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Communicating the carbon savings potential associated with reuse of ICT equipment

Position paper

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Content

Declaration

This paper is a deliverable from a study carried out by Fraunhofer IZM and commissioned by Google. The study was commissioned to arrive at objective and unbiased conclusions. Fraunhofer IZM declares no conflict of interest.

Abbreviations

CFF	Circular footprint formula
CFP	Carbon footprint of products (sometimes PCF)
CO_2e	Carbon dioxide equivalents
EC	European Commission
EOL	End of life
FU	Functional unit
GHG	Greenhouse gases
GWP	Global warming potential
ICT	Information and communication technology
ISO	International Organization for Standardization
LCA	Life cycle assessment
PEF	Product environmental footprint
PFC	Product Carbon Footprint (sometimes CFP)

1 Introduction

The European Commission (EC) estimated the contribution of the information and communication technology (ICT) sector to global greenhouse gas (GHG) emissions to be more than 2 % in 2020[1], which, if unchecked, could increase to 14 % by 2040. One major strategy to mitigate increasing impacts is the transition to a circular economy in which devices are used longer. When devices last longer, resources employed for their production are used more efficiently. The EC estimated that if the lifetime of all smartphones in the EU was extended by one year, 2.1 million tons of CO_2 could be saved per year by 2030 – the equivalent of taking a million cars off the road. This example illustrates the benefits of extending the lifetime of ICT equipment, which is particularly effective for devices where the majority of environmental impacts arise during the production stage. For instance, in the case of smartphones and laptops, the production stage is estimated to contribute around 70 to 80 % of total life cycle GHG emissions[2]. Such devices should be used for as long as is reasonably possible.

Reuse of products to extend their lifetime has been recognised to be an effective strategy to mitigate environmental impacts and is among the highest priorities in both the EU waste hierarchy[3] and the concept of circular economy[4]. In the space of ICT equipment, reuse practices have become increasingly common, with companies and individuals making their devices available for reuse and businesses re-introducing pre-owned, refurbished and remanufactured equipment into the market. Nevertheless, reuse accounts for only around 11 % of the total market in the case of smartphones[5].

The quantification of environmental benefits of reuse is relevant as a basis for communicating advantages to customers and to set incentives for both organisations and private consumers. However, challenges remain in the approach to estimating such benefits. Insights into relevant standards and literature reveal a considerable variance in approaches and communicated data. To date, there is no consensus on a 'best practice' approach to accurately and uniformly estimate environmental benefits.

This paper aims to present, in a condensed form, the challenges associated with quantifying the potential environmental benefits associated with the reuse of ICT equipment as well as approaches described in relevant standards and literature. The focus is laptops and smartphones with a view to carbon-equivalent emissions (global warming potential). Ultimately, the paper provides a basis for discussion as well as recommendations on how environmental benefits can be communicated in the absence of a uniform approach.

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[1] https://ec.europa.eu/commission/presscorner/api/files/attachment/862091/Supporting_the_green_transition_en.pdf.pdf

[2] https://www.fairphone.com/wp-content/uploads/2022/07/Fairphone-4-Life-Cycle-Assessment-22.pdf
https://www.apple.com/environment/pdf/products/iphone/iPhone_14_Pro_PER_Sept2022.pdf
https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE3cVG5
https://www.apple.com/environment/pdf/products/notebooks/14-inch_MacBook_Pro_PER_Oct2021.pdf

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

[4] https://ellenmacarthurfoundation.org/circular-economy-diagram

[5] https://www.persistencemarketresearch.com/market-research/refurbished-and-used-mobile-phones-market.asp

2 Problem statement

The method most commonly used to estimate environmental impacts of products and services is life cycle assessment (LCA). Generally, LCA is considered most useful in assessing linear consumption patterns, accounting for the life cycle of a product from 'cradle' (raw material acquisition through production) to 'grave' (end-of-life treatment). Circular use cases can be accounted for in LCA, but present several challenges: How should positive impacts of circular use cases be accounted for, which may occur outside the typical scope of a product-centric LCA (such as reduced consumption of new products due to longer use of an existing product)? How should the environmental impacts of one product be allocated to several users? Standards and literature describe and apply a number of different approaches and there is currently no consensus on which is considered 'best practice'. Stakeholders wanting to communicate environmental benefits of reuse therefore need guidance on how to approach the issue in the absence of a uniform method.

