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Environmental Impacts of ICT:

Present and Future

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Abstract

Information and communication technology (ICT) is developing rapidly and is playing an increasingly important role in society. In the context of sustainability problems that society is facing today, rather high expectations are being placed on ICT in relation to sustainable development. Some studies claim that ICT could play a crucial role in supporting various sustainability strategies and may enable transition to a less material-intensive economy. In order to provide basis for decision-making and ensure that ICT is used in the best possible way for enabling sustainable development, the sustainability impacts of ICT need to be studied. Regarding environmental effects both negative and positive, direct and indirect impacts need to be considered. It is important to understand the life cycle environmental impacts of individual ICT solutions and to study ICT in a context of a whole society, identifying the potential risks and opportunities for environmental consequences. Moreover, the potential role of ICT in supporting those opportunities for improvements and counteracting the potential risks needs to be explored.

This thesis aims to provide new knowledge on the environmental impacts related to ICT, to explore the potential of ICT to contribute to environmental sustainability, and discuss ways of assessing environmental impacts of ICT and challenges related to such assessments. In order to fulfill the aim a literature review of existing Life cycle assessment (LCA) studies done on ICT was carried out, an LCA case study of traditional and online media products was performed, a methodological framework for sustainability assessment of scenarios was developed and then applied for environmental assessment of future ICT societies.

The results show that impacts other than climate change potential and energy use are not well studied in the ICT sector, creating a risk for sub-optimization and problem shifting. Manufacturing and use phase were concluded to be the life cycle stages contributing the most to the environmental impacts of ICT products. Studying online newspapers showed that online distribution and content production may give significant contribution to the overall impact of this product, depending on newspapers' characteristics and user behavior. In general, user behavior was observed to be crucial for the results of comparisons of ICT solutions with their traditional counterparts.

A number of key issues were concluded to influence the environmental risks and opportunities in future ICT societies. These are energy mix, economic conditions, life styles, technology, and environmental ambitions, incentives and regulation. It was shown that the potential of ICT for sustainability is affected by these key issues.

It was observed that both types of assessments – on product and on societal levels – are important to support decision-making. For the assessment of future scenarios (societal level) a new methodology was developed – Sustainability assessment framework for scenarios (SAFS). For product level an existing method – Life cycle assessment (LCA) - was used. The application of both methods, their benefits and drawbacks, and challenges of assessment were discussed.

The results of this thesis can provide improved grounds for discussions in the ICT community and among policy- and decision-makers concerning the environmental impacts of ICT today and in future. By this, discussions on how ICT can contribute to environmental sustainability can be facilitated. The methodological development and discussion in this thesis can be of interest for researchers and practitioners.

Keywords: Information and communication technology (ICT), Life cycle assessment (LCA), environmental impacts, online media, future scenarios, assessment methodology.

Sammanfattning

Utveckligen inom informations- och kommunikationsteknologi (IKT) sker snabbt och IKT spelar en allt viktigare roll i samhället. Samtidigt finns stora samhällsutmaningar inom hållbarhetsområdet, och ganska höga förväntningar ställs på IKT att kunna bidra till en hållbar utveckling. Vissa studier hävdar att IKT kan spela en avgörande roll för att stödja olika hållbarhetsstrategier och att IKT kan möjliggöra övergången till en mindre resursintensiv ekonomi. För att ge underlag för beslutsfattande och stödja att IKT används på bästa sätt för att möjliggöra hållbar utveckling, behöver hållbarhetseffekter av IKT studeras. När det gäller miljöpåverkan måste både negativa och positiva, direkta och indirekta effekter beaktas. Det är viktigt att förstå miljöpåverkan genom hela livscykeln för specifika enskilda IKT-lösningar men också att studera IKTs sammanvägda effekter i en mer övergripande kontext, för att identifiera potentiella risker och möjligheter ur miljösynpunkt. Dessutom behöver IKTs roll när det gäller att stödja möjligheter till miljöförbättringar och motverka risker identifieras.

Denna avhandling syftar till att ge ny kunskap om IKTs miljöpåverkan, att undersöka IKTs potential för att bidra till en hållbar utveckling, och diskutera metoder för bedömning av miljökonsekvenser av IKT samt utmaningar relaterade till den typen av bedömningar. Avhandlingen omfattar en litteraturstudie av tidigare livscykelanalyser (LCA) av IKT, en LCA-studie av traditionella och online tidningar, utveckling av ett ramverk för hållbarhetsbedömning av scenarier samt användningen av det ramverket för en miljöbedömning av framtida IKT-samhällen.

Resultaten visar att andra typer av miljöpåverkan än klimatpåverkan och energi inte är tillräckligt belysta i miljöbedömningar av IKT, vilket skapar en risk för suboptimering och att miljöproblem flyttas från en typ av påverkan till en annan. Tillverknings- och användningsfasen ger upphov till störst miljöpåverkan i IKT-produkters livscykel. För nättidningar visade det sig att distribution och innehållsproduktion kan ge betydande bidrag till den totala miljöpåverkan, beroende på tidningarnas egenskaper och läsarnas beteende. Generellt har användarnas beteenden visat sig vara avgörande för resultaten vid jämförelser mellan IKT-lösningar och deras mer traditionella motsvarigheter.

Ett antal nyckelområden som påverkar uppkomsten av risker och möjligheter när det gäller miljöeffekter i framtida IKT-samhällen har identifierats. De är energimix, ekonomiska förhållanden, livsstilar, teknik, samt miljöambitioner, -incitament och -lagstiftning. Potentialen för IKT att bidra till hållbar utveckling påverkas av dessa nyckelområden, och potentialen skulle troligen inte realiseras helt utan incitament eller miljölagstiftning.

Båda typerna av miljöbedömningar - på produkt och samhällsnivå - är viktiga för att stödja beslutsfattande. En ny metod utvecklades för bedömning av framtidsscenarier (på samhällsnivå) – Sustainability assessment framework for scenarios (SAFS). För miljöbedömning av produkter användes livscykelanalys (LCA). Tillämpningen av båda metoderna, deras fördelar och nackdelar, och utmaningar vid användning av metoderna diskuteras.

Resultat från avhandlingen kan ge underlag rörande möjliga miljöeffekter av IKT idag och i framtiden för diskussion inom IKT-sektorn och bland politiker och beslutsfattare. På så sätt kan diskussioner om hur IKT kan bidra till hållbarhet underlättas. Metodutveckling och diskussion i denna avhandling kan vara av intresse för forskare och praktiker.

Nyckelord: Informations- och kommunikationsteknologi (IKT), livscykelanalys (LCA), miljökonsekvenser, online media, framtidsscenarier, bedömningsmetod.

Preface

The work presented in this PhD thesis was performed within three different projects at CESC Centre for sustainable communications. CESC is a Centre of Excellence based at KTH Royal institute of technology and funded by VINNOVA (The Swedish Governmental Agency for Innovation Systems). CESC provides an interdisciplinary research environment and works together with partners from industry and public sector.

In 2011 I was involved in a sub-project of the CESC *Media and Sustainability* project, looking at environmental impacts of print and online newspapers. The project was commissioned by Alma Media, one of Finland's major media companies, and performed in collaboration with researchers from CESC and VTT Technical Research Centre of Finland, analyzing the environmental performance of three Alma Media print products and their respective online services. In this project, I worked on performing the life cycle assessment of the Alma Media online newspapers and of the content production for both online and printed newspapers. Papers II and III resulted from this work.

Partly in parallel, in 2012, I took part in working on a smaller task from CESC *Methods* project, looking into what has already been done on assessments of Information and communication technology (ICT) with life cycle perspective. Paper I resulted from this work.

Later on, in 2013, moving from assessments on a product level to a larger scale - societal assessments - I became a part of the research group working on the CESC project *Scenarios and Sustainability impacts of future ICT societies*. This was a large project involving researchers from KTH with various backgrounds as well as CESC partners – Ericsson, TeliaSonera, Stockholm city administration and Stockholm county council. The interdisciplinary group combined expertise in futures studies, environmental and social assessment, and planning. My main contribution to this project was working with the development of a method for sustainability assessment of scenarios and performing an environmental assessment of scenarios. Papers IV and V were the outcome of this work.

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I am grateful to my parents for always supporting me and believing in me no matter what. I am thankful to my brother for being a great inspiration for me, for always encouraging me to do better, and for making a perfect picture for the cover of this thesis. Спасибо, мои родные!

I address my deepest gratitude to my beloved Reynaldo for always believing in me and for being there for me this whole time with endless support and understanding. Gracias, mi amor!

List of papers

Paper I: Arushanyan, Y., Ekener-Petersen, E., and Finnveden, G. (2013). Lessons learned – literature review of LCA for ICT products and services. Computers in Industry 65, 211-234.

Paper II: Arushanyan, Y., Moberg, Å., Nors, M. and Hohenthal, C. (2014). Media content provided on different platforms – Environmental performance of online and printed versions of Alma Media newspapers. Journal of Print and Media Technology Research, 3(1), 7-31.

Paper III: Arushanyan, Y., Moberg, Å., Nors, M., Hohenthal, C. and Pihkola, H. (2014). Environmental Assessment of E-media Solutions - challenges experienced in case studies of Alma Media newspapers. In: Proceedings of the 2nd International Conference on ICT for Sustainability (ICT4S). Stockholm, Sweden.

Paper IV: Arushanyan, Y., Ekener, E. and Moberg, Å. (submitted). Sustainability Assessment Framework for Scenarios - SAFS.

Paper V: Arushanyan, Y., Moberg, Å., Coroama, V. C. and Ekener, E. (submitted). Future ICT Societies – Environmental Opportunities and Challenges.

Contribution of the author

Paper I: Yevgeniya Arushanyan and Elisabeth Ekener-Petersen were equally responsible for reviewing the literature, analyzing it and writing most of the article. Göran Finnveden contributed with ideas, supervision, and written input to the discussion and conclusions.

Paper II: Yevgeniya Arushanyan was responsible for writing the main structure of the article, with contribution and feedback from other authors. The article was based on a project, where Åsa Moberg and Yevgeniya were responsible for data collection, modelling, analysis concerning content production for both printed and online newspapers, and online newspaper assessment. Minna Nors and Catharina Hohenthal were responsible for the assessment of printed newspapers. Discussion and conclusions were written in collaboration between authors, in accordance with the order of the authors.

