Grey Energy and Environmental Impacts of ICT Hardware

Roland Hischier[1], Vlad C. Coroama[2], Daniel Schien[3], and Mohammad Ahmadi Achachlouei[1,4]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland
Roland.Hischier@empa.ch
[2] Measure-IT Research, Bucharest, Romania
vlad.coroama@measureit-research.eu
[3] Department of Computer Science, University of Bristol, UK
daniel.schien@bristol.ac.uk
[4] Centre for Sustainable Communications CESC, KTH Royal Institute of Technology, Stockholm, Sweden
mohammad.achachlouei@abe.kth.se

Abstract. Direct energy consumption of ICT hardware is only "half the story." In order to get the "whole story," energy consumption during the entire life cycle has to be taken into account. This chapter is a first step toward a more comprehensive picture, showing the "grey energy" (i.e., the overall energy requirements) as well as the releases (into air, water, and soil) during the entire life cycle of exemplary ICT hardware devices by applying the life cycle assessment method. The examples calculated show that a focus on direct energy consumption alone fails to take account of relevant parts of the total energy consumption of ICT hardware as well as the relevance of the production phase. As a general tendency, the production phase is more and more important the smaller (and the more energy-efficient) the devices are. When in use, a tablet computer is much more energy-efficient than a desktop computer system with its various components, so its production phase has a much greater relative importance. Accordingly, the impacts due to data transfer when using Internet services are also increasingly relevant the smaller the end-user device is, reaching up to more than 90% of the overall impact when using a tablet computer.

Keywords: Life Cycle Assessment, Sustainability, Grey Energy, Cumulative Energy Demand, ICT Hardware, Information and Communication Technology

1 Introduction

Direct energy consumption of ICT [1], data centers [2], and the Internet [3,4] are described in detail in other chapters in this volume – however, this direct energy consumption (also called "end energy" in energy statistics) is only "half the story." Extraction of the various metals required to produce the different electronic components necessary in the various devices, e.g., in order to transport an e-mail from the sender to the addressee, consumes energy as well. The same is true of the actual production of the various components, for the final assembly of each of the involved devices, etc. Hence, in order to get the "whole story," energy consumption during the entire life cycle of such devices and services has to be taken into account. Such a life-cycle view of (indirect) energy consumption emerged in the late 1970s [5] and can be assessed today via "cumulative energy demand" (CED) [6], or "grey energy" [7]. The term "grey energy" was coined at the end of the last century in a study conducted by the Swiss Federal Office for the Environment, describing a method using cumulative energy demand for ecological assessment [7]. According to the recent standard 2032 of the Swiss Association of Engineers and Architects (sia) [8], "grey energy" is calculated as the sum of non-renewable energy consumption during the life cycle – i.e., equal to the non-renewable part of "cumulative energy demand" as defined in standard 4600 of the Association of the German Engineers (VDI) [6].

However, in order to get a comprehensive picture in terms of the environmental consequences, i.e., of the sustainability of a product or a service, not only total energy consumption is relevant, but consumption of (further) material resources as well as all the releases into the environment (i.e., waste streams, emissions into air and water) along the entire life cycle also need to be taken into account. This chapter is a first step toward such a more comprehensive picture. In addition to the "grey energy" along the entire life cycle (i.e., the overall energy requirements), it also covers the releases (into air, water, and soil) along the entire life cycle. The topic of (non-energetic) material resources along the life cycle will not be covered here, but in the chapter by Wäger et al. [9]. The present chapter is structured as follows: in a first section, various methods and tools for "grey energy" or a more complete sustainability assessment (in order to take into account releases along the life cycle) are critically discussed and compared. The most appropriate of these methods/tools are applied to various examples of ICT hardware components in view of their "grey energy," and their releases along the entire life cycle are assessed in the second part of this chapter.

2 Methods

Since the publication of the Brundtland report [10], which defined the issue of "sustainability," the scientific community has developed a whole set of different methods to measure sustainability – i.e., to measure the overall environmental, social, and economic impacts related to a process and/or service. In 2007, Ness et al. published their effort to categorize various sustainability assessment methods [11]. They realized that neither can any of these methods be used in all situations, nor do these methods take into account the various aspects of sustainability to the same degree. Their investigation put the focus on three key aspects of such methods – (i) the temporal aspect (i.e., is the method used to assess existing products or services, or can the method also be used to look into the future), (ii) coverage (i.e., is the method suitable for products), and (iii) the degree of integration of the three dimensions of sustainability – i.e., ecological, economic, and social aspects. Ness et al. allocated these methods to the following umbrellas: "indicators/indices," "product-related assessment," and "integrated assessment." Among these three umbrellas, "product-related assessment" covers methods focusing on the material and/or energy flows of a product or a service from a life cycle perspective [11]; i.e., the type of method required to measure the overall energy consumption of a laptop computer. Methods belonging under this umbrella include life cycle assessment (LCA), life cycle costing (LCC), substance flow analysis (SFA), process energy analysis, and exergy analysis.

