Gestaltungsmodell für sozialökologische Transformationsprozesse in der Praxis: Entwicklung und Erprobung in drei Anwendungsfeldern

Anlage B.5:
Ökobilanz des Medienkonsums in digitalen Ökosystemen

gefördert durch das Bundesministerium für Bildung und Forschung im Rahmen des Förderschwerpunkts sozial-ökologische Forschung (FKZ 01UT1426)

Freiburg,
April 2019

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DEGREE PROJECT IN ENVIRONMENTAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2018

Environmental Implications of Media Consumption embedded in Digital Ecosystems

A bottom-up systems approach to the perennial case of paperless reading in Germany

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Environmental Implications of Media Consumption embedded in “Digital Ecosystems”
- A bottom-up systems approach to the perennial case of paperless reading in Germany

Miljökonsekvenser av mediekonsumtion inbäddad i "digitala ekosystem"
- En bottom up-analys av det återkommande fallet av papperslös läsning i Tyskland

Degree project course: Strategies for sustainable development, Second Cycle
AL250X, 30 credits

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Abstract

Digitalization has been reshaping the media landscape in recent years, often conveying an implicit promise of becoming less dependent on physical resources. At the same time, the current understanding of digital reading goes beyond dedicated e-readers or definable digital media products such as magazines or newspapers. In fact, it must be perceived as a function or service obtained from existing and ever-expanding "digital ecosystems". There is furthermore a clear and unambiguous trend that relatively small and mobile devices are on the rise for consuming all kinds of media.

Next to potentially enabling environmental gains compared to traditional paper-based media consumption, there are agreeing indications of a shift from overall electricity consumption dominated by end-user devices towards an increasing importance of less tangible data transmission networks and data centers. Therefore, a bottom-up analysis is deemed to compliment more general top-down observations and assessments. To this end, an elaborated reference scenario is proposed as to bridge the mere analytical method of Life Cycle Assessment (LCA) with behavioral aspects based on German market observations and surveys. The prevailing aim of this study is to detect environmental hot-spots and absolute impacts linked to the service of accessing text-based content via connected electronic devices. In doing so, this study takes the position that both types of media consumption – digital and paper-based - are incommensurable due to the very evident differences in provided functions, markets, and industries. Therefore, an attributional and stand-alone LCA is considered appropriate.

The perceived current situation (reference scenario) evolves around substantiated estimates and assumptions concerning production of devices, use of devices as well as operation of essential data transmission network components. Looking at potential hot-spots, electricity consumption linked to data transmission could be a decisive factor for the environmental performance of digital reading. However, the actual importance of data transmission infrastructures depends on both methodological choices and a range of parameters or trends. For instance, the relative importance is shifted when more recent estimates of electricity intensities are incorporated. Depending on actual and localized electricity intensity of data transmission, the amount of data required to provide an expected function may inhibit environmental potentials of digital media consumption.

Postulating average annual consumption of digital contents and assuming actual substitution of equivalent printed media products, about 50 kg CO_2-equivalents. could potentially be avoided. This theoretical potential is based on the calculated global warming potential (GWP) associated with digital reading according to the reference scenario which amounts to about 29 kg CO_2-equivalents. Therefore, this study supports findings from previous studies that indicated environmental benefits of digital reading.

Compared to other functions or services (e.g. video/music streaming, podcasts, audio books) embedded in the same "digital ecosystems", reading requires little amount of data. If allocation of upstream effects is based on time, the relative importance of data transmission networks could be gauged and compared by adopting a "data-to-service time" ratio. Taking the reference scenario as a starting point, a perceivable ratio for digital reading is 0.015 GB/h, including systemic inefficiencies. In contrast, streaming of high-definition video contents can easily consume 3 GB/h, a 200-fold increase.

The audience of this study comprises providers of digital reading services and/or other media services as well as end-users as integral element in "digital ecosystems". Besides, the report proposes a conceptual assessment framework which can be applied to other contemporary digital services or functions.

Sammanfattning

De senaste åren har digitalisering omformat medielandskapet, med ett implicit löfte om att minska beroendet av fysiska resurser. Dessutom finns det tydliga trender som pekar mot en ökad användning av små, mobila enheter för att konsumera alla sorters media. En uppdaterad bottom-up analys bedöms komplettera mer generella observationer och bedömningar. Om man antar årliga genomsnittliga konsumtionsmönster i Tyskland, så är tillverkningen av elektroniska slutanvändarenheter – oavsett om de är till för enskilda ändamål (e-läsare) eller om de är multifunktionella (smartphone, surfplatta) – onekligen en miljömässigt kritisk punkt för digitalt läsande. Elförbrukningen, som sker i samband med dataöverföringen, kan också vara en avgörande faktor för den övergripande miljöpåverkan av digital läsning. Dock beror den faktiska påverkan av dataöverföringsinfrastrukturer dels på metodologiska val men även på ett antal andra parametrar och trender. Genom att undersöka indikatorn för global uppvärmning kan denna studie konstatera att resultaten stödjer tidigare forskning, som redan pekar på de miljömässiga vinsterna av digitalt läsande. Målgruppen för denna studie innefattar både distributörer av digitala läs-tjänster och/eller andra media tjänster såväl som slutanvändare som ett integrerat element i ”digitala ekosystem”.

Acronyms

3G	Third Generation Wireless System
4G	Fourth Generation Wireless System
5G	Fifth Generation Wireless System
ADP	Abiotic Depletion Potential
App	Application
AUO	AU Optronics Corporation
BOM	Bill of Materials
CFWG	Carbon Footprint Working Group
CML	Centrum voor Milieuwetenschappen (Institute of Environmental Sciences)
CPU	Central Processing Unit
DSL	Digital Subscriber Line
E&M	Entertainment & Media
EoL	End-of-Life
EPD	Electronic Paper Display
ESIA	European Semiconductor Industry Association
ETSI	European Telecommunications Standards Institute
GB	Gigabyte
GHG	Greenhouse-gas
GWP	Global Warming Potential
IC	Integrated Circuit
ICT	Information and Communication Technology
IP	Internet Protocol
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCIA	Life Cycle Impact Assessment
LTE	Long Term Evolution
MB	Megabyte
OS	Operating System
PC	Personal Computer
PCB	Printed Circuit Board
RAM	Random-Access Memory
ReCiPe	Recipe to calculate life cycle impact category indicators, representing the major collaborators: RIVM and Radboud University, CML, and PRé Consultants
TFT	Thin-film Transistor
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
TV	Television
VM	Virtual Machine
Wi-Fi	Wireless Fidelity

Table of Contents

1 Preamble

This report is an integral part of a degree project in strategies for sustainable development at the Royal Institute of Technology in Stockholm. It further contributes its findings to a research project[1] at the Oeko-Institut e.V. – Institute of Applied Ecology, sponsored by the Federal Ministry of Education and Research (BMBF, Germany). By developing concrete and scientifically grounded recommendations, the research project aims at initiating and supporting sustainable transformations in selected social-ecological contexts. The particular field of application concerns paperless publishing and reading of, among others, e-books and e-newspapers as well as paperless offices in Germany.

2 Introduction

Digitalization has been reshaping the media landscape in recent years, often conveying an implicit promise of becoming less dependent on physical resources. It is probably fair to say that accessing digital content via highly connected devices marks a new paradigm of reading, characterized by unparalleled possibilities with inherent consequences. Apart from the very tangible electronic devices, many of the underpinning processes are deceptively invisible. Thus, it is little surprise that about every third person surveyed claimed that a perceivably beneficial environmental profile of electronic books or papers was one of the reasons for embracing paperless reading (statista, 2017b; Ballhaus *et al.*, 2015). Yet, the real potential of decoupling environmental impacts from media consumption depends on a range of factors and effects. Arguably, this transformation - mainly facilitated by technological advances and driven by profit-oriented private organizations - deserves scrutiny regarding its socio-ecological implications. Although electronic publishing and reading is not a novel field anymore, it is still considered an emerging market in many countries, evolving in a rather speculative setting in respect of wide-scale adoption and substitution of traditional print equivalents. Research is therefore necessary to assess current developments and provide guidance at this transitional phase. Further, new light is to be shed on an ongoing debate whether and how digital reading can be sustainable.

Given the very specific field of application representing a relatively small fragment of the vast information and communication technology (ICT) sector, a bottom-up analysis is deemed to compliment more general top-down observations and assessments. With energy demand and associated global warming potential being the main focus of current ICT-related assessments, there are agreeing indications of a shift from overall electricity consumption dominated by end-user devices towards an increasing significance of networks and data centers (Cook, 2017; Andrae and Edler, 2015; Stobbe *et al.*, 2015; Prakash *et al.*, 2014). Whether this trend also holds true for paperless reading is yet to be investigated. A life cycle perspective needs to be taken to assess energy-related as well as other environmental impact categories.

2.1 Aim & Objectives

The prevailing aim is to detect environmental hot-spots by calculating absolute impacts linked to subsystems which are needed to provide the designated service of accessing text-based content via connected electronic devices. In doing so, this report seeks to expand on existing research by means of an elaborated, up-to-date reference scenario to describe and examine the current situation of digital reading in Germany. Next to this essential preliminary step, the aim is mostly addressed by the quantitative assessment part of this study. Concurrently, the hypothesized significance of a particular subsystem – e.g. transmission networks and data centers - can be measured and discussed. Subsequently, effective targets for strategies of sustainable development can be highlighted and discussed. As to accomplish and complement the overarching aim, the study seeks to meet the following objectives:

[1] Research project Trafo 3.0: developing a model for socio-ecological transformation processes in practice (http://www.trafo-3-0.de/index.php?id=2&L=1)

- Incorporating behavioral aspects and localized market characteristics in analytical assessment method,
- Gauging the existence of potential environmental benefits compared to traditional print media,
- Establishing a general and transferable assessment approach for services attained from connected and mobile electronic devices

In line with aim and objectives, results and derived suggestions are predominantly meant for providers of digital reading services and/or other types of media services (e.g. Tolino, Amazon, Apple, Google, etc.) as well as end-users as integral element in respective systems. Additionally, identified issues over the course of data acquisition and subsequent numerical analysis may be communicated to manufacturers of electronic devices as well as the scientific community connected with Life Cycle Assessment (LCA) application.

3 Methodology

The intuitional significance of the data transmission subsystem as set out by assessments of ICT-related services can be scrutinized through comprehensive hot-spot analysis. Although there is no globally agreed methodological framework, a detailed environmental LCA may establishes the core of such analysis. The inherent systems perspective coupled with the encouragement of life-cycle thinking is a unique set of features of LCA studies. Moreover, the LCA framework and application is grounded on scientific and regularly updated procedures to quantify relevant environmental impacts which are in turn understood as extractions and releases to the natural environment (Rebitzer *et al.*, 2004). With quantified “cradle to grave” impacts across several impact categories (e.g. global warming potential) at hand, environmental hot-spots associated with the life cycle of a product or service (here: the service of digital reading) are reliably identified (Rebitzer *et al.*, 2004). Overall, the methodological approach of this study comprises two distinct but connected methods (Figure 1). Again, LCA is commonly realized by carrying out four iterative steps (Guinee, 2002).

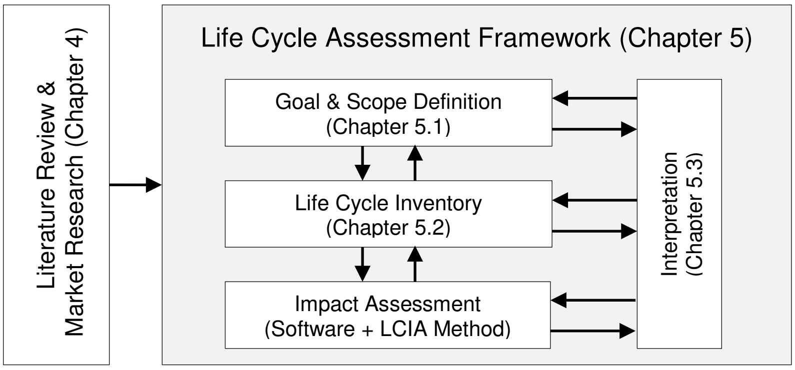

Figure 1. Methodological approach and LCA framework (own depiction based on Guinee (2002)).

3.1 Literature Review & Market Research

Initially a literature review gives an overview of existing research. The main purpose of this review is to feed into supplementing market research and subsequent scenario modeling and assessment parts by setting out an appropriate direction and creating awareness for potential issues in conducting the quantitative assessment by means of LCA. This is to be achieved by highlighting encountered limitations and difficulties with regards to both methodological choices and topic-related issues. The list of incorporated literature is the result of previous knowledge and a web-search using specific search terms connected to the subject. In addition, the following criteria or containments were applied:

- Object of study qualifies as a potential substitute of traditional published media (e.g. printed books, newspaper, magazines),

- LCA method or life-cycle thinking applied,
- Published in German or English language and not before 2010.

Based on insights of the literature review and a complementary country-specific evaluation of the current market situation, a reference capturing the current situation is proposed. The reference scenario takes stock from recent statistics, marketing reports, and surveys as to provide a sound basis to model realistic function-related consequences. An elaborated reference scenario is considered to bridge the mere analytical method of LCA with behavioral aspects, thus remedying an acknowledged downside in common LCA practice (Suckling and Lee, 2015; Carbon Trust and Global e-Sustainability Initiative, 2017). Inevitable assumptions for conducting subsequent numerical analyses are therefore less uncertain and reflect geographically-bound averages. This is why corresponding sections in part 1 of this study attain more detailed descriptions and explanations than in many other LCA studies on this subject.

3.2 Life Cycle Assessment

In part 2 an attributional and stand-alone LCA is conducted. As per definition, average data and parameters are incorporated for attributional modeling and subsequently calculated impacts can be attributed to the current service system (= reference scenario) as well as crucial subsystems (e.g. data transmission system) (Curran, 2012). Consequently, numbers can be put behind certain subsystems and potential hot-spots may be investigated. Adhering to the principles and framework of LCA method and corresponding ISO standards (14040 and 14044), established reference flows are filled with appropriate inventory data (e.g. emissions, resource extractions) and scientifically translated into potential environmental impacts by means of characterization factors (Guinee, 2002; Huijbregts *et al.*, 2016b).

The selection of impact categories for further interpretation is guided by both data quality and intelligibility in the public debate around ICT systems (see chapter 5.1). Applied characterization factors are representative for a global scale and are based on the Life Cycle Impact Assessment (LCIA) method ReCiPe 2016 Midpoint (H) v1.1, which is an update of the method developed in 2008 (Huijbregts *et al.*, 2016a). The crucial and sensitive characterization step is accomplished by utilizing the OpenLCA (version 1.7.0) software solution with implemented LCIA methods as well as the Ecoinvent v3.4 database for background and provider processes. In addition to the general LCIA method (ReCiPe 2016), the methods TRACI and CML 2001 (as implemented in Ecoinvent v3.4) are applied as to facilitate comparisons of intermediate results with literature values.

As to manage data collection efforts for modeling highly complex electronic components and systems, a simplified modeling approach is applied. Apart from simplifications and assumptions inherent in secondary data sources, a major simplification concerns upstream processes (cradle-to-user), ultimately resulting in embodied impacts of end-user devices. Considering the aim and scope of this study, simplifying upstream models without reducing or tempering conclusions is deemed expedient. Therefore, only components known to be decisive for the total environmental impacts are modeled in detail. Calculated embodied impacts are subsequently compared to corresponding literature values as to estimate the reliability of results (see chapter 5.3.2.1).

Final results are compared and referenced to corresponding total annual impacts occurring in Europe per person (= normalization factor) (Benini *et al.*, 2014). Due to the circumstance that normalization factors for the applied LCIA method (ReCiPe 2016) have not been published yet, normalization factors of the predecessor version (ReCiPe 2008) as implemented in Ecoinvent v3.4 are used. However, for some impact categories (e.g. land use, mineral resource scarcity, ozone formation (ecosystems), water consumption) as realized in updated ReCiPe 2016 method, normalization factors are lacking.

Results and analysis of this study are split into two consecutive parts. The first part presents key findings of the literature review and market research. Analysis of both sub-parts leads to a reference scenario which forms the starting point of the second part of this study. In this part, the introduced LCA method is applied to the reference scenario. For this purpose, datasets and resulting impacts are described and analyzed.

4 Part I: Related Work and State of the Art

In this part a synthesis of findings and insights from conducted literature review (see detailed findings in Appendix A) is presented. Guided by these findings, an evaluation of the current situation oriented on German market conditions and outlooks is accomplished.

4.1 Literature Review

For the most part, reviewed papers[2] do not specifically state or claim to be in adherence with the corresponding ISO standards. However, some of the articles mention the ISO framework and most of them follow the principal structure of it. As per minimal standard for this review, all assessments are publicly available and fulfill common standards of scientific work. Consequently, many of the articles are published in peer-reviewed journals. Owing to the LCA practice, reviewed studies predominantly seek to quantify potential environmental impacts associated with respective systems. Although often not specifically stated, the studies exclusively follow an attributional modeling approach, meaning that a specified and static state of a system or product is examined. Thus, average data is used for reviewed assessments. Most of the assessments incorporate an extensive range of impact categories, following the applied assessment method (e.g. ReCiPe). However, special attention is often given to global warming potentials and cumulative energy demands. With only two exceptions, the geographical scope of foreground processes - in particular content production, use stage, and recycling - is northern Europe (e.g. Sweden, Finland, Germany). Moreover, it is noticeable that most studies do not explicitly state any specific audience or further application of results.

In line with the purpose of LCA studies, reviewed assessments usually adopt a cradle-to-grave scope. Therefore, potential impacts associated with production, distribution, use, and disposal of electronic devices are either entirely included or accordingly allocated. It is noteworthy that a majority of studies accounts for impacts from associated operation of internet/network infrastructure. Yet, the inclusion of network and internet usage is done rather superficially as reliable inventory data was often lacking. Interestingly, editorial work or content production is predominantly included in the system boundaries. This circumstance may be owed to mostly product-based perspectives.

There appears to be an overwhelming tendency to compare digital with print media products. If LCAs are not comparative, potential substitutability is implied by putting stand-alone assessments into context through referring to their traditional/digital counterparts. Although particularly relevant for comparative assessments, the discussion and elaboration on establishing an appropriate functional unit is rather limited and perhaps even insufficient for intended purposes. Thus, functional units are usually product-based or oriented towards a specific product. As long as digital media products are concerned, the reference flows and resulting impacts refer to one specific electronic device (e.g. e-reader, tablet PC). Sometimes different devices for accessing and reading media content are included, but usually not in combination. Simultaneous use of several connected devices is not assessed. An exception is the tool developed by Hischier *et al.* (2013) which claims to provide an opportunity to calculate environmental impacts based on a selection of certain types of media and several distinct devices.

Allocation of impacts associated with multifunctional electronic devices is mostly based on the ratio of time for reading to total active use time of a device. Impacts from electronic storage and distribution via internet and data centers are allocated based on data traffic (usually in MB). When content production or editorial work is included, associated impacts are allocated based on either the number of issues or the number of employees attributable to either of the product lines. Apart from detailed specifications of employed electronic devices, some studies specify the characteristics of digital media products in more detail by disclosing information about file size, number of copies, download pattern, etc. Whenever content production or editorial work is further described and consequently included in the assessment,

[2] Reviewed studies (n=9) are not referenced in this synthesized section. Please refer to Appendix A for a list of included papers as well as detailed and paper-specific findings.

it is assumed to be shared, thus equal for both print and digital products. In some cases, however, an additional effort for preparing digital media products is assigned.

For mobile electronic devices the life time ranges from 1 to 4 years, often assumed to be 3 years. The assumptions made in connection with disposal and recycling of electronic devices differ significantly. Consensus is reached concerning the prevailing uncertainty with regards to realistic end-of-life assumptions. In general, assumptions are many and versatile in nature but transparently documented. It is furthermore inevitable that some assumptions are not representing the current situation anymore (e.g. download patterns/times, internet access points, user behavior). As an integral part of LCA studies, sensitivity analyses are made to test the significance of certain assumptions. Therefore, most of the studies tested their models and results by altering e.g. electricity mix, life time of devices, and use intensity. Alternative recycling stages were also part of certain sensitivity analyses.

As far as possible, some studies incorporated specific primary data from certain actors within the supply chain. For the rest, different versions of the Ecoinvent database provided most of the background data. It is further noteworthy that more recent studies build on datasets published by earlier studies (e.g. Moberg *et al.* (2011)). Therefore, the actual body of data on electronic devices or content production seems rather limited. The inferiority of data concerning manufacturing of electronic devices (e.g. electronic ink display for dedicated e-reader) as well as recycling of them is often identified and acknowledged. In addition, some datasets were already considered outdated at the time of the study. Toxicity related data are often missing in applied inventories. Moreover, data on manufacturing of the internet backbone - comprised of data centers and servers - is lacking. As a result, only energy demands from data centers are accounted for.

Some assumptions can be singled out as being very deterministic. Those entail the life span of electronic devices and their use intensity (active use time), as well as the geographical scope. The latter is mostly reflected in potential impacts associated with the underlying electricity mix. Almost without exception, manufacturing-related impacts of electronic devices make up for the largest share of the overall environmental load. Obviously, initial impacts from producing highly complex devices are tremendous and have a negative effect as long as appropriate recycling processes are lacking. Nevertheless, the case-specific significance of the production stage may also be a result of utilizing single-functional devices for reading purposes.

Comparative assessments largely arrive at the conclusion that digital products are environmentally beneficial under the assumptions made. Many studies further calculated a break-even point for certain impact categories (e.g. climate change or cumulative energy demand). In some cases, altering the functional unit changes the outcome. Stand-alone assessments also highlight the potential significance of content production and data center related impacts. Some findings support the hypothesis, that multifunctional and/or smaller devices lead to smaller impacts associated with selected functional units. Interestingly, studies conducting a comparative analysis reflect upon the actual comparability of both systems and acknowledge inherent difficulties in finding an appropriate functional unit. Moreover, it is suggested to expand the scope to other types of media or, more accurately, entire media bundles for individual consumption. In the light of recent technological advances, it is inevitable to update assessments with respect to increased mobility and multi-functionality of devices. There is broad consensus that the influence of user behavior, in general, and induced use patterns, in particular, deserve further scrutiny.

4.2 Evaluation and Understanding of Current Situation

While there is relatively little innovative capacity in the traditional publishing market, electronic publishing - triggered and guided by the presence and affordability of mobile end-user devices in combination with wireless connectivity - stimulates novel business models, complemented with promises of a desirable and sustainable transition . Next to the still dominating business model of selling pre-defined packages of digital content, flat-rate and individual borrowing models emerge (Wischenbart *et al.*, 2017; Ballhaus *et al.*, 2015). Information can be attained by buying access to single articles instead of a whole electronic newspaper issue. This being said, the ubiquitous shift from ownership to access in combination with increasingly mobile societies seems to be altering the way contents are delivered and read (Danet, 2014). Despite tailored and streamlined business models, technological improvements, as well as cheaper and quicker access to digital content (Gaigher *et al.*, 2014), traditional equivalents will most likely continue to exist in most contexts (Acker *et al.*, 2013). As indicated in the preceding literature review, digital and print media products are characterized by very distinct features and largely demand entirely different industries. In many cases, however, digital versions compliment printed versions or are designed for a different target group (Hohenthal *et al.*, 2013). Thus, environmental impacts inevitably occur and are possibly added to a larger system.

Given the inherent uncertainty and difficulty in gauging whether electronic publishing and reading provide a substitute for printed products, it is perhaps more worthwhile and promising to understand and subsequently assess digital reading in isolation. In consideration of increasing market shares of digitally published contents throughout all markets and segments (PwC, 2017b) alongside with remaining importance of text-based media products (Newman *et al.*, 2017), an assessment of environmental effects is vital.

Information and communication technologies not only alter the amount of available information but, more importantly, the provision and interaction with it. Previously clear-cut boundaries between consumers and producers as well as certain types of media begin to vanish (Wischenbart *et al.*, 2017; Kidanu *et al.*, 2015). Further characteristic trends of paperless reading entail quick and non-linear information flows, use of multifunctional electronic devices, reliance on digital infrastructures and networks, and, not least, induced behavioral changes. These and a multitude of other dynamics make it challenging to attribute certain systems and associated impacts to a specific service or function. Therefore, it is suggested to embrace the concept of "digital ecosystems" as an analytical lens for establishing a feasible reference scenario of paperless reading (Gottwald, 2017).

4.2.1 Digital Ecosystems for Paperless Reading

As to prevent possible misunderstandings, the notion of digital ecosystems shall not indicate that digital systems or paperless reading services as such are based on the logic of natural ecosystems, nor are digital ecosystems necessarily environmentally benign. Here, the utilization of the concept shall rather be limited to borrowing certain metaphors from natural or socio-ecological systems. This, in turn, will help to capture crucial elements and interconnections of a system that is subject to transformative forces prompted by technological advances (Jonak *et al.*, 2016).

Apart from its analytical utility, certain market actors think of their portfolios as digital ecosystems providing several services or functions. In contrast to many digital ecosystems, natural ecosystems are always open. Although a trend towards more openness and unified interfaces can be observed, it is no secret that providers of digital ecosystems are keen on establishing rather closed systems to foster customer retention. Two other distinct features of ecosystems – they are complex and in constant flux – seem very appropriate for describing the current evolution of digital media systems. The emergence of digital ecosystems facilitates widespread and seamless distribution of different types of content - no matter whether traditionally published or self-published - to various devices via cloud-based services (Wischenbart *et al.*, 2017). A well-defined linear media system dominated by large-scale publishing companies is being disrupted by new market entrants creating an ecosystem-like, heterogenic, and non-linear system (Schneider, 2013; Ammon and Brem, 2013). In this new setting, ICT technologies and companies play a key role for both user experience (e.g. access and reading, lock-in effects (Kraft and Jung, 2016)) and environmental implications. The latter being largely determined by more or less tangible and highly connected sub-systems that embody the "living space" of digital contents: hardware, software, and particular services in combination with user behavior (Ammon and Brem, 2013).

