery and refurbishment operation; one shipping operation from the refurbishment centre; and two end-of-life treatment operations.
– Scenario 3: the first 30 months of scenario 3 are the same as in scenarios 1 and 2 (① in Figure 4). After 30 months, model A of the equipment is sent to end-of-life treatment and another model A is manufactured and shipped to the second customer (⑧ in Figure 4). After an additional 30 months, this second model A device is sent to end-of-life treatment and a third model A is manufactured and shipped to the third customer (⑨ in Figure 4). At the end of the scenario (i.e., 90 months after the beginning) the equipment is sent to end-of-life treatment (⑩ in Figure 4). To summarize, scenario 3 requires: three complex device manufacturing, shipping and end-of-life treatment operations.

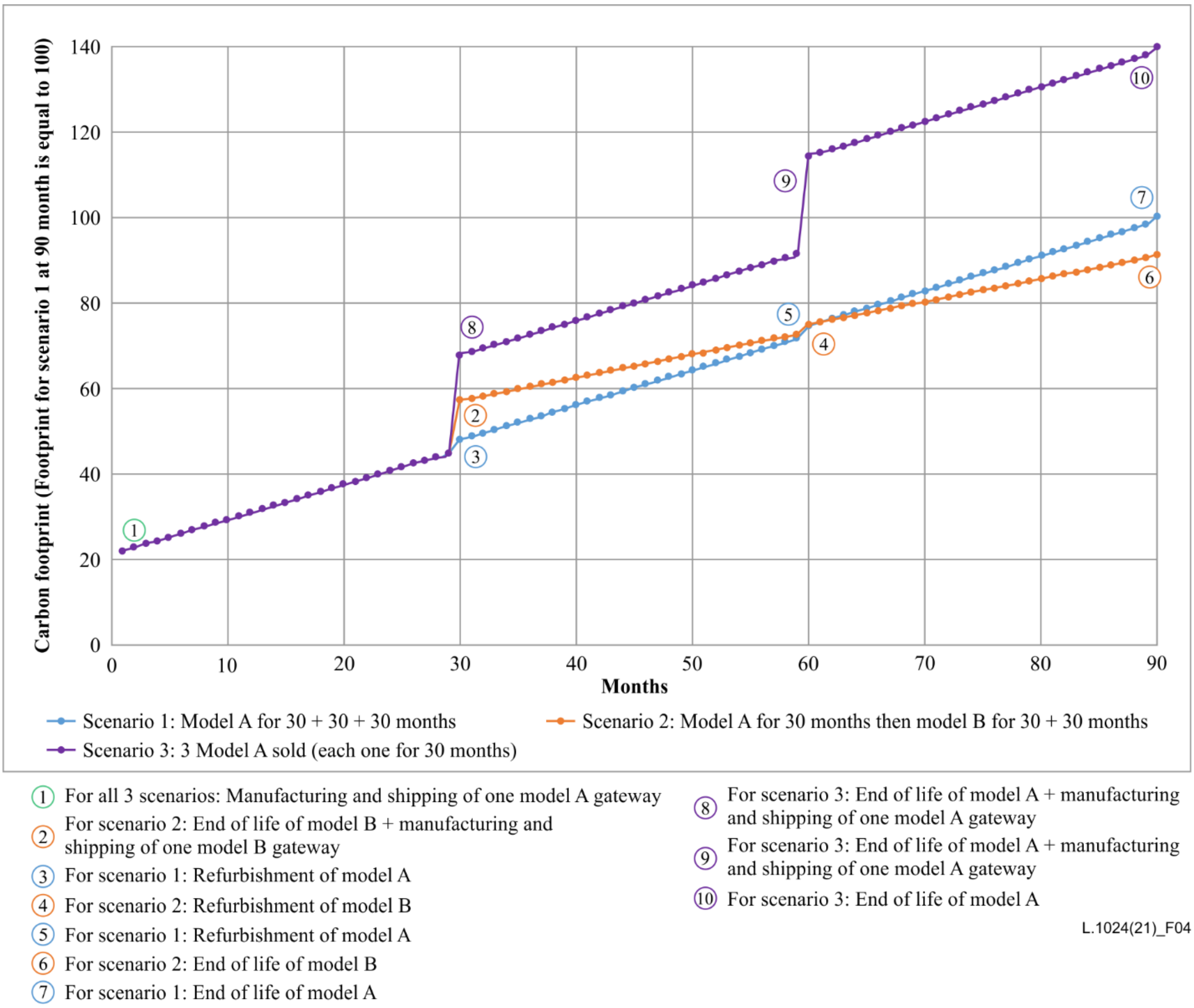

Figure 4 – Carbon footprint comparison between scenario 1 (model A used 90 months with two refurbishments), scenario 2 (model A sold and used for 30 months and then replaced by model B used for 60 months with one refurbishment) and scenario 3 (three model A devices sold and used for 30 months each)

At the end of the life cycle (i.e., after 90 months) – even if scenario 2 requires the manufacture of an additional device (② in Figure 4) – the achieved carbon footprint is lower. This is achieved thanks to the lower energy consumption and better energy efficiency of model B compared to model A. Scenario 3, which requires the manufacture of three complex devices each with a high energy consumption, is characterized by the highest carbon footprint among the three scenarios.

b) Second example considering energy consumption effects

In the first example (see Figure 5) the carbon footprint of the two following scenarios are compared.