Among them, LCA is considered by Ness et al. as the most established and well-developed method in this category [11]. LCA is a method to assess the potential environmental impacts and resource consumption throughout a product's life cycle, i.e., from raw material extraction to waste management, including the production and use phases [12]. According to Ayres, LCA has its seeds in the 1970s, when for the first time, a study was conducted in the United States that looked not only at energy, but also at waste emissions along the various life stages [13]. Roughly in the same period, initial activities began in Europe as well – motivated by efforts in the area of pollution prevention [14]. During the second part of the 1990s and the beginning of this century, the method was then standardized by ISO (International Standardization Organization) as the ISO 14 040 series [15,12]. The ISO standard distinguishes four main steps within an LCA study – i.e., goal and scope definition, inventory modeling, impact assessment, and the final interpretation phase [12]. In the first step, the boundaries of the study are defined – as a study is always established relative to the objectives that are to be achieved (for a more detailed description see, e.g., [14]). The second phase is often the most time-consuming part, as the input and output values of each process within the boundaries have to be collected here – before the totality of all these material and energy flows is assessed in the third step, based mainly on ecological criteria. For this assessment, a whole host of different life cycle impact assessment (LCIA) methods has been developed and is applied nowadays (an overview can be found, e.g., in [16]). Among the most recent developments is the method ReCiPe [17], actually an update and advancement of two older, often-used methods – the CML method [18] and the Eco-Indicator'99 [19]. Applying this method is a very convenient way of presenting the results on a midpoint[1] and an endpoint[2] level at the same time. The large choice of midpoint indicators included in ReCiPe allows fulfillment of the requirements of the ISO standards [15,12] – which prescribe a "selection of impact categories that reflects a comprehensive set of environmental issues related to the product system being studied, taking into account goal and scope."

As mentioned above, measuring (indirect) energy consumption emerged at the end of the 1970s as "cumulative energy requirements analysis (CERA)" [5]. From the beginning, this measure of "cumulative energy demand (CED)" has actually been considered the "most important aggregated result of the inventory used for compari-

1 The midpoint level is defined in [17] as being "at the place where mechanisms common to a variety of substances come into play."

2 The endpoint level is defined in [17] as corresponding "to areas of protection that form the basis of decisions in policy and sustainable development."

sons of product-related systems," as stipulated by Klöpffer in an editorial in the International Journal of Life Cycle Assessment [20]. According to the research by Huijbregts et al., "fossil CED correlates well with most impact categories, such as global warming, resource depletion, acidification […]"; but its use as a stand-alone indicator for the environmental impact of a product is nevertheless limited due to "the large uncertainty in the product-specific fossil CED-based impact scores" resulting from releases and land use due to non-fossil energy consumption [21]. In this study, the non-renewable part of the CED was calculated as described in [22] in order to obtain a value for the "grey energy" of the examined ICT devices. And in order to get "the whole story," a group of mid- and endpoint indicators of the ReCiPe method are shown as well that assess the ecological sustainability of these various ICT devices/services examined here.

3 LCA and ICT – A Short Historical Overview

More than 20 years ago, in a paper entitled "Applications of Life Cycle Assessment in the Electronics Industry for Product Design and Marketing Claims," Rhodes wrote that LCA "offers the electronics and power products industry an opportunity" [23]. He concluded that LCA can help this industry sector to identify the areas for improvement and at the same time determine their potential.

In these more than 20 years, a broad variety of LCA studies dealing with different ICT devices have been published. In a recent publication comparing different modeling strategies for modern ICT devices, the author presented an overview of LCA/LCI studies in the area of modern ICT media devices [24]. Another recent overview is the study by Arushanyan et al. reviewing LCA studies not only of ICT products, but also of ICT services [25]. Both overviews show that popular ICT devices like television devices or desktop computers are covered by several studies, while other devices such as smartphones, game consoles, or network components are hardly covered by such studies so far. An important point raised in both of these review studies is the rapid technological development of the ICT sector – leading to high variability of the results. In their 2010 study, Andrae and Andersen compared results from various LCA studies of consumer electronics devices (desktop and laptop computers, mobile phones, and television devices) in terms of their consistency [26], focusing on global warming potential results and primary energy usage. Andrae and Andersen conclude that "published LCAs for mobile phone and television sets are consistent, whereas for laptop and desktop computers, the studies occasionally give conflicting messages" [26]. However, when digging more deeply into these "conflicting messages," it could be observed that one of the main points highlighted by the authors is the high release of NF_3 in the LCD production step, as modeled in ecoinvent [27] – an erroneous value that was corrected by the ecoinvent team in version v2.2 [28], reducing this release by a factor of almost 1,000 [29] and having a major influence on the laptop computer as well as all desktop computer systems using LCD screens.

Publications expanding the scope beyond a simple view of end-user technologies (e.g., laptop computers) toward an assessment of the services provided by such devices, e.g. the use of the Internet (reported, e.g., in [30-33]) have emerged recently, showing the relevance of end-user devices in comparison to the entire infrastructure required in order to access Internet data. In a recent conference contribution dealing with changes of the environmental impacts from ICT over time, Lunden and Malmodin conclude that although the "impacts per connected device and data volume are lower than in the past," further decreases can be achieved only by reducing energy consumption at core sites, data centers, and in the end user devices [34].