4.2.1.1 Hardware System

To identify relevant hardware, it is expedient to recall three major components of an internet-based ecosystem: data centers, telecommunication networks (mobile, fixed, enterprise), and end-user equipment (Cook, 2017; Carbon Trust and Global e-Sustainability Initiative, 2017; Malmodin *et al.*, 2014;

Malmodin *et al.*, 2013). In order to determine their potential impacts one should account for embodied impacts as well as impacts associated with installation, maintenance, and operation (Carbon Trust and Global e-Sustainability Initiative, 2017). In general, equipment closest to users tends to be the most significant factor with regards to overall carbon footprints (Malmodin *et al.*, 2014). This insight is also in line with summarized findings from reviewed studies (see chapter 4.1).

There is a clear and unambiguous trend that relatively small and mobile devices are on the rise for consuming all kinds of media (Newman *et al.*, 2017; World Economic Forum, 2016; Deloitte, 2015). This consumer preference, in combination with generally more energy-efficient devices, seemingly results in lower energy demand on the part of consumers (International Energy Agency, 2017). For example, smartphones and tablets proved to consume considerably less energy during use for news consumption, compared to laptops and especially desktop PCs (Schien *et al.*, 2013). Apart from these conclusive and evident indications on a product-level, there are first verifications from a top-down perspective. Taking Sweden as an example, the trend of increasing use of smartphones and tablet PCs instead of stationary PCs or laptops as well as TVs has been a factor for decreasing energy and carbon footprints in the ICT as well as entertainment and media (E&M) sectors since 2010 (Malmodin and Lundén, 2016). On the other hand, nowadays consumers own more distinct devices and are generally inclined to expand their digital ecosystems concerning both hardware and services (Lutter *et al.*, 2016; Google, 2014; Ammon and Brem, 2013).

When looking at paperless reading in Germany, described trends may be confirmed. In more recent years, dedicated e-readers, smartphones, and tablet PCs have clearly dominated among available end-user equipment (Berg, 2017; PwC, 2017a). E-readers with e-ink displays are the preferred choice for reading books, while magazines and news are rather read on tablet PCs or smartphones (Berg, 2017; Wischenbart *et al.*, 2017; PwC, 2017a; Ballhaus *et al.*, 2015). Interestingly, in 2017 about 26% (18% in 2015; 23% in 2016) of German e-book customers use more devices parallel for reading (Berg, 2017, 2016), facilitated by an increasing provision and adoption of cloud-based services (Ballhaus *et al.*, 2014).

Inherent in a digital ecosystem built around mobile end-user equipment, necessary connectivity is provided by established internet infrastructures, accessed through either fixed Wi-Fi or mobile telecommunication networks. These wireless access points connect to a vast network of physical data transport networks, enterprise data networks, and (hyperscale) data centers (Cisco, 2018; International Energy Agency, 2017; Malmodin *et al.*, 2013), all of which are crucial building blocks of a digital ecosystem for paperless reading and shared between numerous services and users. Evidently, multifunctional and connected devices do not need stationary PCs or laptops in order to access or download digital contents. Therefore, software is needed to increase user experience and enable desired canalized connectivity with specific data centers.

4.2.1.2 Software System

Energy demands during use of ICT hardware is predominantly determined by running software. It can be distinguished between three categories of software (Carbon Trust and Global e-Sustainability Initiative, 2017):

- Operating systems (OS),
- Applications (Apps),
- Virtual Machines (VMs).

As with ICT hardware, software employed closest to end-users – operating systems and applications – are assumed to be particularly relevant for the environmental profile of paperless reading. The OS every electronic device comes with is the basis for executing service-related applications. These applications are often distributed by newspaper/magazine companies or bookstore platforms. From an environmental perspective it is crucial to understand how these apps request and process data, as this affects energy demands of both the device and data transmission networks (Carbon Trust and Global e-Sustainability Initiative, 2017). In digital ecosystems, regularly updated apps act as an interface for data transmission in both directions; content is sent from data centers to end-user devices and user data is sent back. It becomes apparent that environmental impacts attributable to software are rather indirect than direct. Nevertheless, direct or embodied impacts associated with the full life cycle of software (material acquisition and pre-processing, production, distribution and storage, end-of-use) must be acknowledged (Carbon Trust and Global e-Sustainability Initiative, 2017).

In more general terms, apps are first and foremost a digital distribution channel for publishers but also a tool to gather unique and valuable information about customers. This information, in turn, can be utilized to improve and individualize services. Knowledge about user practices is also important for analyzing environmental implications of a distinct service.

4.2.1.3 Services and User Behavior

Introduced hardware and software systems are capable of providing a range of services and functions. Although accounting for a comparably small share of average daily media consumption, reading in books, newspapers and magazines is still very popular in Germany. The time invested for reading published content increased from 55 min per day in 2014 to 63 min in 2017 (statista, 2017d). A majority of people read on weekends and in the evenings, but also on vacation or during transport are very prominent occasions (statista, 2017c). Despite emerging business models offering flat-rate subscriptions, purchasing single books is still the preferred customer choice. In doing so, books are usually bought via online stores or mobile app-stores (statista, 2017c). With regards to newspapers, however, most people have access to a subscription of a daily issue and read them several times per week (statista, 2017d, 2017e). User preferences concerning magazines are more heterogenic and less straightforward. Statistics reveal that average German consumers acquire magazines several times a month (statista, 2017c, 2017d).

Individual environmental implications of paperless reading are significantly influenced by the use intensity of certain devices. Assuming stable media consumption per person, the use intensity per device can be increased by sharing devices. Although higher use intensity means possibly higher energy demands during use, allocation of impacts from other life cycle stages will most definitely result in a beneficial environmental performance. While smartphones are clearly very personal devices and not shared among users, it is less so with tablet PCs or e-readers. Nevertheless, it is difficult to make viable assumptions. According to an American survey dating back to the year 2010, tablet PCs are more likely shared than smartphones or dedicated e-readers (The Nielsen Company, 2010). For the reference scenario it is therefore assumed that tablet PCs are used by two persons in parallel (see Table 1), equivalent to one device per average German household. Given the circumstance that e-readers are cheap and probably serve as dedicated devices for paperless reading in digital ecosystems, it is fair to assume that consumers will not share them.

Almost inherent in the use of connected mobile devices, wireless connectivity functions are usually constantly turned on. This is not only the case for multifunctional devices such as smartphones or tablet PCs but also increasingly for dedicated e-readers, especially if consumers are to make use of cloud-based services. In addition, energy-efficient standby or idle modes often result in user behavior where devices are never entirely switched off.

4.3 Reference Scenario

The current situation in combination with systemically relevant components and assumptions (e.g. behavioral aspects concerning use patterns) is captured by a so-called reference scenario. A substantiated description of such a scenario is considered an indispensable step in defining a reliable functional unit, a key element of LCA. Based on previous discussion and systematic derivation, Figure 2 summarizes and depicts the main components and sub-systems of a digital ecosystem for media consumption.

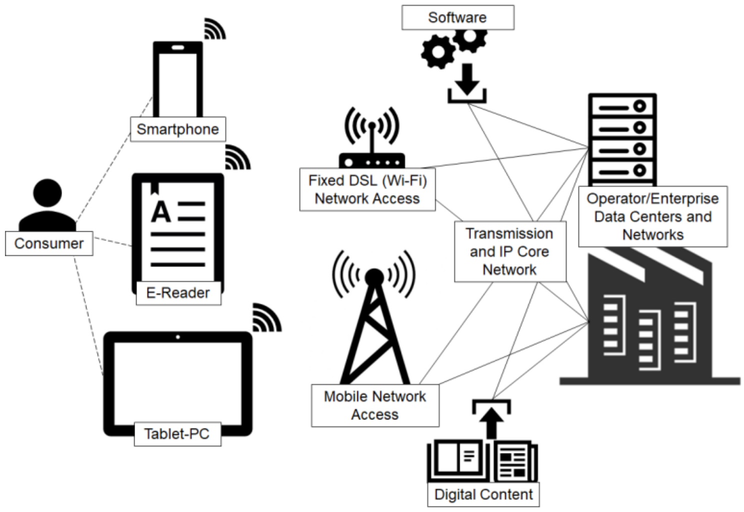

Figure 2. Digital ecosystem for paperless reading (own depiction).

Reading serves several purposes (e.g. information, entertainment, work, and education) and is accomplished by harnessing increasingly heterogenic sources via diverse access points (e.g. apps, webpages). In order to formulate sound assumptions and assign viable reference flows, the scope of the subsequent assessment entails only media products which qualify as potential substitutes for traditional print equivalents. Such products usually fall under the segment of e-publishing comprised of three distinct sub-segments (statista, 2017a):

- E-books: temporary access or single download of editorial content of a book,
- E-magazines: temporary access or single download of editorial content of a magazine,
- E-papers: temporary access or single download of editorial content of a daily/weekly newspaper.

Although digital content is anticipated to be consumed via subscriptions with on-demand access to single articles instead of whole newspaper packages, the defined electronic products are deemed necessary for quantifying reliable reference flows. Using these definitions and embracing a somewhat product-oriented perspective, results can eventually be put into perspective by comparing them to their traditional counterparts.

The focus being on paperless reading, average reading behavior and consumer preferences must be translated into quantifiable reference flows. According to a survey conducted in 2015, consumers prefer reading books (e.g. novels) on dedicated e-reader devices, yet, closely followed by multifunctional tablet computers (Ballhaus *et al.*, 2015). In contrast, magazines or newspapers are predominantly read on multifunctional devices such as smartphones and tablet computers (Ballhaus *et al.*, 2015), perhaps owed to their vivid and colored displays. Accounting for these consumer preferences in combination with average time devoted to reading, dedicated use durations are presented in Table 1.

Device:	Preferred choice for e-books[3]	Annual time for reading books	Preferred choice for e-paper[3]	Preferred choice for e-magazine[3]	Annual time for reading media products other than books	Annual dedicated duration for reading
E-Reader	63.7 %		17 %	14.6 %		113 h
Tablet PC	52.4 %	195 h	42.6 %	41.6 %	189 h	152 h
Smartphone	36.1 %		39.2 %	31.6 %		118 h

Table 1. Average reading behavior and preferences in Germany, based on Ballhaus *et al.* (2015) and statista (2017d).

[3] People surveyed were able to give more than one preference for the respective type of media.

The device-specific annual dedicated duration for reading is determined by dividing the respective preference value by the sum of all three preference percentages and then multiplying it by the annual time for reading of a certain category (e.g. books).

Statistical data is further deployed to estimate crucial parameters concerning individual use of the three proposed end-user devices. By adding previously discussed findings, Table 2 summarizes relevant data on overall use of respective devices, disregarding their actual utilization.

Important assumptions are needed to determine the usage or life time of electronic devices which has been proven to be a crucial factor in environmental assessments. For smartphones the average and realistic life time ranges from 2-4 years with the majority in Germany using a smartphone for about two years (Ercan *et al.*, 2016; Malmodin and Lundén, 2016; Belkhir and Elmeligi, 2018; Manhart *et al.*, 2012; Suckling and Lee, 2015). This circumstance is perhaps owed to the fact that mobile phone transcriptions in Germany usually last for two years until renewal with the option for a new phone. Taking into account that many phones are refurbished and fed into a secondary, often foreign market, the average usage time is assumed to reach 2.5 years (Manhart *et al.*, 2012; Malmodin and Lundén, 2016).

For tablet computers and single-purpose e-reader devices - both usually not coupled with transcriptions – usage times are considerably higher. In the case of tablet computers there is evidence that they are in use for up to 8 years, with a minimum of 3 years (Belkhir and Elmeligi, 2018). It can be observed that innovation cycles concerning e-readers are slower and incentives to purchase new devices are limited due to single-purpose function. Usage times are therefore assumed to be 3.5 years and 4 years, respectively.

Device:	Daily total active use duration per user	Number of parallel users	Annual active use duration	Annual standby time	Annual off time	(First) Usage time
E-Reader	19 min	1	113 h	8647 h	0 h	4 years
Tablet PC	36 min	2	438 h	8322 h	0 h	3.5 years
Smartphone	144 min	1	876 h	7884 h	0 h	2.5 years

Table 2. Average usage patterns concerning end-user devices in Germany (based on assumptions and statista (2014, 2015)).

Since expenditure of time for reading is not necessarily coupled with acquired digital contents and induced data traffic, further assumptions are needed. Following statistical data, it is assumed that German citizens buy on average nine electronic books per year (statista, 2017b). With a majority of citizens having access to daily newspaper subscriptions (statista, 2017e), it is further assumed that five e-paper equivalents are downloaded per week. With regards to magazines, a subscription to a weekly issue is set as baseline. Valid reference flows are determined by adopting median values ($n_{e\text{-}book}$=10; $n_{e\text{-}paper}$=7; $n_{e\text{-}magazine}$=12) of data sizes of exemplary digital products, as shown in Table 3.

Segment:	Data size	Number of annual downloads	Annual data transmission to user for contents
E-Book	2.5 MB	9	22.3 MB
E-Paper	11.5 MB	260	2990.0 MB
E-Magazine	29.5 MB	52	1534.0 MB

Table 3. Annual data sizes associated with downloaded digital contents.

The described key parameters and assumptions are reflected in the functional unit of the succeeding quantitative assessment (see chapter 5.1.1).

5 Part II: Quantitative Assessment of Environmental Impacts

The quantitative assessment consists of four different stages as outlined by the ISO framework: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Guinee, 2002).

5.1 Goal & Scope

In contrast to reviewed studies, the main goal of this quantitative assessment is not to compare digital media consumption to traditional paper-based consumption. Rather, this assessment takes the position that both types of media are incommensurable due to the very evident differences in provided functions, markets, and industries. Guided and suggested by the aim, the following research question is to be answered by means of LCA:

What are potential environmental impacts and hot-spots of meeting average reading patterns by accessing contents through established digital ecosystems (based on current German market characteristics and relevant consumer behavior)?

Further, the assumed and already scientifically indicated environmental potential of digital reading over traditional reading will be tested by means of scientific calculation of life-cycle impacts. Adding to introduced hypothesis that networks and data centers are perhaps gaining more significance in terms of their influence on environmental impacts, the relative importance of certain results and indications may be transferred to other functions or services such as music streaming or video streaming.

In general, the chosen methodological approach (LCA) is capable of delivering robust results with regards to the set aim and derived goal. However, induced effects (e.g. increased consumption through easier and/or cheaper access, potentially leading to "rebound effects") of digitalization cannot be captured in its entirety. Consequently, potential environmental impacts or offsets are not accounted for which might necessitate further assessments (e.g. macro-economic analysis, consequential LCA[4]) to confirm actual results and trends (Erdmann and Hilty, 2010). Due to the nature of ICT, delimitation by means of specific levels of interaction between ICT and the environment may be vital to define the scope. Hilty and Aebischer (2015) distinguish between three levels, as visualized in Figure 3. Direct impacts according to the first level are within the principal scope of this assessment. In addition, impacts due to substitution effects (level 2) are briefly addressed to provide context for final results.

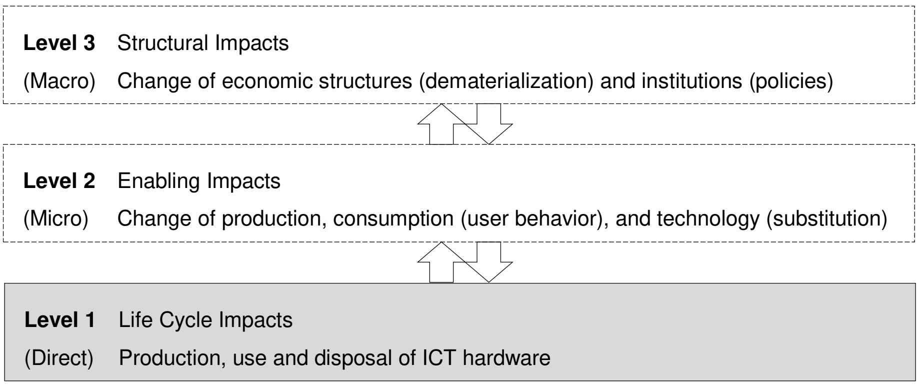

Figure 3. Levels of interaction between ICT and the environment (own depiction according to LES-Model from Hilty and Aebischer (2015)).

The common understanding of direct interactions between digital reading and the environment is often accompanied by promises as to be beneficial for the environment by saving physical resources. Yet, depletion of physical resources is only one of many environmental indicators that may be affected.

[4] In contrast to the descriptive goal and scope of attributional modeling as done in this assessment, a consequential modeling approach accounts for expected changes in broader systems as consequence of change in demand. Instead of average data, marginal data (= effect per unit of an infinitesimal change in a given variable) is implemented (Brandão *et al.* (2017).

Digital reading interacts with more dimensions of sustainability, certainly affecting socio-economic structures as well as human health. While socio-economic impacts (Level 2 and 3) are arguably outside of the scope of traditional LCA studies, human health effects are generally covered by many LCIA methods, including the chosen ReCiPe method. However, direct human health impacts are not part of this assessment for several reasons. First, data availability and quality are assumed insufficient for reliable modeling of human health effects. This is due to the state of affairs that the public and political debate is mostly fixated on environmental effects, thus implicitly creating data gaps concerning relevant toxicological effects and indoor chemical exposure (Finnveden *et al.*, 2009). Moreover, human health effects are considered particularly site-dependent (Finnveden *et al.*, 2009) which is a criteria that cannot be aligned with the generally applicable and broad scope of this assessment.

5.1.1 Functional Unit

As described and established in the reference scenario (see chapter 4.3), the functional unit is formulated as follows:

Average annual text-based media consumption per person by use of mobile electronic devices in connection with data transmission networks in Germany.

An aggregate functional unit with respect to one year of service use follows the recommendation given by the International Telecommunication Union (ITU) (Schien *et al.*, 2012). The delivered function to consumers is comprised of dedicated use of partly multifunctional devices for actual reading and associated data volumes, provided by internet-based networks (see Figure 4). Hence, two decisive parameters are identified:

- Time spent reading in hours,
- Data volumes in MB.

These two parameters are considered and quantified rather separately, therefore based on distinct and not necessarily correlated statistical data. With this multi-parameter (composite) functional unit, an essential finding is taken into account. That is that data traffic can occur disregarding whether downloaded content is eventually read. Apart from hidden data traffic (e.g. user analytics, updates, automatic/default downloads, subscriptions) which is almost impossible to quantify, contents are – albeit rising on-demand offers - often downloaded as packages (e.g. whole e-paper, entire book) or downloads are anticipated to facilitate smooth on-demand reading. In total, data transmission via the internet is needed within two domains of digital ecosystems:

- Download of contents,
- Update for specific software applications and operating systems (OS).

Downloads of contents are expressed as numbers of e-book/paper/magazine equivalents. Therefore, numbers may be perceived as an approximation for data traffic occurring in systems with less clear-cut digital products. Software applications act as an indispensable interface between user and content and must be attributed to the service in question. OS updates are an essential feature for the functioning of electronic devices. As such, OS-related data volumes require allocation between all services obtained from multifunctional devices. Allocation methods and factors as well as quantifications of data volumes (in addition to the quantifications and assumptions made in chapter 4.3) are described in chapter 5.1.2.

Figure 4 depicts the main parameters of the proposed composite functional unit and underlines the finding that reading and acquisition of contents are not necessarily coupled. Not depicted – although included in assessment - are allocated data transmissions associated with downloads for OS updates.

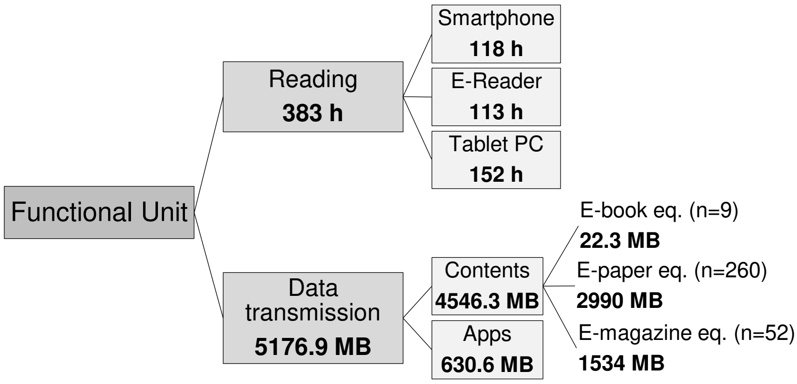

Figure 4. Composite functional unit representing a set of essential parameters (own depiction).

5.1.2 System Boundaries

Evidently, the life cycle of published media products or services begins with the generation and production of contents (e.g. field work, interviews, desk-based research, writing, editing, etc.). In rather specific cases it has been demonstrated that this step can have considerable influence on the absolute environmental impacts associated with digital media products (Ahmadi Achachlouei *et al.*, 2015). However, the inclusion of content production necessitates a very specific system, usually delimited to a certain media product (e.g. magazine). With the reference scenario being a generally applicable case with focus on direct environmental impacts of accessing and reading very different types of media products, it is impossible to include the production of specific contents. In fact, it can be assumed that content production, perhaps apart from editing, is part of a single process step producing contents for a range of channels. Given the circumstance that content is produced for parallel channels – digital and print at the same time – this process should either be allocated or excluded, as done in this assessment (Haeme, 2018). When looking at the aim and audience of this study, this approach can be justified. It is the final distribution and actual consumption of contents which is in the area of influence of both providers of digital ecosystems and end-users.

The creation of software is heterogenic and product-specific. Often, it is not obvious what the production phases of software services entail (Schien *et al.*, 2012). For example, servers waiting for client request are difficult to account for. In any case, production efforts for single software solutions - in this assessment OS and applications - can usually be amortized over a vast range of client requests. Thus, exclusion of this step is assumed to be rather uncritical for the validity of results. Since the assessment includes averaged energy use of utilized hardware (e.g. smartphone in combination with OS), a separate quantification of energy consumed by running distinct user software is not necessary. This means, electricity demands induced by specific software use are already accounted for (Carbon Trust and Global e-Sustainability Initiative, 2017).

Download of contents and software updates are expressed as data volumes to be delivered to the end-user. Adopting a mere process-perspective, data transmission through networks can be considered as an equivalent to the transport phase of physical goods (Schien *et al.*, 2012) and is ascribed to the use stage (= core processes) in this assessment. Data transmission network systems mark an integral part of digital ecosystems, although often outside typical spheres of control and not uncommonly considered to be of minor relevance. In a broader sense, these almost intangible systems are constituted of various access networks (mobile and fixed), the core network, and data centers (Malmodin and Lundén, 2016). With respect to upstream processes of network equipment and data centers it has been demonstrated that production energy demands and correlated emissions of respective hardware has a negligible impact in comparison to the energy demands during operation (Belkhir and Elmeligi, 2018; Suckling and Lee, 2015). Hence, manufacturing related processes of network systems and data centers (= upstream processes) are outside of the system boundary of this assessment. The same applies to the respective downstream processes involving decommissioning, recycling, disposal, etc.

Energy demands and impacts associated with the life cycle of electronic end-user devices (e.g. smartphone) are generally dominated by the manufacturing stages (Suckling and Lee, 2015). Here, it should be highlighted that electricity demands are a very relevant indicator for the overall environmental performance of ICT-related systems. Yet, more indicators are needed to obtain a holistic picture (Moberg *et al.*, 2014). In an ideal but currently perceivable scenario, electronic devices would be introduced to appropriate recycling processes. Potentially avoided extraction of virgin materials could ultimately lead to minor environmental offsets that may be allocated to the service under investigation (Suckling and Lee, 2015; Ercan *et al.*, 2016). In the worst case, however, end-of-life handling of devices could generate further environmental impacts due to energy demands for collection and recycling processes, lack of demand for secondary materials and/or inappropriate recycling with leakage of hazardous materials into the natural environment. On a global scale, both pathways are currently present. In Germany a third pathway seems to be dominating the end of use stage of smartphones and other mobile electronic devices. In absence of attractive incentives to return smartphones or other devices, they are simply stockpiled by consumers. Back in 2012 it was estimated that only about 5% of all smartphones reached controlled recycling facilities (Buchert *et al.*, 2012). More recently, a survey found that roughly 80% of all German citizens are in possession of unused mobile phones and staggering 60% have stockpiled two or more devices (bitkom, 2018). Consequently, near-term downstream processes associated with deployed electronic devices may result in no additional impacts nor offsets under current conditions. Although beyond the scope and temporal boundary of this assessment, recycling-related impacts or offsets could become a factor in the assessment of digital reading. The expected magnitude of this factor is briefly discussed in chapter 5.2.1.3.

In Figure 5, system processes are grouped into upstream, core, and downstream processes. The grouping is aligned with the target group´s spheres of control. More specifically, core processes are expected to be subject to direct exertion of influence by either one of the target groups (e.g. end-users, providers of services).

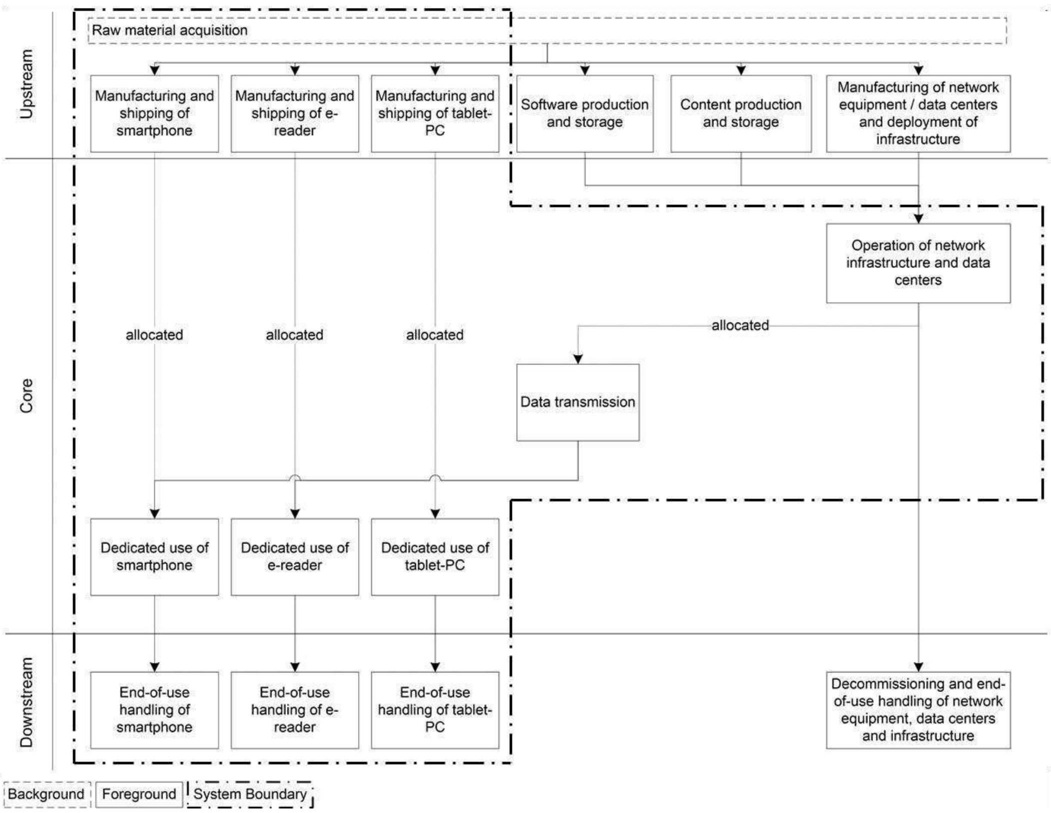

Figure 5. System boundaries and aggregated processes of digital ecosystem for paperless reading (own depiction).