In addition to the methodological challenges, it should be noted that reuse of ICT equipment occurs in a variety of forms, invoking different levels of environmental impact. While there is disagreement on exact definitions[1], relevant terms can generally be understood as follows: Direct reuse typically denotes reuse with only minimal processes between use cycles, such as testing and transportation. Refurbishment may be more elaborate, additionally involving cleaning, data erasure, repair, and parts replacement. Remanufacturing can be a much more elaborate process, potentially involving deep disassembly and the production of a 'like new' product. Environmental impacts introduced by these processes are therefore specific to the condition of a device and to the scope of work carried out by an individual organisation. This means that environmental benefits associated with an extended use are impacted differently, depending on the applied process, as well as the potential for extending the product's lifetime itself.

[1] Gharfalkar M, Ali Z, Hillier G. Clarifying the disagreements on various reuse options: Repair, recondition, refurbish and remanufacture. Waste Management & Research. 2016;34(10):995-1005. https://doi.org/10.1177/0734242X16628981

3 Screening of relevant standards

Reuse of products is often understood as a 'multifunctionality' issue in the context of LCA. Relevant standards typically address two situations in the context of multifunctionality: (1) a production process results in more than one output (products), and (2) material recycling leads to materials being used across multiple subsequent cycles (product systems). The case of product reuse is commonly not explicitly addressed, although it may be considered comparable, as a single product is used across several use cycles by more than one user. The reuse of a product can also be considered to substitute, at least in part, a new product and therefore avoid new production.

There are multiple standards relating to life cycle assessment and carbon footprinting of products. ISO 14044[1], the primary standard for LCA, recommends a hierarchical procedure for solving multifunctionality, as has been summarized by Malabi Eberhardt et al. (2020)[2]: Allocation of environmental impacts deriving from one or more processes to more than one product systems should be avoided by: (1) dividing the processes into sub-processes and 'cutting off' the sub-processes providing the secondary function, or by (2) 'system expansion', where the secondary functions of the initial product system are integrated into the system boundary. This is done using a substitution method in which the initial process is credited with the impact that the secondary function potentially avoids by substituting the most likely corresponding technology and/or practice in the subsequent use cycle. If allocation cannot be avoided, (3) an allocation approach should be applied using (a) the underlying physical relationship (e.g., mass), (b) other relationships (e.g., economic value), or (c) the number of subsequent uses of the recycled material (in that order of preference).

A number of other standards refer to this hierarchy defined in ISO 14044, however, it has been highlighted that beyond the above general understanding, the standard does not provide clear guidance for implementation in practice, leaving room for interpretation and thereby leading to variability[3]. It has also been pointed out that the standard does not clearly distinguish between the consequential and attributional approach to LCA, despite their profound differences[3].

Other related standards describe different approaches to allocation. For instance, BSI PAS 2050[4] prescribes equally sharing production impacts to the number of reuse instances, while adding that more sophisticated approaches may be needed. The Circular Footprint Formula (CFF)[5] of the Product Environmental Footprint (PEF) method has been described[2] to use a mix of methods, employing both system expansion and allocation, using several allocation approaches, and accounting for a quality factor and market situation (both rather related to recycling of materials). In reuse situations, when a material or component is reused for the same purpose, the weight of the reusable components (by which the impact is multiplied) is divided by the number of times it is reused. Thereby, the impacts of reusable components are shared equally between subsequent use cycles.

[1] https://www.iso.org/standard/38498.html

[2] Malabi Eberhardt, L.C.; van Stijn, A.; Nygaard Rasmussen, F.; Birkved, M.; Birgisdottir, H. Development of a Life Cycle Assessment Allocation Approach for Circular Economy in the Built Environment. Sustainability 2020, 12, 9579. https://doi.org/10.3390/su12229579

[3] Pelletier, N., Ardente, F., Brandão, M. et al. Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible?. Int J Life Cycle Assess 20, 74–86 (2015). https://doi.org/10.1007/s11367-014-0812-4

[4] https://knowledge.bsigroup.com/products/specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services/standard

[5] https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf

Screening available standards, it becomes clear that the standards landscape does not paint a clear picture on how the environmental effects of reusing products should be estimated. In effect, LCA and CFP studies employ a multitude of approaches, as is discussed in the next section.