Paper III: Yevgeniya Arushanyan was responsible for writing the main structure of the article, with contribution and feedback from other authors. Discussion and conclusions were written in collaboration between authors, in accordance with the order of the authors. The article was based on a project, where Åsa Moberg and Yevgeniya were responsible for data collection, modelling, analysis concerning content production for both printed and online newspapers, and online newspapers assessment.

Paper IV: Yevgeniya Arushanyan was responsible for coordinating the work on the paper and writing the main structure of the article, with contribution and feedback from other authors. Discussion and conclusions were written in collaboration between authors, in accordance with the order of the authors. The methodological framework was developed in the results of the joint work of the co-authors.

Paper V: Yevgeniya Arushanyan was responsible for coordinating the work on the paper and writing the main structure of the article, with contribution and feedback from other authors. Discussion and conclusions were written in collaboration between authors, in accordance with the order of the authors. The article was based on a project, where Yevgeniya contributed to the joint work on framework development and was responsible for performing the environmental assessment.

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List of abbreviations

BAU	Business as usual
GHG	Greenhouse gas
IC	Integrated circuit
ICT	Information and communication technology
IP	Improved performance
ISO	International organization for standardization
LCA	Life cycle assessment
SAFS	Sustainability assessment framework for scenarios
UCTE	Union for the Coordination of the Transmission of Electricity

1 Introduction

1.1 Research background

Information and communication technology (ICT) is developing rapidly and is playing an increasingly important role in society (Plepys 2002; Berkhout and Hertin 2004; OECD 2011; Hilty and Aebischer 2015b). The contemporary society is facing a number of sustainability problems and in this context rather high expectations are being placed on ICT in relation to sustainable development, claiming that ICT could play a crucial role supporting various sustainability strategies and may enable transition to a less material-intensive economy (Hilty et al. 2011; Höjer et al. 2015).

A number of studies have been carried out by industry, organizations and researchers, exploring the idea of ICT contribution to solving environmental problems (e.g. Mingay (2007); Buttazoni (2008); Coroama and Hilty (2009); Mickoleit (2010); GeSi (2012)). ICT is suggested to be able to contribute to sustainable development and reduction of environmental impacts in a number of ways, such as e.g. replacing products, intensifying use of products/space/transport, increasing efficiency of processes/activities, informing consumption choices (Höjer et al. 2015).

In order to use ICT in the best possible way to enable sustainable development the sustainability impacts of ICT and its potential need to be studied taking into account positive and negative, direct and indirect effects. It has been argued that to ensure the minimization of negative and the facilitation of positive effects of ICT use, it needs to be supported by incentives or regulation (Berkhout and Hertin 2004; Höjer et al. 2015). To provide basis for the decision-making regarding the use of ICT for enabling sustainable development it is important to understand the life cycle impacts of individual solutions, and to study ICT in a context of a whole society. The potential risks and opportunities and their reasons need to be identified, and the potential role of ICT in supporting the opportunities for improvements and counteracting the potential risks needs to be assessed.

A number of studies have been done assessing negative environmental impacts of specific ICT solutions (e.g. Williams (2004); Choi et al. (2006); Duan et al. (2009)) and looking at the potential positive impacts of ICT application (e.g. Hilty et al. (2011); GeSi (2012)). However, many of these studies are only focusing on energy and climate change impact, showing the potential of ICT in reductions in energy use and carbon dioxide emissions. Considering only energy and climate change potential may lead to underestimation or missing of other impacts, e.g. potential geopolitical and environmental problems in the supply chain due to use of (scarse) resources (Hilty et al. 2011) and thus other environmental impacts need to be studied. To address this it is important that the potential of ICT is studied in a life cycle perspective, covering all stages of the ICT life and a wider range of impacts (Hilty et al. 2011).

Except for life cycle environmental impacts of specific ICT solutions it is important to consider the role of ICT in a context of a whole society in order to take into account different kinds of indirect effects as well. For example, many studies claim that there is a high potential of improved energy efficiency with the help of ICT, however, it is not usually considered that "as technological improvements increase the efficiency with which a resource is used, total consumption of that resource may increase rather than decrease" (Polimeni 2008). The number of studies looking at ICT in the context of a whole society is rather limited (e.g. Hilty et al. (2006); Ahmadi Achachlouei and Hilty (2015)). There are also studies looking at possible future scenarios for the ICT sector (e.g. Fujimoto et al. (2009); Misuraca et al. (2012)). However, there is a lack of exploring various scenarios for a whole society with an ICT focus and assessing their potential environmental impacts. This is needed to support decision-makers at different levels (e.g. municipal, regional, state, business, etc), providing knowledge about the role of ICT and its potential impacts in the context of a future society.

Environmental assessments of ICT have shown a number of challenges (Arushanyan et al. 2014; Moghaddam et al. 2014), emphasizing the need for methodological development in this field. Although the challenges of LCA applied on ICT are widely discussed and developments suggested (e.g. Andrae (2011); Stephens and Didden (2013)), no established frameworks are found to address the assessment of ICT in a context of future societies.

There is a need of further exploring the potential negative and positive environmental impacts of ICT today and in the future, and developing methodologies that can be used.

1.2 Aim

The aim of the thesis is to provide new knowledge on the environmental impacts related to ICT, to explore the potential of ICT to contribute to environmental sustainability, and discuss ways of assessing environmental impacts of ICT and challenges of those assessments. By doing this my ambition is to facilitate the discussions in the ICT community and among policy- and decision-makers regarding the environmental impacts of ICT now and in the future, and the ways ICT can promote sustainability, and to contribute to the development of assessment methodology.

In order to fulfil the aim the following research questions were examined:

A. What are the environmental impacts of current ICT solutions in a life cycle perspective?

B. How can environmental impacts of future ICT societies be assessed?

C. What are the potential environmental risks and opportunities of future ICT societies?

D. What are the challenges of environmental assessment of ICT on different levels?

1.3 Scope

The scope of this thesis is assessing the environmental impacts, risks and opportunities of ICT solutions today and in future, on a product and a societal level. Environmental effects of ICT may include a broad range of direct, indirect and structural/behavioral, such as e.g. rebound, effects (Berkhout and Hertin 2001). Direct are the environmental effects of the production and use of ICT; indirect are the environmental effects occurring in the result of change in other systems and processes (e.g. production); structural/behavioral are the effects occurring through changes in life styles and value systems (Berkhout and Hertin 2001). Addressing current environmental impacts of ICT solutions (research question A) the work focuses mainly on the direct negative impacts of ICT products and services over the life cycle. Addressing the environmental risks and opportunities of the future ICT societies (research question C) the work covers different types of impacts related to ICT. The way in which Papers I-V contribute to answering research questions is presented in Figure 1 and described below.

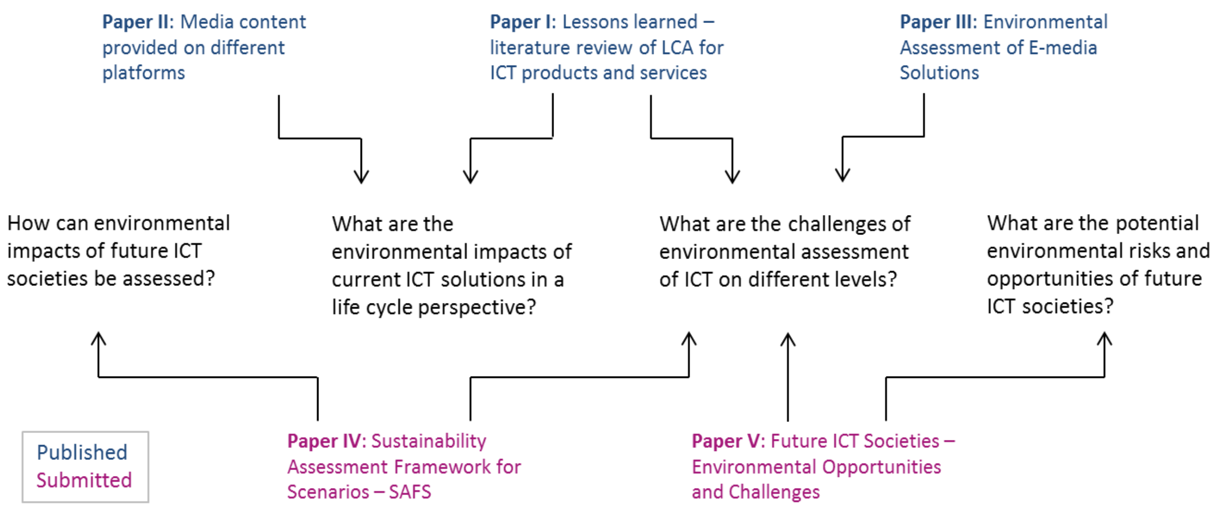

Figure 1 Papers' contribution to research questions

An overview of existing LCA studies done on ICT solutions is made in Paper I. Lessons learned regarding most studied objects, main environmental impacts and their origins, environmentally important materials and components are derived. The challenges of LCAs on ICT, limitations and needs for future research are identified. The study included all types of ICT products or services.

Paper II presents an LCA study of printed and online Alma Media newspapers. The full life cycle of three newspapers in both versions (online and printed) is analyzed. The results are presented individually and as a comparison of the environmental impacts between different newspapers and different versions (online and printed). Online versions of the three newspapers were in focus for this thesis.

Paper III discusses challenges of LCA applied on printed and online newspapers (Paper II). The challenges related to online newspaper assessment are in focus of this thesis.

Paper IV presents a methodological framework for assessing future scenarios. The framework is aimed for sustainability assessment of future scenarios with consumption and life cycle perspective.

Paper V presents the environmental assessment of five future ICT societies. The assessment is done applying the framework developed in Paper IV. Five scenarios for Sweden 2060 with ICT focus are assessed.