Today, various LCA databases contain more or less detailed background data for a variety of different ICT hardware components. Here, the database ecoinvent – in its version v3.01 [35], allocation-based system model – is used, as ecoinvent is the only transparent and easily accessible public LCI database currently available[3].

4 LCA of ICT Hardware

The origin of today's desktop computer has to be seen in the IBM personal computer (PC) model 5150, commercialized in 1981 [36] – which was for the first time a system combining a screen, a computer device, and a keyboard in three different casings. Sales numbers of such systems grew until the mid-2000s, when laptop computers started to take over more and more market share from desktop computers [37]. And since the presentation of the first generation of Apple's iPad, another class of devices has been taking over ever greater parts of the market in mobile computer devices: tablet computers [37].

In this section, the first subsection describes an example of each of the three types of end-user devices mentioned above (i.e., a desktop, a laptop, and a tablet computer), followed by a subsection dealing with some of the most relevant ICT components required for the use of today's Internet services. The third subsection shows a comparison and combination of all the data presented in the two preceding subsections. Active use of all shown devices in Germany is assumed for the calculations.

4.1 End-User Devices

Desktop Computer System. Here, a typical desktop computer system as sold in the mid-2000s is modeled – assuming that such a system is composed of the actual computer device, a keyboard, an optical mouse, as well as a 17-inch LCD flat screen monitor. The inventory data for the computer device, the keyboard, and the mouse are taken directly from the database ecoinvent [28], while the data for the LCD monitor were established in the framework of a study for the Swiss visual communications industry [38], actually representing a 17-inch screen sold around 2010. The resulting inventory data of this entire system are summarized in Table 1. The environmental

[3] Two other LCI databases containing extensive information on electronics products are GaBi and EIME – but due to the high price of access to these data, they are not considered public databases in this article.

impacts due to the production of the devices, as well as for the whole life cycle – based on an assumed lifespan of 6 years (for all four components) and 2 h of daily use of such a system, assuming an average European electricity mix – are summarized in Figure 1.

Table 1. Life cycle inventory data for a desktop computer system. Data represent a standard desktop computer with a keyboard and a mouse (all data taken from [27]), and a 17-inch LCD flat screen (data calculated for [38] – based on a survey of available screens).

Component	Weight [kg]	Modeled as …
Chassis	0.395	100% aluminum profiles
Housing	8.120	7% plastics (ABS), 7% aluminum, 86% steel
Power supply	1.470	Power supply unit
Display	4.010	LCD Module of a 17-inch LCD Screen
HDD & CD-ROM	1.510	1 HDD and 1 CD-ROM
Circuit boards	0.718	printed wiring board, desktop motherboard
	0.493	printed wiring board, unspecified
Keyboard, mouse	1.370	27% steel, 3% Cu, 6% circuit boards, 64% plastics (ABS)
Cable	0.321	45% Cu, 55% plastics (HDPE, ABS)

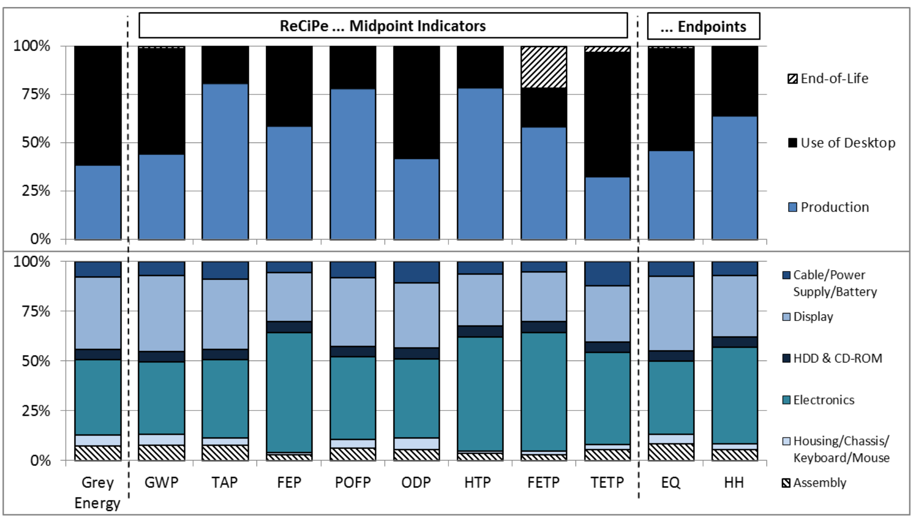

Fig. 1. Upper part: Environmental impact of a desktop computer, used for 6 years (2h/d). Lower part: Environmental impact of its production only. The following indicators are shown: “grey energy” in form of non-renewable cumulative energy demand (CED), the ReCiPe midpoint indicators global warming potential (GWP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), photochemical oxidant formation potential (POFP), ozone depletion potential (ODP), human toxicity potential (HTP), freshwater ecotoxicity potential (FETP), terrestrial ecotoxicity potential (TETP), and the ReCiPe endpoint indicators damage to ecosystem quality (EQ) and damage to human health (HH).