4 Screening of relevant literature

The authors of this paper carried out a screening of scientific literature to gain insight into how environmental benefits of reuse are estimated and how specific values for potential carbon savings are presented. It should be noted that the intention was not a comprehensive literature review, but rather a screening of relatively recent publications that were deemed most relevant for the purpose of this paper.

ADEME (2022)[1] The French Agency for Ecological Transition, ADEME, published a comprehensive study in 2022 assessing environmental impacts of a set of refurbished products, including smartphones and laptops. The work acquired primary data on refurbishment processes from 11 refurbishment companies in France (7) and international (4) to estimate environmental impacts. The benefits of reuse were estimated using a substitution approach, in which it is assumed that a refurbished device can substitute (at least in part) a new device and therefore avoid the (partial) production of a new device. Applying a 'cut-off' allocation, the new device is allocated all impacts arising from production and end-of-life (which is merely delayed by reuse), while the refurbished device is only allocated impacts arising from refurbishment. Using this approach, ADEME estimated:

For smartphones:

- GWP of using a new smartphone: 85.2 kg CO_2e (assumed lifespan: 3 years)
- GWP of using a refurbished smartphone: 7.61 kg CO_2e (assumed lifespan: 2 years)
- GWP avoided by using refurbished over new smartphone: -87 %

For tablets (extrapolation from smartphones):

- GWP avoided by using refurbished over new tablet: -78 %

For laptops:

- GWP of using a new laptop: 177.6 kg CO_2e (assumed lifespan: 5 years)
- GWP of using a refurbished laptop: 24.28 (assumed lifespan: 3 years)
- GWP avoided by using refurbished over new laptop: -77 %

For desktop computers:

- GWP of using a new desktop: 289.8 kg CO_2e (assumed lifespan: 5 years)
- GWP of using a refurbished desktop: 46.25 kg CO_2e (assumed lifespan: 3 years)
- GWP avoided by using refurbished over new desktop: -73 %

As an alternative to the default cut-off approach, ADEME (2022) apply a 'depreciation approach', in which the refurbished device is allocated a share of manufacturing and EOL impacts in case the new device, if refurbishment takes place before the theoretical end of the usage period in the first cycle. This is implemented to discourage overconsumption of relatively new, refurbished products. Results are presented in scenarios and in diagrams only, therefore, they cannot easily be reproduced here.

[1] Erwann Fangeat, ADEME, Laurent Eskenazi, Eric Fourboul, Hubblo, Julie Orgelet-Delmas, DDemain, Etienne Lees Perasso, Firmin Domon, LCIE Bureau Veritas 2022. Assessment of the environmental impact of a set of refurbished products final report - 180 pages. Available: https://librairie.ademe.fr/dechets-economie-circulaire/5833-assessment-of-the-environmental-impact-of-a-set-of-refurbished-products.html

A study published by **André et al. (2019)**[1] from Chalmers University of Technology investigated the environmental impacts of using second-hand laptops, mediated by a Swedish reuse company (Inrego AB), instead of new ones, based on LCA. Based on data from the company, the study assumes that laptops have typically been used for three years and little more than two-thirds (70%) can be reused without requiring any spare parts that are resold. The functional unit (FU) was "one year of access to a laptop computer". This FU was motivated since the second-hand laptops can be argued functionally equivalent to new laptops considering the high-quality, "as-new" condition and given warranties. Laptops do not require any spare parts, indicating a relatively lighter refurbishment process. The principal activities of preparation for reuse consist of sourcing and transport from supplying companies, sorting, testing, data erasure, resale and transport to customers. Transportation utilises airplanes, freight ships and light and heavy-duty trucks. Laptops are mostly sourced in Sweden while customers are predominantly located within Europe but also in Asia.