– Scenario 1: a rather complex and energy hungry device (denoted model A) is manufactured (① in Figure 5) and rented to a first customer. After 30 months, the equipment is recovered by the telecommunication operator (the owner of the device) to carry out a refurbishment operation (② in Figure 5). The equipment is then shipped to a second customer for 30 months of use. A second recovery and refurbishment step happens at the end of the life cycle (④ in Figure 5). The device is then shipped to the third and last customer for 30 months of use. At the end, i.e., 90 months after the introduction of the device, the equipment is sent to end-of-life treatment (⑥ in Figure 5). To summarize, scenario 1 requires: one complex device manufacturing and shipping operation; two recovery and refurbishment operations; two shipping operations from the refurbishment centre; and one end-of-life treatment operation.

– Scenario 2: the first 30 months of scenario 2 are the same as in scenario 1 (① in Figure 5). After 30 months, model A of the equipment is sent to end-of-life treatment instead of being refurbished. A more simple and energy efficient device (denoted model B in Figure 5) is manufactured and shipped to a second customer (③ in Figure 5). After an additional 30 months, this model B device is sent to end-of-life treatment and another model is manufactured and shipped to a third customer (⑤ in Figure 5). At the end of the scenario (i.e., 90 months after the beginning) the equipment is sent to end-of-life treatment (⑦ in Figure 5). To summarize, scenario 2 requires: manufacture of one complex device and two less complex devices; one shipping and end-of-life treatment operation for all.

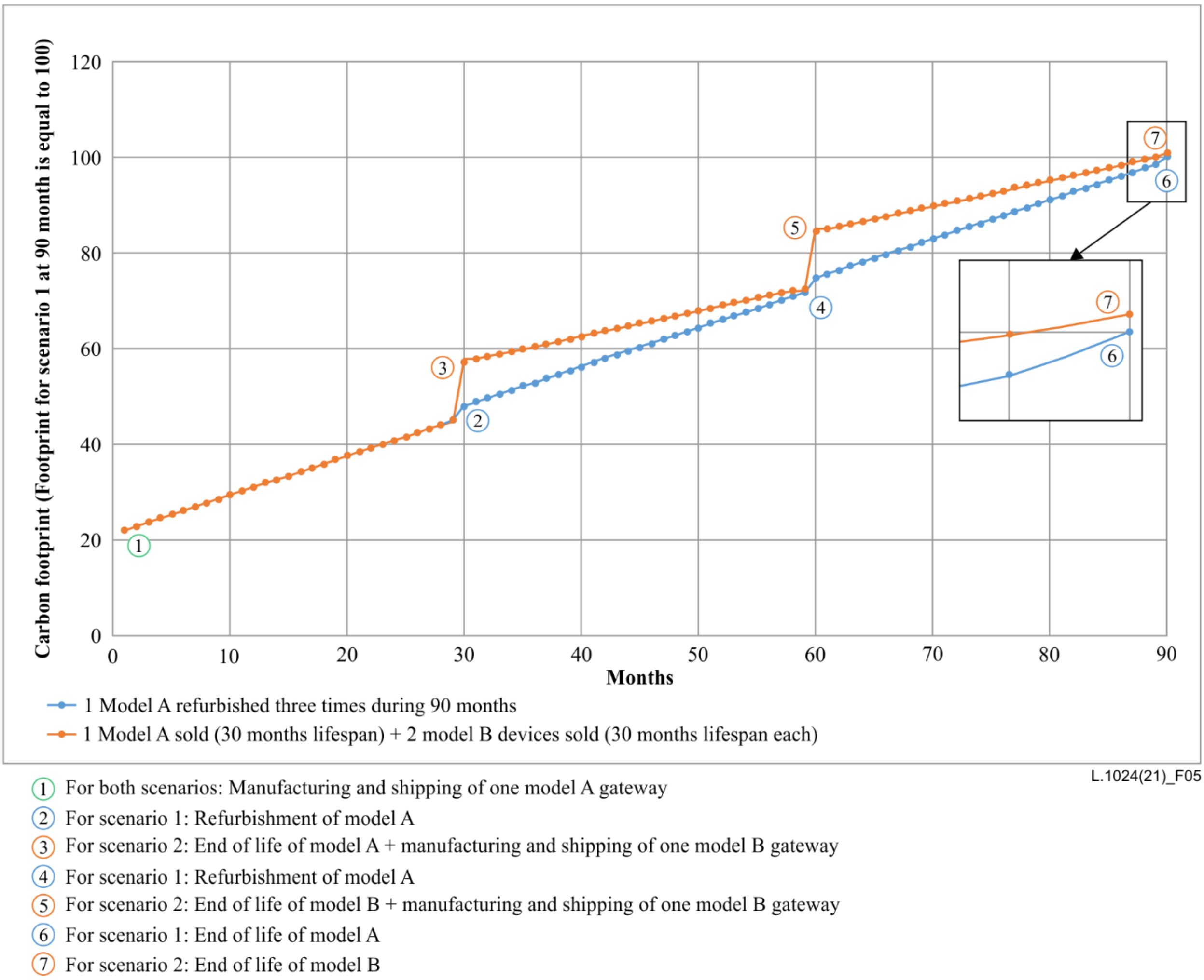

Figure 5 – Carbon footprint comparison between scenario 1 (model A used 90 months with two refurbishments) and scenario 2 (model A sold and used for 30 months and then replaced by two successive model B devices sold and used for 30 months each)