A comparison with published values for desktop computers can be made for the first two impact categories shown in Figure 1 – "grey energy" and GWP, as these are the only factors that have been systematically reported in the studies published to date. Teehan and Kandlikar compared these two impact categories in their recent article, dealing with exactly this topic [39]. One of the models taken into account is the desktop computer reported in the ecoinvent database [27]; i.e., the model used here. The authors conclude in their study that "the weight of evidence strongly suggests that (…) the use phase is the dominant life cycle phase" – however, they take only the bare desktop computer device into account, but no screen. This makes a direct comparison of the results from [39] with the results here impossible. In the study by Andrae and Andersen [26], entire desktop systems from various data sources are compared; among them again the system reported in ecoinvent (however, as stipulated above, based on the erroneous version v2.1 of the LCD screen). From [26] it became evident that apart from the ecoinvent dataset, only one further data source reports a system using an LCD flat screen, the preparatory study for the eco-design requirements of the European Commission [40]. A comparison of the results from these two studies revealed rather large differences, especially concerning the production and the EoL phases. In these two life stages, the (absolute) values from the modeling here (and thus from the model within the database ecoinvent) are about 3 times higher ("grey energy" and GWP); while the value for the use phase show a similar result. This result for the production phase is even more astonishing, as the composition of the two desktop computers is rather similar (as shown in figure 2 of [39]). From this it could be concluded that the dataset here – based on the ecoinvent database – represents a more comprehensive and thus more appropriate picture of this type of device.

Laptop Computer. Developments in recent years at both the economic and the technological levels in the area of portable computer systems have been enormous; resulting in a strong propagation of this kind of device, including in private acquisitions since the mid-2000s.

Table 2. Life cycle inventory data for a typical 14/15-inch laptop computer. Data represent an unweighted average of three laptop computers, reported in [41] and in [42].

Component	Weight [kg]	Modeled as …
Heat sinks	0.026	aluminum profiles
Housing, bottom	0.361	equally split between aluminum, ABS/PC, & magnesium alloy
Housing, top	0.247	equally split between aluminum, ABS/PC, & magnesium alloy
Glass	0.044	coated flat glass
Display	0.561	LCD module
HDD & CD-ROM	0.267	1 HDD and 1 CD-ROM
Circuit boards	0.206	printed wiring board, laptop motherboard
Battery	0.363	Li-Ion battery
External power supply	0.531	power adapter
Keyboard, track pad	0.144	100% as ABS (proxy)
Remaining parts	0.305	assumed as 30% Cu, 30% steel, 40% plastics (ABS)

The basis for this publication is a typical 14/15-inch laptop computer, as sold in the years 2008 to 2011, modeled in the framework of a study for the Swiss visual communications industry [38]. The efforts for the final assembly of this laptop are extrapolated from the reported efforts for the (older) laptop model in ecoinvent [27]. The inventory data of the modeled laptop computer are summarized in Table 2; the resulting environmental impacts (the impacts due to the production of the device, as well as for the whole life cycle – in this case based on an assumed lifespan of 4 years, and again on 2 h daily use) are shown in Figure 2.

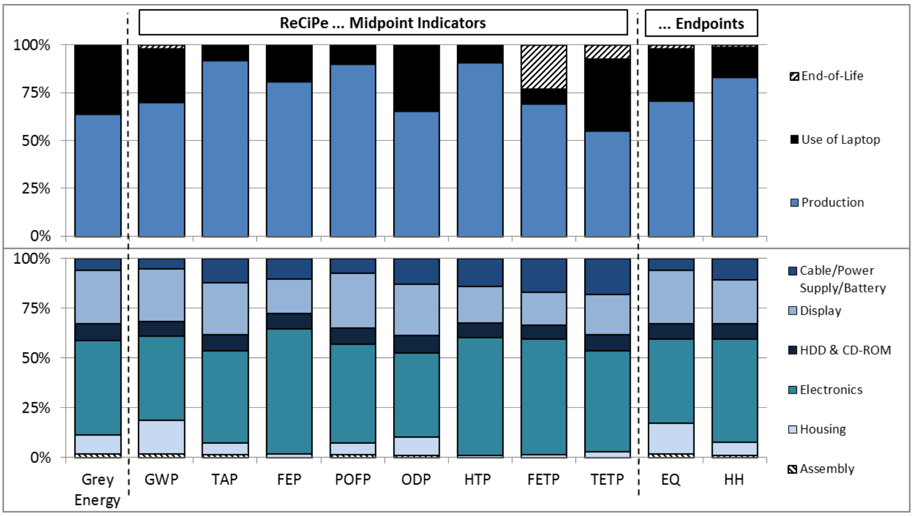

Fig. 2. Upper part: Environmental impact of a laptop computer, used for 4 years (2h/d). Lower part: Environmental impact of production only. The same factors as in Fig. 1 are shown.