Simplified and aggregated depiction of one process step comprising the operation stage of data transmission networks and data centers should not be mistaken for a small or simplistic provider process. In fact, these systems are highly complex, perhaps even beyond individual's comprehension. It is safe to say that these systems cover a wide geographical area, often transcending national borders and making use of thousands of distinct ICT equipment and periphery (Carbon Trust and Global e-Sustainability Initiative, 2017). As with all processes, assumptions regarding the geographical locations are crucial. In particular, the electricity mix of a specific country can be an influential factor for the environmental performance of ICT systems (Cook, 2017). The generic geographical boundaries for each category of processes are as follows (see also chapter 5.2.1 and Appendix D):

- Upstream: According to specific data on manufacturing or assumptions based on market characteristics; as far as possible adoption of global averages concerning raw materials and sub-components (=background processes)
- Core: Germany
- Downstream: Germany

Next to geographical boundaries, the temporal boundaries of this assessment vary. With regards to upstream processes, distinct reference years are inherent in respective datasets and inventories. Core processes refer to the year 2014 as those processes are determined by supply-chain effects of the electricity market in Germany.

Apart from the three major categories of processes, a distinction between foreground and background processes is made in Figure 5. Generally, foreground processes are subject to further description (e.g. inventories, bill-of-materials) in chapter 5.2.1 and will inevitably draw upon background processes which can be referred to as provider processes feeding into foreground processes.

5.1.2.1 Allocation Issues

With the justified exclusion of some processes (see Figure 5), significant allocation issues can be avoided without limiting the validity of final results. Nevertheless, controversial allocation issues remain (Schien *et al.*, 2013).

First and foremost, environmental burdens related to upstream processes of electronic devices – often referred to as embodied emissions - must be allocated to the specific service as well as to the period under review. In addition, use stages expressed as specific electricity demands must be ascribed to the distinct service. Several allocation factors could be envisaged, such as the duration for use or the actual electricity demand per task. The latter may be the most accurate when it comes to allocation of electricity demands during the use stage (core processes). Measuring the energy intensity per active task is, however, not only difficult but will open up further allocation issues with respect to unavoidable background tasks. Hence, allocation by the duration of usage seems most convincing and backs the assumption that user's attention is the limiting factor for using respective devices (Schien *et al.*, 2013; Malmodin *et al.*, 2014). This assumption appears particularly valid taking into account the very nature of reading as to require the exclusive attention of users.

Another major allocation issue arises from the operation of network equipment and data centers required to provide downloads and updates. Due to a dependency of electricity demands on transmitted data volumes, the most common approach is to allocate associated effects based on the amount of data (Malmodin *et al.*, 2014; Schien *et al.*, 2013; Coroama and Hilty, 2014). Consequently, a linear correlation between data intensity and electricity demands during operation is assumed (see also chapter 5.2.1.2.2).

5.1.3 Impact Categories

The global warming potential (GWP) – often referred to as carbon footprint and greenhouse-gas (GHG) emissions, respectively – often receives greater attention than any other environmental impact category (Suckling and Lee, 2015). As a result, awareness around GWPs expressed as CO_2-equivalents has been manifested. Although literature, policies as well as ICT-specific assessment standards (e.g. ETSI, ITU) highlight the importance of GWP as a crucial indicator, it must be acknowledged that one single measure is insufficient to give robust support in decision making and answering the research question (ETSI, 2015; International Telecommunications Union, 2015). Thus, more impact categories must be taken into consideration, such as toxicity effects and resource depletion, both highly relevant for the assessment of ICT-dependent services (Ercan *et al.*, 2016; Proske *et al.*, 2016).

Although results will be presented as midpoint impact categories, the endpoint areas of protection provide guidance as to which impact categories are discussed in more detail. In line with the general scope and goal of this study, impact categories that lead to either damage to ecosystems or resource availability deserve special attention. Consequently, impact categories solely following damage pathways towards human health are excluded from interpretation and discussion. With reference to the impact assessment method and implemented damage pathways, 11 out of 17 impact categories (see Figure 6) are selected to answer the research question and test the assumption made with regards to the potential significance of data transmission infrastructures.

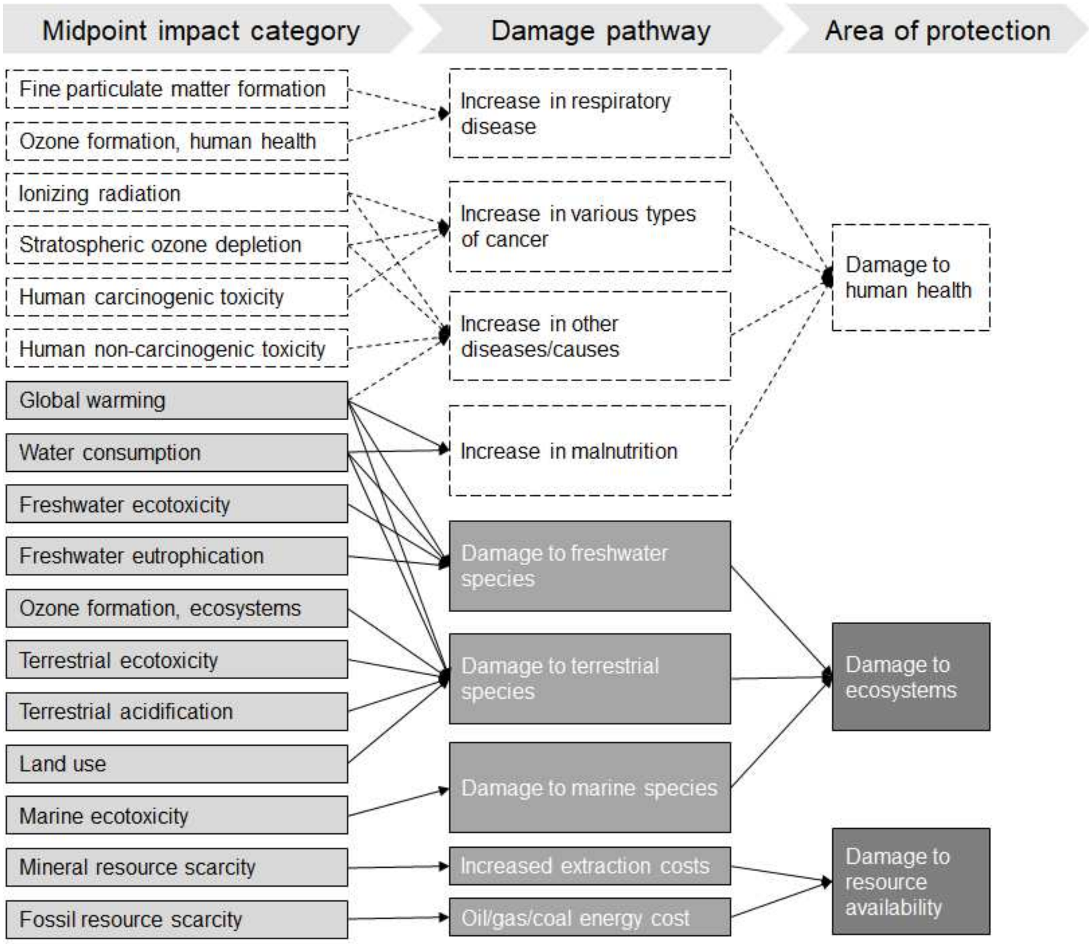

Figure 6. Overview of impact categories with selected impact categories in grey (own depiction based on Huijbregts et al. (2016)).

5.2 Life Cycle Inventory Analysis

The process flowchart (Figure 7) acknowledges the system boundaries (see Figure 5) and shows all major processes included in the quantitative assessment. Processes outside the system boundary as discussed in chapter 5.1.2 are not depicted. The degree of detail is considered sufficient in the light of the aim and objectives. Moreover, system processes cover the full life cycle from cradle-to-grave, clustered in upstream, core, and downstream.

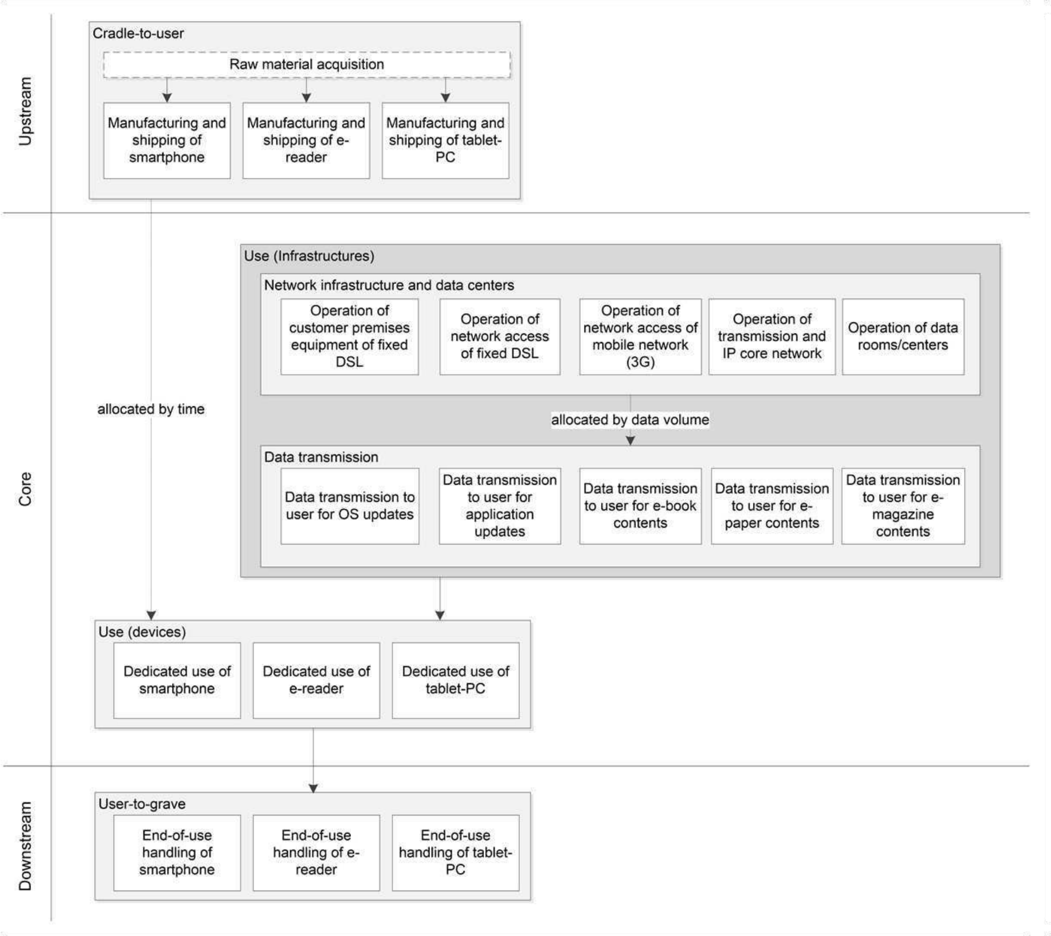

Figure 7. Detailed process flowchart from cradle-to-grave (own depiction).

5.2.1 Data & Data Quality Assessment

This section provides data sources, assumptions, and limitations concerning all three groups of processes. If information is vague, this assessment rather excludes some minor processes and components from the assessment instead of simulating unjustified and deceptive precision. Whether this leads to systematical underestimations is discussed by means of uncertainty analysis (see chapter 5.3.2.1). More specifically, the accuracy of data sources and intermediate results will be discussed and compared to available literature. Detailed inventories of customized or created processes as realized in OpenLCA v1.7.0 in combination with the Ecoinvent v3.4 database are disclosed as appendices (see Appendix D).

5.2.1.1 Upstream Processes

In line with introduced simplified modeling approach, it is suggested that the following components or processes are generally shared between all three types of devices and make up a major share of embodied environmental impacts (Proske *et al.*, 2016; Moberg *et al.*, 2014; Ercan *et al.*, 2016):

- Integrated Circuits (ICs)
- Printed Circuit Boards (PCBs)
- Display
- Battery
- Final assembly
- Final shipping (air transport)

In addition to above listed components, other identified raw materials (e.g. for casing, retail box) are incorporated. However, several passive components and connectors are not modelled in detail or excluded from the assessment. This is not only to manage data collection efforts but also an inevitable limitation of desk-based assessments, often lacking access to detailed inventories (e.g. bills of materials) of respective devices. The following estimates concerning total amounts of key components of electronic user equipment (see Table 4) are based on a range of references (see Appendix B) and presented values have been assimilated or supplemented according to best knowledge.

To prevent any misconceptions, the notion "simplified" is added to respective BOMs. The devices shall not be considered as individual components but as a realistic portfolio of required components to deliver expected services to the user. Thus, comparisons on a product level or conclusions concerning single devices or their combination are not a prevalent objective of this study. Due to the different reference years of used data, product-specific conclusions are limited. In fact, this assessment is rather disentangled from a product-specific perspective as to give recommendations on a meta-level.

Category/Component:	(Scaling) Unit	Simplified Smartphone	Simplified Tablet-PC	Simplified E-Reader
Integrated circuit (IC) packages	mm^2 die area	395	253	156
Rigid multilayer printed circuit boards (PCB)	cm^2	90	98	165
TFT-LCD/EPD display	cm^2	73.7 (5.0'' diagonal)	368 (9.7'' diagonal)	140 (6'' diagonal)
Lithium-ion battery	g	34	140	51
Materials:				
- Aluminum sheet	g	24	93	25
- Stainless steel sheet	g	23	14	-
- Polycarbonate	g	7	11	74
- Retail box	g	165	275	200
Assembly electricity	kWh	4.7	1.67	1.11
Final transport	kg	0.5	1	0.5

Table 4. Estimated bills of materials for electronic end-user devices (based on Appendix B)

For above reasons, subsequently listed components and associated processes are not taken into consideration:

- Power-supply adapters (charger and cable)
- Flexible printed circuit boards
- Plugs and connectors
- Touchscreen film and protection glass
- Camera lens
- Microphone, Speakers
- Supporting activities

Obviously, listed components contribute to the absolute impacts. However, given the application of allocation factors, their contribution to the reference scenario is assumed to be less significant. Whether this limitation affects the conclusions, will be tested by means of uncertainty analysis (chapter 5.3.2.1).

The reasoning behind the allocation procedures has been discussed in chapter 5.1.2.1 and the calculated factors affect all upstream processes by distributing associated inventories or impacts to the specific service under consideration. Given the inherent linear relationship between potential impacts and reference amounts in LCA models, the calculated allocation factors can directly be applied to the respective amounts of key components from Table 4 and linked provider processes. The device-specific allocation factors are calculated using the following formula:

$$\text{Allocation factor} = \frac{\frac{\text{Annual dedicated duration for reading [h]}}{\text{Annual active use duration [h]}} * 100\%}{\text{Usage time [yr]}}$$

With values previously presented (see Table 1 and Table 2), the following allocation factors are obtained which can be understood as the shares of key components attributable to the reference scenario:

- E-Reader: 25 %/yr.
- Tablet PC: 10 %/yr.
- Smartphone: 5 %/yr.

The following datasets are subject to above allocation factors in combination with quantities specified in Table 4.

5.2.1.1.1 Integrated Circuit (IC) Packages

LCA studies assessing smartphones or tablet PCs have identified IC packages – both CPU and memory types – as a major contributor to environmental impacts (Ercan *et al.*, 2016; Moberg *et al.*, 2014; Proske *et al.*, 2016; Teehan and Kandlikar, 2013). Apart from the generic types (e.g. CPU, logic, memory, ASIC, etc.), increasing integration of additional functionalities, stacked silicon dies and a general trend towards miniaturization determine both complexity of production and environmentally relevant factors such as energy demands (Teehan and Kandlikar, 2013; Prakash *et al.*, 2013). Stacked dies are particularly common in flash memory ICs and CPUs for mobile phones and other mobile devices (Teehan and Kandlikar, 2013). Therefore, bills of materials as presented in Table 4 take this circumstance into account, as far as possible.

Publicly available inventory data or studies on environmental impacts of IC packages are rare and only little progress has been made to update databases considering the fundamental developments in production technologies and provided functionalities (Liu *et al.*, 2011; Prakash *et al.*, 2016). Moreover, adopting IC mass as reference as done by default in the Ecoinvent database is considered inappropriate for modern IC packages, often characterized by significantly less mass than older generations (Prakash *et al.*, 2013; Prakash *et al.*, 2016; Teehan and Kandlikar, 2013; Proske *et al.*, 2016). In fact, the integrated die area is considered a more precise reference which is in line with the recommendation given by the European Semiconductor Industry Association (ESIA) (Prakash *et al.*, 2016).

This assessment incorporates inventory data comprising both front and back-end processes, as well as intermediate transports between assumed production locations. Hence, inventory data refers to a cradle-to-gate scope and product parameters as briefly specified in Table 5[5].

Data source:	Prakash et al., 2013; Prakash et al., 2016
Reference location:	Global; Electricity: China/US
Reference year:	approx. 2002-2009
Production parameter:	
Semiconductor scale	45 nm
Technology node	300 mm
Wafer material	Silicon
Wafer area	0.071 m^2/wafer
Wafer thickness	0.75 mm
Weight	approx. 150 g/wafer
Process yield	84 %
Production capacity	120 m^2/week

Table 5. Key parameters with reference to production of logic ICs and corresponding inventory data.

The origin of quantified input and output flows was compiled by Schmidt *et al.* (2012) and was further validated as to ensure relevance to more recent conditions (Prakash *et al.*, 2016). For this purpose, listed chemicals and quantities were checked by SEMATECH Carbon Footprint Working Group (CFWG) and compared with industry data from actual wafer labs (Prakash *et al.*, 2016). The modeled manufacturing process describes a microchip for mobile applications, unlike the default dataset implemented in Ecoinvent v3.4 which describes a rather generic computer chip (Prakash *et al.*, 2016).

Although the dataset is representative for logic (CPU) ICs, it is also used as an approximation for all other IC types in this assessment. This is deemed a rather conservative approach since reviewed logic ICs are

[5] Please refer to Appendix D for full inventory data and associated provider processes as implemented using the Ecoinvent v3.4 database.

generally associated with slightly higher environmental impacts than memory ICs. The four selected[6] impact categories shown in Figure 8 exemplify a possible range of absolute impacts related to the production of distinct IC packages with $1cm^2$ silicon die area. Presented ranges comprise values from both literature (Ercan *et al.*, 2016; Proske *et al.*, 2016; Boyd, 2012) and computations using OpenLCA and Ecoinvent v3.4 data base in combination with the TRACI[7] impact assessment method and inventories as introduced above.

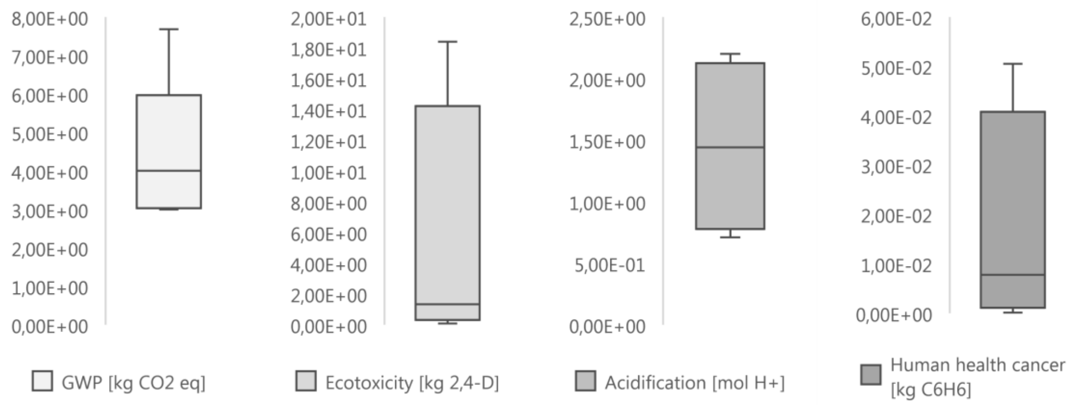

Figure 8. Box plot (n=6) of possible set of absolute impacts (LCIA method: TRACI as implemented in Ecoinvent v3.4) related to the production of IC packages (CPU and memory) with $1cm^2$ die area. Median values shown as inner line.

The chosen inventory data results in impacts that lie well within the range depicted in Figure 8 (4.01E+00 kg CO_2-eq., 1.68E+00 kg 2,4-D, 9.80E-01 mol H+, 1.16E-02 kg C6H6). The lower ends of the three given ranges are predominantly marked by IC memory types. With regards to the GWP, the dataset as implemented in the Ecoinvent v3.4 database (integrated circuit production, logic type | integrated circuit, logic type | APOS, S) is likely an overestimation compared to the other results and literature values. In summary, the calculated and published values are within a rather narrow range, thus the choice of inventory data seems reasonable for the purpose of this study.

5.2.1.1.2 Rigid Printed Circuit Boards (PCB)

Printed circuit boards (PCBs) are key elements of ICT systems and contribute significantly to potential environmental impacts during their cradle-to-gate production. Here, the most influential factors are the number of layers, coating materials, and the area (Prakash *et al.*, 2016; Yu *et al.*, 2014; Schödwell *et al.*, 2018). For unmounted PCBs, the area is usually used as reference. PCBs are not necessarily rectangular as often the case in small mobile devices with limited space. Therefore, environmental assessments have to account for potentially resulting losses (Prakash *et al.*, 2016). Presented BOMs, however, do not factor in these losses, except for the production of smartphone PCBs.

This assessment incorporates inventory data for production of an unmounted PCB (production including waste water treatment) in combination with surface-mounting of default quantities of microelectronic components (e.g. transistors, capacitors, diodes, connectors) as implemented in in the Ecoinvent dataset (printed wiring board production, surface mounted, unspecified, Pb free | printed wiring board, surface mounted, unspecified, Pb free | APOS, S)[8]. The production parameters of the unmounted PCB are detailed in Table 6.

[6] The selection of impact categories is mainly influenced by availability of respective values and inventories. Further, important impacts linked to ICT systems are reflected.

[7] The varying LCIA method (here: TRACI) is applied to facilitate comparability with published literature values.

[8] Please refer to Appendix D for full inventory data and associated provider processes as implemented using the Ecoinvent v3.4 database.

Data source:	Prakash et al., 2016
Reference location:	Global (Estimates refer to European production facility)
Reference year:	2012-2013

Production Parameter:	
Number of layers	6
Substrate material	FR4
Surface coating	Ni/Au
European standard measurement	0.016 m^2

Table 6. Key parameters with reference to production of unmounted PCB and corresponding inventory data.

As can be taken from Appendix B, electronic devices contain numerous PCBs with variable numbers of layers. Due to unavailability of datasets concerning PCBs with an appropriate number of layers, the described inventory data is deployed as an average for the summarized surface area of PCBs. Whether upstream impacts associated with the modeling of rigid PCBs are overestimated or underestimated cannot be assessed. In any case, the range of results from available alternatives (Ecoinvent v3.4 dataset unmounted and surface mounted; selected dataset unmounted and surface-mounted) is narrow in selected impact categories, as depicted in Figure 9. Given the available alternatives, the choice of inventory data is assumed to be uncritical with regards to the final results and conclusions.

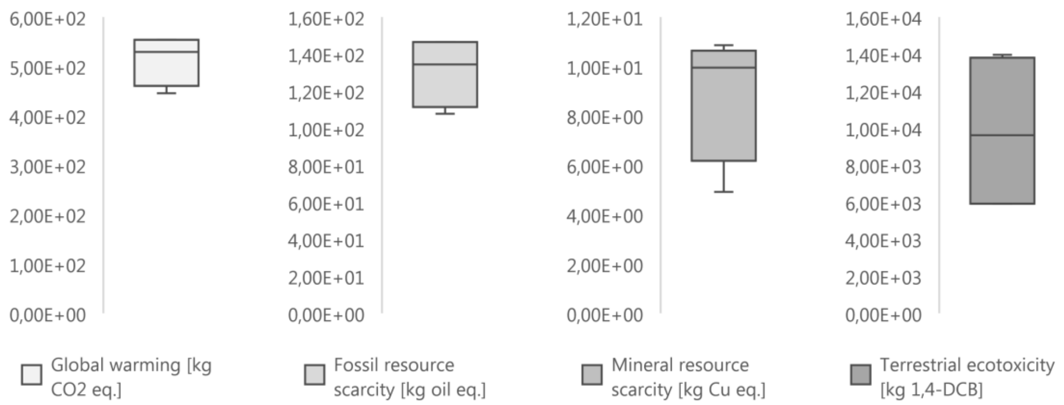

Figure 9. Box plot (n=4) of possible set of absolute impacts (LCIA method: ReCiPe 2016 Midpoint (H) v1.1) related to the production of 1 m^2 PCB (unmounted and surface-mounted). Median values shown as inner line.