1.4 Outline of the thesis

The thesis consists of this cover essay and five appended papers. The cover essay summarizes the papers and puts them into context. The research background, aim and scope of the thesis are described in this introductory Chapter 1. Chapter 2 presents the scientific context of the thesis and Chapter 3 gives an overview of the methods used throughout the work. Chapter 4 presents the results of Papers I-V in relation to research questions A, B, C and D, and a discussion of those in relation to other research. Conclusions are drawn in Chapter 5.

2 Scientific context

The work described in this thesis has been performed in a context of the ICT for sustainability research field, and combined knowledge and experience of environmental assessment and futures studies. The work started with using Life cycle assessment (LCA) as a systems analysis tool (Papers I-III), and continued (Papers IV-V) with integrating fields of environmental assessment and futures studies. Transdisciplinary principles, i.e. involving experts and stakeholders from outside of academia, were applied in Papers IV-V and to some extent in Paper II. The theoretical context of the work is described below.

2.1 Sustainability and environmental assessment

Global environmental threats of the current development have been of concern for decades now, raised by Club of Rome as early as in 1972 in their “Limits to growth” report (Meadows et al. 1972) and further reflected in the 1987 Brundtland report (BrundtlandCommission 1987), defining sustainability and sustainable development. Sustainable development was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”(BrundtlandCommission 1987). Various views and interpretations of sustainability have been explored since then; suggesting how various dimensions of sustainability – environmental, social, and economic – should be viewed and addressed (e.g. Lozano (2008); Rockström et al. (2009); Raworth (2012); Steffen et al. (2015)).

In order to address the sustainability challenges various sustainability targets have been set globally (e.g. UN (2015)), regionally (e.g. EEA (2013)) and nationally (e.g. SEPA (2013)). To ensure achievements of those targets, sustainability assessments of various products, services and solutions, systems, industrial sectors, and whole countries´ production and consumption are needed. A systems approach is important for these kinds of assessments in order to avoid sub-optimizations and problem shifting. Various tools for systems analysis with focus on environmental, social and economic sustainability have been developed (Finnveden and Moberg 2005). Different tools have different purposes, focus and scope, addressing environmental or social impacts of products, e.g. Life cycle assessment (LCA) or Social LCA respectively; or projects, e.g. Environmental impact assessment (EIA) or Social impact assessment (SIA); or plans, e.g. Strategic environmental assessment (SEA); or considering economic implications, e.g. Cost-Benefit analysis (CBA). LCA is a tool for assessing a broad range of environmental impacts throughout the whole life cycle of a product or service. LCA was used as a method in parts of this thesis considering negative environmental impacts of ICT solutions (further described in 3.1).

A recent methodological development in assessment is Sustainability assessment, attempting to combine assessments of different dimensions of sustainability in one framework (Weaver and Rotmans 2006; Bond et al. 2012). The principles of both LCA and Sustainability assessment were utilized when developing a new methodological framework for assessment of future scenarios (further described in 3 and 4.2).

2.2 ICT for Sustainability

Information and communication technology (ICT) is “an umbrella term that includes any communication device or application, encompassing: radio, television, cellular phones, computer and network hardware and software, satellite systems and so on, as well as the various services and applications associated with them, such as videoconferencing and distance learning” (TechTarget 2016). Various studies use terms “ICT”, “ICT products”, “ICT solutions”, “ICT goods”, “ICT services”. For example, European statistics (Eurostat 2016) uses term “ICT”, covering “all technical means used for handling information and supporting communication”. Organization for Economic Cooperation and Development (OECD 2011) uses term “ICT products and services” covering an extensive list of categories. Studies addressing mainly end user devices use term “ICT products” (e.g. GeSi (2012)). Some studies (e.g. Malmodin et al. (2010); Malmodin et al. (2014)), address ICT sector, covering fixed telecom, mobile telecom, PCs, data centers, enterprise networks and transport networks. In this thesis ICT is addressed in two ways – as ICT solutions and as ICT societies. ICT solutions, as defined in Arushanyan (2013), cover ICT products and ICT services. ICT society is a society where ICT plays a crucial role in societal life and development. In case of ICT society all ICT solutions are considered.

A number of scientific studies advocate that ICT can be a means of enabling the transition of society to a less material-intensive economy, and therewith sustainability (e.g. Hilty et al. (2011)). The Smarter2020 report (GeSi 2012) defined a potential role of ICT in reducing future energy use and climate change impact through digitalization and dematerialization, data collection and communication, systems integration, and process, activity and functional optimizations. These are suggested to be applied on such sectors as power, transportation, manufacturing, consumer and service, agriculture and land use, and buildings. Mitchell (2000) discusses the way ICT can contribute to the reduction of energy use in cities. He defines the opportunities as follows: dematerialization, demobilization, mass customization, intelligent operation, and soft transformation.

In order to assess the potential contribution of ICT to sustainability it is important to take into account different types of sustainability implications. Environmental impacts of ICT can be divided into effects of different orders, classified in different ways by various studies. For example, Berkhout and Hertin (2001) define those effects as direct, indirect, and structural/behavioral effects. Direct effects are exclusively negative effects resulting from the processes related to manufacturing, use and waste disposal of ICT devices. Indirect effects can be both negative and positive and are related to the application of ICT, e.g. dematerialization and efficiency gains. Structural/behavioral effects are related to lifestyle and structural changes caused by ICT, e.g. shift from material economy to service economy, and can be both positive and negative, including rebound effect (i.e. increased demand stimulated by efficiency improvements).

Hilty and Aebischer (2015a) point out that the rebound effect within the ICT sector is strong, however, have been largely missed out by the studies assessing the potential role of ICT for reducing energy use and greenhouse gas emissions, basing their claims of the great potential of ICT on only efficiency considerations.

Other types of rebound effects are also discussed in the literature, e.g. Håkansson and Finnveden (2015) discuss reverse rebound effect, when due to increased consumption of ICT consumption of other goods decreases leading to overall reduced environmental impact.

Considering ICT for sustainability all these effects need to be studied and weighed together in order to estimate the potential overall environmental effects. The main focus of this thesis is on addressing direct negative effects on a product level (ICT solutions) and all types of effects on a societal level (future ICT societies). When discussing the environmental impacts of ICT solutions, some indirect effects are also lifted. In case of societal level of assessment, the indirect effects are included as society is addressed as a whole. Structural/behavioral effects are implicitly covered, however, without further analysis. The types of effects covered in this work are presented in Table 1.

Table 1 Types of environmental effects of ICT addressed in this thesis

Types of effects	ICT solutions	Future ICT societies
Direct effects	Yes	Yes
Indirect effects	Partly discussed	Yes
Structural/behavioral effects	No	Implicitly covered

2.3 Futures studies

Futures studies are a research approach, where systematic and explicit thinking about alternative futures is used to discover and propose possible, probable and preferable futures, and analyze them (Bell and Olick 1989; Bell 2003). Futures studies aim to uncover future possibilities, prepare for the unpredictable, and increase human control over future through understanding how a certain future can be reached or avoided (Bell and Olick 1989; Bell 2003).

One of the basic concepts in futures studies is scenario (Börjeson et al. 2006). Scenario can be defined as a description of a possible future situation, which may not be a complete picture of the future, but would, however, emphasize main elements and highlight key factors and important drivers of the future development. A scenario may include a description of the development path leading to that situation (Kosow and Gaßner 2008).

There are three major approaches to futures studies (Börjeson et al. 2006): predictive, explorative and normative. The predictive approach is aiming at answering the question "What will happen?" by creating predictive scenarios (forecasts and what-if scenarios). The explorative approach is aiming at answering the question "What can happen?" by creating either external or strategic scenarios. External scenarios explore what can happen in case of change of external factors (uncontrollable by an actor), while strategic scenarios explore what can happen if an actor acts in a certain way. Explorative scenarios are considered to be useful in the process of developing and assessing policies and strategies and are usually constructed with a long-term perspective and able to include large changes. The third approach, normative, aims at answering the question "How can a specific target be reached?" by creating normative scenarios of either adjusting the current situation in order to reach a target (preserving scenarios), or making significant changes (transforming scenarios). According to Höjer and Mattsson (2000) this type of scenarios is helpful to explore what measures should be taken in order to achieve a target, and facilitate further search for alternative paths of development.

There is a variety of different ways in which futures studies can be used. One of the purposes of futures studies could be to learn about present, about expectations on future development, and about actions to be taken in the present (Svenfelt 2010). Another purpose could be to discuss different alternatives of future development in order to emphasize that there are other ways than business as usual. Scenario analysis could also be used as a means of exploring current goals and targets and identifying what is important for future development (Gunnarsson-Östling 2014).

The development of ICT and its integration in everyday life is often seen as something happening on its own, however, using scenarios it can be demonstrated that ICT can be used as a tool for creating different futures, and how different actors can influence the development in different ways (Gunnarsson-Östling et al. submitted). Different ways of using ICT for future development may lead to different scenarios, some more sustainable than others. Therefore, it is important to assess the scenarios in order to identify potential environmental risks and opportunities of those alternative developments. Using futures studies as a support for various system analysis tools was explored and discussed by Höjer et al. (2008), pointing out that different types of scenarios could be useful depending on the purpose of a study. However, the authors point out the limited experience of such combinations, discuss the challenges of those and suggest that further research is needed in this area. There are examples of environmental or sustainability assessments of future scenarios, however, those often concern a specific sector or technology (e.g. Bouvart et al. (2011); Dandres et al. (2012); Singh and Strømman (2013)).

Assessing a whole society in the future is not common yet, although there are examples of future scenarios assessments done (e.g. Nijkamp and Vreeker (2000); IPCC (2014)).

In one part of this thesis (Papers IV and V) an attempt was made to combine the two approaches – futures studies and environmental assessment – to assess environmental implications of future ICT societies.

3 Methods

The research presented in this thesis was conducted using different methods, combining quantitative and qualitative approaches in a transdisciplinary context. To study environmental impacts of current ICT solutions in a life cycle perspective both literature review and own assessment using Life cycle assessment (LCA) were used (Paper I and II). To understand how environmental impacts of future ICT societies can be assessed a literature review was conducted and based on this review a framework was developed which was later called "Sustainability assessment framework for scenarios" (SAFS) (Paper IV). SAFS was then applied to study potential environmental risks and opportunities in future ICT societies (Paper V). SAFS is described in the Results section (4.2). In the process of assessment using SAFS, literature reviews and workshops were utilized. When looking at challenges of assessments, findings from the literature review (Paper I) and own experience of applying LCA (Paper II) were used, and developing and applying SAFS (Papers IV and V) were analyzed. The methods used in the different papers are presented in Table 2 and further described below.