With this configuration, the lower energy consumption and better energy efficiency of model B is not enough to compensate for the additional environmental burden related to the manufacture of two model B devices. Thus, scenario 2 is worse regarding the carbon footprint at the end of the 90 months of the life cycle (see inset in Figure 5 as the results are quite close).

When comparing different business models such as rent and refurbish vs. sell and recycle, the two examples in Figure 4 and Figure 5 show that comparative environmental footprint analysis of refurbishment shall consider the following parameters.

– Each instance of equipment manufacture, e.g., model A and model B.

– Transport of each device upstream and downstream (e.g., from parts components or sub-assembly supplier factories to final assembly plant; from final assembly plant to use location).

– Energy consumption of each device. Note that if one device has vastly better capabilities (such as number of clients served, system capacity, etc.), the energy consumption should be scaled according to the specifications of the other equipment for a correct comparison, as it is done in comparative LCA functional units.

– End-of-life treatment of each equipment.

– For equipment undergoing refurbishment:
  - if recovery rate is <100%, the manufacture of an additional device;
  - whether parts, components or sub-assemblies require replacement due to wear or need an update;
  - an allocation of the refurbishment plant energy or ancillary materials consumption.

The lifespan of each device in both scenarios should also be adjusted according to actual data.

7 Analytical approaches

Another approach useful in the context of this Recommendation is a framework of mathematical equations [b-Ardente], e.g., Equation 1, by which the environmental benefit of remanufacturing and refurbishment of ICT goods can be estimated. That framework and formulae will here be re-verified and explained for the enterprise server in [b-Ardente] and then applied to some other ICT goods.

$$\delta_i = 1 + \frac{(\Delta P_j - P_{\mathrm{RE},j})}{U_{\mathrm{A},j}} \qquad (1)$$

δ_i is the environmental benefit for impact category *j* of remanufacturing;

ΔP_j is the potential environmental impact for impact category *j* of parts of the ICT good that are new in baseline scenario A and reused in scenario B;

NOTE 1 – Simply put, this term represents the potential environmental impacts of manufacturing reusable parts (as in Tables 2, 4, 6, 8 and 10).

$P_{\mathrm{RE},j}$ is the potential environmental impact, relative to the impact category *j*, resulting from the reuse of parts for the remanufacturing scenario

NOTE 2 – The impact is assumed to be very low at 0.5% of those for the production of the part. Reused parts are extracted from other products (during some stage of their life cycle) and are used as inputs for the remanufacture of product B. The percentage will be higher if extensive repairs of the parts are necessary.

$U_{\mathrm{A},j}$ is the potential lifetime environmental impact from using product A for impact category *j*

7.1 Remanufacturing trade-off for enterprise server

Scores like those in Table 3 can be obtained by using the LCA standard [ITU-T L.1410]. The re-use rates in Table 4 are used to identify which parts to include in Equation 1.

Table 3 – Summary of approximate environmental impacts of the life cycle of an enterprise server without remanufacturing (scenario A) [b-Ardente]

Environmental impact category	Manufacturing	Use (4 years)	End-of-life
GWP, kg CO_2e	858.3	3 077.2	−58.9
ADP, kg Sb-e	0.11	0.001	−0.07
CED, MJ	12 724	71 500	−696

Table 4 – Hypotheses for reused parts of server and reuse rates [b-Ardente]

Sub-part	Mass (g)	kg CO_2e, GWP/piece	kg Sb-e, ADP/piece	Re-use rate (%)
HDD	1 750	83	0.01	47.7
Memory cards	135	140	0.013	40.1
CPUs	54	200	0.028	5.2
Power supply	3 426	340	0.004 3	5.0
Motherboard	1 662	210	0.029	2.7
Raid card	5.2	0.37	0.000 023	2.1
Chassis	13 454	99	0.004 7	1.4
Expansion card	349	50	0.007 8	0.7

Applying Equation 1 to remanufacturing the server with reused HDD and memory cards leads to Equation 2 and Equation 3:

$$\delta_{\text{GWP,server}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(83+140) - 0.5\% \times (83+140)]}{3077.2} = 1.07 \quad (2)$$

$$\delta_{\text{ADP,server}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(0.01+0.013) - 0.5\% \times (0.01+0.013)]}{0.001} = 23.9 \quad (3)$$

The higher the value of δ, the higher the environmental benefit.

Equation 2 suggests that remanufacturing is not environmentally beneficial when the energy consumption of the remanufactured server is more than 7% higher than the energy consumption of a new server.