Again, the study by Andrae and Andersen [26] is used as a starting point in order to compare the results from the current study with other studies of laptop computers. In this study, apart from the original ecoinvent dataset, GWP results for four further datasets of laptop computers (taken from [43,40,44,45]) are reported and compared to each other. A comparison of these values reported in [26] with the results of the present study is shown in Figure 3 (top, left, line "original") over the entire life cycle of such a device. Actually, the main information in this figure is a comparison of these studies, based on corrected values, assuming a similar use phase for all studies. With such corrected values, two of the studies show quite similar results to the dataset above. As can be seen from the data for the production and end-of-life phases (i.e., the two graphs on the right side of Figure 3), the values reported in the various studies do not vary much. In every case, the study showing the biggest deviation is the one by PE International; a study for which this adaptation of the use phase has not been possible due to the qualitative description of the modeled use phase in [43]. Therefore, as a proxy we assume that for the original data the models from [40] for office and home use (with $^2/_3$ office, $^1/_3$ home) were used. For the data from Lu et al., no adaptation was possible due to the high degree of aggregation of the results in the original presentation.

All in all, based on the comparison in Figure 3, the model of a laptop computer presented here is a reasonable compromise between all the currently existing models.

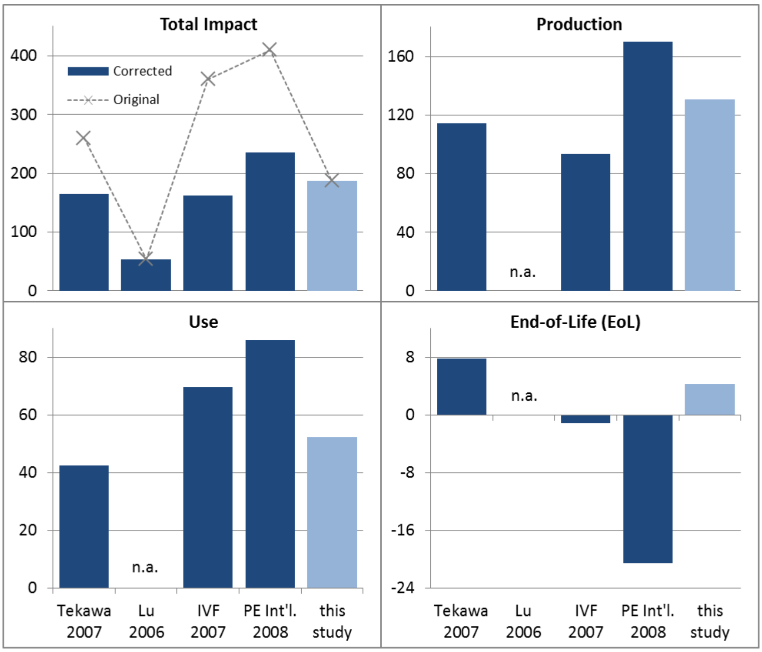

Fig. 3. Global warming potential (in kg CO_2-Eq) for the life cycle of a laptop computer. The figures show the total value (top left) as well as the contribution to the individual life stages production, use and end-of-life. For the use phase (bottom left) the use profile of all studies was aligned to the use profile of this study (2 hours daily for 4 years).

Tablet Computer. Another type of end-user device that emerged very rapidly in the 2000s is the tablet computer –situated between a traditional laptop computer and a cellular phone [37]. One of the most popular such tablet computers – Apple's iPad 2 model – has been modeled in various studies (see, e.g., [38]; [46]). A recent comparison of various approaches for modeling this device has shown that the production phase has a distinctly higher impact in the case of a lab-based approach [24]. The main reason is the higher density (per m^2 of printed wiring board) of integrated circuits (ICs) in comparison to, e.g., the laptop computer used in other studies as the basis for the tablet model. The lab-based approach using inventory data on the level of individual components (i.e., on the level of ICs, resistors, etc.) results in a more complete, and thus more appropriate model for the whole device. The inventory data of this lab-based model are summarized in Table 3. The corresponding environmental impacts (again for the production of the device, as well as per hour of active use –

assuming for this device a lifespan of 2 years, and again with 2 h of daily use) of such a tablet are then shown in Figure 4.

Table 3. Life cycle inventory data for a tablet computer. The data represent an Apple iPad2, as reported in [24] (the result of the lab-based approach in[46]) connected with ecoinvent data.

Component	Weight [kg]	Modeled as …
Housing, back panel	0.140	aluminum sheets
Housing, plastics	0.018	equally split between ABS & rigid PUR
Battery	0.135	Li-Ion battery
Circuit boards	0.039	modeled at the component level, as described in detail in [46]
Display	0.145	LCD module
Glass	0.109	coated flat glass
Other materials	0.026	assumed are 50% copper, 50% steel (unalloyed)