Table 2 Overview of the methods applied in different papers

	LCA	Literature review	Workshops	SAFS
Paper I		X		
Paper II	X			
Paper III	(X)[1]			
Paper IV		X	X	
Paper V		X	X	X

3.1 LCA

Life cycle assessment (LCA) is a method for assessing potential environmental impacts of a product or service over its life cycle, i.e. from raw material acquisition through manufacturing, use to final waste management (ISO 2006). LCA aims to assess the potential impacts from a systems perspective to avoid problem shifting when identifying strategies for improvement (Hellweg and i Canals 2014). In order to ensure that, LCA considers all life cycle stages of a product's life and covers a wide range of environmental impacts.

The process of applying LCA consists of four phases performed in iteration – goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 2006).

[1] LCA is not used directly in this paper; however, the experience from the assessment using LCA is presented in the paper.

When performing an LCA a number of methodological choices need to be made in each specific case, such as defining system boundaries, defining functional unit, choosing method for impact assessment, defining allocation procedures, etc. An LCA was used in this thesis in the case study on online newspapers compared to printed newspapers (Paper II), addressing the research question *What are the current environmental impacts of ICT solutions with a life cycle perspective?* The application of LCA and methodological choices done in this study are shortly presented below (for more detail see Paper II).

3.1.1 Scope

Paper II presents an LCA of printed and online versions of two Finnish Alma Media newspapers – morning newspaper Aamulehti and Aamulehti.fi and evening newspaper Iltalehti and Iltalehti.fi. For the online newspapers (which are in focus in the thesis) the product system covered content production, electronic storage and distribution, manufacturing and disposal of user electronic devices (desktops and laptops), and electricity needed for downloading and reading the online newspapers. Content production was shared between printed and online newspapers.

The readers were located in Finland, however, some of the processes occurred in other countries, e.g. manufacturing and transportation of user devices. The data used represents year 2010.

3.1.2 Functional unit

Functional unit is a quantitative measure of a function performed by a product or service. All calculations are related to the functional unit (Baumann and Tillman 2004; Curran 2015). Defining a common functional unit is especially important when comparing two products (Baumann and Tillman 2004) and may be challenging when the functions of two products are not exactly the same, as e.g. for ICT solutions and their traditional counterparts.

For the study in Paper II it was decided to use several functional units to reflect the differences in the function provided. Printed newspapers were assessed *per copy of printed newspaper*, while online newspapers were assessed *per year of online newspaper production*. In order to compare the two systems two other functional units were used for both systems – *per reader and week*, and *per reading hour*.

3.1.3 Allocation

When a product or process in focus is shared between two or more product systems, a so-called allocation problem may arise (Finnveden et al. 2009). ISO 14040 (ISO 2006) suggests dealing with allocation problems through system expansion. System expansion means that an additional process or product with a function equivalent to a co-product is included in the system in order to account for a benefit of replacing that process or product with a co-product, i.e. avoiding the original use of that process or production of that product (Curran 2015). Alternatively, partitioning the input and output between the systems can be done based on the underlying physical or other relationship (ISO 2006).

In Paper II allocation problems arise in different parts of the systems. Content production is shared between printed and online versions. The impact from content production is allocated based on the number of full-time employees involved in working on the respective version. For online newspapers allocation problems arise due to multi-functionality of end-consumer devices and internet infrastructure. These are allocated based on the overall use time and traffic (in MB) respectively. Open-loop recycling is applied for the end-of-life disposal of electronic devices. Open-loop recycling means that recycling into a different (than original) product is considered and the effects of that are accounted for (Curran 2015). In this case it meant accounting for the benefit of recycling of the metal scrap from electronic devices (e.g. copper, aluminum, gold, silver) into secondary raw materials.

3.1.4 Impact assessment

A number of impact assessment methods can be applied within LCA, such as e.g. CML (Guinée 2002), Ecoindicator (Goedkoop and Spriensma 2001), ReCiPe (Goedkoop et al. 2009). ReCiPe was used in the case study, including 13 out of the suggested 18 impact categories: climate change, ozone depletion, human toxicity, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, mineral resource depletion/metal depletion, and fossil depletion. Five impact categories were left out due to lack of data in the datasets applied. These were: ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation and water depletion.

3.2 Literature review

Literature reviews were used in Papers I, IV and V in different ways.

In Paper I literature review was used to address two research questions: *What are the environmental impacts of current ICT solutions in a life cycle perspective?* and *What are the challenges of environmental assessment of ICT on different levels?* In this paper existing LCA studies were reviewed and analyzed looking for "lessons learned" regarding potential environmental impacts of ICT and their assessment. The literature search was done in online scientific library Science Direct, using key words, including ''LCA'', ''ICT'', ''computer'', ''laptop'', ''environmental assessment'', ''carbon footprint of ICT/ computer/ laptop/ electronics'', etc. Additionally, some studies done on consumer electronics and published as reports were included based on their relevance. Around 70 studies were found, after the first revision 60 studies were left for the deeper analysis as the most relevant. The papers were analyzed according to the following questions in focus:

- What types of products/objects are covered in the studies (e.g. laptops, phones, etc.)?
- What types of impacts are addressed (e.g. climate change impact, energy use)?
- What are the main findings concerning the reasons for environmental impacts, important parameters and assumptions?
- What lessons can be learned concerning methodological challenges and limitations?
- Which methodological issues need further attention?

The analysis was summarized in a spread sheet presented in Appendix A in Paper I.

To address the research question *How can environmental impacts of future ICT societies be assessed?* a literature review was used as a starting point to search for existing frameworks for future scenarios assessments (Paper IV). Based on the purpose of the study the focus was qualitative or semi-quantitative sustainability (environmental and social) assessment of future scenarios (explorative and normative). The search was done in online scientific library Science Direct. The search words used were: “scenarios assessment”, “future (environmental/social) assessment”, “environmental/ social assessment of future (scenarios)”, “assessment of future society”, “large scale assessment”, “assessment tool”, “social/ environmental assessment”, “evaluation method/tool”, “sustainability assessment”, “environmental assessment tools”, “environmental impacts of scenarios”, “(LCA for) large scale environmental assessment”, “social sustainability”, “sustainable cities”, “technology assessment”, “methodology for scenario assessment”. Around 60 studies were screened and used for ideas on criteria, methodological aspects and concepts in the development of SAFS.

Literature reviews were also used for defining environmental aspects to be used in the assessment of future ICT societies and for collecting information on the current aspect performance (Papers IV and V). As a basis for a workshop, where the environmental aspects were discussed and agreed on, an overview of existing official documents and reports describing environmental goals and targets on different levels (country, EU, global), and reports of existing assessment methodologies and indicators used in various assessments, was done. When the aspects were defined, another literature review was done in order to collect information on current state of those aspects. Relevant scientific articles, reports, official documents and databases were studied.

3.3 Workshops

Workshops with actors and stakeholders, and expert groups were used in Papers IV and V while addressing two research questions: *How can environmental impacts of future ICT societies be assessed?* and *What are the potential environmental risks and opportunities of future ICT societies?* These were used for development of SAFS (Paper IV) and later the environmental assessment of future ICT societies (Paper V). In this work "experts" are experts in assessment or areas of the aspects (environmental and social), and "actors and stakeholders" are representatives of ICT industry and city and regional administrations. The actors and stakeholders were chosen in relation to the focus of the project – ICT societies. The workshops were used for a number of purposes – for support in collecting information, for feedback on suggested ideas, and as a platform for knowledge exchange and mutual learning. An overview of the workshop themes and participants involved is given in Table 3.

Table 3 Overview of the workshops and participants

Workshop theme	Paper	Participants
SAFS development (Draft framework design)	Paper IV	Assessment group (4) Project group (2) Ericsson, environmental expert (1) TeliaSonera, environmental expert (1) KTH, environmental experts (2)
SAFS development (Environmental aspects)	Paper V	Assessment group (3) Ericsson, environmental expert (1) TeliaSonera, environmental expert (1) Stockholm city, environmental and urban planning expert (1) SCB, environmental expert (1) KTH, environmental experts (2)
SAFS development (Framework design)	Paper IV	Assessment group (3) Ericsson, environmental expert (1) TeliaSonera, environmental expert (1) KTH, urban planning expert (1) KTH, environmental expert (1)
Assessment	Paper V	Environmental protection agency, environmental expert (1) Stockholm county council, environmental and regional planning experts (2) Ericsson, environmental expert (1) KTH, environmental expert (2)

3.3.1 SAFS development

For the development of Sustainability assessment framework for scenarios (SAFS) three workshops were held – to discuss the framework design and environmental and social aspects to be addressed (see Table 3). All workshops were organized in a semi-structured way, where the discussion was led by the research group around suggested framework design and suggested aspects respectively with time for open discussion. At the workshops on framework design the draft design for the framework was presented, including the main steps and key issues to be covered. The aspects to be assessed and contextual factors[2] to be considered were introduced as well. After introducing the elements of the framework the participants were offered to try out applying parts of the framework on suggested examples. The discussion was held in smaller groups, focusing on the following issues:

- Is the suggested framework feasible and applicable?
- Would it lead to expected results?
- Are there missing elements?
- What challenges can be expected when applying the framework and how to address them?
- Are contextual factors and suggested aspects feasible, reasonable, and comprehensive enough?
- How can the results of such assessment be presented?

Workshop on aspects consisted of two parallel sessions, discussing environmental and social aspects. The lists of suggested aspects, including the reasoning for choosing them and description of what is to be covered, were presented at each workshop. The focus was on discussing relevance of the aspects for the context, their usefulness and feasibility of assessing. The following questions were addressed during the discussions:

- Is this a good set of aspects to be assessed?
- Is something crucial missing?
- Are any of the aspects overlapping?
- Are any of the aspects redundant and can be left out?
- How can the aspects be developed?