7.2 Refurbish trade-off for smartphone

Here the analytical approach is applied to a contemporary smartphone. Scores like those in Table 5 can be obtained by using the LCA standard [ITU-T L.1410].

Table 5 – Summary of approximate life cycle environmental impacts of a smartphone without refurbishment

Environmental impact category	Manufacturing	Use (4 years)	End-of-life
GWP, kg CO_2e	43	8.6	−1.5
ADP, g Sb-e	12	0.5	−2.6

Several typical LCA results exist and the practitioner can choose the best available scores to fit the purpose. The re-use rates in Table 6are used to identify which parts to include in Equation 1.

Table 6 – Hypotheses for reused parts of smartphone and reuse rates

Sub-part	kg CO_2e, GWP/piece	g Sb-e, ADP/piece	Re-use rate (%)
Screen	4.8	1.5	
Battery	1.8	2.7	
Charger	1	1.1	
Motherboard	19	6.7	
Cover	2.2		

Applying Equation (1) to refurbish a smartphone with a reused screen and charger leads to Equation 4 and Equation 5:

$$\delta_{\text{GWP,smartphone}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(4.8+1) - 0.5\% \times (4.8+1)]}{8.6} = 1.67 \quad (4)$$

$$\delta_{\text{ADP,smartphone}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(1.5+1.1) - 0.5\% \times (1.5+1.1)]}{0.5} = 6.17 \quad (5)$$

The higher the value of δ, the higher the environmental benefit.

Equation 4 suggests that refurbishment is not CO_2 beneficial when the energy consumption of the refurbished smartphone is more than 67% higher than the energy consumption of a new smartphone.

7.2.1 Direct reuse benefits

Applying Equation 1 to refurbish the smartphone with all sub-parts reused leads to Equation 6 and Equation 7:

$$\delta_{\text{GWP,smartphone}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(43) - 0.5\% \times (43)]}{8.6} = 5.9 \quad (6)$$

$$\delta_{\text{ADP,smartphone}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(1.5+2.7+1.1+6.7) - 0.5\% \times (1.5+2.7+1.1+6.7)]}{0.5} = 24.9 \quad (7)$$

The higher the value of δ, the higher the environmental benefit.

Equation 6 suggests that a small refurbishment and direct reuse – perhaps without disassembly – is more CO_2 beneficial than Equation 4 featuring disassembly, reuse of two parts and reassembly.

7.3 Set-top box refurbish trade-offs

Here the analytical approach is applied to the example in clause 6.2. See Tables 7 and 8.

Table 7 – Summary of approximate life cycle environmental impacts of a set-top box without refurbishment

Environmental impact category	Manufacturing	Use	End-of-life
GWP, kg CO_2e	27.86	61.10	0.59
ADP, g Sb-e	4.49	0.014	0.000 018
ADP fossil, MJ	189.30	350.00	3.33

Table 8 – Hypotheses for reused parts of a set-top box and reuse rates

Part	kg CO_2e, GWP/piece	g Sb-e, ADP/piece	Re-use rate (%)
Power supply unit	3.02	0.492	65
Registered jack 45 cable	0.27	0.027	40
Société des Constructeurs d’Appareils Radiorécepteurs et Téléviseurs (SCART) standard cable	0.46	0.018	40
Remote control unit	1.15	0.081	55
Top housing part	2.44	0.000 064	30
Bottom housing part	1.70	0.000 045	60
Printed circuit board assembly	18.37	3.87	95
Kitting (primary packaging and documentation)	0.45	0.000 24	0

Applying Equation 1 to refurbish the set-top box (STB) with reused PCBA, power supply unit (PSU) and bottom housing part leads to Equation 8 and Equation 9:

$$\delta_{\text{GWP,STB}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(18.37+3.02+1.7) - 0.5\% \times (18.37+3.02+1.7)]}{61.1} = 24.09 \quad (8)$$

$$\delta_{\text{ADP,STB}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{[(3.87 + 0.492 + 0.000\,045) - 0.5\% \times (3.87 + 0.492 + 0.000\,045)]}{0.014} = 311 \tag{9}$$

The higher the value of δ, the higher the environmental benefit.

Equation 8 suggests that refurbishment is not CO_2 beneficial when the energy consumption of the refurbished STB is likely not more than 24 times higher than the energy consumption of a new STB.

7.4 Desktop box refurbish trade-offs

Here the analytical approach is applied to the example in clause 6.1 considering those parts of a desktop or laptop [b-André] personal computer are reused (most) and those replaced with new parts.

Table 9 – Summary of approximate life cycle environmental impacts of a desktop without refurbishment [b-Song]

Environmental impact category	Manufacturing	Use	End-of-life
GWP, kg CO_2e	444	1340	3.28
ADP, kg Sb-e	3.13	8.47	−0.001
CED, MJ	N/A	N/A	N/A

Contrary to the server scenario in [b-Ardente], in the personal computer refurbishment reported in clause 6.1, the computer is mostly reused, except that the motherboard button battery is replaced by a new one, as they are usually exhausted. Data storage components (HDDs) can change too. Some organizations with stringent data protection policies dispose of computers without the HDD, which is destroyed separately to prevent data leaks. Some HDDs are replaced by reused HDDs or solid-state discs (SSDs) when failing in a diagnostic and stress test or when the drive has had too many usage hours. Sometimes random access memory (RAM) capacity is expanded (if there is room) with RAM chips extracted from equivalent but faulty computers, avoiding additional impacts.