The results show clear benefits of using second-hand laptops for all included environmental impact categories. Although Inrego's average resale distance extends beyond Europe, preparation activities for reuse have almost no comparable impact. Consequently, the results for each impact category essentially depend on two key features: use extension, which reduces the need for primary laptop production and steering of flows into recycling, which reduces the need for primary metal production. Since the preparation for reuse is mostly negligible, the contribution of use extension to the total impact reduction for any impact category depends on the reuse efficiency (70%) and the duration of use extension. Therefore, use extension results in a quite constant reduction across all impact categories. In the baseline scenario (3 years first and 3 years second use), André et al. estimated:

- GWP avoided by using used over new laptop: -41 %

In the view of the authors of this paper, the core difference between results between André et al. and ADEME stems from differing allocation approach. André et al. apply a 'shared burden' approach, where impacts from production are equally assigned to each year of use, while ADEME apply 'cut-off' as their default approach. The argument given by André et al. is that the functionality of laptops remains the same for several years and the laptops for reuse are in a 'like new' condition.

A study published by **Pamminger et al. (2021)**[2] from TU Wien analysed the environmental impacts of three circular end-of-use scenarios for smartphones via LCA: Repairing, refurbishing and part remanufacturing. Environmental impacts are allocated to the reuse instance based on an economic allocation that references the ratio between the residual market value and the original price. Data on prices is retrieved from a retailer of refurbished smartphones. In addition, the study assumes that the second use cycle of a smartphone is shorter than the first use cycle. The refurbishment scenario takes account of a range of activities, including collection, transportation, sorting (incl. recycling of rejected devices), charging, testing, replacing components, data erasure, factory resetting, and distribution. The remanufacturing scenario takes into account the reuse of individual components, including semiconductors, which – in the view of the authors of this paper - is not a commonly employed process in industry at the current time. This scenario is therefore not evaluated further.

[1] Hampus André, Maria Ljunggren Söderman, Anders Nordelöf, Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse, Waste Management, Volume 88, 2019, Pages 268-279, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2019.03.050

[2] Pamminger, R., Glaser, S. & Wimmer, W. Modelling of different circular end-of-use scenarios for smartphones. Int J Life Cycle Assess 26, 470–482 (2021). https://doi.org/10.1007/s11367-021-01869-2

Results compare the environmental impact of refurbishment compared to a linear reference scenario (34.6 kg CO2e for materials, production and distribution of a smartphone), aligned to the declared unit of 2.5 years of use. In the refurbishment scenarios, Pamminger et al. estimated:

- GWP avoided by using a refurbished over new smartphone: -55 %

The main contributor to the impact of the refurbished smartphone is the allocated burden from the phone's first life (78 % contribution) through economic allocation.

A study by **Cordella et al. (2021)**[1] from the European Commission analysed the potential to reduce the carbon footprint of smartphones using a life cycle model. An attributional LCA was carried out for the analysis, applied to a baseline scenario (linear consumption of new smartphones), compared with the purchase of remanufactured or second-hand devices. In the baseline scenario, Cordella et al. assume smartphones are replaced with a new device every 2 years (i.e. 2.25 units for a chosen reference period of 4.5 years) and kept unused at home at the end of the use period. In the remanufacturing scenario, the lifetime and EOL behaviour are identical, but battery change, display change and energy for manufacturing and transport are accounted for. In the reuse scenarios, replacement cycle and EOL behaviour are also the same, with additional impacts arising due to battery change, display change, and transport. Using these assumptions, Cordella et al. estimated:

For smartphones:

- GWP of using new smartphones: 77.2 kg CO_2e (2.25 units over 4.5 years)
- GWP of using remanufactured smartphones: 37 kg CO_2e (2.25 units over 4.5 years)
- GWP of using second-hand smartphones: 16.3 g CO_2e (2.25 units over 4.5 years)
- GWP avoided by using a remanufactured smartphone: -52 %
- GWP avoided by using a second-hand smartphone: -79 %

The authors of this paper assume that Cordella et al. implicitly applied a 'cut-off' allocation, given that the use of second-hand devices is associated with carbon savings of almost 80 % in the reuse scenario where the lifetime of the device is doubled (including display and battery replacement).