[2] Contextual factors define information that is requested from the scenario descriptions for the purpose of assessing the defined aspects.

3.3.2 Assessment

Workshops with experts were used as support for the analysis in the process of assessing future scenarios (Paper V). Assessment using SAFS implies analyzing the interrelation between contextual factors and environmental and social aspects (see section 4.2). Experts' knowledge was used here as a way of dealing with the large scale of assessment, lack of data and uncertainty. Workshops were held in parallel for environmental and social assessment, and were organized in a semi-structured way with discussion around the draft assessments and specific questions as well as a possibility for open feedback and questions from the experts. During the workshop the interrelations between contextual factors and aspects were discussed, going through the assessment process. A table with such interrelations for environmental aspects is presented in Supplementary material to Paper V. The following questions were addressed during the discussions:

- Are the defined interrelations reasonable?
- How can lack of data be addressed?
- How can the results be presented to be most useful?

4 Results and discussion

The results of the thesis are presented and discussed for each research question based on findings from the appended papers.

4.1 What are the environmental impacts of current ICT solutions in a life cycle perspective?

In order to address the research question *What are the environmental impacts of current ICT solutions in a life cycle perspective?* a literature review and an LCA case study were conducted. The literature review (Paper I) was aimed at gathering information on existing LCA studies of ICT solutions and draw generic conclusions on environmental impacts of ICT. The case study (Paper II) was looking at environmental impacts of online newspapers compared to printed newspapers.

To answer this research question the following issues were considered: what are the environmental impacts addressed in various studies; which life cycle phases, components and materials contribute most to the environmental impacts of various ICT solutions.

LCA guidelines (ISO 2006) instruct covering a comprehensive set of environmental issues related to the product or service system being assessed. In this way it is possible to avoid sub-optimization and problem shifting, i.e. solving a problem for one type of impact while neglecting another type of impact. However, as discussed in Paper I, rather high number of ICT assessments (roughly 40% of the reviewed) only address energy use and/or climate change impact. This is often argued for by pointing out that climate change is a global concern and is the main focus in various types of policies. Another reason for focusing on climate change and energy use is that data are available and considered more certain than for other impacts. One of the arguments is that the results for climate change impact can also be used as an approximation for fossil fuels depletion. However, as concluded by Moberg et al. (2014) on an example of mobile phone, climate change potential cannot be representative of other types of impact as the pattern of impacts differs among the impact categories. The studies that have considered wider range of impacts when assessing ICT point out the importance of impacts on resource depletion and human health (Paper I).

In Paper II 13 impact categories were considered when assessing online newspapers. The results for Iltalehti.fi and Aamulehti.fi are presented in Figure 2 and Figure 3 demonstrating that the shares of the environmental impacts from different life cycle stages may vary depending on the specific product and between impact categories. This once again supports the statement that all impacts cannot be judged based on climate change results only.

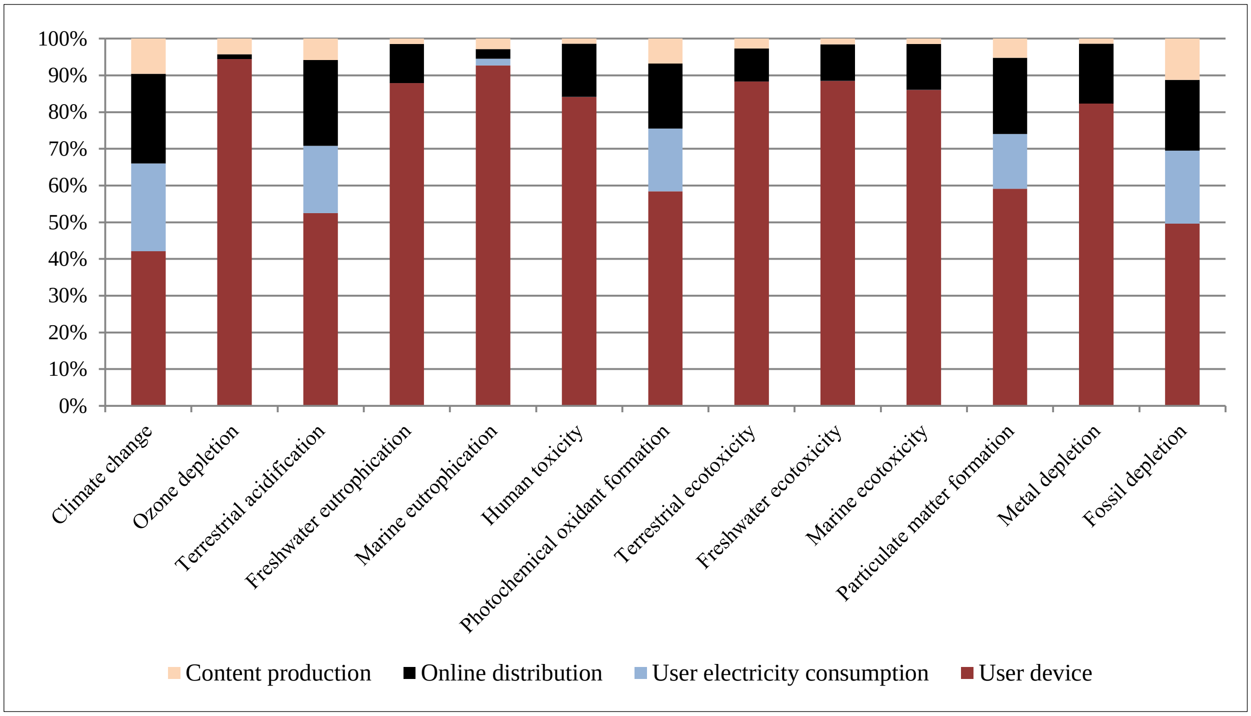

Figure 2 Environmental impact potential of Iltalehti.fi, per reader and week, percentage shares of life cycle stages (Source: Paper II)

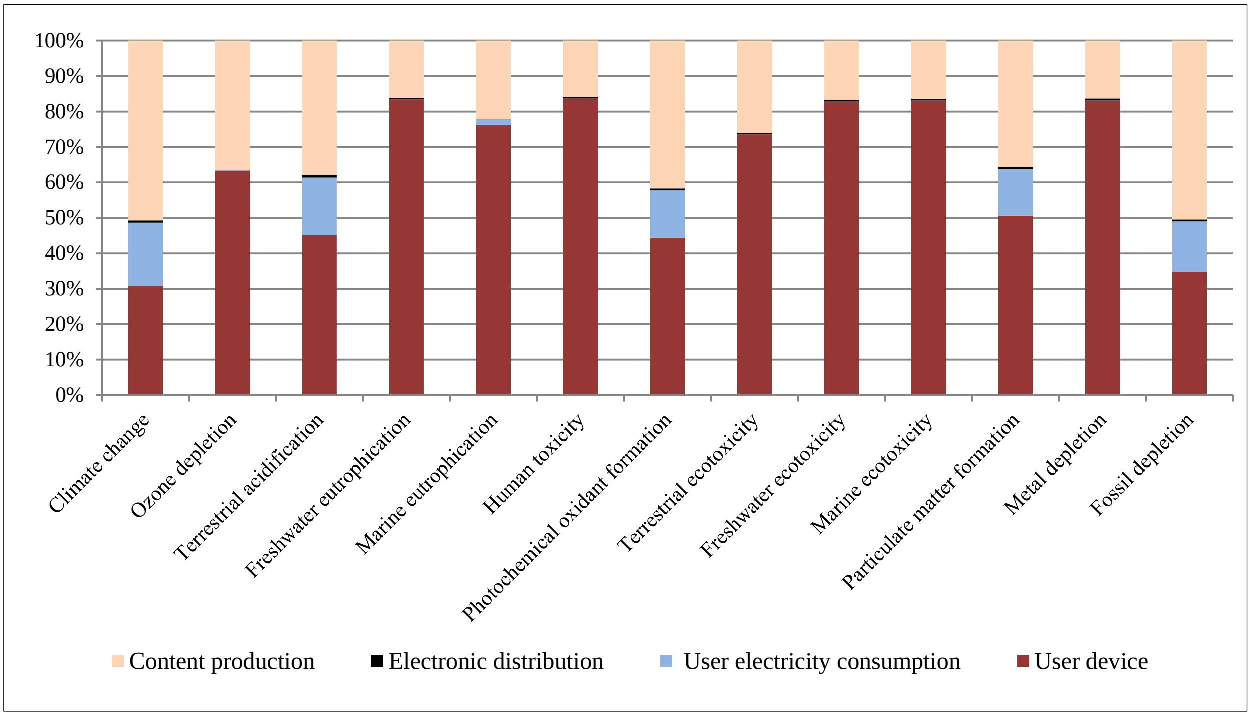

Figure 3 Environmental impact potential of Aamulehti.fi, per reader and week, percentage shares of life cycle stages (Source: Paper II)

Content production covers all activities related to producing the newspaper content, e.g. use of office electronic devices, business trips, electricity use and heating of the office areas, paper use, etc. The content production is shared between the printed and online versions of the same newspaper and is allocated based on the number of full-time employees working with the respective version. Online distribution considers the use of internet infrastructure and its energy consumption, calculated based on traffic (in MB). The user device is represented here by a mix of laptops and desktops used at home and at an office. The assessment covers a share of the manufacturing, transportation to a user, and end-of-life treatment, which corresponds to reading the online newspaper, based on the reading time and overall use time of a device. User electricity consumption is the electricity needed for reading the newspaper.

A review of the existing studies (Paper I) showed that the two life cycle phases that potentially have the highest share of the environmental impact of an ICT product are manufacturing and use phase. Some studies point out that manufacturing usually dominates for products with low weight and high energy efficiency, such as phones. Use phase is usually the most important for products with long life span and high energy demands, such as servers and data centers. Studies on computers seem to show contradictory results as some studies show the dominance of manufacturing in the environmental impacts and others – use phase. It was observed that those results were dependent on a number of parameters and assumptions, such as system boundaries (which processes exactly are included or excluded), user location (and therewith electricity mix used) and user behavior (service life of a device, overall use time, etc.). Since the resulting environmental impacts from manufacturing and use phase depend on a number of parameters and may both be rather significant, it can be pointed out that both should be prioritized and those parameters considered.