The upper ends throughout shown impact categories are represented by the two alternative datasets for surface-mounted PCBs which have generally very similar results. A very similar picture is attained for other impact categories.

5.2.1.1.3 TFT-LCD Panel

Generally, LCA studies and associated references refer to entire TFT-LCD module units, including display control PCB and ICs as well as the actual TFT-LCD panel. For cradle-to-gate impacts of smartphones, the display module has proven to be a major contributor to GHG emissions (approx. 3.5 kg CO_2-eq.) (Ercan *et al.*, 2016). This section, however, only concerns the actual TFT-LCD panel production as additional components (PCB and ICs) are already covered by the quantities assumed for the respective components. Owed to insufficient inventory data and the simplified modeling approach, other components of display modules (e.g. touch film and protection glass) are excluded from this assessment. Thus, the inventory data for this assessment does not include upstream processes associated with driver IC and PCB. Moreover, the backlight panel and the touch panel are not included since available manufacturing data did not reveal any information concerning these components. The incorporated inventory data[9] which is extracted from the publicly available CSR report of AUO[10] (see Table 7) is limited to a few crucial inputs and outputs, but still considered a valid reference given the inferiority of other available datasets. Published data refer to annual inputs and outputs of manufacturing activities. Therefore, the annual production output has been estimated according to stated information as to obtain input/output values per m^2 of TFT panel production (see Appendix C). Basing the scaling of production processes of LCD panels on the area is deemed reasonable (Moberg *et al.*, 2014).

Data source:	AU Optronics Corporation, 2017
Reference location:	Taiwan
Reference year:	2016
Production parameter:	
Annual production output	58,000,000 m^2

Table 7. Key parameters with reference to production of TFT-LCD panels and corresponding inventory data.

When comparing the upstream results of the selected inventory dataset on the basis of a 73,7 cm^2 (equals 5.0'') display module (including display PWB and IC), the values in Table 8[11] are obtained which can furthermore be compared to published results from Proske *et al.* (2016) which are also based on an environmental report of AUO from the year 2016.

Impact Category:	Unit	TFT-LCD module (simplified smartphone)	Proske *et al.*, 2016
Climate change - GWP 100a	kg CO_2-eq.	2.03E+00	2.68E+00
Resources - depletion of abiotic resources	kg Sb-eq.	1.42E-02	2.73E-05
Human toxicity - HTP 100a	kg 1,4-DCB-eq.	9.38E-01	5.50E-01
Terrestrial ecotoxicity - TAETP 100a	kg 1,4-DCB-eq.	7.94E-04	9.63E-03

Table 8. Comparison of manufacturing-related results for TFT-LCD modules (LCIA method for TFT-LCD module (simplified smartphone): CML 2001 as implemented in Ecoinvent v3.4).

Whereas results as incorporated in this assessment are lower for the categories of GWP and terrestrial ecotoxicity, results for abiotic resource depletion and human toxicity are higher. In particular, depletion of abiotic resources exhibits a significant deviation. The main cause for this deviation is rooted in the respective datasets for ICs and PCBs as both display-specific components make up about 80% of abiotic resource depletion associated with the modeled TFT-LCD module. With regards to the GWP, shown results are in the same range as the result published by Ercan *et al.* (2016) which is 3.5 kg CO^2-eq. per 73.2 cm^2 surface area.

5.2.1.1.4 TFT-EPD Panel

Electronic paper displays (EPD) are an integral component and distinct feature of e-readers but have not been properly assessed in any of the reviewed studies. Instead, if e-readers were concerned, LCD panels were used as approximation. This study seeks to provide more specific inventory data on the production of EPD panels. The production of electronic ink and final EPD panels relies upon a variety of raw materials, such as polymers, reaction agents, solvents, and colorants as well as glass substrate for the TFT backplane (Henzen *et al.*, 2004). Unfortunately, the only publicly available environmental declaration concerning EPD panel production does not specify any material inputs or outputs. However,

[9] Please refer to Appendix D for full inventory data and associated provider processes as implemented using the Ecoinvent v3.4 database.

[10] AU Optronics Corporation (AUO) is one of the leading manufacturers of LCD panels and displays.

[11] The varying LCIA method (here: CML 2001) is applied to facilitate comparability with published literature values.

detailed information on energy inputs as well as emissions are disclosed as part of annual reporting on environmental performance. Like the inventory data for the LCD panel production, upstream processes concerning driver IC, PCB, backlight panel, touch panel, as well as transportation between production sites are not included here. Due to partly vague data published in the respective reports of E Ink Holdings[12], estimates have been made concerning the production output per production site involved (see Appendix C). According to E Ink Holdings Inc. (2016, 2017) three production sites in Taiwan and China are responsible to produce certain consecutive components:

- Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels,
- Linkou Plant (Taiwan): Production of electronic ink,
- Yangzhou (China): Module assembly (back-end).

It is therefore assumed that disclosed inputs and outputs per production site are to be added to obtain manufacturing-related inventory data of complete TFT-EPD panel production. Consequently, annual numbers as given in the report are divided by the assumed production capacities as summarized in Table 9. With obtained numbers, the scaling of TFT-EPD modules can be based on the surface area[13].

Data source:	E Ink Holdings Inc., 2016, 2017
Reference location:	Hsinchu/Linkou (Taiwan); Yangzhou (China)
Reference year:	2015
Production Parameter:	
Annual production outputs	Hsinchu (front-end TFT panels): 30,000 m^2 Linkou (electronic ink): 13,000 m^2 Yangzhou (back-end module assembly): 300,000 m^2

Table 9. Key parameters with reference to production of TFT-EPD panels and corresponding inventory data.

In the absence of applicable literature values or environmental declarations of competitors, attained impacts are compared to results from above described TFT-LCD panel. Considering all impact categories, the impacts associated with the assumed production of 1 cm^2 of TFT-EPD panel are significantly higher than for the described TFT-LCD panel. For instance, the respective global warming potential is about 29 times higher for the production of TFT-EPD panels. Other impact categories exhibit similar deviations. The reason for the observed deviations predominantly lies in the specific electricity consumptions. Whereas the above dataset from AUO assumes an electricity consumption of about 0.008 kWh/cm^2 for TFT-LCD panel manufacturing, the disclosed electricity consumptions for the production of TFT-EPD panels amounts to about 0.224 kWh/cm^2, an almost 30-fold increase. However, Ercan *et al.* (2016) estimates the electricity consumption for LCD display manufacturing (incl. touch layer) to about 0.1 kWh/cm^2, thus somewhat in the middle of both datasets.

Reasons for observed deviations can be manifold and given the information at hand, conclusive statements are prohibited. Consequently, the implemented datasets concerning the manufacturing of displays remain a source of uncertainty. The selected inventories, nevertheless, are deemed a valid point of reference as to make up for outdated or lacking alternatives.

5.2.1.1.5 Battery

A popular type of batteries in mobile devices are lithium-ion batteries (see also BOMs in Appendix B). On a battery module level, the actual battery cell is the largest contributor to most environmental impacts (Proske *et al.*, 2016). Other components of whole battery packs are plastics for the casing, contacts, adhesive tape, and most importantly the battery management system which is principally comprised of PCBs and ICs as already included in the respective sections. Therefore, the Ecoinvent inventory data on lithium-ion battery cell production (market for battery cell, Li-ion | battery cell, Li-ion

[12] E Ink Holdings is the leading manufacturer of EPD panels and displays

[13] Please refer to Appendix D for full inventory data and associated provider processes as implemented using the Ecoinvent v3.4 database.

| APOS, S) has been implemented and scaled based on the total mass of battery packs as specified in Table 4.

5.2.1.1.6 Materials

Obviously, utilization of materials can be highly diverse and numerous. Materials can be associated with both manufacturing processes (e.g. auxiliary materials) and final devices (embodied). This assessment will only consider embodied materials that are part of the casing or the inner structure (steel plates) as well as materials for final packaging. Inventories of materials are implemented according to Ecoinvent processes as specified in Table 10.

Material:	(Scaling) Unit	Ecoinvent v3.4 process
Aluminum sheet	g	- market for aluminium, wrought alloy | aluminium, wrought alloy | APOS, S – GLO - market for sheet rolling, aluminium | sheet rolling, aluminium | APOS, S - GLO
Stainless steel sheet	g	- market for steel, low-alloyed | steel, low-alloyed | APOS, S – GLO - market for sheet rolling, steel | sheet rolling, steel | APOS, S - GLO
Polycarbonate	g	market for polycarbonate | polycarbonate | APOS, S - GLO
Retail box materials	g	- 60%: market for waste paperboard, sorted | waste paperboard, sorted | APOS, S – GLO - 37%: market for solid bleached board | solid bleached board | APOS, S – GLO - 3%: market for extrusion, plastic film | extrusion, plastic film | APOS, S - GLO

Table 10. Composition of upstream processes for major materials.

Any occurring material losses due to subtractive manufacturing processes are neglected as BOMs only reveal material masses embodied in complete products. However, significant losses are usually not present in modern industrialized production or not attributable to single devices.

5.2.1.1.7 Final Assembly & Transport

Final assembly efforts are expressed in electricity demands. Any potential auxiliary materials and other accruing inputs or emissions are excluded from this assessment. Therefore, environmental impacts are solely associated with generation and distribution of electricity. China has been chosen as geographical boundary for this process step (market group for electricity, medium voltage | electricity, medium voltage | APOS, S – CN).

Concerning final shipping to a retail destination in Germany, distances and transportation means have been factored in, as estimated in Table 11.

Distance	(Scaling) Unit	Ecoinvent v3.4 process
8,830 km	kg*km	market for transport, freight, aircraft | transport, freight, aircraft | APOS, S - GLO
300 km	kg*km	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER

Table 11. Final transport scenario China-Germany.

5.2.1.2 Core Processes

Core processes are entirely represented by certain electricity demands, prompted by charging of mobile end-user devices and operating network equipment as well as data centers. As all of the mentioned processes are assumed to take place within Germany, the corresponding Ecoinvent dataset (market for electricity, low voltage | electricity, low voltage | APOS, S[14]) has been linked to electricity demands calculated in the following sections.

5.2.1.2.1 Device Usage

Electricity demands of mobile devices are calculated on an annual basis, taking into account specific energy demands during active use and stand-by or idle mode. Due to continuous connectivity of mobile devices and consumer behavior as elaborated previously, smartphones and tablet PCs run 24/7 during the year, however, only active hours require considerable energy (see Table 12). Moreover, no-load losses are assumed to occur as power adapters are often plugged in for longer time spans than the actual charging process (e.g. due to overnight charging process). For the reference scenario, losses of 0.075 W for 7 hours per day are added to the annual electricity demands of smartphones and tablet PCs. Since single-purpose e-readers are generally sparsely used and exhibit exceptionally long battery life times, no-load losses are not present or neglected.

Table 12 summarizes device-specific median values ($n_{smartphone}$=8; $n_{tablet\ PC}$=11) of power input at the adapter (primary side) for both active use and stand-by mode. In the case of e-readers, the median battery capacity and life ($n_{e\text{-}reader}$=9, with combination of backlight and Wi-Fi enabled/disabled) has been taken as point of reference to determine the overall electricity demand. For this purpose, it is calculated that 3 full charge cycles (adapter efficiency: 75%) are needed to provide enough electricity to power e-readers for the assumed hours of reading per year.

Device:	Power input active mode	Power input standby mode	Battery capacity	Battery life	Annual no-load losses	Annual electricity demand
E-Reader	-	-	5.0 Wh	39 h	0 Wh	0.02 kWh
Tablet PC	7.0 W	0.4 W	22.0 Wh	-	191.6 Wh	6.2 kWh
Smartphone	3.4 W	0.1 W	8.2 Wh	-	191.6 Wh	4.2 kWh

Table 12. Assumptions for usage of devices.

Calculated annual electricity demands are assumed to occur disregarding the specific use of devices. Therefore, the values are to be allocated to the reference scenario based on device-specific use durations by means of the following formula:

$$\text{User electricity} = \text{Annual electricity demand [kWh]} * \frac{\text{Annual dedicated duration for reading [h]}}{\text{Annual active use duration [h]}}$$

Applying above formula to calculated values from Table 12, the reference scenario is associated with a total electricity demand for device usage - comprised of allocated use of all three devices - of 2.76 kWh, all of which can be ascribed to reading purposes.

5.2.1.2.2 Network Usage

The total amounts of data transmission to the user and respective devices is assumed to directly correlate with specific electricity consumptions arising from operating network access technologies, transmission networks, data centers, etc. Although electricity consumption of network equipment or data centers can remain static during changes in processed data volumes (Shehabi *et al.*, 2014), linear estimates concerning electricity intensities seem the only reasonable approach to account for network usage. In addition to the bulk of data volumes related to downloads of contents (see Table 3, pg. 10), data transmission is required to facilitate updates of applications and operating systems.

Application updates are assumed to be only relevant to multi-purpose devices (smartphone and tablet PC) and median update sizes are estimated for distinct applications providing access to each type of

[14] This dataset describes electricity available on the low voltage level in Germany for year 2014.

generic media type (Book store app: 67.9 MB (n=3); E-Paper app: 35.9 MB (n=7); E-Magazine app: 53.9 MB (n=12)). It is furthermore assumed that each application is updated twice per year. Concerning updates of respective operating systems, it is assumed that one comprehensive update is required per year (E-Reader: 209 MB (n=9); Tablet PC/Smartphone: 878.25 MB (n=6)). Annual data transmission for OS updates are apportioned to the reference scenario based on the same allocation logic as presented for user electricity.

In summary, the following total amounts of data are prompted by digital reading according to the reference scenario, all of which are proportionally transmitted via two distinct network access systems, as shown in Table 13.

	OS updates	Software (Apps) updates	Content downloads	Proportion per access system
Amount of data	0.63 GB	0.63 GB	4.55 GB	
Access system:				
Fixed DSL (Wi-Fi)	100%	100%	50%	3.54 GB
Mobile Network (3G)	0%	0%	50%	2.27 GB

Table 13. Distribution of total amounts of data.

According to Malmodin *et al.* (2014) data is transmitted via distinct network components or sections, all of them inducing specific electricity consumptions as depicted in Figure 10. It is further assumed that operation of respective infrastructure equipment is confined to national conditions in the country of use (Morley *et al.*, 2018), thus Germany.

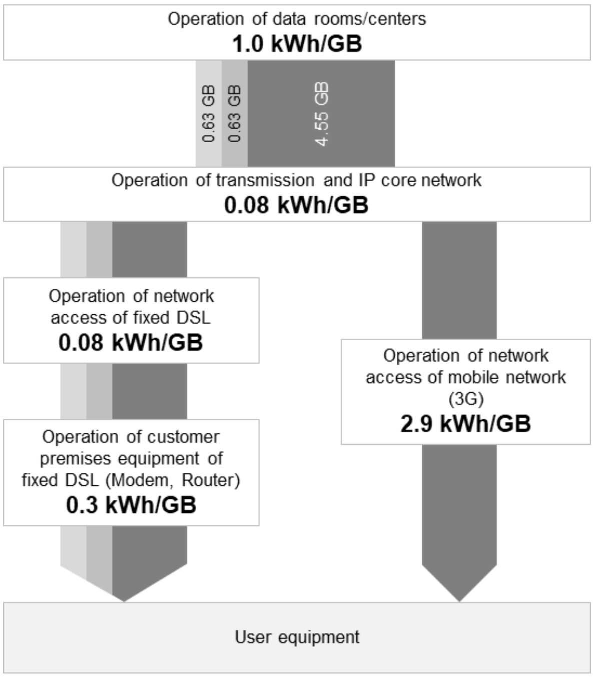

Figure 10. Electricity consumption per data volume (Malmodin *et al.*, 2014) and transmission routes of reference scenario (own depiction).

Presented quantifications of average electricity intensities constitute an important input to ICT-related LCA studies. Specific electricity consumptions are, in fact, functions of both volume of data and time which creates an unavoidable allocation problem (Aslan *et al.*, 2017). Also, it must be remembered that electricity intensities are estimates based on conditions in Sweden and the year 2010 (Malmodin *et al.*, 2014). Arguably, measuring accurate numbers of electricity demands due to network usage as well as accounting for national conditions is challenging. Hence, the selected approximation is deemed a substantiated and reasonable reference to this end. Nevertheless, conclusions will be discussed and tested by means of uncertainty and sensitivity analysis (see chapter 5.3.2.2., pg. 32).

5.2.1.3 Downstream Processes

As elaborated in chapter 5.1.2, the near-term end-of-use (or EoL) stage is associated with no further environmental impacts nor credit. This statement is further based on findings from LCA studies accounting for EoL stages. For instance, accounting for a feasible recycling scenario of a smartphone has been found to have negligible influence on the overall life-cycle impacts (Proske *et al.*, 2016). A possible explanation may be that positive impacts resulting from potentially substituted virgin materials are often balanced with negative impacts due to recycling activities (Moberg *et al.*, 2014). In the best case, environmental offsets (e.g. 0.3 – 1.1 kg CO_2-eq.) are realized by appropriate recycling operations (Proske *et al.*, 2016; Ercan *et al.*, 2016). These results are, however, often related to further assumptions and uncertainties. It is therefore not only a realistic assumption to exclude recycling of electronic devices but also an approach to avoid additional sources of uncertainties.

5.3 Life Cycle Interpretation

This section presents quantitative results of the conducted impact assessment, based on data and assumptions described in this report. Final results are further analyzed and interpreted by means of uncertainty and sensitivity analysis.

5.3.1 Results

The described reference scenario postulates average annual consumption of contents for reading to be entirely met by utilizing digital end-user devices in combination with inextricably linked internet-based services. This service is associated with potential environmental impacts as presented in Figure 11. Next to calculated totals, expected contributions from distinct spheres or subsystems can be taken from Figure 11. With this information at hand, the relative significance of subsystems and whether they are a serious hot-spot of digital reading can be discussed. The presented degree of detail is assumed to be adequate as to derive envisaged conclusions and recommendations for the target groups of this study. In fact, a more detailed breakdown of contributors could be deceptive and results may be misinterpreted. Due to discussed data availability and quality constraints, this assessment cannot facilitate recommendation concerning certain devices or components, nor shall it provide a deeper hot-spot analysis of manufacturing related processes or design decisions. The results are, nevertheless, considered to be generally robust and valid with regards to the aim of this study.

The quantitative investigation of the current situation in Germany reveals two mayor environmental hot-spots related to digital reading: Manufacturing (incl. final shipping) of averagely utilized mobile devices and data transmission networks. The magnitude of the latter, again, is mostly determined by relatively high electricity intensities associated with mobile network access (2.9 kWh/GB) and operation of data centers (1 kWh/GB). Taken together, manufacturing of devices and operation of data transmission network are responsible for more than 90% of total environmental impacts. Consequently, the use of devices (electricity for charging) plays an inferior role which supports general observations and trends towards more energy-efficient devices.

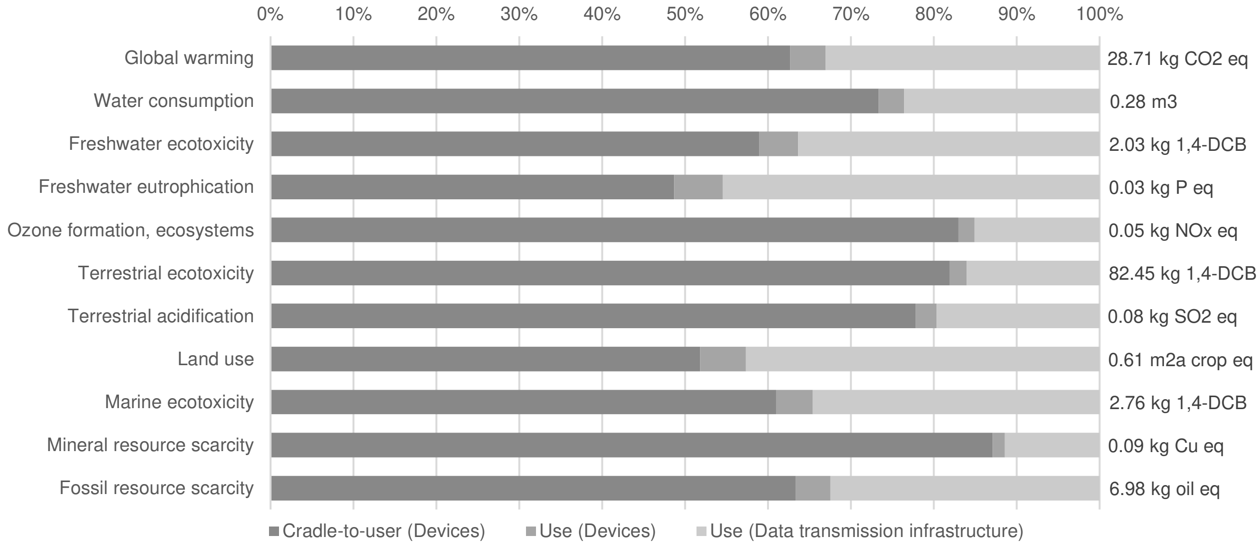

Figure 11. Final results and relative contributions (hot-spots) to selected midpoint impact categories (LCIA method: ReCiPe 2016 Midpoint (H) v1.1).

Although a majority of environmental impacts is associated with manufacturing and distribution of electronic end-user devices, a significant share (e.g. up to 50% of freshwater eutrophication) of environmental contributions can be attributed to the supply-chain implications of electricity generation and distribution which is the dominant driver behind use stages of both devices and data transmission infrastructures. More specifically, emissions are linked to the life cycles of certain electricity inputs (e.g. electricity generation in Germany or imports) under consideration of the German electricity mix in 2014. In gauging the significance of the use stage, the geographical scope is thus of paramount importance. Next to crucial assumptions that have been made regarding the electricity intensities of both end-user devices and data transmission components, the composition of the national grid and the location of use/operation is decisive. With the location of use and operation being determined by the scope and goal of this assessment, the respective electricity mix is rendered an influential factor for the environmental performance of digital reading. In the reference year 2014, the average gross electricity generation in Germany was compounded of about 44% coal, 26% renewables, 16% nuclear, 10% gas, and 5% others (e.g. oil) (Bayer, 2015). In recent years, the share of renewables increased to about 33% in 2017 and fossil energy sources have been displaced to some extent (Statistisches Bundesamt, 2018). Consequently, impacts associated with the use stages - particularly emissions contributing to global warming - could have been slightly mitigated. Moreover, it must be remembered that actual emissions associated with electricity consumption vary depending on time and location. With the reference scenario describing an annual service, however, the adoption of averages (attributional LCA approach) seems appropriate.

Absolute results as presented in Figure 11 are often unintelligible to a broader audience. Therefore, results can be contextualized and validated by comparing them to specific values such as normalization factors or literature values of impacts associated with competing or similar services. Normalized results for the impact categories global warming, terrestrial acidification, and fossil resource scarcity fall well below 1%. In contrast, normalized values for toxicity related impacts (freshwater, marine, terrestrial) are significantly higher. The total result shown for terrestrial ecotoxicity corresponds to the 10-fold of what an average European citizen is estimated to cause over the course of one year. This value is, therefore, either overestimated in this assessment or a potential reason for concern. Similarly to other ecotoxicity impact categories, upstream processes associated with manufacturing of PCBs and ICs as well as the use stage (electricity generation and imports in Germany) play a dominant role. The impacts associated with copper mining and provision of ultrapure process water appear to be crucial for the upstream ecotoxicity impacts of electronic end-user devices. Absolute and relative results concerning toxicity effects should, however, be handled with caution as results may be influenced by the simplified approach adopted for this assessment and/or uncertainties related to applied datasets and parameters.

The calculated global warming potential – an impact category that has been manifested in the public debate - is considered to be less uncertain. This is statement is mainly rooted in the fact that selected inventory datasets tend to focus on climate-relevant emissions (e.g. environmental declarations of display manufacturers). The normalized value for global warming amounts to 0.26 % of the overall annual GHG emissions per European citizen. A more tangible point of reference is therefore the potential impact associated with the equivalent quantity of media consumption met by traditional print products. Following LCA application recommendations, system expansion would be the most accurate approach to account for any potentially substituted products or services. However, due to the inherent complexity in modelling respective systems, literature values are deemed a reasonable compromise as to provide a realistic comparison and to put results into context. Therefore, the existence of potential environmental benefits with regard to global warming implications can be examined.

The perennial and controversial question whether digital media products are preferable over their traditional counterparts remains difficult to answer since products are not necessarily substitutable and part of complex systems. However, the general potential of digital reading may be demonstrated by comparing relevant impact categories. As generally the case for environmental assessments, published numbers are often restricted to climate-relevant impacts (CO_2 equivalents) (Pihkola *et al.*, 2010; Grießhammer *et al.*, 2010; Wells *et al.*, 2012; Boguski, 2010). Although a single environmental indicator does not allow for ultimate conclusions, the impact calculated in this assessment can be put into context and perhaps made more intelligible to a broader audience. For this purpose, carbon footprints associated with print media products have been screened (see Appendix E). Even though reviewed studies date back to the years 2009-2013 and the geographical scope mostly refers to Scandinavia (Finland and Sweden), the results are considered reasonable to this end. In fact, estimates are rather underestimating if applied to a German context. This is because greenhouse gas emissions associated with domestic electricity generation play a vital role. Taking into account specific emission factors for respective reference years in Sweden and Finland and comparing them to past as well as current emission factors for Germany (Koffi *et al.*, 2017; Icha and Kuhs, 2017), presented numbers in Table 14 are possibly an underestimation. This is due to the fact that average German grid emissions in terms of CO_2-eq. have been considerably higher. Moreover, carbon dioxide emissions concerning paper production and subsequent process steps towards final media products are linked to several other sources (e.g. forgone carbon sequestration in forest products, physical transports, etc.) which are assumed unconditionally valid today.

Generic print product:	LCA-Footprint	Reference quantity	Total
Book (hardcover)	1.2 kg CO2-eq.	9	10.8 kg CO2-eq.
Newspaper	0.18 kg CO2-eq.	260	46.8 kg CO2-eq.
Magazine	0.49 kg CO2-eq.	52	25.7 kg CO2-eq.
			83.3 kg CO2-eq.

Table 14. Median literature values of carbon footprints (see Appendix E for detailed references) in combination with annual quantities assumed for the reference scenario.