A study carried out by **Maga et al. (2018)**[2] from Fraunhofer UMSICHT in cooperation with a German refurbishment company investigated environmental savings achieved through refurbishment of smartphones and tablets. For production data, the study chose an iPhone 6 and an iPad Pro as representative devices due to their relatively high market share in the refurbishment sector at the time. The study obtained primary data on the refurbishment process and accounts for transportation, data erasure, testing, inspection, and swapping of displays and batteries where needed. The environmental benefits of reuse are estimated by comparing impacts of using new versus refurbished devices over a period of 4 years. The use cycle of both new and used equipment is assumed to be 2 years. Therefore, in the 'new' scenario, two new devices are procured and used within 4 years. In the 'refurbished' scenario, only one new device is produced, used for 2 years, refurbished, and reused for another 2 years. Based on this, Maga et al. (2018) estimate:

For smartphones:

- GWP of using new smartphones: 127 kg CO_2e (over 4 years)

[1] Cordella, M, Alfieri, F, Sanfelix, J. Reducing the carbon footprint of ICT products through material efficiency strategies: A life cycle analysis of smartphones. J Ind Ecol. 2021; 25: 448– 464. https://doi.org/10.1111/jiec.13119

[2] Daniel Maga, Markus Hiebel, Elisabeth Banken, Paola Viehof, Treibhausgas- und Ressourceneinsparungen durch Wiederverwendung von Smartphones und Tablets, Müll und Abfall, 50. Jahrgang, Mai 2018, Seite 217 – 280. Available (in German): https://www.interzero.de/fileadmin/Aktuelles/PMs_PDF/2018/Artikel_MuellundAbfall_2018.pdf

- GWP of using a refurbished smartphone: 68 kg CO_2e (over 4 years)
- GWP avoided by using refurbished over new smartphone: -46 %

For tablets:

- GWP of using new tablets: 301 kg CO_2e (over 4 years)
- GWP of using a refurbished tablet: 162 kg CO_2e (over 4 years)
- GWP avoided by using refurbished over new smartphone: -46 %

Several **other studies** were screened but found to not align with the goals of this paper, including work by Zink et al. (2014)[1], Mann et al. (2022)[2], Fatimah and Biswas (2016)[3]. Older studies were not taken into account for this screening.

[1] Zink, T., Maker, F., Geyer, R. et al. Comparative life cycle assessment of smartphone reuse: repurposing vs. refurbishment. Int J Life Cycle Assess 19, 1099–1109 (2014). https://doi.org/10.1007/s11367-014-0720-7

[2] Mann, A.; Saxena, P.; Almanei, M.; Okorie, O.; Salonitis, K. Environmental Impact Assessment of Different Strategies for the Remanufacturing of User Electronics. Energies 2022, 15, 2376. https://doi.org/10.3390/en15072376

[3] Ad Yun Arifatul Fatimah, Wahidul Karim Biswas, Sustainability Assessment of Remanufactured Computers, Procedia CIRP, Volume 40, 2016, Pages 150-155, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2016.01.087

5 Discussion of findings

It has been highlighted that ISO 14044 remains unclear on key aspects of how multifunctionality should be handled in LCA and that among the various allocation approaches, there are coherent arguments to be made for each of them[3]. Therefore, at this time, there is no objective 'right' or 'wrong' way to approach the issue. Consequently, this paper can only make a number of observations as follows:

- Various studies agree in principle that reuse of ICT equipment is associated with a positive environmental effect compared to purchasing a new device.
- The calculation of environmental benefits of reuse is a complex task with a multitude of variables. Simplifying assumptions or scenario analysis are therefore necessary to arrive at tangible results.
- Available studies apply a number of different methods and differ in their underlying assumptions and data, leading to a wide range of results.
- Not all effects can be captured. Typically, in the attributional LCA studies carried out, societal aspects are outside the scope of analysis, such as rebound effects associated with the increased availability of reuse operators, where consumers use devices for shorter periods due to the availability of resale options, or the re-spending effect, which assumes that the cost saving effect of purchasing 'cheaper' used equipment leads to environmental impacts in other areas, where the saved money will be spend[1].