Table 10 summarizes the impacts of the replaced components, negligible to the overall impact of the device (storage data from [b-Boyd]).

Table 10 – Hypotheses for replaced by new and reused parts of desktops

Part	kg CO_2e, GWP/piece	g Sb-e, ADP/piece
New battery (button)	0.489	1.69
New storage (boot drive)	8.6 (HDD) to 28 (SSD)	<0.011
Reused desktop (remaining parts)	1 778.191	9.898

Applying Equation 1 to refurbish a desktop computer reusing all except battery and data leads to Equation 10 and Equation 11:

$$\delta_{\text{GWP,desktop}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{(1\,778.191 - 0.5\% \times 1\,778.191)}{1\,340} = 2.32 \tag{10}$$

$$\delta_{\text{ADP,desktop}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{(9.898 - 0.5\% \times 9.898)}{8.47} = 2.16 \tag{11}$$

The higher the value of δ, the higher the environmental benefit.

Equation 10 and Equation 11 show the large CO_2 margin for refurbishment as 99.49% of GWP and 85.33% of ADP is saved (or 0.51% of GWP and 14.67% of ADP added by the new parts).

7.5 Optical network terminal refurbish trade-offs

Here the analytical approach is applied to an optical network terminal (ONT). See Tables 11 and 12.

Table 11 – Summary of approximate life cycle environmental impacts of an optical network terminal without refurbishment

Environmental impact category	Manufacturing	Use	End-of-life
GWP, kg CO_2e	15	41	
ADP, g Sb-e	63	~0.000 06	
CED, MJ			

Table 12 – Hypotheses for reused optical network terminal parts and reuse rates

Sub-part	kg CO_2e, GWP/piece	g Sb-e, ADP/piece	Re-use rate (%)
Optical module	0.062	48	
Signal cable	0.63	7.7	
PSU	9.2	4.3	
Motherboard	3.9	2.5	

Applying Equation 1 to refurbish the ONT with reused Signal cable and PSU leads to Equation 12 and Equation 13:

$$\delta_{\mathrm{GWP,ONT}} = 1 + \frac{(\Delta P_{\mathrm{GWP}} - P_{\mathrm{RE,GWP}})}{U_{\mathrm{A,GWP}}} = 1 + \frac{[(0.63+9.2) - 0.5\% \times (0.63+9.2)]}{41} = 1.24 \quad (12)$$

$$\delta_{\mathrm{ADP,ONT}} = 1 + \frac{(\Delta P_{\mathrm{ADP}} - P_{\mathrm{RE,ADP}})}{U_{\mathrm{A,GWP}}} = 1 + \frac{[(7.7+4.3) - 0.5\% \times (7.7+4.3)]}{0.000\,06} = 199\,000 \quad (13)$$

The higher the value of δ, the higher the environmental benefit.

Equation 12 suggests that refurbishment is not CO_2 beneficial when the energy consumption of the refurbished ONT is more than 24% higher than the energy consumption of a new ONT.

7.6 Base station remanufacturing trade-offs

Here the analytical approach is applied to a wireless base station from Tables V and VII in [b-Goldey]. See Tables 13 and 14.

Table 13 – Summary of approximate life cycle environmental impacts of a base station without refurbishment

Environmental impact category	Manufacturing	Use	End-of-life
GWP, kg CO_2e	2 887	~60 000 NOTE – All base stations have different use stage impacts.	135
ADP, g Sb-e	14 000	~4 NOTE – All base station have different use stage impacts.	Not available

Table 14 – Hypotheses for reused parts of base station and reuse rates

Part	kg CO_2e, GWP/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	1 438		100
Cabling	33		100

Applying Equation 1 to remanufacture with 100% reuse of all sub-parts leads to Equation 14 and Equation 15:

$$\delta_{\text{GWP,base station}} = 1 + \frac{(\Delta P_{\text{GWP}} - P_{\text{RE,GWP}})}{U_{\text{A,GWP}}} = 1 + \frac{(2\,887 - 0.5\% \times 2\,887)}{60\,000} = 1.05 \quad (14)$$

$$\delta_{\text{ADP,base station}} = 1 + \frac{(\Delta P_{\text{ADP}} - P_{\text{RE,ADP}})}{U_{\text{A,GWP}}} = 1 + \frac{(14\,000 - 0.5\% \times 14\,000)}{4} = 4.48 \quad (15)$$

The higher the value of δ, the higher the environmental benefit.

Equation 14 suggests that 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 parts are reused, and if the remanufacturing cost as well as the use stage impacts are higher.

8 Global change effect of servitization of desktops, laptops and gateways

8.1 Desktops

Estimates of global shipments are listed in Table 15.