The total carbon footprint calculated in Table 14 can be understood as an approximation for carbon dioxide emissions that would potentially be generated if the proposed consumption scenario was met by means of traditional print products and assuming single use per print product. The emissions refer to a cradle-to-grave scope and do not or only sparsely account for editorial work. Hence, comparing 83.3 kg CO_2-eq. to 28.7 kg CO_2-eq. from the reference scenario is justified and highlights the theoretical potential of digital reading, at least in terms of climate change implications. This potential can be referred to as a desirable enabling effect (see chapter 5.1, pg. 11) of this specific type of media substitution through ICT.

5.3.2 Uncertainty Analysis

Apart from unavoidable uncertainties in datasets, allocations, assumptions, and impact assessment methods, two study-specific sources of uncertainty have been identified to have the potential to alter final results and conclusions concerning previously identified hot-spots. Therefore, uncertainties will be discussed and analyzed with regards to both upstream and core processes.

5.3.2.1 Upstream Processes

There is an inherent uncertainty in the applied simplified modeling approach concerning digital end-user devices. Although the simplifications made have been reasoned (see chapter 5.2.1.1, pg. 17), potential effects must be discussed. Due to incomplete modelling of minor components and/or perhaps outdated BOMs, an underestimation of upstream impacts may be present. Yet, as elaborated, some components (e.g. TFT-EPD display panel) are likely to be overestimated. Moreover, most simplifications entail a selection of components that expectedly result in higher impacts than the actual components (e.g. logic type IC instead of memory type, 6-layer PCB as approximation for all PCBs). It is therefore indispensable to investigate occurring effects on a product level.

Environmental data with regards to respective devices are rare and detailed information on several impact categories is often missing. Therefore, calculated results cannot be entirely evaluated. Once again, global warming potentials are the only results that can be verified for tablet PCs and e-readers. Somewhat more data sources are available for smartphones. In gauging model uncertainty concerning upstream impacts, it must be remembered that results shall give an indication of environmental impacts associated with an exemplary generic electronic device, thus are not necessarily associated with a specific brand or device generation.

A legitimate point of reference for calculated impacts of the simplified smartphone are published results from Proske *et al.* (2016), as adopted BOM largely relies upon detailed assumptions and quantifications made for the assessment of a Fairphone 2 smartphone. Those assumptions were further supplemented and checked against declarations and studies published for the Apple iPhone 7 and the Sony Ericsson Z5 (Ercan *et al.*, 2016; Apple Inc., 2016). Applying the CML 2010[15] impact assessment method to the simplified smartphone model, obtained values can reasonably be compared to results from Proske *et al.* (2016). Moreover, results concerning global warming potentials are available for both the Apple iPhone 7 and the Sony Ericsson Z5 (see Table 15).

Impact Category:	Unit	Simplified smartphone	Proske *et al.*, 2016 (Fairphone 2)	Ercan *et al.*, 2016 (Sony Ericsson Z5)	Apple Inc., 2016 (iPhone 7)
Climate change - GWP 100a	kg CO_2-eq.	29.18	35.98	46.8	43.68
Resources - depletion of abiotic resources (ADP)	kg Sb-eq.	0.20	0.0015	0.002	-
Human toxicity - HTP 100a	kg 1,4-DCB-eq.	14.88	8.35	-	-
Terrestrial ecotoxicity - TAETP 100a	kg 1,4-DCB-eq.	0.01	0.11	-	-

Table 15. Comparison of impact results concerning smartphones (LCIA method for simplified smartphone: CML 2001 as implemented in Ecoinvent v3.4).

While results for the impact categories ADP and human toxicity are significantly higher, results for climate change impact and terrestrial ecotoxicity are lower in the present model. Given the information at hand, it is only possible to investigate the source of uncertainty for the resulting GWP and ADP. The calculated ADP of the simplified smartphone is about two orders of magnitude higher than corresponding results published in Proske *et al.* (2016) and Ercan *et al.* (2016). Dominant drivers in the modeled simplified smartphone are supply-chain effects of electricity provided for IC and PCB

[15] The varying LCIA method (here: CML 2001) is applied to facilitate comparability with published literature values.

manufacturing as well as final assembly. Considering an ADP associated with a mobile phone of 0.13 kg Sb-eq., as suggested by Moberg *et al.* (2014), values given by Proske *et al.* (2016) and Ercan *et al.* (2016) are perhaps underestimations.

If impacts associated with respective IC datasets implemented in this study are compared with Proske *et al.* (2016), differences in GWPs (see Table 15) can be explained. More specifically, if the delta in GWP per cm^2 die area is scaled up to the assumed die area (see Table 4, pg. 18), the adopted dataset for ICs is associated with about 5.5 kg CO2-eq. less than the alternative dataset implemented in Proske *et al.* (2016). Consequently, lower GWPs can predominantly be ascribed to the dataset applied in this study. This could suggest, in turn, that the simplified modeling approach is a minor source of uncertainty in this assessment, at least when it comes to the accuracy of GWPs. Investigating potential effects associated with simplified models of tablet PC and e-reader is limited due to scarcely available points of reference. Therefore, only publicly available carbon footprints can be compared for both types of devices (see Table 16 and Table 17).

Impact Category:	Unit	Simplified tablet PC	Ahmadi Achachlouei *et al.*, 2015 (iPad 2)	Teehan and Kandlikar, 2013 (iPad 1)	Apple Inc., 2011 (iPad 2)	Apple Inc., 2017 (iPad 8)
Climate change	kg CO_2-eq.	23.66	31	25.5	63	80.4

Table 16. Comparison of impact results concerning tablet PCs (LCIA method for simplified tablet PC: ReCiPe 2016 Midpoint (H) v1.1).

The GWP of the simplified tablet PC lies in a similar range as impacts published by the two other scientific references. Slightly lower results can be explained by the same reasoning as done for smartphones, thus be attributed to adopted datasets. Environmental declarations, however, reveal significantly higher results. For a similar device – the iPad 2 - results are more than twice as high compared to the simplified tablet PC as well as the result published in Ahmadi Achachlouei *et al.* (2015). Given the generally opaque reporting of manufacturers, this difference cannot be further scrutinized.

Looking at results for the simplified e-reader, it can be noted that the GWP lies in the same range as reported in Moberg *et al.* (2011). In contrast, Teehan and Kandlikar (2013) present a considerably lower result. One reason for this circumstance is the contribution of the modeled TFT-EPD display which is potentially overestimated in this assessment. Moreover, the assumed PCB area for the simplified e-reader seems high compared to corresponding values of smartphone or tablet PC. This is perhaps due to the fact that the respective BOM refers to an Amazon Kindle model (3rd generation) from 2010. Nevertheless, the assumed value constitutes the only available measurement and hence identified uncertainty remains.

Impact Category:	Unit	Simplified e-reader	Teehan and Kandlikar, 2013 (Amazon Kindle)	Moberg *et al.*, 2011
Climate change	kg CO_2-eq.	46.49	13.3	40

Table 17. Comparison of impact results concerning e-readers (LCIA method for simplified e-readers: ReCiPe 2016 Midpoint (H) v1.1).

In total, upstream GWPs may be slightly underestimated for the modeled smartphone and tablet PC, whereas the upstream GWP associated with the e-reader device is probably overestimated. Owing to data availability constraints, identified model uncertainty can only be analyzed with regards to GWP. To this end, Figure 12 presents absolute result and contributions if highest GWP values (tablet PC: 80.4 kg CO2-eq.; smartphone: 46.8 kg CO2-eq.) are introduced to the model.

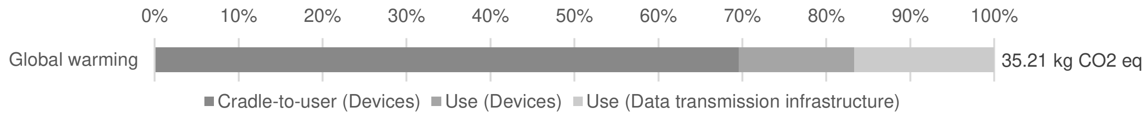

Figure 12. Final GWP result and contributions under consideration of highest GWP values for cradle-to-user scope (LCIA method: ReCiPe 2016 Midpoint (H) v1.1).

The total result associated with the reference scenario is obviously higher but the potential positive enabling effect in terms of GWP still holds true. Moreover, upstream (cradle-to-user) contributions of devices come out more dominantly, making up about 70% of total GWP compared to slightly more than 60 % in the reference scenario (see Figure 11, pg. 28). It is evident that cradle-to-user processes become a major GWP hot-spot.

5.3.2.2 Core Processes

The use stage (core processes) poses another potential source of uncertainty which can only be rooted in the parameters for electricity consumptions of both end-user devices and data transmission infrastructures. Assumed electricity consumptions for device use – comprised of allocated active and stand-by consumptions - are deemed reliable and furthermore have only little influence on overall results, as can be taken from Figure 11. For instance, assumed annual electricity consumption for a smartphone of 4.2 kWh is comparable to estimates made in Proske *et al.* (2016) and Ercan *et al.* (2016), who are assuming 4.9 kWh and 3.87 kWh, respectively. Electricity intensities of data transmission infrastructures, however, prove to be decisive for both absolute impacts and the hypothesized significance of the use stage. In particular, assumed electricity intensities of mobile network access points (2.9 kWh/GB) and data centers (1 kWh/GB) deserve further scrutiny. With respect to data proportions in the reference scenario (see Table 13, pg. 26), the mobile network access (3G) and data centers together account for 87 % (46% and 41%, respectively) of electricity consumption related to data transmission infrastructures, which is equal to 87% of environmental impacts linked to this domain[16].

It must be acknowledged that the year of reference – in this assessment 2010 (Malmodin *et al.*, 2014) - may has a significant influence on efficiency parameters of network equipment which is arguably subject to rapid innovation cycles and efficiency gains (Coroama and Hilty, 2014). On the one hand, ever increasing data usages per user and accompanying energy efficiency gains realized in ICT-systems suggest decreasing energy intensities per amount of data (Andrae, 2016). Looking at Germany, data volumes transmitted over mobile networks have been increasing almost exponentially over recent years (Bundesnetzagentur, 2017). The actual operation of network equipment, on the other hand, is often well below their capacities which has potentially negative impacts on the overall efficiency (Yoro *et al.*, 2017). The network utilization is, in turn, dependent on subscriber density, consequently the geographical location becomes an essential factor (Suckling and Lee, 2015). Since data from Malmodin *et al.* (2014) refers to conditions in Sweden, deviations may reasonably be expected when looking at conditions in Germany as geographical distribution as well as population density differ significantly (Auer *et al.*, 2011).

Similarly to Malmodin *et al.* (2014), several, often less substantiated estimates concerning efficiency of network components have been made. The most relevant values are summarized in Table 18.

[16] Due to LCA methodology, environmental impacts are linearly related to the scaled input value, in this case electricity consumption.

<table>
<tr><th></th><th></th><th>Malmodin et al., 2014</th><th>Auer et al., 2011</th><th>Schien and Preist, 2014</th><th>Krug et al., 2014</th><th>Andrae and Edler, 2015</th><th>Schien et al., 2015</th><th>Aslan et al., 2017</th></tr>
<tr><td>Geographical scope</td><td></td><td>Sweden</td><td>Europe</td><td>Global</td><td>UK</td><td>Global</td><td>Global</td><td>Global</td></tr>
<tr><td>Reference year</td><td></td><td>2010</td><td>2020 (Case study)</td><td>2011</td><td>2012</td><td>2010 - 2012</td><td>2014</td><td>2015</td></tr>
<tr><td></td><td>Unit</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mobile network access</td><td rowspan="5">kWh /GB</td><td>2.9 (3G)</td><td>0.22 (4G)</td><td>-</td><td>-</td><td>2.9 (3G);
0.6 (4G);
0.06 (5G)</td><td>-</td><td>-</td></tr>
<tr><td>Customer premises equipment (CPE) for fixed access</td><td>0.3</td><td>-</td><td>-</td><td rowspan="2">0.26</td><td rowspan="3">0.1 - 0.2</td><td>-</td><td>-</td></tr>
<tr><td>Fixed DSL (Wi-Fi) network access</td><td>0.08</td><td>-</td><td>-</td><td>-</td><td rowspan="2">0.06</td></tr>
<tr><td>Transmission and IP core network</td><td>0.08</td><td>-</td><td>0.02</td><td>0.04</td><td>0.052</td></tr>
<tr><td>Data rooms/centers</td><td>1</td><td>-</td><td>-</td><td>0.002 - 0.11</td><td>0.14</td><td>-</td><td>-</td></tr>
</table>

Table 18. Literature estimates of electricity intensities of certain network components.

Although above list of values and corresponding references raises no claim to completeness, it can be stated that scientifically sound and all-encompassing assessments concerning internet data transmission infrastructures are rare. Often, studies are only concerned with certain sub-systems or components which is evidently owed to inherent difficulties and complexities of assessing the whole data transmission system. Due to obvious and inevitable differences in modeling approaches (e.g. top-down, bottom-up), system boundaries, assumptions, reference years, and geographical scopes, comparability and substitutability of presented values is limited, even if Table 18 may suggest so. Nevertheless, unavoidable parameter uncertainties can be put into context and analyzed in more detail.

Compared to electricity intensities adopted for this assessment from Malmodin *et al.* (2014), Andrae and Edler (2015) present significantly lower electricity intensities for mobile networks (4G), fixed (Wi-Fi) networks, and data centers and further assume a decline of up to 30% per year in the case of mobile networks. Whereas broad-scale introduction of 5th Generation (5G) mobile network technology is expected in the foreseeable to distant future (Andrae and Edler, 2015), 4G (also referred to as LTE) can be considered state of the art in Germany and many other European countries. Consequently, the assumed value referring to a 3G mobile network access (2.9 kWh/GB) is perhaps resulting in an overestimation of electricity demands associated with mobile network access. Yet, identified parameter uncertainties remain as studies investigating mobile access systems are based on extrapolations and uncertain estimates concerning future scenarios or expected developments (Andrae and Edler, 2015; Auer *et al.*, 2011). More recent studies furthermore suggest lower electricity intensities of data centers as well as core networks or fixed access networks. In line with the ITU standard, potential effects resulting from evident parameter uncertainty concerning network transmission efficiencies are part of the sensitivity analysis (Schien *et al.*, 2012).

5.3.3 Sensitivity Analysis

The comprehensive reference scenario as well as included (sub-)systems and components entail a vast array of parameters and assumptions, thus many sensitive parameters may be present. Statistical values with regards to surveyed behavior in Germany set the anchor point of this assessment and therefore are not considered as variables. Following this, the core of the proposed composite functional unit – total hours spent reading – is assumed to remain constant. The same applies to general use patterns and preferences concerning deployed electronic devices. Yet, assumptions and parameters presented in Table 19 are deemed essential as to test the validity and robustness of results. Four distinct scenarios, each taking into account specific alterations of certain parameters as outlined in Table 19, are analyzed. Apart from below variations, all other assumptions and parameters are kept unchanged for the proposed scenarios.

Varied parameter / assumption:	Reference scenario	Worst-case	Multi-functional	Data volume	Internet efficiency
Number of parallel users of tablet PC	2	1	1	-	-
(First) Usage time of e-reader	4 years	2 years	*excluded*	-	-
(First) Usage time of tablet PC	3.5 years	2 years	2 years	-	-
(First) Usage time smartphone	2.5 years	2 years	2 years	-	-
Amount of data via fixed access system	3.54 GB	-	-	5.31 GB	-
Amount of data via mobile access system	2.27 GB	-	-	3.41 GB	-
Electricity intensity of mobile network access	2.9 kWh/GB	-	-	-	0.6 kWh/GB
Electricity intensity of CPE and fixed network access	0.38 kWh/GB	-	-	-	0.26 kWh/GB
Electricity intensity of transmission and IP core network	0.08 kWh/GB	-	-	-	0.04 kWh/GB
Electricity intensity of data rooms/centers	1 kWh/GB	-	-		0.14 kWh/GB

Table 19. Scenarios for sensitivity analysis and varying parameters/assumptions.

The worst-case scenario expectedly results in considerably higher impacts, underlining findings from previous studies which suggest that the life time of electronic devices is decisive. Depending on the impact category, results are up to 90% higher compared to the reference scenario (see Figure 13). The total global warming potential of 51.71 kg CO2-eq. would, however, be still lower than the approximated result for the paper scenario in Table 14 (pg. 29). Other impact categories- in particular toxicity effects and resource scarcities - could become a major source of concern though. The scenario assuming increased internet efficiency exhibits the lowest results for all selected impact categories. It is evident from the assumptions relative to the reference scenario that impacts of both scenarios – worst-case and internet efficiency – are dominated by cradle-to-user processes for end-user devices. On the other hand, utilization of multifunctional devices and/or higher volumes of data transmission render data transmission infrastructures as a hot-spot alongside with manufacturing and shipping of devices.

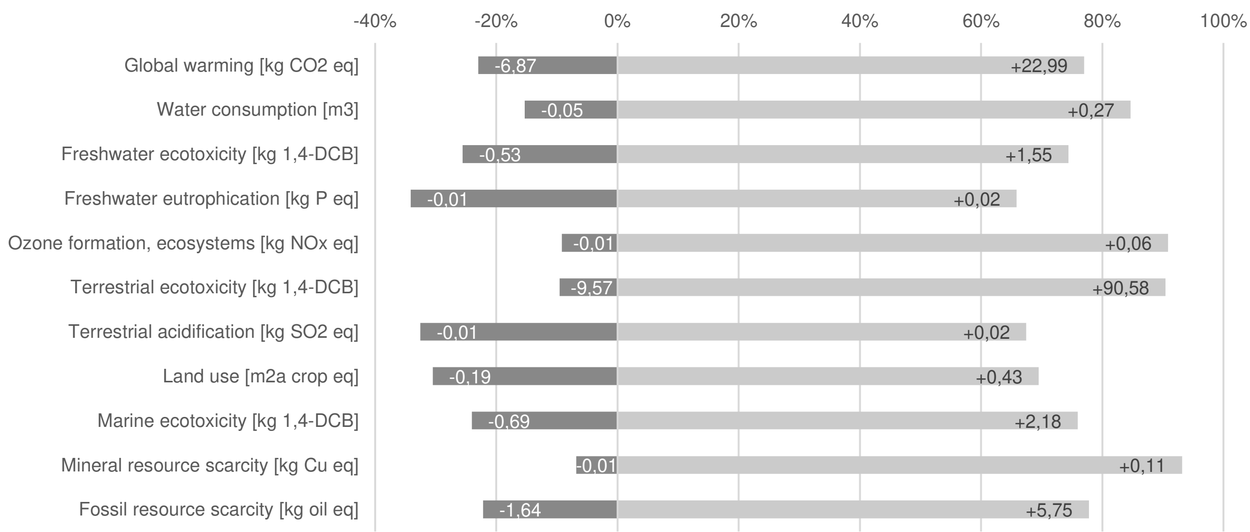

Figure 13. Potential maximum variation of total results based on assumptions of proposed scenarios (LCIA method: ReCiPe 2016 Midpoint (H) v1.1).

The presented range in Figure 13, spanning from lower to higher impacts relative to the reference scenario is assumed to cover most perceivable configurations with regards to user profiles and electricity intensities associated with data transmission. Due to unavoidable uncertainties and potential underestimations in the assessment, it has primarily been tried to account for highest possible impacts associated with the functional unit. At the same time, mitigation of impacts relative to the proposed reference scenario (see 0%-line in Figure 13) can be expected due to realistically assumed efficiency gains in data transmission infrastructures. A potential reason for concern could be significant increases in data volumes, ultimately compensating for efficiency gains. Yet, traditional reading and associated text-based contents as well as plain pictures are not expected to show significant increases in data sizes. Whether ICT facilitates or even encourages more consumption of text-based contents is outside of the scope of this assessment. It is therefore suggested that efficiency gains have the potential to outweigh any occurring increases in data volumes associated with digital reading. If combined with utilization of multifunctional devices – even with short usage times as assumed for sensitivity analysis – paperless reading offers promising possibilities as to further minimize total environmental impacts. Figure 14 shows results associated with a combined scenario, comprised of assumptions made for the multifunctional and internet efficiency scenario (see Table 19). Here, absolute impacts are up to 40% less than in the reference scenario. The relative significance of contributors, however, is shifted. Impacts are largely dominated by cradle-to-user impacts, followed by electricity demands for charging of devices. Apart from obviously lower impacts linked to data transmission, the dominance of cradle-to-user stages is caused by the circumstance that surveyed device preferences in combination with typical user behavior would suggest that tablet PCs are only utilized for reading purposes, consequently upstream processes are entirely attributed to the service under investigation. Whether this circumstance reflects reality, depends on many factors and cannot be answered conclusively. As with traditional books and assumed in the reference scenario, sharing of tablet PCs as well as prolonging the usage time is not only a very intuitive measure to mitigate environmental impacts but also a very effective one.

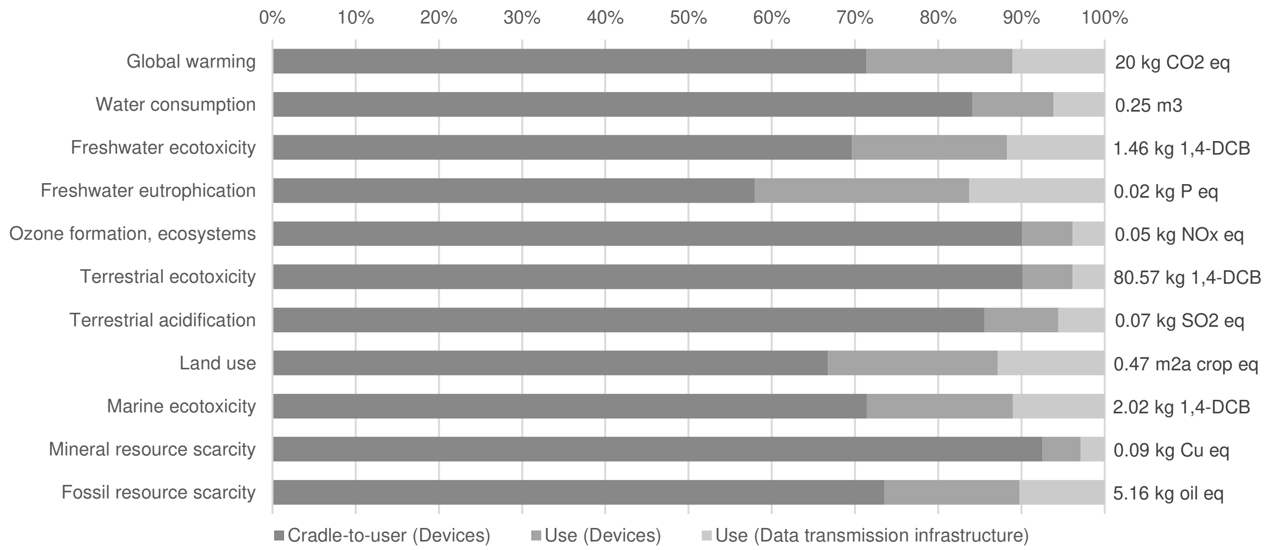

Figure 14. Final results and contributions to selected midpoint impact categories under consideration of increased internet efficiency and exclusion of e-reader device (LCIA method: ReCiPe 2016 Midpoint (H) v1.1).

Considering baseline results linked to the current situation (reference scenario) together with findings of the sensitivity analysis, cradle-to-user processes of devices are clearly an important environmental hot-spot of digital reading. In contrast, the significance of other potential hot-spots depends largely on the assumed efficiency of the underlying data transmission system.

6 Discussion & Conclusion

This final chapter summarizes and synthesizes findings and calculated results. For this, the initially set aim and objectives serve as clusters. Targeted recommendations are given whenever possible.

6.1 Market Characteristics & User Behavior

The current understanding of digital reading goes beyond dedicated e-readers or definable digital media products such as magazines or newspapers. In fact, it must be perceived as a function or service obtained from existing and ever-expanding digital ecosystems. A product-oriented perspective – as often taken in previous assessments - is obsolete for many reasons. Not only is text-based information continuously delivered and seamlessly embedded in versatile channels or formats, it is also in line with LCA methodology to attribute environmental impacts to a function, not a product. Evidently, reading as a function has undergone several changes (e.g. embedded dictionary, hyperlinks, dynamic visualizations, collaboration, etc.) through the introduction of electronic devices to this segment. While certain consumer groups are embracing additional possibilities brought about by digital reading, others appreciate reading comfort and haptic of print issues or books. Consequently, it can be debated whether life-cycle based comparisons between digital and print-based reading are justified or even rewarding. Considering doubtful substitution effects and obvious disparity of respective systems, the perennial and controversial question whether digital media products are preferable over their traditional counterparts remains difficult to answer.

Observed trends and consumer preferences constitute a strong case for dedicated e-readers, at least as an intermediate device at this transitional stage. However, from an environmental perspective, fewer and/or multifunctional devices show advantages. In the light of consumer preferences and diversity of digital contents, conventional e-readers remain a niche product and as such are assumed to add environmental upstream impacts that could be avoided without dampening the service quality. Therefore, expected benefits (e.g. reading comfort, low electricity demand during use, low purchase price) have to be weighed against additional environmental burdens.

6.2 Environmental Hot-spots

It is obvious from the present assessment and perceivable alternative scenarios that manufacturing of electronic end-user devices – no matter if single-purpose (e-reader) or multifunctional (smartphone, tablet PC) – is undoubtedly a major environmental hot-spot of digital reading. The hypothesized significance of data transmission infrastructures, however, depends on both methodological choices (e.g. linear electricity intensity of data transmission) and a range of parameters or trends. The baseline describing the current situation in Germany (reference scenario) evolves around substantiated estimates concerning electricity intensities of essential network components and eventually suggests that electricity consumption associated with data transmission could be an environmental hot-spot of digital reading. Incorporating more recent estimates of electricity intensities, however, causes a shift in the relative importance. The electricity needed to run end-user devices contributes only marginally to overall environmental impacts. Therefore, often cited beneficial electricity demand of e-readers plays a tangential role in the overall environmental profile of digital reading under current circumstances. Next to identified deviations and uncertainties, the geographical location is definitely an influential aspect. Apart from evident environmental implications inextricably linked to the supply-chain of the respective national or local electricity mix, population or subscriber density as well as geographical distribution may affect the environmental performance of digital reading. This is due to the fact that electricity demands of mobile network access technologies depend on exact these parameters. Given a general trend towards increasing data volumes to be delivered via mobile networks, an updated and localized assessment of electricity intensities would be a desirable subject of future studies.