With regards to the methods encountered during the screening of literature, the authors of this paper note the following:

- The quantification of environmental effects of reuse typically involves a comparative analysis, comparing a reuse scenario to a reference scenario, in which new products are consumed. Such analyses quantify positive effects of extending the lifespan of equipment through reuse, resulting in fewer new devices that need to be produced / consumed in a given timeframe in the reuse scenario (cf. Figure 1).
- Some studies adopt a wider **system perspective** for the comparison that includes both a first and a second use cycle and therefore also includes the production and distribution of the in the reuse scenario (cf. Figure 1). Adopting this perspective, the environmental benefits of reuse are approximately proportionate to the extent to which the lifespan of the 'reuse product' is extended (deducting impacts from preparation for reuse processes, such as refurbishment). Such studies tend to report the environmental benefits of reuse in general, but do not necessarily explicitly express the share of the savings allocated to the second use cycle or user.
- Other studies adopt a more narrow system boundary, with the comparison only on a **second use perspective** (cf. Figure 1). In such studies, allocation becomes relevant to determine whether the second use cycle in the reuse scenario shares a part of the environmental load from the production and distribution stages (outside the system boundary) or not.
- Yet other studies adopt a 'product-centric' perspective, in which the environmental load of life cycle processes of one single product (incl. production, distribution, preparation for reuse

[1] Itten, R., Jattke, M., Bieser, J., Minimising rebound effects of lifetime extension : sustainable business models for mobile, internet-enabled devices, 3rd Life Cycle Innovation Conference (LCIC), Berlin, Germany (hybrid), 29 June - 1 July 2022. Available: https://digitalcollection.zhaw.ch/handle/11475/25875

and end-of-life treatment) are distributed to multiple use cycles via allocation, without considering the wider system-level benefits of reuse[1].

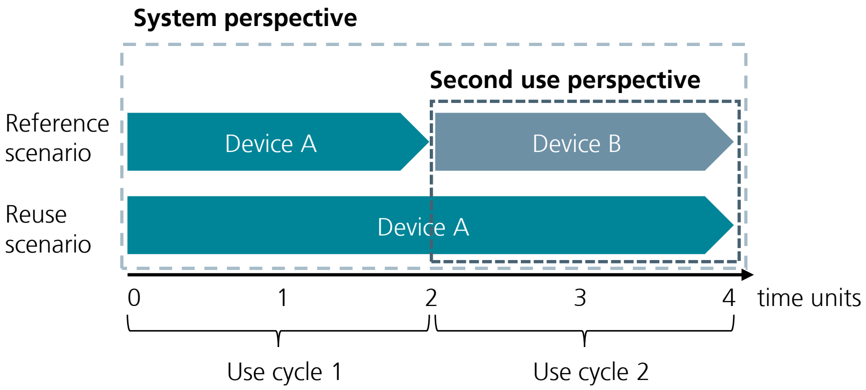

Figure 1: Illustration of differences in system boundaries between 'system' and 'second use' perspective

With regard to the different allocation approaches encountered in the literature screening, the authors of this paper note:

- **'Cut-off' allocation** follows the logic that environmental impacts are assigned at the time of their occurrence. It incentivizes reuse by making pre-owned devices available for a very low relative 'carbon cost'. The drawbacks of this approach are first, the first user is not incentivized to make their used devices available for reuse and second, the second user receives a used device at a very low 'carbon cost', even if the first use phase is relatively short. Savings potentials estimated using this approach tend to be relatively high (such as results from ADEME (2022) in the range of 70 – 90 %) and may be considered one-sided by some.
- The **'depreciation' approach** to allocation, as described by ADEME (2022), assumes that environmental burdens arising from the production stage are depreciated over a fixed period of time. If reuse occurs before this period is elapsed, some of the carbon (or other) impact is carried over to the reuse product. In the authors' view, this approach is suitable to meet the shortcomings of the cut-off allocation approach described above. The drawbacks are that first, a time period for carbon depreciation needs to be fixed per product or product group, and second, information on the duration of the first use is required in order to allocate potentially 'residual' carbon to the second use. It is therefore not as simple in its application.
- **'Shared burden' approaches** distribute the environmental burdens from production and other processes among multiple use cycles and users using allocation keys. Typical allocation keys are the number of reuse cycles, the relative duration of each reuse cycle, or economic value retention[1] (price of used relative to price of new product). These approaches assume that products are manufactured to provide a defined utility to users, resulting in environmental impacts. Therefore, each user benefiting from the utility of the device is proportionately responsible for the caused impacts. Therefore, the estimated environmental savings using this approach tend to be more moderate compared to 'cut-off' approaches. Environmental impacts arising from the use phase are always allocated to the individual user.