Table 15 – Estimated shipments of desktops 2015-2030 [b-Andrae]

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Desktops, millions	142	139	136	134	131	128	126	123	121	118	116	114	112	109	107	105

Table 16 shows how the global numbers are derived for desktops.

Table 16 – Using Table 1 and Table 2 with Table 15

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Scenario A – One use of one desktop over 5 years																	
1 304 kg CO_2e (Table 1)	GWP, Mt CO_2e (total)	185	182	178	174	171	168	164	161	158	155	151	148	145	143	140	137
0.146 4 g Sb-e	ADP, kt Sb-e (total)	21	20	20	20	19	19	18	18	18	17	17	17	16	16	16	15
26 246 MJ	CED, EJ (total)	3.7	3.7	3.6	3.5	3.4	3.4	3.3	3.2	3.2	3.1	3.0	3.0	2.9	2.9	2.8	2.8
0.029 771 689 kg CO_2e	GWP, t CO_2e/h	4.2	4.1	4.1	4.0	3.9	3.8	3.7	3.7	3.6	3.5	3.5	3.4	3.3	3.3	3.2	3.1
3.342 47E-06 mg Sb-e	ADP, mg Sb-e/h	475	466	456	447	438	429	421	412	404	396	388	380	373	365	358	351

Table 16 – Using Table 1 and Table 2 with Table 15

0.599 223 744 kJ	CED, GJ/h	85	83	82	80	79	77	75	74	72	71	70	68	67	65	64	63
Scenario B – One desktop used twice over 10 years																	
2 329 kg	GWP, Mt CO_2e (total)	331	324	318	312	305	299	293	287	282	276	270	265	260	255	249	244
0.146 8 g	ADP, kt Sb-e (total)	21	20	20	20	19	19	18	18	18	17	17	17	16	16	16	15
50 079 MJ	CED, EJ (total)	7.1	7.0	6.8	6.7	6.6	6.4	6.3	6.2	6.1	5.9	5.8	5.7	5.6	5.5	5.4	5.3
0.026 586 758 kg	GWP, t CO_2e/h	3.8	3.7	3.6	3.6	3.5	3.4	3.3	3.3	3.2	3.2	3.1	3.0	3.0	2.9	2.8	2.8
1.675 8E-06 mg	ADP, mg Sb-e/h	238	233	229	224	220	215	211	207	203	199	195	191	187	183	179	176
0.571 678 082 kJ	CED, GJ/h	81	80	78	76	75	73	72	71	69	68	66	65	64	62	61	60
Scenario C – Two desktops used 5 years each over 10 years																	
2 608 kg	GWP, Mt CO_2e (total)	371	363	356	349	342	335	328	322	315	309	303	297	291	285	279	371
0.292 8 g	ADP, kt Sb-e (total)	42	41	40	39	38	38	37	36	35	35	34	33	33	32	31	42
47 242.8 MJ	CED, EJ (total)	6.7	6.6	6.4	6.3	6.2	6.1	5.9	5.8	5.7	5.6	5.5	5.4	5.3	5.2	5.1	6.7
0.029 771 689 kg	GWP, t CO_2e/h	4.2	4.1	4.1	4.0	3.9	3.8	3.7	3.7	3.6	3.5	3.5	3.4	3.3	3.3	3.2	4.2
3.342 47E-06 mg	ADP, mg Sb-e/h	475	466	456	447	438	429	421	412	404	396	388	380	373	365	358	351
0.539 301 37 kJ	CED, GJ/h	77	75	74	72	71	69	68	67	65	64	63	61	60	59	58	77

Table 17 shows the increased burden of using two new desktops instead of one.

Table 17 – Global effect of using two new desktops over 10 years (scenario C) instead of one new desktop twice over 5 + 5 years, scenario C (business as usual) minus scenario B

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
GWP, Mt CO_2e (total)	40	39	38	37	37	36	35	34	34	33	32	32	31	30	30	29
ADP, kt Sb-e (total)	21	20	20	20	19	19	18	18	18	17	17	17	16	16	16	15
CED, EJ (total)	−0.4	−0.4	−0.4	−0.4	−0.4	−0.4	−0.4	−0.3	−0.3	−0.3	−0.3	−0.3	−0.3	−0.3	−0.3	−0.3
GWP, t CO_2e/h	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3
ADP, mg Sb-e/h	237	232	227	223	218	214	210	206	202	197	194	190	186	182	179	175
CED, GJ/h	−5	−5	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−3	−3

Table 18 shows the hourly effect of lifetime extension for desktops.

Table 18 – Global effect per hour of reusing one desktop 5 extra years instead of just using the desktop 5 years, scenario B minus scenario A

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
GWP, t CO_2e/h	−0.45	−0.44	−0.43	−0.43	−0.42	−0.41	−0.40	−0.39	−0.39	−0.38	−0.37	−0.36	−0.36	−0.35	−0.34	−0.33
ADP, mg Sb-e/h	−237	−232	−227	−223	−218	−214	−210	−206	−202	−197	−194	−190	−186	−182	−179	−237
CED, GJ/h	−3.91	−3.84	−3.76	−3.68	−3.61	−3.54	−3.47	−3.40	−3.33	−3.26	−3.20	−3.13	−3.07	−3.01	−2.95	−2.89

Scenario B is 11% better than scenario A per hour for global warming potential at 100 years (GWP100).