Depending on the actual electricity intensity of data transmission, the amount of data required to provide an expected function may inhibit environmental potentials of digital media consumption. Apart from hidden data traffic (e.g. user analytics, updates, automatic/default downloads, subscriptions) which is challenging to quantify, contents are – albeit spreading of on-demand offers - often downloaded as packages (e.g. e-paper issue, entire book) or downloads are anticipated to facilitate smooth on-demand reading. Data sufficiency is thus a possibility that could be leveraged by means of on-demand subscriptions. Assumed annual data volumes could be significantly reduced as only a fraction of downloaded content is eventually read. Therefore, on-demand access to contents could be envisaged as a major advantage over conventional media products which are inherently redundant and commonly delivered as packages.

In this assessment, a significant share of upstream processes and associated impacts has been attributed to the function of digital reading. Compared to other functions or services (e.g. video/music streaming, podcasts, audio books) embedded in the same digital ecosystems, reading requires little amount of data. If allocation of upstream effects is based on time, the relative importance of data transmission networks could be gauged and compared by adopting a “data-to-service time” ratio. In times where consumers’ attention is the limiting factor and several services compete for it, this ratio could further provide guidance as to compare different means of delivering similar content or information (e.g. video-tutorial vs. textbook). Taking the reference scenario as a starting point, a perceivable ratio for digital reading is 0.015 GB/h, including systemic inefficiencies. In contrast, streaming of high-definition video contents can easily consume 3 GB/h, a 200-fold increase. It can therefore be assumed that electricity demands for data transmission may pose an environmental hot-spot of video streaming or other data-intense media consumption.

6.3 Enabling & Structural Impacts

Looking at possible enabling effects (level 2, Figure 3), this study delivers convincing evidence and a substantiated rationale that paperless reading has a great and realistic potential to be less carbon intense compared to equivalent consumption of printed contents. Based on current circumstances and assuming actual substitution of printed media products, about 50 kg CO2-eq. could theoretically be avoided over the course of one year. Though, other environmental dimensions such as toxicity and resource depletion implications should be given attention to.

While neglected in this assessment, structural impacts (level 2, Figure 3) may be of high importance for the environmental profile of digital reading. Arguably, an extensive shift towards digital publishing and reading perhaps necessitates or at least contributes to the expansion of existing network components and data centers. Yet, data traffic and bandwidth requirements related to text-based contents are reasonably expected to have minor structural impacts on network technologies and capacities. On the other hand, facilitated streamlined publishing and distribution may have significant structural impacts which are attributable to digital reading. Whole industries and branches (e.g. traditional publishing and paper industry, bookstores and warehouses) can become obsolete due to system-dependent mechanisms such as self-publishing and digital distribution.

6.4 Conceptual Assessment Framework

Given the adopted systems perspective on digital reading, this assessment has inevitably touched upon a range of highly complex subsystems and components, ultimately revealing manifold issues with respect to data availability and quality. For instance, up-to-date bills of materials or detailed information on component specifications (e.g. total die area of ICs) are generally not publicly available. Moreover, appropriate datasets concerning essential components or processes of ICT-systems are either outdated or not implemented in the Ecoinvent v3.4 database. In response to aforementioned issues, a somewhat novel approach has been adopted as to close decisive data gaps. In addition, simplified modeling of upstream effects associated with electronic end-user devices has been proven expedient. If compared to appropriate points of reference, simplified modeling of electronic devices is perhaps less of a source of uncertainty than alternative datasets. Although datasets established and implemented for both LCD and EPD panels are incomplete and perhaps inexact, environmental declarations of manufacturers could be a valid reference as to quantify process parameters. Subsequently, datasets can be created or existing datasets may be updated, supplemented, and/or validated.

Acknowledging a time-based allocation of electronic end-user devices and decoupling of dedicated use (= service time) from transmitted data volumes, life-cycle impacts of services embedded in digital ecosystem may reliably assessed with the datasets and the composite functional unit (Figure 15) as presented in this report.

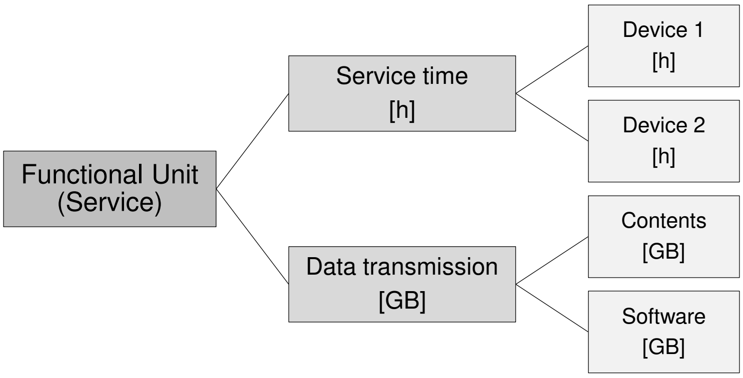

Figure 15. Generic composite functional unit for LCA on certain services obtained from digital ecosystems.

Supplemented with appropriate assumptions concerning use patterns (e.g. daily use and life time of devices) and electricity intensities of deployed network components, the proposed assessment structure and framework could be applied to other functions (e.g. video streaming, messaging, social media) embedded in similar or equal digital ecosystems. Hence, contemporary digital services could be assessed on a common basis and ultimately scientifically grounded and fair comparisons between different types of digital media consumption are facilitated.

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Appendices

Appendix A

Detailed Literature Review

		Moberg et al. 2010	Moberg et al. 2011	Manhart et al. 2011	Arushanyan and Moberg 2012	Hohenthal et al. 2013*	Hischier et al. 2013*	Ahmadi Achachlouei et al. 2015	Naicker and Cohen 2016*	Amasawa et al. 2017
General	ISO-compliance	*not specified*	*not specified*	*not specified*	*not specified*	claimed to be in accordance with ISO 14040-14044; Critical review is excluded as products are not compared to competitors etc.	not specifically stated but paper adheres to ISO framework (four steps)	ISO methodology employed	Paper is structured according ISO standard	LCA is claimed to follow ISO procedure
	Type of study	Journal Article	Journal Article	Publicly available Report	Conference Proceeding	Publicly available Report	Conference Proceeding	Journal Article	Journal Article (doubtful credibility of journal)	Journal Article
Goal	Rationale/objective	Description of potential environmental impacts of two distinct product systems (printed newspaper and tablet e-paper)	Analysis of environmental impacts of e-book and e-reader device with hotspot analysis; in addition, comparison to printed equivalent	Assessment and localization of environmental impacts associated with e-book-readers	Impacts of online newspaper not well studied and lack of data related to electronic devices and distribution	Evaluation of environmental performance of specific Alma Media products, both print and online; Media company is assigned a key role in sharing environmental information in order to improve user/stakeholder practices along the whole value chain	Establishment of scientific basis (=LCA model) for web-based tool to calculate environmental impacts related to various types of print and electronic media in combination with specific use patterns	Assessment of environmental impacts of production and consumption of magazines read on tablets; In particular, identification of main impacts and key factors of environmental profile	Comparison of print media system with digital counterpart in relation to reading university books in South African context	Identification whether reading on e-books can reduce global warming potential in comparison to reading only paper books by acknowledging that reading digital content can alter reading patterns
	Comparative/stand-alone	Comparative	Comparative	Stand-alone (but: comparison for context)	Stand-alone	Stand-alone assessments for both print and online version	Stand-alone assessment for further use as input data for comparisons by means of web-based tool	Stand-alone	Comparative	Comparative
	Modeling approach	Attributional (average data)	Attributional (average data)	*not specified (presumably attributional)*	*not specified (presumably attributional)*	*not specified (presumably attributional)*	*not specified (presumably attributional)*	*not specified (presumably attributional)*	*not specified (presumably attributional)*	*not specified (presumably attributional)*
	Application & Audience	*not specified*	*not specified*	Development of criteria for climate protection - related certification	*not specified*	Specific media company and its stakeholder, as well as broader public	Primarily presentation/communication to users without knowledge in LCA methodology	*not specified*	Students and universities in South Africa	*not specified*
Scope	Functional Unit	Consumption of a newspaper during one year by one unique reader	One specific book bought and read by one person	Annual use of e-book-reader by private person	One reader during one year	- one year online newspaper production - one reader for one week - one reading hour	- 1 hour of (active) use (for digital version) - 1 kg if print products (for print version)	One readers use of one copy of "Sköna Hem´s" tablet edition in 2010	Reading of 21 books by a single user two hours per day over a four-year period	- book reading activities per person - book reading activities per person-book (book reading activities per person divided by the number of books purchased per person in a specific time period)
	Product/service characteristics	- e-paper size 5 MB (downloaded in two parts á 2.5 MB)	- e-book as equivalent to an average 360-page (hardcover) novel in the form of 1.5 MB pdf-file - dedicated e-reader with e-ink display - paper book for comparison is a hardback 360-page novel produced in Sweden and printed on average European wood-free paper and sold in a traditional bookshop	Specifications of device: - e-ink display (alternative: LCD color display) - 6 inch display size - weight of 250 g	- mix of 55% desktop and 45% laptop for reading - tablet reader	- devices for accessing online newspaper: desktop PC or laptop (17 inch display, including needed periphery such as keyboard, mouse, network access device	- Smartphone: Weight: 136g; Composition data: mix of data about iPhone 3 and iPhone 4S - Tablet (I): 10-inch model with LCD display; Composition data of iPad 2 - Tablet (II): 10-inch model with an e-paper display; Composition data of iRex 1000 Further devices are: Netbook, Laptop Computer, Desktop Computer; LCD TV	- Tablet computer with LCD screen (generic tablet, similar to iPad): height 241.1 mm, width 185.7 mm, depth 8.8 m, weight 613 g - electronic edition of magazine (Swedish interior design magazine as example): two distinct versions of magazine; current emerging version (low number of copies/downloads with 2,215/year and short reading time 9min/magazine) as of 2010 and a possible mature version (653,500 downloads/year and reading time of 41 min/magazine); size of magazine 163 MB/copy	Apple iPad "Air"	- designated e-book device (e-reader): Amazon Kindle - tablet: iPad, first generation

System boundaries	Geographical context: Europe and Sweden in particular; electronic equipment produced in China cradle-to-grave; field work research of journalists is excluded	Geographical context: production and consumption of content, purchase/use/disposal of device in Sweden/ production of device in China	Production, distribution, use, and disposal of e-reader	System includes extensive, site-specific (Finland) content production (all activities related to production of newspaper, e.g. office heating and electricity, business trips with cars etc.), electronic storage and distribution and reading on device; Thus, network access and internet infrastructure is included	Cradle-to-grave perspective (manufacturing of cables, construction and maintenance of ICT network are included); also extensive and detailed assessment of content production (e.g. office use, marketing, administration, equipment, business travel and mailing) Geographical scope: Finland, some manufacturing/raw material extraction takes place in other regions though	Two-part (modular) LCAs with cradle-to-gate scope for electronic devices and separate LCA on use stage incl. Electricity production; Additional infrastructure required to access the Internet is taken into account by using the relevant dataset from Ecoinvent	Life cycle includes: - content production (business trips, transport, photo sessions, electronic office equipment, office paper, district heating/cooling, electricity) - electronic storage and distribution (electricity, manufacturing of network infrastructure) - reading on tablet (electricity for reading; production, distribution, disposal of device included)	Life cycle of digital system: - iPad production/distribution/disposal - e-book formatting - e-book download - personal transportation - reading of e-books on device	Life cycle of digital system includes: - Editorial work - production/distribution of electronic device - download of e-book - reading on electronic device
Assumptions/limitations	- biotic carbon dioxide excluded from climate change potential - Editorial work is included and assumed to be the same for all editions (print, internet-based, e-paper) - Direct transmission via internet (wireless LAN) to the e-reader device - transport of e-reader from China to Europe by ship and truck - Life time of electronic product only 1 year (very conservative assumption) - Reading of 30 min / day, which is assumed to be 50 % of total use of the device - upload and download via servers of e-paper content is included - power during reading is assumed to be 0.001 W - an estimation was done for the inclusion of the internet infrastructure by accounting for operation of modem and energy use of core network - average internet use is 9.3 h/week - base scenario largely excludes the energy use of servers and data storage; however, data partly includes energy use for servers - e-reader recycling: 70% material recycling, 30% incineration with energy recovery	- biotic carbon dioxide excluded from climate change potential - editorial work (= content production) identical for print and electronic book, with additional energy use for e-book due to distribution via specific web shop - transport from China to Central Europe by boat and lorry; pick-up of device by car at 2km away local store - average Swedish electricity mix for use stage and content production/distribution - utilization of desktop computer for download - necessary (short-time (8min)) internet/PC use was accounted for - reading one specific book requires 2.5 Wh - lifetime of device 2/4 years, which corresponds to 48 specific books being read on one device (1/2 books/month depending on lifetime) - 75% of the e-reader is recycled, of which 48 weight-% is recycled, 29 weight-% energetically recovered, and 23 weight-% landfilled in Sweden. (for recycling virgin equivalents were offset); potential impacts from the not recycled parts (25%) are cut off/not included	- lifetime of device 3 years - transport from Shanghai to Hamburg (50% via Ship and 50% via air freight) - energy use is assumed according to own calculations and includes efficiency and idle losses during charging - 20% of device is recycled appropriately; Thus, 100 % of contained copper is recycled and 95% of gold, silver, and palladium; 0% of other metals (e.g. aluminum), glass and plastics is recycled; other 80% of devices is recycled via domestic waste system - Assumption made for break-even calculation/reference system: 10 books á 200 DIN A5 pages per year; Disposal of books is cut-off as books are usually kept and not disposed of. - content production, distribution, and digital infrastructure are excluded from assessment	- tablet with WIFI connection - tablet use life 3 years - Finnish electricity mix for content production, distribution, and reading - climate change impact was assumed to correlate with the amount of data transmitted (in MB) - reader´s average size of download is 100 MB/week	- electricity mix as 5-year Finnish average (2005-2009) - same form of content production is performed for both print and online content - content is uploaded on website and then accessed through readers device - Company´s electronic distribution is done via servers of subcontractor at another location - Electricity demand of internet use is based on MB of information transmitted (Swedish figures) - Reading time 6-11 min/week - Total download size 2-100 MB/week - Average size of daily upload 22.6 - 745.4 MB - total computer use time at home 17 h/week (8.6 h/person) - lifetime of electronic devices 5.6-6.6 years - distinction between office and home computer use was done based on the access statistics, assuming office hours between 8:00 and 17:00 - mobile reading devices (smartphones/tablets) were not considered - electricity consumption during non-active (idle/stand-by/off) times was accounted for by redistributing usage over active use hours	<u>Assumptions for use patterns and life span:</u> - Smartphone: 2h/d active; 22h/d sleep; 0h/d off; Life span 2 years - Tablets: 2h/d active; 22h/d sleep; 0h/d off; Life span 2 years - electricity consumption during non-active (stand-by/off) times was accounted for by redistributing consumption over active use hours - As impacts of data centers are not included in Ecoinvent dataset, the energy consumption is estimated to be 0.275Wh/MB (range from 0.19 to 0.36 Wh/MB) - electronic devices are manually depolluted and subsequently mechanically treated - recycled materials are accounted for by system expansion (avoided burden approach)	- digital magazine version is distributed over Wi-Fi network and downloaded to an application (app) - only 1 reader per electronic copy of magazine - life time of tablet: 3 years - active use time of tablet: 14 h/week - content production is shared by print and tablet editions of magazine with additional dedicated effort for tablet edition - App files are stored in private cloud of Amazon Web Services - distribution of tablet by boat/truck from Shanghai to Stockholm - energy use for reading is calculated based on electricity consumption for charging and maximum battery life in Wi-Fi mode according to manufacturer (Apple) information - waste treatment is considered very uncertain; it is assumed that 20% of devices will not enter an appropriate recycling system and ends up in municipal waste incineration; for remaining 80% of tablet, 51 weight-% are directly recycled and rest is passed through mechanical process in which remaining aluminum can be recovered; residuals are incinerated/landfilled - production of advertisement was excluded	- Chinese datasets for assembly parts of iPad are used as assembly is assumed to take place in Foxconn's Chinese factories - energy/materials associated with assembly of single parts is not included - iPad is shipped via UK from China to South Africa - each e-book is formatted for 50 h using a standard computer; one e-book is formatted for 1000 readers - download is based on energy use of user modem and router access network DSLAM, internet, data center, cables and operational activities - production/maintenance of network infrastructure is excluded; only energy use is incorporated - energy use is based on battery life of iPad and the reading time - battery and packing are landfilled; otherwise recovery is entirely excluded - use stage is only determined by the energy required to download and read the 21 books - it is assumed that the iPad is used for 2 (out of 3.1) h/day for reading; this equals 64.5% of the overall use time	- paper book does not contain recycled fibers - Swedish LCI is assumed to be applicable for US context - no additional lightning is needed for reading activities - Internet infrastructure and disposal of electronic device are excluded from assessment - life time of electronic devices: 3 years - devices are assumed to be used exclusively for reading e-books - energy use during reading was calculated based on battery capacity and hours of operation - during reading, energy consumption for operation without Wi-Fi is assumed for the Kindle device; for iPad energy consumption is assumed constant - download time for one e-book: 8 min

	Allocation	- Content production was allocated between each unique reader of the newspaper, disregarding the newspaper version - Allocation of modem use based on energy used for download and attributable stand-by energy use	- web shops energy/heat demand allocated based on total sales of books - Desktop PC production impacts were allocated based on time	*not discussed*	- climate change impact of entire content production was allocated based on the number of employees working for the respective versions (print/online) of the newspaper - internet infrastructure is allocated based on the amount of data transferred - impacts from tablet device is allocated based on the share of reading time of total active use time	- allocation of content production based on the number of employees working for either of the alternatives - Impacts from devices were allocated based on the time spent reading in comparison to total active use over whole lifetime - system expansion for recycling of electronic devices (closed-loop); recycled materials are assumed to replace virgin material - internet system allocation is based on total amount of data transferred (in MB)	- impacts/benefits from manufacturing and disposal of devices are allocated based on active use time	- joint content production was allocated based on the number of copies sold - home networking (modem/router) is allocated based on active use time; otherwise, electronic storage and distribution is allocated based on data traffic (MB) - production/distribution impacts of tablet are allocated based on use time for reading	- impacts resulting from iPad life cycle are allocated based on use time for reading in relation to total active use	*not discussed/not relevant*
	Impact categories/ Assessment method	Resources used (non-renewable, renewable and total), acidification, climate change, eutrophication, photochemical oxidant (photo oxidant) formation, ozone depletion and toxicity; Weighting according Eco tax 02 (monetary method) and Eco-indicator 99 (three damage categories)	CML	Cumulative energy demand, GWP, AP, EP, POCP	Only climate change potential	ReCiPe Mid/Endpoint; due to lack of data or insufficient data set, the following impact categories were excluded: - ionizing radiation - agricultural land occupation - urban land occupation - natural land transformation - water depletion	- Global warming potential - non-renewable cumulative energy demand - ReCiPe endpoints (Human health, ecosystem quality, resources)	ReCiPe08 Midpoint (H) as well as cumulative exergy and energy demand Climate change, cumulative energy/exergy demand, metal depletion, photochemical oxidant formation, particulate matter formation, terrestrial acidification, freshwater/marine eutrophication, fossil depletion, human toxicity, and ecotoxicity	ReCiPe 1.09 midpoint (H) and cumulative energy demand (CED)	Global Warming Potential (GWP)
Inventory	Database	Ecoinvent 1.2 and earlier studies on print newspaper; electronic device modelled by LBO (Stuttgart University)	General data from Ecoinvent 2.0 and site-specific data from participants	Database is the inventory data of Moberg et al. 2011 which has been scaled down to the assumed weight of 250g	Ecoinvent Database, KCL EcoData database	Generic and specific data from Alma Media and suppliers	Ecoinvent v2.2 database	Primary data from actors in the supply chain and background data from Ecoinvent v2.2/3.0	Ecoinvent v3.01	*majority of data were directly adopted from Borggren (2011) and Moberg (2011).*
	Data quality	- uncertain data on e-reader production and subsequent waste handling - large uncertainties for toxicological impact categories	specific device was dismantled to identify single components with subsequent linking to average data from Ecoinvent (usually from western Europe, Therefore not necessarily representative for assumed (actual) production in China) - data is assumed to be generally uncertain, especially with regards to waste management (e.g. exchange for virgin material)	*not discussed*	- site-specific, primary data for content production from Finnish newspaper company - generic data for electronic devices, which were considered already rather old at the time of the study	- manufacturing data for electronic devices is limited and partly very old (2002-2004) - many approximations for lacking data	*Quality of data is not further assessed/discussed*	- detailed inventory data on iPad 2 (identified components are modeled using Ecoinvent data) - specific data on Amazon Web Service cloud storage was not obtained; therefore, average data on the electricity use per MB was implemented to model cloud services - possible waste treatment activities are based on communication with recycling company	*not discussed*	*majority of data were directly adopted from Borggren (2011) and Moberg (2011).*
	Data gaps	- Data for e-reader is considered insufficient as still under development at the time of the study - no data on e-ink display production - little information on user behavior (time for reading etc.) - no readily available data on recycling of electronic device	Inventory data on e-ink screen production and assembly of device - toxicity related data	*not discussed*	- data concerning the handling of e-waste was inferior but was assumed to not influence that accuracy of climate change impacts too severely	- limited data sources for toxicity related impact categories - no specific data for energy consumption of servers - no data for data center manufacturing/servers; These are assumed to be equal to desktop PCs - missing data on manufacturing of some office	*Specific data gaps are not discussed/revealed*	- lack of data on data centers; data was approximated by using data sets for desktop computers - limited data on electronic devices	*not discussed*	*majority of data were directly adopted from Borggren (2011) and Moberg (2011).*

		- construction of internet infrastructure				equipment (fax, stationary phones, iPads, cables)				
Interpretation	Results	- e-paper with less than half the impact for total energy use, eutrophication, photochemical ozone creation, and aquatic/terrestrial ecotoxicity; Furthermore, weighted results indicate that the e-paper is environmentally beneficial - Life time extension or longer use of electronic device results in considerable impact reductions - impacts depend on user behavior: total use and life time	Number of e-books read is crucial; thus, the lifetime of electronic device is decisive; The study provides a feasible order of magnitude - lowest break-even point for cumulative energy demand at less than 20 books	Similar results for break-even points as given in Moberg et al. 2011; Therefore e-book-reader are assumed to be environmentally beneficial assuming average use intensity (10 books per year)	If newspaper is read on desktop PC, the main contribution to climate change stems from the manufacturing of the device. However, when reading on a tablet, online distribution makes up for the largest share (38%), followed by device manufacturing (31%) Reading the newspaper on a tablet is associated with lower climate change impacts than reading on a desktop PC	- in terms of content production, the highest climate change impacts are due to business trips, electricity, and heating - user device manufacturing (desktops, screens, laptops) is the main contributor to environmental impacts - the content production can have significant impacts on the overall environmental performance of online newspapers (up to 50% of carbon footprint) - content distribution had insignificantly low impact as amount of data was small - environmental impacts associated with online media consumption occur primarily in other countries - print with larger impact when assessment based on one year or one reader/week; however, when impact related to active reading time, print performs better	*specific results/findings are not presented in paper (only accessible through fee-based online tool*	- emerging magazine has higher environmental impacts associated than the (potential) mature version - in the light of electronic media products for small target groups (which is assumed to be enabled digital content distribution as it is economically feasible), content production can become a major contributor to environmental impacts - data center related impacts are important for environmental profile - use and allocated impacts of production of device are not the main contributor to environmental impacts, as opposed to previous studies	- Digital system is associated with lower impacts in 14 (out of all 18) categories - CED of print system is approx. 3-times higher than digital system	- GWP break-even at 4.7 books purchased per year when reading on e-reader instead of printed books; when reading on a tablet (iPad), the GWP break-even is at 9 books / year
	Significant impacts/assumptions	- toxicological impacts mainly resulting from electricity generation	production of e-ink display excluded which would potentially increase the environmental burden considerably	Life span of devices	Total active use of device and electricity mix	- relation of reading time and efforts of content production - according to normalized results: Human toxicity, freshwater eutrophication, freshwater/marine ecotoxicity - number of readers (especially relevant in the light of distribution of impacts from content production) and reading time - total use time of devices (user practice)	*not specified*	- use intensity of tablet (time for reading) - size of magazine file - geographical scope and electricity mix - dedicated content production in terms of FTE for tablet version apart from shared content production - number of readers per produced content	*not discussed*	*not discussed*
	Significant life cycle stages/processes	- paper production for traditional newspaper, followed by printing and distribution (exemplified by looking at global warming potential - device production, followed by editorial work and download of e-paper; also e-waste incineration was a main contributor to human toxicity - energy use for reading on device and substitution of printed content	Production of e-reader main determinant of environmental load, in particular electricity; considerable offsets from recycling stage	- production makes up for 99% of energy demand and global warming potential of e-e-book-reader - paper production is most relevant contributor to reference system	- generally, manufacturing and online distribution are decisive - electricity mix for online distribution and reading on device	- Manufacturing of electronic devices and content production - Electricity	*not specified*	- content production (emerging version) and electronic storage/distribution (mature version) - for mature version, the electronic storage/distribution was main contributor to climate change (within this process, data centers for storage make up the main impacts on climate change with 68%) - for mature version, electronic storage/distribution is also main contributor to other impact categories except marine eutrophication (mainly	- production of iPad is major contributor to most impact categories, followed by reading the e-books	*not discussed*

								due to electricity use in data centers)		
	Sensitivity analysis	- Inclusion of energy use for servers - life time of 2 years for e-reader device	- multiple reader per book (but only considered for the printed version and not for digital books)	- effects of recycled paper - LCD display instead of e-ink	- electricity mix of European average - variation of total use time of device from 2h/week to 60h/week	- recycling of metals from e-waste - total use of home computers - service life of a computer - inclusion of long-term emissions	*not specified (implicitly conducted by altering user patterns and devices for media consumption via online tool)*	- electricity mix (Swedish mix for distribution, reading and waste handling is replaced with average European mix) - lower overall use of device (1 h/week instead of 14 h/week) - Smaller size of electronic magazine (5 MB instead of 163 MB; this would be the case for text-dominant content)	- alternative (future) electricity mix - impact of multiple readers	*not conducted*
Conclusion	Recommendations	- the comparability of the two newspaper version is questioned - reading on mobile phones was assumed to be an interesting issue to study; also: transmission via mobile communication networks - further assessment of user behavior	- user practices deserve further scrutiny - reading books on multifunctional devices would decrease the associated environmental load of production - also paperback books should be considered - use of devices for accessing different kinds of media - studies on macro level are needed	*only very general conclusions*	*no specific recommendations / future directions given*	- necessity of more specific data related to electronic devices/infrastructure - increase/enhance knowledge about toxicological aspects - Assessment of mobile devices for reading newspaper	*no specific recommendations / future directions given*	- more specific information regarding the storage is needed - detailed consideration of specific environmental impacts related to certain content production process - need for further focus on toxicity and land use impacts - gather more data on user behavior	*no specific recommendations / future directions given*	- determine appropriate allocation for multifunctional devices - pattern of room lights during reading requires further consideration - expansion of assessment to other digital media
Other characteristics	Consideration of enabling/systemic effects	comparative nature of study assumes substitution	comparative nature of study assumes substitution	yes, by means of introduced reference system (printed books) as well as utility analysis	no	no	no	no	no	yes
	Assessment of digital infrastructure (data centers, network)	yes, partly	yes, partly	no	yes	yes (servers, cables, data centers, etc.)	yes	yes	yes, partly (energy use)	no
	Electricity mix	Europe / Sweden	Sweden	Germany	Finland	Finland/Sweden	not specified	Sweden	South Africa	USA
	Assessment of toxicity	Yes, as far as data was available	Yes, as far as data was available	yes (limited, not quantified)	no	very limited due to data availability	not specified		no	no
	End-of-use scenario for recycling of hardware (end-user devices as well as infrastructure)	Yes	Yes	Yes	yes	yes	yes	yes	no	no
	Rare earth metals (Conflict metals)	no	no	no	no	no	no		no	no
	Other general Social/Economic considerations	no	no	yes, LCC; but no social impact assessment		no	no	no	no	yes
	Spatial context / Geographical Scope	Sweden	Sweden	Germany	Finland	Finland/Sweden	not specified	Sweden	South Africa	USA
	Content production included?	yes	yes	no	yes	Yes, very detailed and site-specific	no	yes	no	yes
	Life span of devices	1 or 2 years	2 or 4 years	3 years	3 years	5.6-6.6 years	2-6 years	3 years	not specified	3 years
	User behavior		pace of reading is not specified, just total amount and number of recharging the device		different reading intensities assessed		Accounted for by individual tool settings	yes, for instance reading time and overall active use of devices	no	yes
	Transparency with regards to data, methods, assumptions, etc.					high transparency and very detailed description of processes and data sources	only examples of inventories are given; most information is not disclosed	high transparency and very detailed description of processes and data sources	low transparency	low for LCA part