When looking at manufacturing of ICT devices, a number of materials contributing the most to various environmental impacts can be pointed out. Based on the studies overviewed in Paper I the manufacturing of integrated circuits (IC) is the most environmentally intense process for many ICT products. This is also confirmed by findings of Paper II. The environmental impact of IC manufacturing is caused by energy use, and gold mining and processing.

Figure 2 and Figure 3 demonstrate the life cycle stages contribution to the potential environmental impact of Iltalehti.fi and Aamulehti.fi online newspapers (Paper II). Although the user device stands out as the main contributor to the potential environmental impacts in most impact categories, different life cycle stages contribute differently depending on the product and impact category. The reasons for such differences here lie in differences of newspaper characteristics. As discussed in Ahmadi Achachlouei et al. (2015) the environmental impact of electronic media depends highly on the content size, number of readers and overall maturity of the media source. Depending on maturity the content production may also have a higher or lower environmental impact per reader.

The relative contribution of the reader device and its electricity use is affected by the reading time of the user. The average reading time of Iltalehti.fi is higher than that of Aamulehti.fi (9 and 6 min respectively), which consequently implies that Iltalehti.fi has a higher relative impact.

The contribution of online distribution to the environmental impact of the online newspaper per reader and week depends on the size of the uploaded and downloaded content. Aamulehti.fi is an emerging online version of the Aamulehti newspaper with light website content, while Iltalehti.fi, on contrary, has heavy content, and thus more significant shares of environmental impact from online distribution.

As can be observed from Figures 2 and 3, the content production has a rather high share in the overall environmental impact of Aamulehti.fi, but not in the case of Iltalehti.fi. The reason is that Aamulehti.fi has a lower number of readers and thus the environmental impact is split over fewer readers. This may change completely as the online newspaper matures and acquires higher number of readers (Ahmadi Achachlouei et al. 2015).

As discussed in Paper I the electricity mix is one of the significant parameters that affect the share of impact originating from the use phase. This was confirmed in two sensitivity analyses in Paper II. The electricity mix used in the reference case was Finnish 5-year average electricity mix from EcoData database (Pihkola et al. 2010). For the sensitivity analyses the reference electricity mix was substituted by alternative electricity mixes: 1) Finnish electricity from Ecoinvent 2.0 (Dones et al. 2000), and 2) UCTE[3] electricity from Ecoinvent 2.0 (Dones et al. 2000). An overall comparison of environmental performance of Iltalehti.fi with three different electricity mixes is presented in Figure 4, demonstrating the increase in the environmental impact with the alternative electricity mixes.

It was observed that the use of the UCTE mix led to the highest environmental impacts in almost all impact categories. Furthermore, when looking at the shares of the impacts (Figure 5), the share of the impact from the use phase was observed to be higher than when using the reference mix (Figure 2).

[3] UCTE - Union for the Coordination of the Transmission of Electricity. The electricity mix in Ecoinvent 2.0 is an average of electricity mixes of all countries members of UCTE.

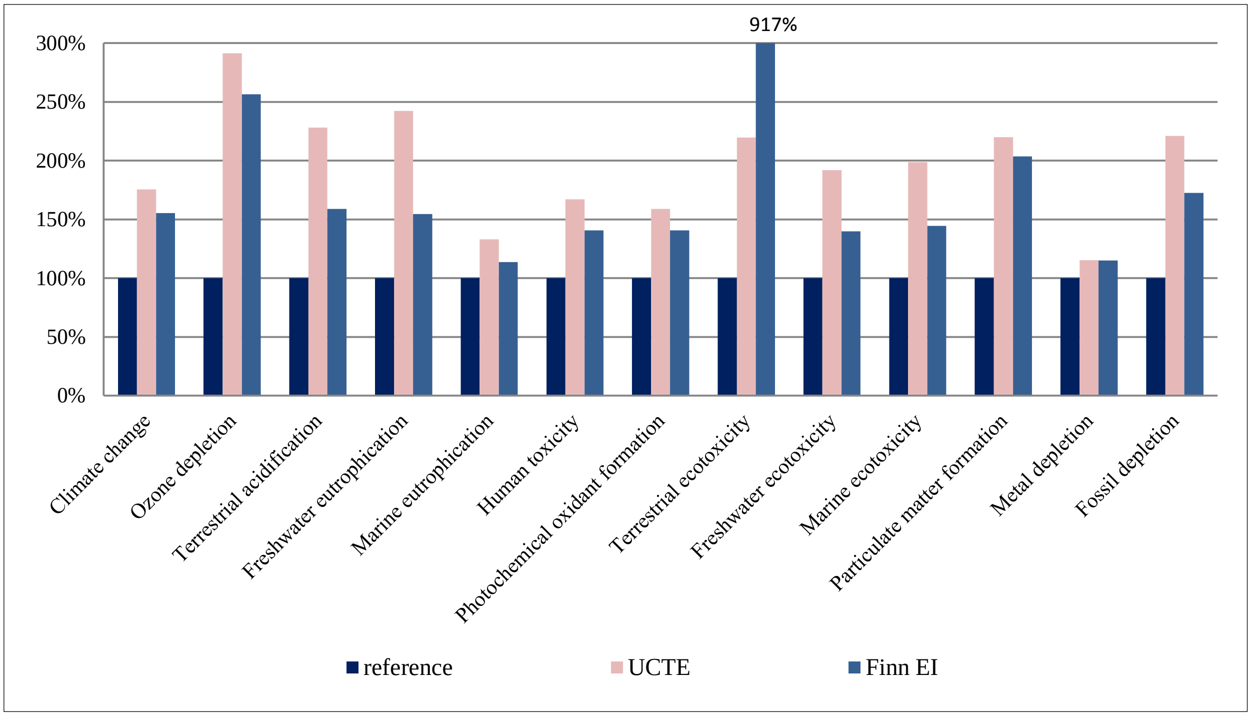

Figure 4 Sensitivity analyses for Iltalehti.fi: reference case (Finnish 5-year average electricity 2005-2009, EcoData), UCTE (year 2004, Ecoinvent 2.0), Finn EI (Finnish electricity, year 2004, Ecoinvent 2.0). The reference case is set to 100% (Source: Paper II)

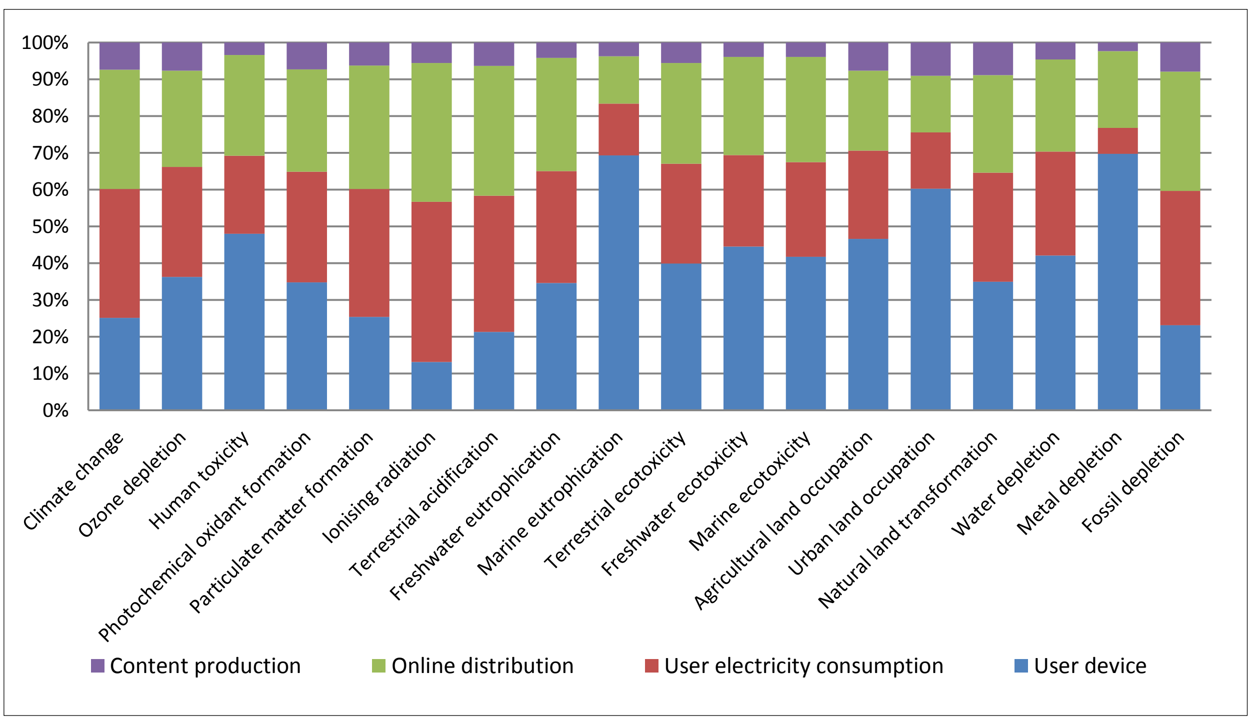

Figure 5 Environmental impact potential of Iltalehti.fi, with UCTE electricity mix, per reader and week, percentage shares of lifecycle stages (Source: Paper II)

In the studies reviewed in Paper I, transportation shows to have rather low share of the overall environmental impact of products such as computers, TVs and semiconductors, however, it is rather high for mobile phones, especially when air freight is used. Some studies (e.g. Socolof et al. (2005); Scharnhorst (2008)) point out that transportation may not have been studied enough yet, and thus, its impact may be underestimated. In the case study (Paper II) transportation did not show to have a significant share of the overall impact. A combination of sea, air freight and road transport was assumed for the transportation of electronic devices from the manufacturing country to the user.

End-of-life phase is not in focus in most of the studies reviewed in Paper I. Studies looking only at electronic waste disposal are more common than studies discussing this life cycle stage within the overall environmental impact of ICT. In the case study presented in Paper II the waste management of the electronic devices did not have a large contribution to the overall environmental impact. However, there were a number of limitations in modeling this part of the life cycle and only formal recycling was modeled, which may not entirely correspond to the reality with informal electronic waste handling being a problem (Umair 2015).