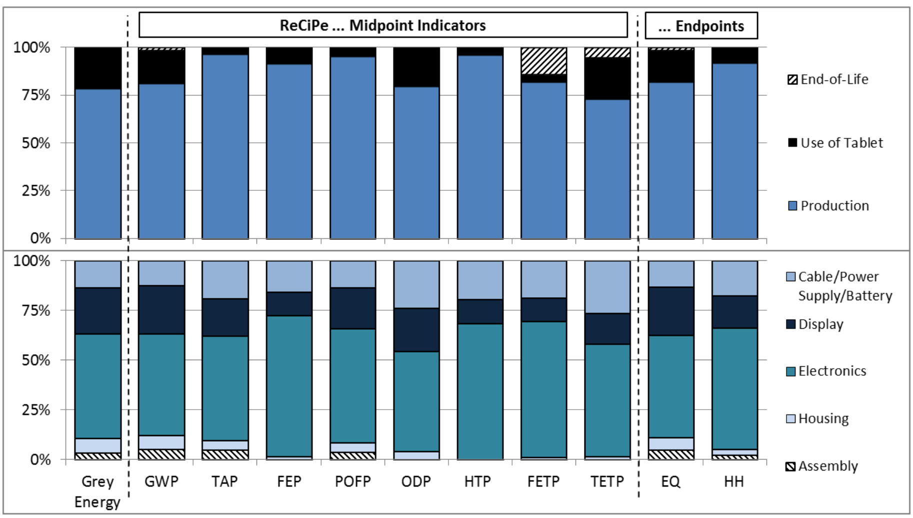

Fig. 4. Upper part: Environmental impact of a tablet computer, used for 2 years (2h/d). Lower part: Environmental impact of production only. The same factors as in Fig. 1 are shown.

4.2 Internet (Services) and Data Centers

According to Coroama et al. [3], in addition to the end-user device (e.g., a tablet), Internet services require four types of devices: (i) the customer premises equipment, CPE (= equipment used by the user for accessing the Internet, e.g., the ADSL modem and/or WiFi routers), (ii) the access network (i.e., the connection between CPE and the actual data network, including cables and multiplexing nodes such as DSLAMs), (iii) the edge & core network with the edge switches and the large (metro and core) routers for transferring all the data between the various users and data providers, and lastly (iv) the actual data centers. Table 4 summarizes exemplary components for each of type by showing key technical information (weight & energy consumption) and the data sources used for the modeling of these components in the LCA calculation.

Table 4. Key data for modeling various infrastructure components used to access/use Internet services. Data represent exemplary devices. The energy consumption of the CPE and the access network takes Power Usage Effectiveness (PUE) into account (as reported in [3]).

Component [Energy consumption]	Weight [kg]	Data sources / Modeled as …
[i] Customer premises equipment (CPE)		Source(s): [3]; [47]; [48] – market dataset "Internet access equipment" from [35] is used as a proxy; adjusted according to weight
- Modem + WiFi router [8 W]	0.486	
[ii] Access network		Source(s): [3]; [48] – market dataset "Internet access equipment" from [35] is used as a proxy; adjusted according to weight
- DSLAM [4 W]	15	
[iii] Edge & core network (*)		Source(s): [4]; [49] – market dataset "Router, Internet" from [35] is used as a proxy in all three cases; adjusted each time according to weight
- Edge ethernet switch [6.25 J/Gb]	13	
- Network, metro router [39 J/Gb]	133	
- Network, core router [26.7 J/Gb]	503	
[iv] Data center		Source(s): [50]; [51] – market dataset "Computer, desktop, without screen" from [35] is used as a proxy in all three cases; adjusted each time according to weight
- Volume server [222 W]	21	
- Mid-range server [607 W]	55	
- High-end server [8'106 W]	1,318	

(*) In case of the edge & core network, reported energy consumption is multiplied with a factor of 26 in order to take into account overcapacity and redundancy of these devices, as well as the electricity consumption of the optical transport along this network.

Information about the core components (including their energy consumption and their weight) is only one element necessary in order to calculate the grey energy and all further environmental impacts due to Internet use. The other necessary element is information about the number of these components in use, their lifetimes, as well as the actual data capacity per time unit of these devices, finally allowing an allocation of the impacts per MB of downloaded data. Table 5 summarizes this additional information for the exemplary components taken into account here.

Estimating the number of Internet servers installed worldwide is challenging, and different sources report divergent numbers. DCD Intelligence, the research division of a provider of B2B services for the data center industry, estimates the power consumption of all data centers in the world at 40 GW in 2013 [52]. Assuming a power consumption of 222 W per volume server and doubling this number for cooling and other overhead implies around 90 million servers in use worldwide. We follow Malmodin et al. [53] in assuming that half of these servers communicate over the Internet, while the other half are used by organizations and enterprises in closed "intranet" environments. This estimate leads to 45 million Internet servers. A different approach to estimate the number of Internet servers is to start from sales numbers. IDC, a market research firm specialized in the IT market, reports around 8 million servers sold worldwide in 2012 [54]. Assuming a lifespan of 3-5 years, and considering that some of these servers are not being used, yields a figure of around 30 million servers in use worldwide. The same assumption as above then leads to a number of 15 million Internet servers in use. We use this smaller estimate, because it compares better to a third figure, the number of worldwide Internet servers reported by the 24 largest companies owning such devices (based on information reported in [55-57]).[4]

For all components it is assumed that they are active 24h a day during the whole year; even the ADSL modem. This latter is based on the split of 4h active and 20h idle (i.e., consuming energy, but without active data transfer) time, reported in a study published in the framework of the European Eco-Design Directive [58] and used in the chapter dealing with the energy consumption of the Internet as well [3].