* Review refers mainly to assessed online (digital) products

Appendix B

Bill of Materials

Component: Simplified Smartphone
References: Proske et al., 2016 — Ercan et al., 2016 — Apple Inc., 2016 — Andrae et al., 2014

Category	Process flow metric	Scaling unit	Part/Assembly 1	Value 1	Part/Assembly 2	Value 2	Part/Assembly 3	Value 3	Part/Assembly 4	Value 4	Alt. Value 4	Average value	**Assimilated BOM**	**Assimilated value**	**Unit**
(Rigid) Multilayer Printed Circuit Board (PCB)	Board area	cm^2	Mainboard (12 layers)	60.92					Mainboard (8 layers)	25.56			Rigid PCB (12 layers) production	63	cm^2
			Antenna grounding (12 layers)	0.54					Keyboard (4 layers)	28.25			Rigid PCB (4 layers) production	62	cm^2
			Antenna coaxial board (12 layers)	1.46					Camera image sensor	0.4225					
			Top module board (4 layers)	12.58											
			Display board (4 layers)	9.59											
			Camera board (4 layers)	9.02											
			Bottom module board (4 layers)	31.19											
Total PCB area				125.3						54.233		89.77			
Flexible Printed Circuit Board (FPC)	Mass | Area	g | cm^2			Flex-films	6.5			Keyboard, camera, link flex (2 layers)		10.47	-	Flexible PCB (2 layers) production	?	cm^2
Total FPC mass / area															
Integrated Circuit (IC)	Silicon die area	mm^2	CPU	111.28									Logic IC production	233	mm^2 (die)
			Memory	68.63									Memory IC production	162	mm^2 (die)
			Storage	93.64											
			Display driver	26.2											
			Top module	1.9											
			Mainboard	93.3											
Total IC die area				394.95		950 / 750									
Display	Screen area	cm^2	TFT-LCD Module	73.7	TFT-LCD Module	73.2	TFT-LCD Module	60.8					TFT-LCD module production	73.7	cm^2
Battery	Mass	g	Lithium cobalt oxide (LCO) battery	38	Li-Ion battery	48	Lithium-ion polymer battery	26	Li-Ion battery	24.526		34.13	Li-Ion battery production	34	g
Mechanics/Materials	Mass	g	Polycarbonate for housing	15.7	Plastics for frame/backside	27	Aluminum for housing	24	Polycarbonate for housing	20.3			Primary aluminum sheet production	24	g
			Thermoplastic polyurethane for housing	4	Metal sheets (stainless steel?)	15	Stainless steel	23	Stainless steel for housing	24.9			Primary stainless steel production	23	g
							Unspecified plastics	7					Primary polycarbonate production	7	g
							Glass for display/touchscreen	16							
Assembly	Electricity	kWh	Final assembly process per product	4.698									Electricity for final assembly	4.7	kWh
Packaging materials	Mass	g	Paperfoam for sales packaging	42			Fiber (fiberboard, paperboard, non-wood fiber) for retail box	165	Duplex-triplex cardboard	90.6			Retail box materials	170	g
			Paper for sales packaging	36.5			Plastic film	5	Paper	7.9					
			Cardboard for sales packaging	91.5					Polyethylene low density	4.2					
			Plastic and glue strip for sales packaging	1											
Transport	Kilogram-kilometers	kg*km	Transport of final products to distribution hub by airplane	2213.6									Transport scenario China-Germany	0.5	kg
			Transport of final products to distribution hub by truck	56.9											
			Transport of final phone to customer in GER	154.8											

Component: Simplified Tablet-PC
References: Ahmadi Achachlouei et al., 2015 | Teehan and Kandlikar, 2013 | Apple Inc., 2011

Category	Process flow metric	Scaling unit	Part/Assembly 1	Value 1	Alt. value 1	Part/Assembly 2	Value 2	Alt. value 2	Alt. value 2	Part/Assembly 3	Value 3	Average value	**Assimilated BOM-Process**	**Assimilated value**	**Unit**
(Rigid) Multilayer Printed Circuit Board (PCB)	Board area | mass	cm^2 | g	Display PBA (0.6mm)	16	2	Main logic board (10 layers)	55	12					Rigid PCB (10 layers) production	47	cm^2
			GSM/3G (8 layers)	13.1	6	Wireless assembly - small logic board (2 layers)	2.5	0.8					Rigid PCB (8 layers) production	13	cm^2
			Battery PBA (0.6mm)	9.9	3	Tiny power supply mainboard (2 layers)	12.5	1.5					Rigid PCB (6 layers) production	11	cm^2
			Mainboard (10 layers)	47	20								Rigid PCB (2 layers) production	1	cm^2
			WLAN/Bluetooth subboard (6 layers)	2.88	2								Rigid PCB (unspecified layers) production	26	cm^2
			Motion PBA (6 layers)	7.9	2										
			Home key button PBA (2 layers)	1.32	1										
Total PCB area / mass				98.1	36		70	14.3							
Flexible Printed Circuit Board (FPC)	Area | mass	cm^2 | g	Display backlight flex (0.5mm)	20.6	1								Flexible PCB (4 layers) production	18	cm^2
			Docking connector (4 layers)	6	0.5								Flexible PCB (3 layers) production	1	cm^2
			SIM card flex (4 layers)	12.4	0.5								Flexible PCB (2 layers) production	10	cm^2
			Side key button flex (2 layers)	4.3	0.5								Flexible PCB (unspecified layers) production	42	cm^2
			GPS antenna flex (0.2mm)	9	0.5										
			Proximity sensor flex (2 layers)	5.9	1										
			Microphone flex (3 layers)	1.2	0.5										
			Camera flex (0.3mm)	12.12	0.7										
Total FPC area				71.52	5.2										
Integrated Circuit (IC)	Package size | mass | die area	mm^2 | g | mm^2	IC components for display	63	0.35	Solid state memory, 2x 8GB	252	0.6	39				Logic IC production	214*	mm^2 (die)
			IC components for GSM/3G modem	311	1.1	A4 processor	196	0.6	120				Memory IC production	39	mm^2 (die)
			IC component for battery	9	0.05	Medium IC´s	-	0.5	9.2						
			IC components on mainboard	797	1.55	Small IC´s	-	1.6	-						
			IC components on subboard	56	0.3	Mainboard chip	-	0.1	1.8						
			IC components on motion PBA	34	0.2	IC´s and SMT components for power supply		2							
			IC component for proximity sensor	9	0.05	Other bits		1							
			IC components for camera	61	0.4										
Total IC package size / mass				1340	4		448	6.4							
Display	Screen area | mass	cm^2 | g	TFT-LCD Module	368.42		LCD module		154					TFT-LCD module production	368	cm^2
Battery	Mass	g	Li-Ion polymer cells	136		Single cell, lithium-ion battery	129			Lithium-ion polymer battery	156	140.33	Li-Ion battery production	140	g
Mechanics/Materials	Mass	g	Touchscreen/protection glass	90		LCD glass (and small plastic frame)	188			Glass for display/touchscreen	61		Primary aluminum sheet production	93	g
			Aluminum for housing	148		Aluminum (production + sheet rolling) for casing	136			Aluminum for housing	93		Primary stainless steel production	14	g
						Plastic (ABS) for battery housing	20			Unspecified plastics	11		Primary polycarbonate production	11	g
										Unspecified metals	14				
Assembly	Electricity	kWh	Final assembly process per product	1.67		Final assembly process per small product	1.11						Electricity for final assembly	1.67	kWh
Packaging materials	Mass	g	Paper (corrugate, molded fiber) for retail box	210						Fiber (corrugate, molded fiber) for retail & shipping box	340	275	Retail box materials	275	g
			Plastics for retail box	70						High-impact polystyrene	60				

			Paper for leaflets	25			Other plastics	14			
Transport	Kilogram-kilometers	kg*km	Transport of final package by boat	22444.22	Transport of final assembly by rail	200			Transport scenario China-Germany	1	kg
			Transport of final package by truck	1484.7	Transport of final assembly by lorry (> 16t)	100					
					Transport of final assembly by transoceanic ship	21300					

* Assuming a best-fit mass ratio of about 18mm2 of silicon die per gram of packaged chip (Teehan and Kandlikar, 2013)

Component: Simplified E-Reader
References: Teehan and Kandlikar, 2013

Category	Process flow metric	Scaling unit	Part/Assembly 1	Value 1	Alt. value 1	Alt. value 1	**Assimilated BOM-Process**	**Assimilated value**	**Unit**
(Rigid) Multilayer Printed Circuit Board (PCB)	Board area / mass	cm^2 / g	Mainboard (6 layers)	152.5	21		Rigid PCB (6 layers) production	152.5	cm^2
			Power supply board (2 layers)	12.5	1.5		Rigid PCB (2 layers) production	12.5	cm^2
Total PCB area / mass				165	22.5				
Flexible Printed Circuit Board (FPC)	Area / mass	cm^2							
Total FPC area									
Integrated Circuit (IC)	Package size / mass / die area	mm^2 / g / mm^2	IC´s for mainboard	848	1.6	66	Logic/memory IC production	156*	mm^2 (die)
			Tiny bits		2				
			Tiny IC´s and SMT components for power supply		2				
			Other bits		1				
Total IC package size / mass				848	6.6				
Estimated/Measured IC die area		mm^2				66			
Display	Screen area / mass	cm^2 / g	E-ink module	140	34		TFT-EPD module production	140	cm^2
Battery	Mass	g	Single cell, lithium-ion battery	51			Li-Ion battery production	51	g
Mechanics/Materials	Mass	g	Polycarbonate for casing	57			Primary polycarbonate production	74	g
			Polycarbonate for power supply casing	17			Primary aluminum sheet production	25	g
			Aluminum (production + sheet rolling) for internal backplate	25					
			Plastic (ABS) for other	16					
Assembly	Electricity	kWh	Final assembly process per small product	1.11			Electricity for final assembly	1.11	kWh
Packaging materials	Mass	g					Retail box materials	200	g
Transport	Kilogram-kilometers	kg*km	Transport of final assembly by rail	100			Transport scenario China-Germany	0.5	kg
			Transport of final assembly by lorry (> 16t)	50					
			Transport of final assembly by transoceanic ship	10650					

* Assuming a best-fit mass ratio of about 18mm2 of silicon die per gram of packaged chip (Teehan and Kandlikar, 2013)

Appendix C

Process Parameters

Due to lacking provider processes in the Ecoinvent 3.4 database or insufficient information, the following process parameters are only partly implemented in the LCA model. Resulting unit processes are disclosed in Appendix D.

System Process: TFT-LCD panel production
Data source: AU Optronics Corporation 2017
Location of Production: Longtan (Taiwan)
Reference year: 2016

Input	Unit	Total	per m^2 substrate area	Conversion	Description/Comment
Materials:					
Glass substrate	t	6.22E+04	1.07E-03		
Liquid crystal	t	8.38E+01	1.44E-06		
Photoresist	t	5.82E+03	1.00E-04		
Arrey stripper	t	3.70E+03	6.38E-05		
CF Thinner	t	1.13E+03	1.95E-05		
Developer	t	1.14E+04	1.97E-04		
Etchant	t	1.12E+04	1.94E-04		
Energy:				**t**	
Purchased electricity	GJ	1.60E+07	2.75E-01		
Natural gas	GJ	6.24E+05	1.08E-02		
LPG	GJ	1.22E+04	2.10E-04	4.04E-05	1 GJ = 1.9227094677848E10-8 Mt LNG
Diesel	GJ	9.11E+04	1.57E-03		
Self-generated solar power	GJ	4.69E+02	8.09E-06		
Grid-Tie solar power	GJ	9.84E+04	1.70E-03		
Wind power	GJ	7.70E+00	1.33E-07		
Water:				**Mt**	
Fresh water	Ml	2.69E+04	4.64E-04	4.64E-07	
Ground water	Ml	4.00E+01	6.90E-07	6.90E-10	
Rainwater	Ml	1.55E+01	2.67E-07	2.67E-10	

Output					
Scope 1 (direct emissions)	tCO2-eq.	2.61E+05	4.50E-03		includes emissions from PFCs and ODSs
Gas emissions:					
SOx	t	4.07E+01	7.02E-07		
NOx	t	6.95E+01	1.20E-06		
HF	t	2.90E+00	5.00E-08		
HCI	t	3.10E+00	5.34E-08		
VOCs	t	1.68E+02	2.89E-06		
Waste water discharge:				**l**	Destination: not specified
Waste water	Ml	2.01E+04	3.46E-04	3.46E+02	
COD	t	8.53E+02	1.47E-05		
BOD	t	1.66E+02	2.86E-06		
TSS	t	2.84E+02	4.89E-06		Total suspended solids
Waste output:					
Hazardous waste	t	3.26E+04	5.62E-04		60% recycled (as no information on recycling is given, 60% of the hazardous waste products are cut-off); 5% incinerated; 5% buried; 30% other treatment (cut-off)

Non-hazardous waste	t	7.41E+04	1.28E-03		75% recycled (as no information on recycling is given, 75% of the non-hazardous waste products are cut-off); 10% incinerated; 15% buried

Assumed annual panel output at factory gate	**m^2**	**5.80E+07**
Production output based on published energy intensity	m^2	5.68E+07
Production output based on published water intensity	m^2	5.67E+07
Production output based on published waste intensity	m^2	5.67E+07
Production output based on published GHG intensity	m^2	6.10E+07
Average		5.78E+07

System Process: TFT-EPD panel production
Data source: E Ink Holdings Inc. 2016, 2017
Location of production: Hsinchu (Taiwan); Linkou (Taiwan); Yangzhou (China)
Reference year: 2015

Input	Unit	Total	per m^2 substrate area	Conversion	Description/Comment
Materials:					
n.a.					Data on material consumption are not disclosed
				GJ/m^2	Electricity: 3,600 GJ/GWh; Steam: 2.8 GJ/t; Diesel: 0.035 GJ/l; Gasoline: 0.033 GJ/l; LPG: 0.026 GJ/l
Energy for front-end display panel (TFT) manufacturing:					Electricity and gas consumption for dormitories are not included
Purchased electricity for production	GWh	5.90E+01	1.97E-03	7.08E+00	Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels
Diesel	l	3.25E+03	1.08E-01	3.79E-03	Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels
Gasoline	l	5.78E+03	1.93E-01	6.35E-03	Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels
LPG (Liquefied Petroleum Gas)	l	5.82E+02	1.94E-02	5.04E-04	Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels
Energy for electronic ink production:					
Purchased electricity for production	GWh	2.49E+00	1.92E-04	6.90E-01	Linkou Plant (Taiwan): Production of electronic ink
Diesel	l	9.79E+01	7.53E-03	2.64E-04	Linkou Plant (Taiwan): Production of electronic ink
Energy for module assembly:					Electricity and gas consumption for dormitories are not included
Purchased electricity for production	GWh	2.41E+01	8.02E-05	2.89E-01	Yangzhou (China): Module assembly (back-end)
Purchased steam	t	1.06E+04	3.53E-02	9.87E-02	Yangzhou (China): Module assembly (back-end)
Diesel	l	1.77E+04	5.90E-02	2.06E-03	Yangzhou (China): Module assembly (back-end)
Gasoline	l	7.58E+04	2.53E-01	8.34E-03	Yangzhou (China): Module assembly (back-end)

Water:					
Tap water consumption	m^3 (t)	2.86E+05	9.53E+00		Hsinchu Plant (Taiwan): Manufacturing of front-end (TFT) display panels
Tap water consumption	m^3 (t)	1.73E+03	1.33E-01		Linkou Plant (Taiwan): Production of electronic ink
Process water consumption	m^3 (t)	2.36E+05	7.87E-01		Yangzhou (China): Module assembly (back-end)
Output					
Direct Emissions (Scope 1) at Hsinchu Plant:	**tCO2-eq.**		**2.23E-01**		
CO2	tCO2-eq.	5.57E+01	1.86E-03		
CH4	tCO2-eq.	2.81E+01	9.36E-04		
N2O	tCO2-eq.	2.06E+01	6.88E-04		
PFC (with NF3)	tCO2-eq.	1.38E+03	4.61E-02		
SF6	tCO2-eq.	5.21E+03	1.74E-01		
Direct Emissions (Scope 1) at Linkou Plant:	**tCO2-eq.**		**3.45E-04**		
CO2	tCO2-eq.	3.90E-01	3.00E-05		
CH4	tCO2-eq.	4.10E+00	3.15E-04		
Direct Emissions (Scope 1) at Yangzhou Plant:	**tCO2-eq.**		**1.44E-03**		
CO2	tCO2-eq.	2.11E+02	7.03E-04		
CH4	tCO2-eq.	2.17E+02	7.23E-04		
N2O	tCO2-eq.	2.85E+00	9.50E-06		
Waste water discharge at Hsinchu Plant:				**mg/m³**	Destination: Transport to HSP sewage treatment plant for processing
Discharge volume	m^3	2.33E+05	7.75E+00		
BOD	mg/l	6.35E+01	2.12E-03	1.64E+01	
COD	mg/l	2.73E+02	9.10E-03	7.05E+01	
SS	mg/l	3.11E+01	1.04E-03	8.03E+00	
Waste water discharge at Yangzhou Plant:					Destination: Discharge to urban sewer network
Discharge volume	m^3	1.89E+05	6.29E-01		
BOD	mg/l	-			
COD	mg/l	7.70E+01	2.57E-04	1.62E-01	
SS	mg/l	4.87E+01	1.62E-04	1.02E-01	
Waste output at Hsinchu Plant:					
General waste for incineration	t	1.66E+02	5.53E-03		
General waste for landfill	t	2.76E+01	9.21E-04		
Hazardous waste for incinera-tion	t	5.88E+01	1.96E-03		
Hazardous waste for recycling	t	2.20E+02	7.34E-03		cut-off
Hazardous waste for other treatment	t	4.98E+00	1.66E-04		cut-off
Waste output at Linkou Plant:					
General waste for incineration	t	3.37E+01	2.59E-03		
General waste for recycling	t	7.46E+00	5.74E-04		cut-off
Hazardous waste for incinera-tion	t	1.34E+01	1.03E-03		
Waste output at Yangzhou Plant:					
General waste for recycling	t	1.04E+02	3.45E-04		cut-off
Hazardous waste for other treatment	t	1.00E-02	3.33E-08		cut-off

Assumed annual panel output at factory gate	**3.00E+04**	**1.30E+04**	**3.00E+05**
Estimates for panel production output in 2015:			
	Hsinchu	**Linkou**	**Yangzhou**
tco2/m2	1.40E+00	1.00E-01	1.20E-01
Scope 1	6.69E+03	4.49E+00	4.31E+02
Scope 2	3.12E+04	1.32E+03	2.66E+04
Total	3.79E+04	1.32E+03	2.70E+04
m2 (Total)	**2.70E+04**	**1.32E+04**	**2.25E+05**
t (tap water)/m2	9.33E+00	1.30E-01	7.20E-01
t (tap/process water consumption)	2.86E+05	1.73E+03	2.36E+05
m2	**3.07E+04**	**1.33E+04**	**3.28E+05**
GJ/m2	6.92E+06	6.93E+05	3.56E+05
GJ electricity	2.12E+05	8.98E+03	9.40E+04
GJ steam			2.97E+04
m2	3.07E-02	1.29E-02	3.48E-01
m2 (factor 10^6)	**3.07E+04**	**1.29E+04**	**3.48E+05**
Average	**2.95E+04**	**1.32E+04**	**3.00E+05**

Appendix D

Input/Output-Sheets

System Process:
TFT-EPD panel production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4)
electricity, medium voltage	6.90E-01	GJ	market for electricity, medium voltage | electricity, medium voltage | APOS, S - TW
electricity, medium voltage	2.89E-01	GJ	market group for electricity, medium voltage | electricity, medium voltage | APOS, S - CN
electricity, medium voltage	7.08E+00	GJ	market for electricity, medium voltage | electricity, medium voltage | APOS, S - TW
hazardous waste, for incineration	-1.03E-03	t	market for hazardous waste, for incineration | hazardous waste, for incineration | APOS, S - RoW
hazardous waste, for incineration	-1.96E-03	t	market for hazardous waste, for incineration | hazardous waste, for incineration | APOS, S - RoW
heat, from steam, in chemical industry	9.87E-02	GJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | APOS, S - RoW
municipal solid waste	-5.53E-03	t	treatment of municipal solid waste, incineration | municipal solid waste | APOS, S - TW
municipal solid waste	-9.20E-04	t	treatment of municipal solid waste, sanitary landfill | municipal solid waste | APOS, S - RoW
municipal solid waste	-2.59E-03	t	treatment of municipal solid waste, incineration | municipal solid waste | APOS, S - TW
tap water	9.53E+00	t	market for tap water | tap water | APOS, S - RoW
tap water	7.87E-01	t	market for tap water | tap water | APOS, S - RoW
tap water	1.33E-01	t	market for tap water | tap water | APOS, S - RoW

Output flows	Amount	Unit	Category
TFT-EPD Module Production	**1.00E+00**	**m2**	**-**
Carbon dioxide	3.40E-04	t	Emission to air/unspecified
Carbon dioxide	1.44E-03	t	Emission to air/unspecified
Carbon dioxide	2.23E-01	t	Emission to air/unspecified
BOD5, Biological Oxygen Demand	1.64E+01	mg	Emission to water/unspecified
COD, Chemical Oxygen Demand	7.05E+01	mg	Emission to water/unspecified
COD, Chemical Oxygen Demand	1.62E-01	mg	Emission to water/unspecified
Suspended solids, unspecified	1.02E-01	mg	Emission to water/unspecified
Suspended solids, unspecified	8.03E+00	mg	Emission to water/unspecified
Water, CN	6.29E-01	m3	Emission to water/unspecified
Water, TW	7.75E+00	m3	Emission to water/unspecified

System Process:
TFT-LCD panel production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4)
electricity, medium voltage	2.75E-01	GJ	market for electricity, medium voltage | electricity, medium voltage | APOS, S - TW
glass, for liquid crystal display	1.07E-03	t	market for glass, for liquid crystal display | glass, for liquid crystal display | APOS, S - GLO
hazardous waste, for incineration	-2.81E-05	t	market for hazardous waste, for incineration | hazardous waste, for incineration | APOS, S - RoW
hazardous waste, for underground deposit	-2.81E-05	t	market for hazardous waste, for underground deposit | hazardous waste, for underground deposit | APOS, S - GLO
heat, district or industrial, natural gas	1.08E-02	GJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, S - RoW
municipal solid waste	-1.28E-04	t	treatment of municipal solid waste, incineration | municipal solid waste | APOS, S - TW
municipal solid waste	-1.92E-04	t	treatment of municipal solid waste, sanitary landfill | municipal solid waste | APOS, S - RoW

polarizer, liquid crystals and colour filters, for liquid crystal display	1.44E-06	t	market for polarizer, liquid crystals and colour filters, for liquid crystal display | polarizer, liquid crystals and colour filters, for liquid crystal display | APOS, S - GLO
tap water	4.64E-07	Mt	market for tap water | tap water | APOS, S - RoW
Water, rain	2.70E-04	m3	-
Water, well, in ground, TW	6.90E-04	m3	-