[1] For instance: Makov, Tamar; Wolfram, Paul; Blass, Vered; What is my share? Using market data to assess the environmental impacts of secondary consumption. 2019. Proceedings of the 3rd PLATE conference, September 18-20, 2019, Berlin, Germany.Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4160513

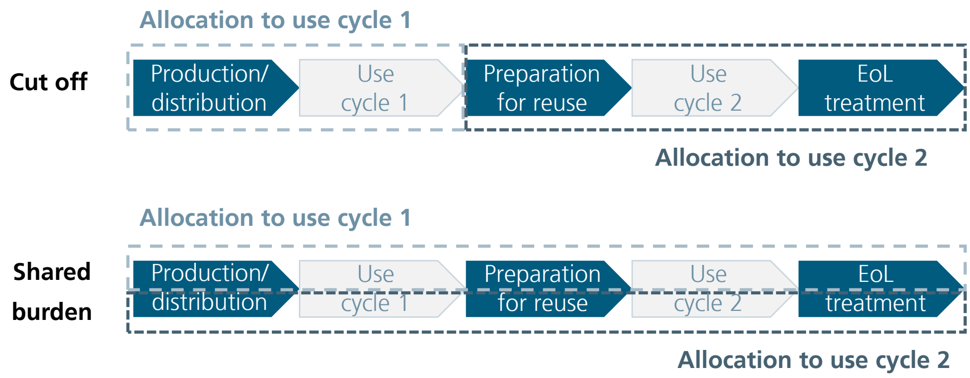

Figure 2: Illustration of 'cut-off' and 'shared burden' allocation

The following table summarizes the values for relative carbon-equivalent emission savings associated with using used instead of new ICT equipment estimated by the screened literature (cf. section 4).

Product group	Reuse type	Allocation type	CO_2e savings	Source
Smartphones	Refurbishment	Cut-off	87 %	ADEME (2022)
	Refurbishment	Economic depreciation	55 %	Pamminger et al. (2019)
	Refurbishment	No explicit allocation	46 %	Maga et al. (2018)
	Remanufacturing	Cut-off (assumed)	52 %	Cordella et al. (2021)
	Reuse[1]	Cut-off (assumed)	79 %	Cordella et al. (2021)
Tablets	Refurbishment	Cut-off	78 %	ADEME (2022)
	Refurbishment	No explicit allocation	46 %	Maga et al. (2018)
Laptops	Refurbishment	Cut-off	77 %	ADEME (2022)
	Refurbishment	Shared (assumed)	41 %	André et al. (2019)
Desktop PCs	Refurbishment	Cut-off	73 %	ADEME (2022)

It should be noted that Maga et al. (2018) estimate benefits of reuse on a system perspective without allocating benefits to the first or second use cycle or user. It is therefore not clear, which share of the benefits would be allocable to a second user in a comparison that is meant to compare reuse with the consumption of new devices. This makes the values reported by Maga et al. not directly comparable to other values in this table. André et al. (2019) also do not explicitly allocate benefits to first and second users, but state that "*the results show clear benefits of using second-hand laptops for all included environmental impact categories*" and "[…] *use extension results in a quite constant reduction across all impact categories. In the baseline scenario this reduction is about 41% in comparison to using new laptops*", which the authors of this paper interpret as an

[1] Reuse accounts for replacing display and battery once during the lifespan

application of a shared allocation approach. Cordella et al. (2021) also do not explicitly allocate to first and second user, but the authors of this paper assume a cut-off allocation was applied, leading to the high reported CO_2e savings rate of 79 % in the 'reuse' scenario.

As indicated in section 2 'problem statement', the terms 'refurbishment', 'remanufacturing' and 'reuse' do not imply the exact same processes. In one paper, refurbishment consists of data erasure, testing and cleaning of devices (André et al. 2019, based on input from a Swedish refurbishment company), while refurbishment may include replacing displays and batteries in other papers (e.g. Cordella et al. 2021). This contributes further to the variance observed from the data summarized in the above table, but also reflects the industrial practice, in which processes do not follow a standardized protocol and differ between companies. Ultimately, the impacts from preparation for reuse processes are typically reported to have a minor impact compared to the production stage and therefore play a secondary role.