Table 5. (Cont.) Key data for modeling various infrastructure components. The second column shows the allocated number of devices for using Internet services for the components (i) to (iii), and an estimate for all servers in data centers worldwide for component (iv). All these are allocated to corresponding data in column 4 (data capacity as traffic flows per second in the first three cases, as total annual Internet traffic in the world for the last case), thus leading to compatible/comparable allocation results.

Component	No. of devices	Lifetime [years]	Data Capacity	Data sources
[i] CPE				
- modem + WiFi-Router	1+1	6	7.2 Mb/s (average xDSL value for Europe)	[59] plus own assumptions
[ii] Access network				
- DSLAM	1 port	6	(similar to the ADSL-Modem)	own assumptions
[iii] Edge & core network				
- Edge ethernet switch	1	6	32 Gb/s	[4]; [49]; [60]
- Network, metro router	6	6	47 Gb/s per router	
- Network, core router	6	6	828 Gb/s per router	
[iv] Data center				
Total no. of devices	15 million		1.1 ZB	[50]; [55-57];
- Of this: volume Servers	[96.6%]	3	(annual global data	and [61]
- Of this: mid-range servers	[3.0%]	3	center IP traffic 2010)	
- Of this: high-end servers	[0.4%]	3		

Figure 5 summarizes the resulting impacts per MB of data downloaded, using these assumptions. When distinguishing merely between the different elements of the Internet (shown in the top part of Figure 5), the picture of the environmental impacts shown here is rather similar, despite some slight variations, i.e., in almost all cases, about 50% of the impact is due to the data center and another roughly 40% to the edge & core network, while the access network together with the CPE contributes only about 10% to the impact. The bottom part of Figure 5 distinguishes between the infrastructure and the energy consumption within each of these three parts of the Internet. In most impact categories, energy consumption is responsible for a large majority of

4 4.5 million. It seems more plausible that the likes of Google, Amazon and Facebook together own roughly 1/3 (and not only 1/10) of the Internet servers.

the respective environmental impact; only two of the toxicity categories (HTP and FETP), in which the server infrastructure causes around 15% of the overall impact, are slightly different. But in general, the infrastructure shows a very low impact only with regard to the consumed electricity.

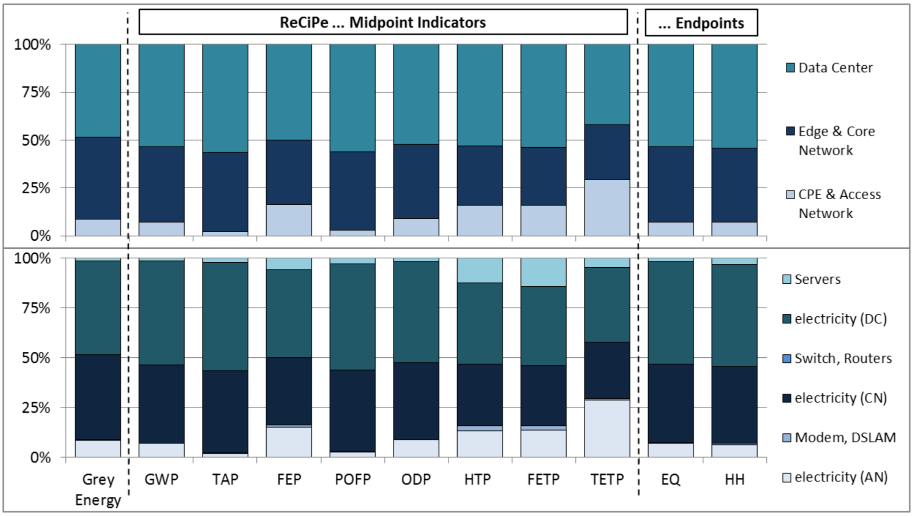

Fig. 5. Environmental impact per MB of data downloaded – broken down by the various parts (top) and further distinguishing between infrastructure and energy consumption within each part (bottom) of the Internet, as in Tables 4-5. The same factors as in Fig. 1 are shown (with AN = CPE & access network , CN = edge & core network, and DC = data center).

4.3 Comparison and Combination

In a first part of this third subsection, the impacts due to one hour of use of the end-user devices described above (i.e., desktop computer, laptop computer, and tablet) are compared to each other; again assuming that each of these devices is used for 2 hours per day. Figure 6 shows the resulting impacts (per hour of use) for the three devices. As clearly shown in this figure, the picture for all examined impact assessment factors – including grey energy– is rather similar; i.e., the laptop computer results in an environmental load that is about 5 times lower than the desktop computer – and the impact of the tablet, in turn, is lower by a factor of 3 to 4 than that of a laptop computer.

Last but not least, the impact of these three end-user devices is combined with the data for Internet services, which were detailed in the preceding subsection. Figure 7 shows the results – this time not per hour of use, but per MB of downloaded data. While the bottom part of Figure 7 is similar to Figure 6 – simply adding the impact for downloading 1 MB to the impacts for the life cycle of the three different end-user devices – the top part of Figure 7 shows the relative relevance of this download process in comparison to the use of the end-user device (the latter one again over the complete life-cycle). And this latter part of the figure shows clearly that the more mobile (and small) the end-user device, the more relevant the impact from the download process – i.e., while in the case of a desktop computer, the download is responsible for about 60% of the overall impact; this same download operation is responsible for more than 90% of the overall impact in the case of a tablet.