As shown in Table 17, emission of around 30-40 Mt CO_2e can be avoided globally by reusing all desktops produced. Also per hour it is better to prolong the lifetime of the desktop as emission of 0.33 to 0.45 t CO_2e and consumption of 2.89 to 3.91 GJ energy can be avoided (Table 18).

8.2 Laptops

Estimates of global shipments of laptops are listed in Table 19.

Table 19 – Estimated shipments of laptops 2015-2030 [b-Andrae]

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Laptops, millions	384	443	511	590	680	785	659	554	465	391	328	276	232	195	163	137

In Table 20, 296 kg per laptop comes from roughly 300 cm^2 PCB area (200 g CO_2e/cm^2), 30 cm silicon die area (4 000 g/cm^2), 0.4 kg aluminium (16 kg/kg), 0.1 kg steel (4 kg/kg), 0.5 kg cables (8 kg/kg), 0.2 kg charger (10 kg/kg), 0.5 kg battery (60 kg/kg), 500 cm^2 screen (45 g/cm^2), 40 kg others. 275 kg in the use stage comes from 11.4 W, 8 760 h, 5 years and 0.55 kg CO_2e/kWh. −31 kg CO_2e/laptop is based on the material content and the circular footprint formulae [b-Wolf].

Table 20 – Estimated GWP100 for average laptops

Environmental impact category	Manufacturing	Use	End-of-life
GWP100, kg CO_2e	296	275	−31

Table 21 shows how the method explained in Table 2 is applied to laptops with Table 19 and Table 20.

Table 21 – Using Table 2 and Table 20 with Table 19

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Scenario A – One use of one laptop over 5 years																	
540 kg CO_2e	GWP, Mt CO_2e (total)	207	239	276	318	367	424	356	299	251	211	177	149	125	105	88	74
0.012 3 kg CO_2e	GWP, t CO_2e/h	4.7	5.5	6.3	7.3	8.4	9.7	8.1	6.8	5.7	4.8	4.0	3.4	2.9	2.4	2.0	1.7
Scenario B – One laptop used twice over 10 years																	
815 kg CO_2e	GWP, Mt CO_2e (total)	313	361	417	481	554	640	537	451	379	318	267	225	189	159	133	112
0.009 3 kg CO_2e	GWP, t CO_2e/h	3.6	4.1	4.8	5.5	6.3	7.3	6.1	5.2	4.3	3.6	3.1	2.6	2.2	1.8	1.5	1.3
Scenario C – Two laptops used 5 years each over 10 years																	
1 080 kg CO_2e	GWP, Mt CO_2e (total)	415	478	552	637	735	847	712	598	502	422	354	298	250	210	176	148
0.012 3 kg CO_2e	GWP, t CO_2e/h	4.7	5.5	6.3	7.3	8.4	9.7	8.1	6.8	5.7	4.8	4.0	3.4	2.9	2.4	2.0	1.7

Table 22 shows scenario C minus scenario B for laptops.

Table 22 – Global effect of using two new laptop 10 years (scenario C) instead of one new laptop twice over 5 + 5 years, scenario C minus scenario B

GWP, Mt CO_2e (total)	102	117	135	156	180	208	175	147	123	104	87	73	61	52	43	36
GWP, t CO_2e/h	1.2	1.3	1.5	1.8	2.1	2.4	2.0	1.7	1.4	1.2	1.0	0.8	0.7	0.6	0.5	0.4

Table 23 shows the hourly effect of lifetime extension for laptops.

Table 23 – Global effect per hour of reusing one laptop 5 extra years (after the 5 initial years) instead of just using the laptop 5 years once, scenario B minus scenario A

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GWP, t CO_2e/h	−1.2	−1.3	−1.5	−1.8	−2.1	−2.4	−2.0	−1.7	−1.4	−1.2	−1.0	−0.8	−0.7	−0.6	−0.5	−0.4

Scenario B is 25% better than scenario A per hour for GWP100.

As shown in Table 22, annually around emission of 40-100 Mt CO_2e can be avoided globally by reusing all laptops produced. Also per hour it is better to prolong the lifetime of the laptops as emissions of 0.4 to 1.2 t CO_2e can be avoided (Table 23).

8.3 Modems (Wi-Fi)

Estimates of global shipments of Wi-Fi modems are listed in Table 24.

Table 24 – Estimated shipments of modems (Wi-Fi) 2008-2015

	2008	2009	2010	2011	2012	2013	2014	2015
Modems (WiFi), produced, millions	250	275	300	315	315*1.05=331	347	365	383

Assuming 5 years lifetime and 5% annual growth rate from 2011 to 2030 (Table 25), the numbers of Modems (Wi-Fi) in use at the same time become relatively reasonable.