An important factor affecting the overall environmental impact and the distribution between various life cycle phases is the user behavior and location. The importance of the user behavior was pointed out by a number of studies overviewed in Paper I (e.g. Reichart and Hischier (2002); Moberg et al. (2011); Arushanyan and Moberg (2012)) and in Papers II and III. This could be the overall use of the device, the service life of the device, sharing of the devices, keeping it on all the time, the location of the user, the way a device is handled in the end of life, etc. In Paper II some assumptions regarding the user behavior were tested. The life span was decreased from 5.5 (laptop) and 6.5 (desktop) years to 3 years for each. The overall use time was (for home devices) increased four times compared to the reference case. As presented in Figure 6 decreased life span (service life) of a device may increase the environmental impact of reading an online newspaper, while the increased overall use on contrary decreases the share of impact attributed to reading an online newspaper.

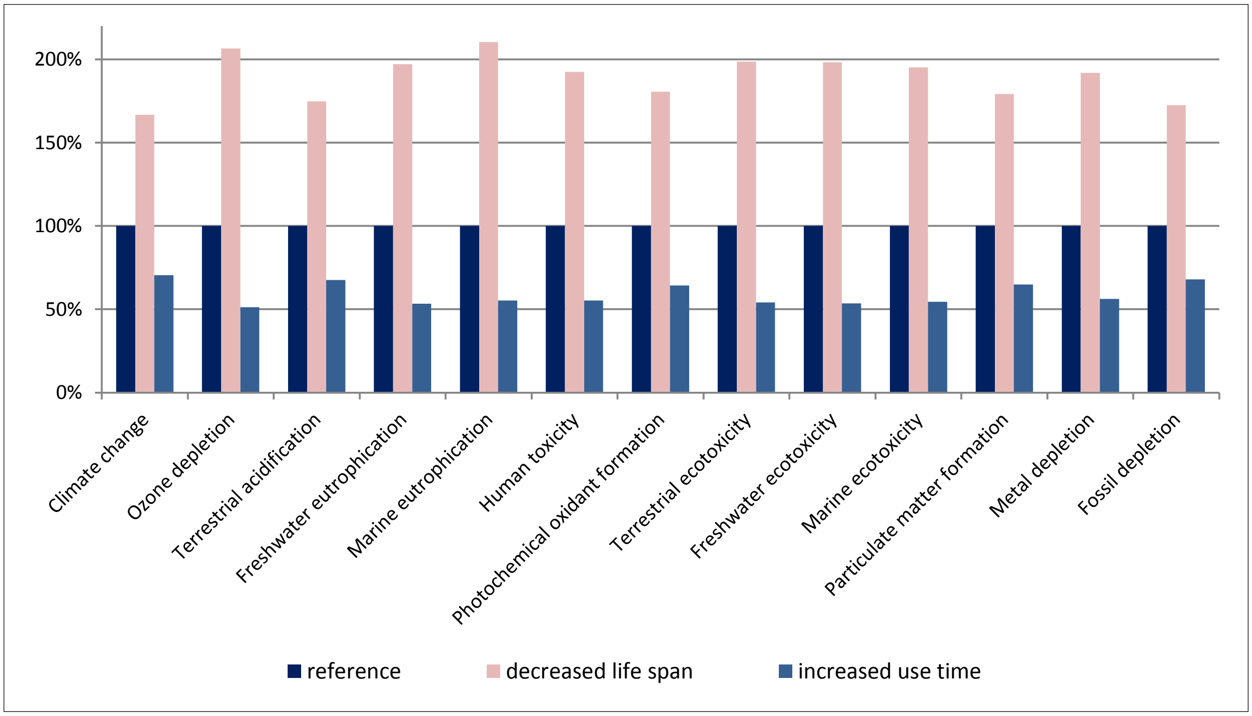

Figure 6 Sensitivity analyses for Iltalehti.fi: reference case, decreased life span of the user device, increased use time of the user device. The reference case is set to 100% (Source: Paper II)

When discussing the environmental impacts of electronic media, the device on which the media is read is important. In Paper II the reader's device was represented by a mix of desktop and laptop, used from home and office. However, Arushanyan and Moberg (2012) compared reading the same online newspaper on a computer and on a tablet, demonstrating the decreased impact on climate change from reading on a smaller, more efficient device. It was also pointed out that the overall environmental impact is dependent on the overall device use and if a tablet is rarely used and a computer is used intensely it may become more environmentally beneficial to read the newspaper from a computer.

When assessing environmental performance of an ICT service or ICT-based activity, such as e.g. reading an online newspaper or an electronic book, they are often compared to their traditional counterparts (e.g. Moberg et al. (2011); Ahmadi Achachlouei and Moberg (2015)). In Paper II printed and online versions of the Alma Media newspapers were compared. An example of comparison of Aamulehti and Aamulehti.fi is presented in Figure 7.

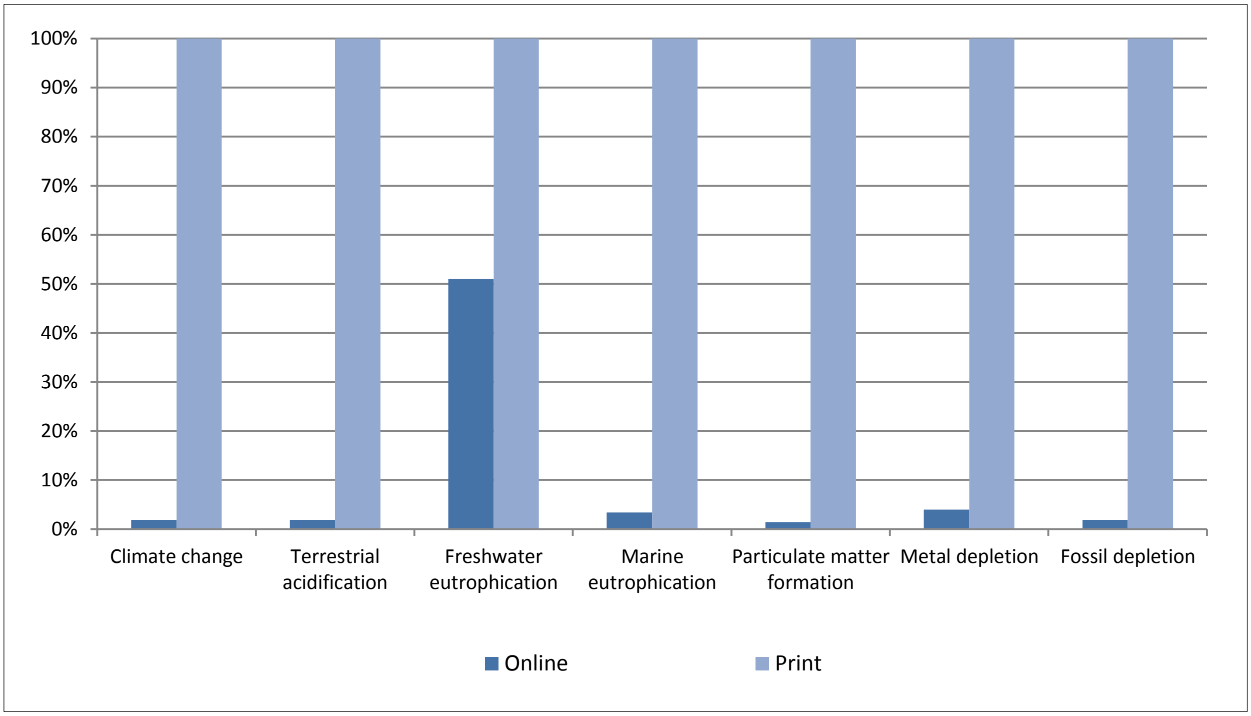

Figure 7 Environmental impact potential of Aamulehti.fi and printed Aamulehti (including supplement), per reader and week. The printed version set to 100%. The total reading time per reader and week: 245 min (printed) and 6 min (online). Size of download for Aamulehti.fi: 2 MB per reader and week (Source: Paper II)

The total reading time per reader and week and how well it reflects the reality is a subject for discussion. Both reading times were received from Alma Media. The time of reading the printed copy is based on surveys, while the reading time of the online newspaper was taken from the newspaper website statistics provided by TNSGallup (2010). As the information is collected in a different way, this may not be good for comparison, which was one of the reasons to test alternative functional units.

The results of the comparison indicated, in line with other studies, that the conclusions on which version is better for environment depend on a number of factors, such as e.g. reading time, the size of the content for online newspaper and format of the printed one, the device used for reading online newspaper, the number of readers per copy of a printed newspaper, etc. Figure 8 presents the results for Iltalehti and Iltalehti.fi, demonstrating slightly different results. Iltalehti.fi has longer reading time per reader and week and larger content compared to Aamulehti.fi, which leads to smaller difference in environmental performance of online and printed versions. The comparison of the two versions may not be as straightforward as they may not fulfill the same function. Thus, an assessment using alternative functional unit was done, showing that the choice of different functional units may lead to completely different results. This is further discussed in section 4.4.