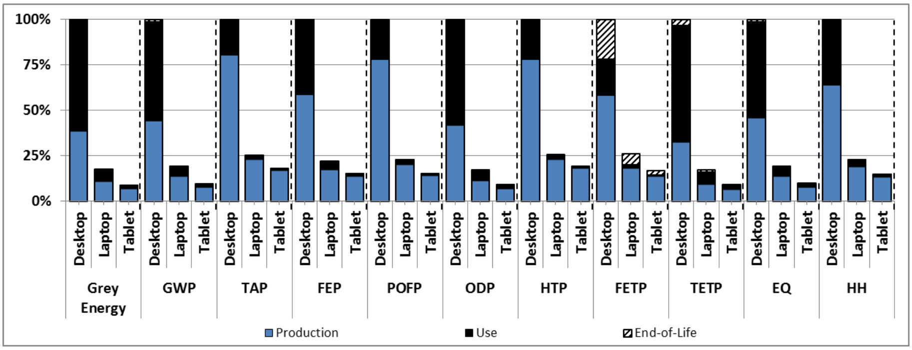

Fig. 6. Environmental impact for 1 hour of use of desktop computer, laptop computer, and tablet, shown relative to the impact of the desktop computer for each impact factor. The same impact factors are shown as in Fig. 1.

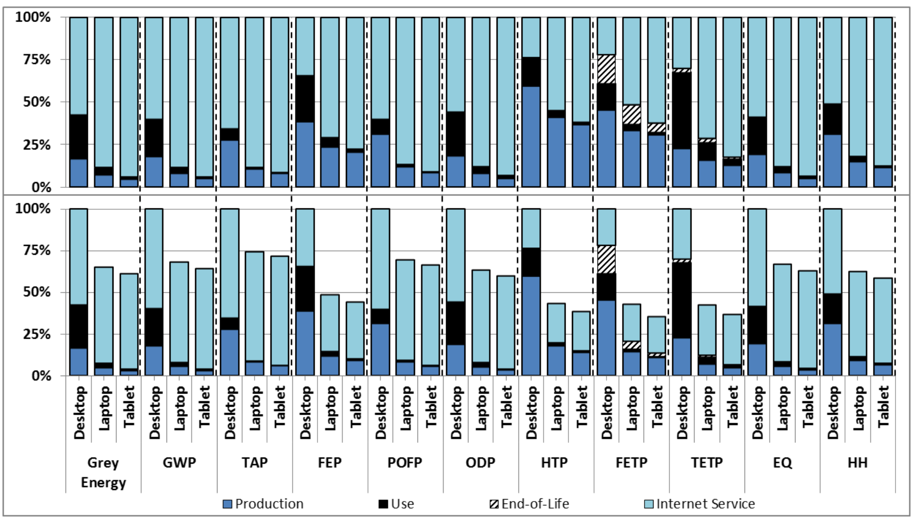

Fig. 7. Environmental impact of downloading 1 MB of data via desktop computer, laptop computer, and tablet (including end-user devices and Internet infrastructure, assuming a constant download rate of 7.2 Mbps), shown relative to the impact for the desktop computer for each impact factor. The same impact factors are shown as in Fig. 1.

5 Conclusion and Outlook

The various figures in section 4 show clearly that a focus on direct energy consumption alone excludes relevant parts of the real (and total) energy consumption of ICT hardware – especially when taking into account the entire "data chain" (i.e., the Internet). Taking into account the entire life cycle of devices such as desktop computers shows the relevance of the production phase, which becomes more and more important the smaller (and the more energy-efficient) the devices are. Correspondingly, when comparing the upper parts of Figures 1, 2, and 4, it is evident that the relevance/importance of the use phase drops with the decreasing size of the device – due to the fact that a tablet computer is much more energy-efficient than a desktop computer system with its various components. On the other hand, the relevance of the impacts due to the data transfer in the use phase is more relevant, the smaller the end-user device. For a tablet computer, the upper part of Figure 7 shows a contribution of 90% and more by (the production and the energy consumption of) various components along the whole network, as well as the data centers.

These results demonstrate at the same time that the technological shift towards distributing computing with low-power user devices (e.g., tablet computers) connected to server systems as part of "the cloud" presents a form of burden-shifting away from the manufacturing and the use phase of the end-user device, and toward the Internet and data centers. The behavior related to the consumption of distributed services is becoming a major aspect with regard to environmental impact. Inducing consumer demand by increasing the efficiency of a production or a consumption process is also known as the rebound effect, an issue further elaborated in a later chapter [62].

Does the development of modern ICT hardware such as tablet computers and of novel paradigms such as cloud computing lead to more or less sustainability? In order to answer this question, a focus on individual devices – as done in this chapter – is not sufficient. Rather the general behavior of our society related to the consumption of distributed services is becoming a major aspect for the determination of the environmental impact. Hence, calculating absolute changes of the impacts due to such a technological shift depends in large parts on individuals' behavior and their use and handling of ICT hardware, another topic dealt with in a later chapter of this book [63].

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