Table 25 – Estimated shipments of modems (Wi-Fi) 2015-2030

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Modems (Wi-Fi), millions	383	402	422	443	465	489	513	539	566	594	624	655	688	722	758	796

For example, 1 471 million modems in use in 2012 comes from 250 + 275 + 300 + 315 + 331 = 1 471 million. As a result, perhaps around 2 000 million modems (Table 26) were in use in 2020 [b-Andrae].

Table 26 – Estimated modems (Wi-Fi) in use 2012-2030

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Modems (WiFi),in use, millions	1 471	1 568	1 658	1 741	1 828	1 919	2 015	2 116	2 221	2 333	2 449	2 572	2 700	2 835	2 977	3 126	3 282	3 446	3 619

Estimates of typical Wi-Fi modem life cycle GWP are listed in Table 27.

Table 27 – Estimated GWP100 for average modems (Wi-Fi)

Environmental impact category	Manufacturing	Use	End-of-life
GWP100, kg CO_2e	27	89	−0.03

In Table 27, 29 kg per modem comes from roughly 340 cm^2 PCB area (35 g CO_2e/cm^2), 4 g integrated circuits (1 600 g/g), 7 g aluminium (16 g/g), 0.8 g steel (4 g/g), 40 g cables (8 g/g), 8 kg others. 89 kg in the use stage comes from 3.7 W, 8 760 h, 5 years and 0.55 kg CO_2e/kWh.

NOTE – The modem is similar to the ONT in Table 11.

Table 28 – Using Table 2 and Table 25 with Table 27

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Scenario A – One use of one modem (Wi-Fi) over 5 years																	
115.97 kg CO_2e	GWP, Mt CO_2e (total)	44	47	49	51	54	57	60	62	66	69	72	76	80	84	88	92
0.002 6 kg CO_2e	GWP, t CO_2e/h	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1
Scenario B – One modem (Wi-Fi) used twice over 10 years																	
204.97 kg CO_2e	GWP, Mt CO_2e (total)	78	82	87	91	95	100	105	110	116	122	128	134	141	148	155	163
0.002 33 kg CO_2e	GWP, t CO_2e/h	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.9
Scenario C – Two modem (Wi-Fi)s used 5 years each over 10 years																	
231.94 kg CO_2e	GWP, Mt CO_2e (total)	89	93	98	103	108	113	119	125	131	138	145	152	159	167	176	185
0.002 6 kg CO_2e	GWP, t CO_2e/h	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1

Table 29 shows scenario C minus scenario B for modems.

Table 29 – Global effect of using two new modems (Wi-Fi) 5 years each (scenario C) instead of one new modem (Wi-Fi) twice over 5 + 5 years, scenario C minus scenario B

GWP, Mt CO_2e (total)	10	11	11	12	13	13	14	15	15	16	17	18	19	19	20	21
GWP, t CO_2e/h	0.12	0.12	0.13	0.14	0.14	0.15	0.16	0.17	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.25

Table 30 shows the hourly effect of lifetime extension for modems.

Table 30 – Global effect per hour of reusing one modem (Wi-Fi) 5 extra years (after 5 initial years) instead of just using the modem (Wi-Fi) 5 years, scenario B minus scenario A

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GWP, t CO_2e/h	−0.12	−0.12	−0.13	−0.14	−0.14	−0.15	−0.16	−0.17	−0.17	−0.18	−0.19	−0.20	−0.21	−0.22	−0.23	−0.25

Scenario B is 12% better than scenario A per hour for GWP100.

As shown in Table 29, annually emissions of around 10-20 Mt CO_2e can be avoided globally by reusing all modems (Wi-Fi) produced. Also, per hour it is better to prolong the lifetime of the modems (Wi-Fi) as 0.12 to 0.25 t of CO_2e emissions can be avoided (Table 30).

In summary, emissions of 80 to 160 Mt CO_2e can be avoided by extending the lifetime of desktops, laptops and modems (Wi-Fi) by 5 years. This saving represents 0.25-0.5% of anthropogenic CO_2e (34 Gt) emissions.

9 Discussion

The servitization model promotes the expansion of the operational lifespan of components and devices for as long as possible. This model spreads the manufacturing and end-of-life impacts over a longer usage period; however, not at the expense of the performance. The performance requirement for many uses may not need the latest performance provided by newer devices. These cases may present the largest untapped potential for refurbished products. A refurbished or remanufactured device may provide the required functionality. While in some scenarios the evolution of the performance and impact of devices changes significantly over a few years (technological obsolescence), other scenarios are more mature, with small improvements across generations.

Reuse allows the identification and service of less demanding users and usage requirements with previous generation devices. This has been clearly seen in the COVID-19 crisis, where many schoolchildren benefit for home schooling from second-hand computers decommissioned from public and private offices.

There are potentially several trade-offs between use stage energy, closed-loop waste management, and software upgrade driven obsolescence that could be investigated further. The role of machine learning is also not understood well enough in the present context.

It seems like environmental benefits are much more evident for impact categories (e.g., ADP) more sensitive to environmental impacts during manufacturing and categories that are almost independent of electricity consumption during operation.

Direct reuse is often more environmentally friendly than reuse of some parts followed by reuse.

In the future, standardization on batteries may be important, e.g., in calculation methods for environmental reuse benefits.

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