Output flows	Amount	Unit	Category
TFT-LCD Module Production	**1.00E+00**	**m2**	**-**
Carbon dioxide	4.50E-03	t	Emission to air/unspecified
Hydrogen chloride	5.34E-08	t	Emission to air/unspecified
Hydrogen fluoride	5.00E-08	t	Emission to air/unspecified
Nitrogen oxides	1.20E-06	t	Emission to air/unspecified
Sulfur oxides	7.02E-07	t	Emission to air/unspecified
VOC, volatile organic compounds	2.89E-06	t	Emission to air/unspecified
BOD5, Biological Oxygen Demand	2.86E-06	t	Emission to water/unspecified
COD, Chemical Oxygen Demand	1.47E-05	t	Emission to water/unspecified
Suspended solids, unspecified	4.89E-06	t	Emission to water/unspecified
Water, TW	3.46E-01	m3	Emission to water/unspecified

System Process:
CPU back-end production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4, except **bold** provider processes which are shown in detail below)
copper	2.30E-03	kg	market for copper | copper | APOS, S - GLO
electricity, medium voltage	2.88E+03	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, S - CN
epoxy resin insulator, SiO2	1.84E-08	kg	market for epoxy resin insulator, SiO2 | epoxy resin insulator, SiO2 | APOS, S - GLO
Good die out	1.00E+00	m2	**transported CPU chip**
metal working, average for copper product manufacturing	2.30E-03	kg	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | APOS, S - GLO
metal working, average for metal product manufacturing	4.51E-01	kg	market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | APOS, S - GLO
potassium carbonate	7.07E-06	kg	market for potassium carbonate | potassium carbonate | APOS, S - GLO
silver	1.81E-02	kg	market for silver | silver | APOS, S - GLO
tin	4.33E-01	kg	market for tin | tin | APOS, S - GLO
water, ultrapure	9.00E+03	kg	market for water, ultrapure | water, ultrapure | APOS, S - GLO

Output flows	Amount	Unit	Category
CPU	**1.00E+00**	**m2**	**-**

System Process:
Transported CPU chip

Input flows	Amount	Unit	Provider (Ecoinvent 3.4, except **bold** provider processes which are shown in detail below)
Good die out	9.40E-01	cm2	**CPU front-end production (good die out)**
transport, freight, aircraft	0.2/1000000 *6250	t*km	market for transport, freight, aircraft | transport, freight, aircraft | APOS, S - GLO

Output flows	Amount	Unit	Category
transported CPU chip	**9.40E-01**	**cm2**	

System Process:
CPU front-end production
(good die out)

Input flows	Amount	Unit	Provider (Ecoinvent 3.4, except **bold** provider processes which are shown in detail below)
1,1-difluoroethane, HFC-152a	2.95E-02	kg	market for 1,1-difluoroethane, HFC-152a | 1,1-difluoroethane, HFC-152a | APOS, S - GLO
1-propanol	2.49E+01	kg	market for 1-propanol | 1-propanol | APOS, S - GLO
acetone, liquid	1.39E+00	kg	market for acetone, liquid | acetone, liquid | APOS, S - GLO
ammonia, liquid	1.19E+02	kg	market for ammonia, liquid | ammonia, liquid | APOS, S - RoW
argon, liquid	4.51E+01	kg	market for argon, liquid | argon, liquid | APOS, S - GLO
butyl acetate	2.94E+00	kg	market for butyl acetate | butyl acetate | APOS, S - GLO
carbon monoxide	3.68E-03	kg	market for carbon monoxide | carbon monoxide | APOS, S - RoW
chemical, organic	2.00E+01	kg	market for chemical, organic | chemical, organic | APOS, S - GLO
copper sulfate	5.73E+01	kg	market for copper sulfate | copper sulfate | APOS, S - GLO
diethanolamine	5.45E+00	kg	market for diethanolamine | diethanolamine | APOS, S - GLO
EDTA, ethylenediaminetet-raacetic acid	2.88E+00	kg	market for EDTA, ethylenediaminetetraacetic acid | EDTA, ethylenedia-minetetraacetic acid | APOS, S - GLO
electricity, medium voltage	3.02E+04	kWh	market group for electricity, medium voltage | electricity, medium volt-age | APOS, S - US
electricity, medium voltage	4.55E+01	kWh	natural gas, burned in gas turbine, for compressor station | electricity, medium voltage | APOS, S - RoW
hexamethyldisilazane	2.28E-01	kg	market for hexamethyldisilazane | hexamethyldisilazane | APOS, S - GLO
hydrochloric acid, without wa-ter, in 30% solution state	1.22E+02	kg	market for hydrochloric acid, without water, in 30% solution state | hy-drochloric acid, without water, in 30% solution state | APOS, S - RoW
hydrogen fluoride	8.82E+01	kg	market for hydrogen fluoride | hydrogen fluoride | APOS, S - GLO
hydrogen peroxide, without wa-ter, in 50% solution state	5.26E+01	kg	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | APOS, S - GLO
hydrogen, liquid	1.98E+00	kg	market for hydrogen, liquid | hydrogen, liquid | APOS, S - RoW
isopropanol	3.07E+01	kg	market for isopropanol | isopropanol | APOS, S - GLO
natural gas, from medium pres-sure network (0.1-1 bar), at ser-vice station	0.00E+00	kg	market for natural gas, from medium pressure network (0.1-1 bar), at service station | natural gas, from medium pressure network (0.1-1 bar), at service station | APOS, S - GLO
NF3	1.61E-01	kg	**NF3 production**
nitric acid, without water, in 50% solution state	5.04E+00	kg	market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | APOS, S - GLO
nitrogen, liquid	5.36E+03	kg	market for nitrogen, liquid | nitrogen, liquid | APOS, S - RoW
nitrous oxide	3.65E-01	kg	market for nitrous oxide | nitrous oxide | APOS, S - GLO
oxygen, liquid	2.28E+02	kg	market for oxygen, liquid | oxygen, liquid | APOS, S - RoW
perfluoropentane	7.11E-01	kg	market for perfluoropentane | perfluoropentane | APOS, S - GLO
phosphoric acid, industrial grade, without water, in 85% solution state	6.84E+00	kg	market for phosphoric acid, industrial grade, without water, in 85% so-lution state | phosphoric acid, industrial grade, without water, in 85% solution state | APOS, S - GLO
potassium hydroxide	1.16E+02	kg	market for potassium hydroxide | potassium hydroxide | APOS, S - GLO
silica sand	9.45E+00	kg	market for silica sand | silica sand | APOS, S - GLO
silicon tetrachloride	2.52E-03	kg	market for silicon tetrachloride | silicon tetrachloride | APOS, S - GLO
Si-wafer	1.38E+00	m2	**wafer production - GLO**
sodium hydroxide, without wa-ter, in 50% solution state	7.44E-01	kg	market for sodium hydroxide, without water, in 50% solution state | so-dium hydroxide, without water, in 50% solution state | APOS, S - GLO
sulfur hexafluoride, liquid	7.25E-01	kg	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | APOS, S - GLO
sulfuric acid	7.31E+01	kg	market for sulfuric acid | sulfuric acid | APOS, S - GLO
tetrafluoroethane	2.68E-01	kg	market for tetrafluoroethane | tetrafluoroethane | APOS, S - GLO
trifluoromethane	6.90E-03	kg	market for trifluoromethane | trifluoromethane | APOS, S - GLO
water, ultrapure	1.60E+05	kg	market for water, ultrapure | water, ultrapure | APOS, S - GLO

Output flows	Amount	Unit	Category
Good die out	**1.00E+00**	**m2**	**-**
1,4-Butanediol	2.70E-03	kg	Emission to air/high population density
2-Propanol	3.36E-01	kg	Emission to air/high population density

Acetone	1.39E-01	kg	Emission to air/high population density
Aluminium	2.42E-06	kg	Emission to air/high population density
Ammonia	5.48E-02	kg	Emission to air/high population density
Arsenic	3.71E-05	kg	Emission to air/high population density
Arsine	3.14E-05	kg	Emission to air/high population density
beta-butyrolactone	4.40E-04	kg	Emission to air/high population density
Boron	3.71E-5+0.000000673	kg	Emission to air/high population density
Bromine	7.82E-05	kg	Emission to air/high population density
Butane, perfluorocyclo-, PFC-318	8.70E-04	kg	Emission to air/high population density
Butyl acetate	1.11E-02	kg	Emission to air/high population density
Carbon dioxide, fossil	3.12E+01	kg	Emission to air/high population density
Carbon monoxide, fossil	5.69E-03	kg	Emission to air/high population density
Chlorine	2.00E-04	kg	Emission to air/high population density
Chlorosilane, trimethyl-	2.98E-03	kg	Emission to air/high population density
Diborane	3.22E-07	kg	Emission to air/high population density
Diethyl ether	1.84E-03	kg	Emission to air/high population density
Dimethyl ether	7.71E-05	kg	Emission to air/high population density
Dinitrogen monoxide	2.68E-01	kg	Emission to air/high population density
Ethane, hexafluoro-, HFC-116	1.06E-02	kg	Emission to air/high population density
Fluorine	1.02E-03	kg	Emission to air/high population density
Helium	2.26E-01	kg	Emission to air/high population density
Hexamethyldisilizane	2.69E-05	kg	Emission to air/high population density
HFE-329mcc2	3.96E-03	kg	Emission to air/high population density
Hydrogen	4.19E-01	kg	Emission to air/high population density
Hydrogen chloride	6.75E-03	kg	Emission to air/high population density
Hydrogen fluoride	9.86E-03	kg	Emission to air/high population density
Hydrogen fluoride	2.20E-04	kg	Emission to air/high population density
Methane, bromo-, Halon 1001	1.70E-04	kg	Emission to air/high population density
Methane, difluoro-, HFC-32	5.13E-05	kg	Emission to air/high population density
Methane, fluoro-, HFC-41	3.35E-05	kg	Emission to air/high population density
Methane, fossil	2.09E+00	kg	Emission to air/high population density
Methane, monochloro-, R-40	5.40E-04	kg	Emission to air/high population density
Methane, tetrafluoro-, R-14	2.61E-02	kg	Emission to air/high population density
Methane, trifluoro-, HFC-23	6.90E-05	kg	Emission to air/high population density
Methyl lactate	4.37E-01	kg	Emission to air/high population density
Monoethanolamine	2.05E-02	kg	Emission to air/high population density
Nitric acid	5.21E-03	kg	Emission to air/high population density
Nitrogen	7.14E+05	kg	Emission to air/high population density
Nitrogen dioxide	1.96E-01	kg	Emission to air/high population density
Nitrogen fluoride	5.10E-04	kg	Emission to air/high population density
Nitrogen monoxide	3.34E-05	kg	Emission to air/high population density
Phosphine	1.56E-02	kg	Emission to air/high population density
Phosphorus	3.90E-04	kg	Emission to air/high population density
Propylene glycol methyl ether	2.00E-02	kg	Emission to air/high population density
Sulfur dioxide	8.40E-04	kg	Emission to air/high population density
Sulfur hexafluoride	2.85E-02	kg	Emission to air/high population density
Sulfuric acid	4.61E-02	kg	Emission to air/high population density
Tetramethyl ammonium hydroxide	7.26E-03	kg	Emission to air/high population density
Water	2.33E+04	kg	Emission to air/high population density
Hexachlorocyclopentadiene	3.48E-03	kg	Emission to air/low population density
Ammonium chloride	1.97E-05	kg	Emission to air/unspecified
Argon	4.51E+01	kg	Emission to air/unspecified
Arsenic trioxide	1.14E-07	kg	Emission to air/unspecified
Hydrogen bromide	2.10E-04	kg	Emission to air/unspecified
Oxygen, in air	2.01E+05	kg	Emission to air/unspecified

Phosphorus pentoxide	5.77E-05	kg	Emission to air/unspecified
Arsenic trioxide	3.05E-03	kg	Emission to soil/agricultural
Ammonia	1.76E-07	kg	Emission to soil/industrial
Ammonium, ion	9.79E-01	kg	Emission to soil/industrial
Arsenic	1.60E-04	kg	Emission to soil/industrial
Boron	2.10E-04	kg	Emission to soil/industrial
Bromide	1.03E-05	kg	Emission to soil/industrial
Bromine	1.72E-07	kg	Emission to soil/industrial
Calcium hydroxide	1.46E-05	kg	Emission to soil/industrial
Calcium, ion	8.80E-04	kg	Emission to soil/industrial
Carbon	4.21E-05	kg	Emission to soil/industrial
Carbon dioxide, to soil or bio-mass stock	9.20E-04	kg	Emission to soil/industrial
Chloride	9.34E-03	kg	Emission to soil/industrial
Chlorine	7.02E-08	kg	Emission to soil/industrial
Copper	1.20E-04	kg	Emission to soil/industrial
Copper compounds	2.69E+01	kg	Emission to soil/industrial
Copper, ions, unspecified	2.16E+01	kg	Emission to soil/industrial
Ethanol	1.47E-06	kg	Emission to soil/industrial
ethylenediaminetetraacetic acid	1.45E-07	kg	Emission to soil/industrial
Fluoride	1.03E+00	kg	Emission to soil/industrial
Hydrogen fluoride	1.63E+01	kg	Emission to soil/industrial
Iron	5.71E-06	kg	Emission to soil/industrial
Magnesium	1.14E-03	kg	Emission to soil/industrial
Methanol	6.90E-08	kg	Emission to soil/industrial
Nitrate	4.86E-05	kg	Emission to soil/industrial
Nitric acid	2.57E-02	kg	Emission to soil/industrial
Phosphate	1.50E-04	kg	Emission to soil/industrial
Phosphoric acid	3.22E-07	kg	Emission to soil/industrial
Phosphorus	6.08E-03	kg	Emission to soil/industrial
Phosphorus pentoxide	2.33E-02	kg	Emission to soil/industrial
Potassium	1.72E-02	kg	Emission to soil/industrial
Propylene glycol methyl ether	2.40E+00	kg	Emission to soil/industrial
Silicon	7.42E-03	kg	Emission to soil/industrial
Sodium	1.22E-03	kg	Emission to soil/industrial
Sulfate	3.26E+01	kg	Emission to soil/industrial
Sulfuric acid	4.22E+01	kg	Emission to soil/industrial
Tungsten	2.29E-01	kg	Emission to soil/industrial
Ammonium chloride	4.15E-02	kg	Emission to soil/unspecified
ETHYL LACTATE	1.34E+01	kg	Emission to soil/unspecified
2-Propanol	1.54E-01	kg	Emission to water/unspecified
Acetone	6.93E-02	kg	Emission to water/unspecified
Ammonium, ion	5.23E+00	kg	Emission to water/unspecified
Arsenic	1.36E-03	kg	Emission to water/unspecified
Arsenic trioxide	2.35E-05	kg	Emission to water/unspecified
Borate	1.48E-02	kg	Emission to water/unspecified
Bromine	1.00E+00	kg	Emission to water/unspecified
Calcium, ion	5.76E+00	kg	Emission to water/unspecified
Carbonate	1.25E+02	kg	Emission to water/unspecified
Chlorides, unspecified	4.65E+01	kg	Emission to water/unspecified
Copper	2.83E-02	kg	Emission to water/unspecified
Copper, ion	1.25E+00	kg	Emission to water/unspecified
Ethanol	7.16E-03	kg	Emission to water/unspecified
ethylenediaminetetraacetic acid	2.84E+00	kg	Emission to water/unspecified
Fluoride	3.91E-01	kg	Emission to water/unspecified
Hypochlorite	6.39E+00	kg	Emission to water/unspecified
Iron, ion	6.18E-01	kg	Emission to water/unspecified
Magnesium, ion	6.39E+00	kg	Emission to water/unspecified

Methanol	3.40E-04	kg	Emission to water/unspecified
Nitrate	6.39E+00	kg	Emission to water/unspecified
Nitrogen dioxide	2.67E-06	kg	Emission to water/unspecified
Organochlorine, unspecified	1.24E-08	kg	Emission to water/unspecified
Phosphate	6.38E+00	kg	Emission to water/unspecified
Potassium, ion	8.39E+01	kg	Emission to water/unspecified
Silicate particles	1.90E+00	kg	Emission to water/unspecified
Silicon dioxide (silica)	1.41E-01	kg	Emission to water/unspecified
Sodium hydroxide	5.10E-04	kg	Emission to water/unspecified
Sodium, ion	6.77E+00	kg	Emission to water/unspecified
Sulfate	6.27E+01	kg	Emission to water/unspecified
Tungsten	4.03E-02	kg	Emission to water/unspecified
Water	1.37E+05	dm3	Emission to water/unspecified
sulfur trioxide	3.35E-01	kg	Emissions to water/Emissions to fresh water

System Process:
NF3 production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4)
ammonia, liquid	1.14E+02	kg	market for ammonia, liquid | ammonia, liquid | APOS, S - RoW
fluorine, liquid	1.70E+01	kg	market for fluorine, liquid | fluorine, liquid | APOS, S - RoW

Output flows	Amount	Unit	Category
NF3	**6.39E+01**	**kg**	**-**

System Process:
Wafer production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4, except **bold** provider processes which are shown in detail below)
graphite	1.60E-04	kg	market for graphite | graphite | APOS, S - GLO
hydrochloric acid, without water, in 30% solution state	6.75E-03	kg	market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | APOS, S - RoW
petroleum coke	6.00E-04	kg	market for petroleum coke | petroleum coke | APOS, S - GLO
sawnwood, hardwood, raw, dried (u=10%)	1.99E-06	m3	market for sawnwood, hardwood, raw, dried (u=10%) | sawnwood, hardwood, raw, dried (u=10%) | APOS, S - RoW
silica sand	4.87E-03	kg	market for silica sand | silica sand | APOS, S - GLO
electricity mix wafer production	3.85E-01	kWh	**electricty mix wafer production**
wood pellet, measured as dry mass	1.83E-03	kg	market for wood pellet | wood pellet, measured as dry mass | APOS, S - RoW

Output flows	Amount	Unit	Category
Si-wafer	**1.00E+00**	**cm2**	**-**
Carbon dioxide, fossil	8.33E-03	kg	Emission to air/high population density
Carbon monoxide, fossil	1.70E-04	kg	Emission to air/high population density
Ethane	2.90E-05	kg	Emission to air/high population density
Hydrogen	1.30E-04	kg	Emission to air/high population density
Methane	6.88E-05	kg	Emission to air/high population density
Methanol	8.51E-05	kg	Emission to air/high population density
Nitrogen oxides	1.38E-05	kg	Emission to air/high population density
Particulates, > 2.5 um, and < 10um	2.00E-04	kg	Emission to air/high population density
Sulfur dioxide	3.44E-05	kg	Emission to air/high population density
Water	1.88E-03	kg	Emission to air/high population density
Silicon dioxide	1.63E-05	kg	Emission to water/surface water
Chlorides, unspecified	7.90E-04	kg	Emission to water/unspecified

System Process:
electricity mix wafer production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4)
electricity, medium voltage	1.25E-01	kWh	market for electricity, medium voltage | electricity, medium voltage | APOS, S - DE
electricity, medium voltage	6.60E-01	kWh	market for electricity, medium voltage | electricity, medium voltage | APOS, S - JP
electricity, medium voltage	8.50E-02	kWh	market for electricity, medium voltage | electricity, medium voltage | APOS, S - KR
electricity, medium voltage	8.50E-02	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, S - US
electricity, medium voltage	4.00E-02	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, S - RAS

Output flows	Amount	Unit	Category
electricty mix wafer production	**1.00E+00**	**kWh**	**-**

System Process:
PCB (surface mounted) production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4, except **bold** provider processes which are shown in detail below)
capacitor, for surface-mounting	3.26E-02	kg	market for capacitor, for surface-mounting | capacitor, for surface-mounting | APOS, U - GLO
diode, glass-, for surface-mounting	4.08E-03	kg	market for diode, glass-, for surface-mounting | diode, glass-, for surface-mounting | APOS, U - GLO
electric connector, peripheral component interconnect buss	1.94E-02	kg	market for electric connector, peripheral component interconnect buss | electric connector, peripheral component interconnect buss | APOS, U - GLO
light emitting diode	1.02E-03	kg	market for light emitting diode | light emitting diode | APOS, U - GLO
mounting, surface mount technology, Pb-free solder	2.32E-01	m2	market for mounting, surface mount technology, Pb-free solder | mounting, surface mount technology, Pb-free solder | APOS, U - GLO
PCB (unmounted) - GLO	2.32E-01	m2	**PCB (unmounted) production**
resistor, surface-mounted	2.35E-02	kg	market for resistor, surface-mounted | resistor, surface-mounted | APOS, U - GLO
transistor, surface-mounted	1.02E-02	kg	market for transistor, surface-mounted | transistor, surface-mounted | APOS, U - GLO
used printed wiring boards	-2.04E-02	kg	market for used printed wiring boards | used printed wiring boards | APOS, U - GLO

Output flows	Amount	Unit	Category
PCB (surface mounted)	**2.32E-01**	**m2**	**-**

System Process:
PCB (unmounted) production

Input flows	Amount	Unit	Provider (Ecoinvent 3.4)
aluminium oxide	1.60E-03	kg	market for aluminium oxide | aluminium oxide | APOS, S - GLO
aluminium, primary, ingot	2.17E-01	kg	market for aluminium, primary, ingot | aluminium, primary, ingot | APOS, S - RoW
cellulose fibre, inclusive blowing in	5.64E-01	kg	market for cellulose fibre, inclusive blowing in | cellulose fibre, inclusive blowing in | APOS, S - GLO
chemical, inorganic	4.44E+00	kg	market for chemicals, inorganic | chemical, inorganic | APOS, S - GLO
chemical, organic	2.15E-01	kg	market for chemical, organic | chemical, organic | APOS, S - GLO
copper	1.36E+00	kg	market for copper | copper | APOS, S - GLO
dipropylene glycol monomethyl ether	1.82E-02	kg	market for dipropylene glycol monomethyl ether | dipropylene glycol monomethyl ether | APOS, S - GLO

electricity, medium voltage	3.38E+02	kWh	market group for electricity, medium voltage | electricity, medium voltage | APOS, S - GLO
ferrite	1.00E-01	kg	market for ferrite | ferrite | APOS, S - GLO
glass fibre	3.12E-01	kg	market for glass fibre | glass fibre | APOS, S - GLO
glass fibre reinforced plastic, polyester resin, hand lay-up	4.03E+00	kg	market for glass fibre reinforced plastic, polyester resin, hand lay-up | glass fibre reinforced plastic, polyester resin, hand lay-up | APOS, S - GLO
gold	2.00E-04	kg	market for gold | gold | APOS, S - GLO
heat, district or industrial, natural gas	2.07E+02	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, S - GLO
iron (III) chloride, without water, in 40% solution state	9.82E-01	kg	market for iron (III) chloride, without water, in 40% solution state | iron (III) chloride, without water, in 40% solution state | APOS, S - GLO
metal working, average for aluminium product manufacturing	2.17E-01	kg	market for metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | APOS, S - GLO
metal working, average for copper product manufacturing	1.36E+00	kg	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | APOS, S - GLO
nickel sulfate	1.20E-01	kg	market for nickel sulfate | nickel sulfate | APOS, S - GLO
polyester resin, unsaturated	1.66E+00	kg	market for polyester resin, unsaturated | polyester resin, unsaturated | APOS, S - GLO
sheet rolling, aluminium	2.17E-01	kg	market for sheet rolling, aluminium | sheet rolling, aluminium | APOS, S - GLO
sheet rolling, copper	1.36E+00	kg	market for sheet rolling, copper | sheet rolling, copper | APOS, S - GLO
sodium chloride, powder	7.58E-01	kg	market for sodium chloride, powder | sodium chloride, powder | APOS, S - GLO
sodium hydroxide, without water, in 50% solution state	2.08E-01	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, S - GLO
water, ultrapure	3.35E+03	kg	market for water, ultrapure | water, ultrapure | APOS, S - GLO

Output flows	Amount	Unit	Category
PCB (unmounted)	**1.00E+00**	**m2**	**-**

Appendix E

Literature values for print media products

Product	System Boundary	Geographical scope	Reference amount	Reference/study year	GWP [kg CO2-equ.]	Reference
Newspaper	Cradle-to-grave, without content production	Finland	200g	2013	0.15	Hohenthal et al. 2013
Newspaper (71% recycled paper content)	Cradle-to-grave, without content production and excluding system expansion (alternative utilization of wood)	Germany	n.a.	2007	0.21	Grießhammer et al. 2010
Newspaper (48 pg., 60% recycled paper content)	Cradle-to-grave (no editorial work considered)	Finland	200g	2010	0.18*	Pihkola et al. 2010
Median value of newspapers					0.18	
Book (hardcover, 360 pg.)	Cradle-to-grave; purchase via internet bookstore (including minor impacts due to editorial work)	Sweden	600g	2009	1.1	Borggren et al. 2011
Book (hardcover, 320 pg.)	Cradle-to-grave (no editorial work considered)	US	750g	2012	2.46	Wells et al. 2012
Book (hardcover, 300 pg.)	Cradle-to-grave (no editorial work considered)	Finland	500g	2010	1.2	Pihkola et al. 2010
Median value of books					1.2	
Magazine (weekly magazine, 86 pg.)	Cradle-to-grave (no editorial work considered)	Finland	250g	2010	0.33*	Pihkola et al. 2010
Magazine (weekly magazine, 56 pg.)	Cradle-to-grave (no editorial work considered)	Finland	170g	2010	0.22*	Pihkola et al. 2010
Magazine (National Geographic)	Cradle-to-grave; purchase via internet bookstore (no editorial work considered)	US	349g	2007/2008	0.81	Boguski 2010
Magazine (184 pg.)	Cradle-to-grave; purchase via internet bookstore (including minor impacts due to editorial work)	Sweden	499g	2010	0.66	Achachlouei and Moberg 2015
Median value of magazines					0.49	

* according to "LF low scenario" (Pihkola et al. 2010)

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