6 Recommendations

Despite the ambiguous situation, the authors of this paper can make the following **general recommendations** on the communication of environmental (carbon) benefits associated with reuse of ICT equipment:

- Data on carbon savings is available in literature on product group level rather than product-specific level, on the basis of which carbon savings can be communicated.
- Sources (studies) on which communicated values are based, should be transparently communicated, making the original source accessible (e.g. providing a URL or link), ideally in addition to a rationale for choosing an individual study.
- Relative carbon savings (percentages) may be less uncertain than absolute values (e.g. kg CO_2e) and may be more easily understood by consumers (absolute values require context).
- It appears relevant to communicate that carbon savings are not achieved simply through purchasing used equipment, but rather via its (extended) use.

Providing more concrete guidance, in the authors' view, there are two pathways to communicating information on environmental benefits of reuse in the absence of a standard approach, which are outlined below as options A and B. The order in which the options are listed does not imply a ranking or preference. Another option may be to make one's own estimations, which, however, is not considered feasible within the scope of the current work due to the described ambiguity in choosing an available method.

Option A: Cite data ranges from relevant studies

Given the fact that there is not one standard or recognized 'best practice' approach to estimating environmental benefits of reuse, in the authors' view, communicating ranges of data reported by the several relevant studies is a suitable option. In doing so, the communicating party does not explicitly favour one approach, study, or publishing organisation over others, thereby remaining in a neutral position.

Following this option, communication of environmental benefits of reuse may take the following form, for example: *"The use of a refurbished [product group] has the potential to save [data point min.] to [data point max.] compared to using a new [product group]. This is based on…"*

A complication to this option is that not all data points reported in published studies are comparable and should therefore not be mixed to form a data range. For instance, as illustrated in Figure 1, a different perspective can lead to different results: Analysing carbon (equivalent) emission savings from reuse of a device over its lifetime produces data on system-level, where benefits are not necessarily allocated to first or second users explicitly, while focusing on the second use cycle produces data relating specifically to the second use cycle, typically employing allocation. In the context of this study, this leaves relatively few data points, and arguably too few to form proper ranges. Therefore, while option A appears to be most neutral, it may not be the most practical.

Option B: Cite data from one relevant study

Communicating data reported from one individual study eliminates complications described for option A, but requires rationale for choosing a specific study. To this end, it is recommendable to select a study that fulfils at least several criteria, including (not all may be fulfilled by all publications): It is relevant for the product type; provides rationale for the chosen approach; follows established methods and / or is compliant with relevant standards (such as ISO 14040/44); carries out sensitivity analyses for relevant aspects; was critically reviewed by a third party; is carried out by a scientifically neutral organisation or authorship; is a peer-reviewed scientific publication.

Following this option, communication of environmental benefits of reuse may take the following form, for example: *"The use of a refurbished [product group] has the potential to save [data point] compared to using a new [product group]. This is based on…"*

In the context of the goals of this paper and the screening of relevant literature, the authors of this paper recommend to cite data from ADEME (2022) at the current time. The rationale is as follows:

- It is the most recent publication on the topic,
- carried out by an independent (government) organisation,
- reports environmental savings in several impact categories (carbon, materials, e-waste),
- explicitly estimates savings potential due to second users (applies allocation),
- carries out sensitivity analyses for key aspects that influence results, and
- presents values for several product groups based on the same method (avoiding the dilemma of comparing values from different studies using different methods).

As pointed out, a drawback to the study is, in the view of the authors of this paper, that the applied reference approach relies on cut-off allocation, as described in section 5. In the longer run, in the view of the authors, it may be preferable to apply allocation that results in more balanced distribution of benefits to first and second users, depending on factors such as supply and demand ratios of used equipment or economic value retention. However, at the time of writing, the ADEME study is highly suitable due to the reasons listed above.

It should be noted that the study (ADEME 2022) has a focus on the French situation. Carrying out similar analyses for different regions may impact the results. While differences may lie in various factors, the authors of this paper assume that differences to other industrialized nations, such as Germany or the USA, may not necessarily differ systematically. Transport distances may differ, but this was found by ADEME to be of comparatively minor relevance. The estimated savings potential using the reference (cut-off) approach can be expected to be approximately the same.

7 Outlook

With regard to future work, the authors consider that a standard approach to quantifying environmental benefits of reuse is needed. Work towards a standardized approach in the ICT sector (or beyond) would require a broad group of stakeholders from industry and academia, led by a neutral institution, to make decisions on the methods, assumptions, and required data.