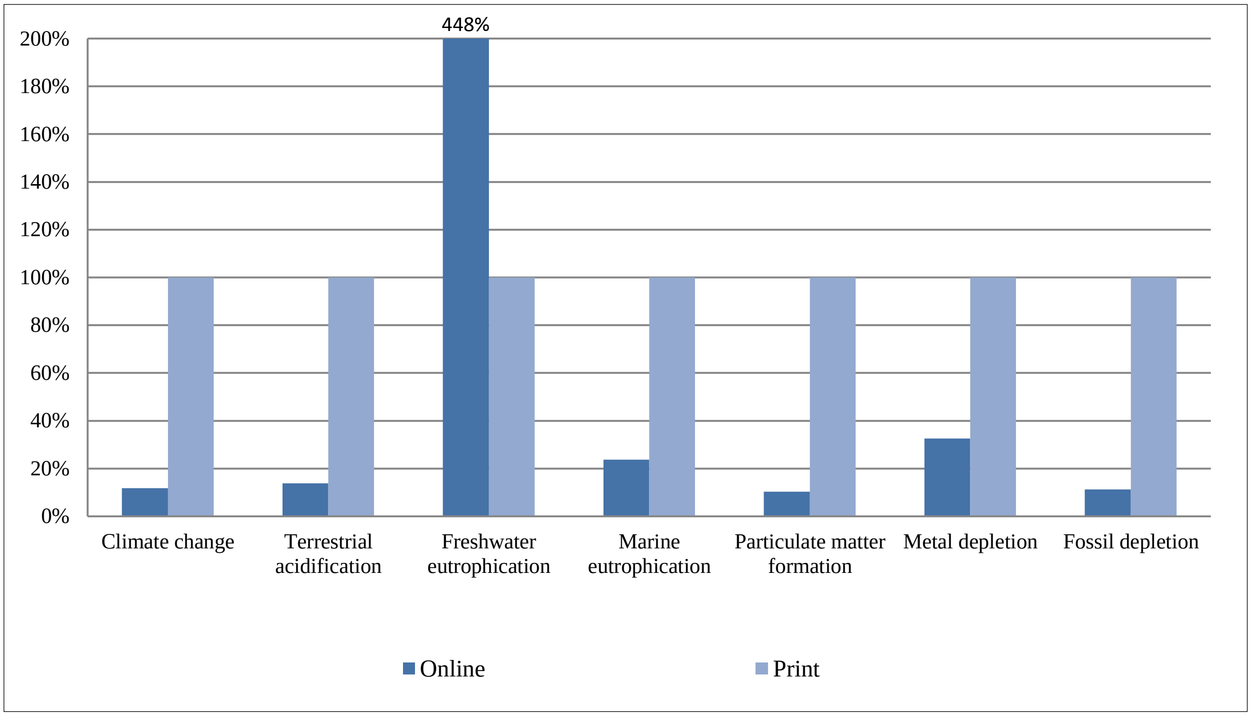

Figure 8 Environmental impact potential of Iltalehti.fi and printed Iltalehti, per reader and week. The printed version set to 100%. The total reading time per reader and week: 138 min (printed) and 9 min (online). Size of download for Iltalehti.fi: 100 MB per reader and week (Source: Paper II)

4.2 How can environmental impacts of future ICT societies be assessed?

The study of environmental impacts of future ICT societies was done within a larger project "Scenarios and sustainability impacts of future ICT societies". In this project a multidisciplinary research group collaborated with ICT industry, city administration and county council, and a group of experts, and looked into future scenarios for Swedish ICT societies in order to study the potential sustainability (environmental and social) implications of those scenarios and developing policy suggestions based on the findings. ICT society here is a society where ICT plays an important role in people's everyday life and societal development.

Based on the goals of the study it was decided that an assessment method should be applicable for explorative and normative future scenarios of a whole society, assessing a broad range of environmental and social issues. A large share of impact from Swedish consumption occurs outside of its borders (SEPA 2011, 2015; Brolinson et al. 2012), and it was considered important to have a consumption perspective of the assessment. In order to ensure that all processes related to the products were taken into account it was also decided to include a life cycle perspective.

A literature review was conducted (see 3.2) to identify existing frameworks that could be used or built upon for the assessment of future ICT societies. While none were identified that fit the purpose of the outlined criteria, concepts and methodological aspects from existing frameworks or methodologies were combined and further developed in a new framework which was later called "Sustainability assessment framework for scenarios" (SAFS).

SAFS is a methodological framework for a qualitative sustainability assessment of future scenarios compared to today, on a society level with consumption perspective and life cycle thinking. SAFS consists of four main steps: scoping, inventory analysis, impact assessment and interpretation. The expected results of the assessment using SAFS are to be presented in terms of environmental and social risks and opportunities. The framework is presented in Figure 9 and each step is further described below with some guidelines for application.

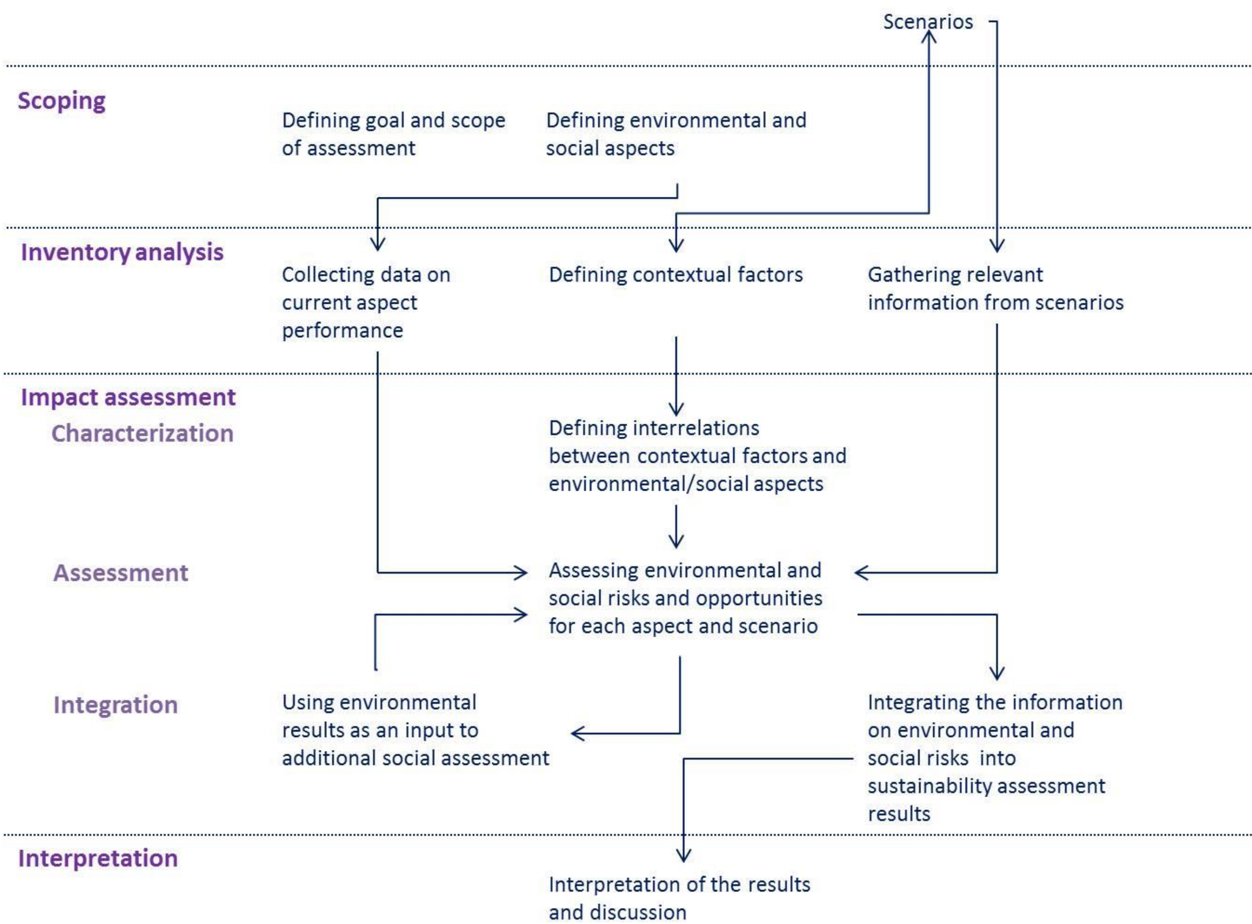

Figure 9 Overview of SAFS and its steps (Source: Paper IV)

In the *Scoping* step the goal and scope of the study are defined. In this step it should be defined what kind of question(s) the study is aiming to answer, who is the intended target group for the results, what aspects (social and environmental) should be addressed, what are the geographical and time boundaries of the assessment and if there is any specific focus area.

SAFS suggests that this is done in discussion with a project group, possibly with involvement of actors and stakeholders.

For defining aspects using a combination of top-down (using established frameworks) and bottom-up (involving stakeholders) approaches is suggested. The aspects should be relevant for the scope of assessment and not redundant with each other. The choice of aspects should be justified and on overarching level consider the following areas of protection: natural environment and natural resources (for environmental aspects) (ISO 2006), and human well-being, equity and justice (for social aspects) (Benoît and Mazijn 2009; Colantonio 2009). SAFS suggests using literature reviews in combination with workshops/discussions with actors, stakeholders and experts to discuss and define the set of aspects.

During *Inventory analysis* the information about scenarios and current aspect performance is gathered. In order to make this data gathering more structured it is important to identify first which activities described in scenarios would have an effect on environmental and social aspects. In SAFS these are called contextual factors. The information on current aspect performance is needed to assess the sustainability risks and opportunities within the scenarios in relation to the situation today. Collecting this information also helps identifying the current hotspots for various aspects, i.e. which are the activities affecting a certain aspect today. These activities then could be in focus when assessing the future scenarios, which helps to focus/delimit the assessment. However, this may also pose a risk of missing issues that are not important today, but could be important in the future.

During the *Impact assessment* step the information gathered is analyzed and translated into environmental and social assessment results. This is done through three sub-steps: 1) characterization, where the interrelation between the contextual factors and aspects is defined and described for each scenario; 2) assessment, where the characterization descriptions are summarized in a single aspect performance result; and 3) integration, where the environmental and social assessment results are integrated through a feedback loop, taking the environmental results back to the social assessment as additional contextual factors. All of these are suggested to be done with the help of project group discussions and workshops with experts and stakeholders. In order for the integration to be successful it is important to consider it already in the scoping step, when defining the aspects for assessment, otherwise there is a risk that the chosen aspects will not be fitted for integration.

In the *Interpretation* step the assessment results are related to the context of the study, assumptions and limitations. Reflections are made on issues defined as especially relevant, e.g. role of ICT as in this case.

4.3 What are the environmental risks and opportunities of future ICT societies?

The environmental risks and opportunities of future ICT societies were explored in Paper V, assessing five scenarios of future ICT societies applying SAFS. The scenarios assessed were (Gunnarsson-Östling et al. (submitted) as presented in Paper V):

Economic decline (explorative): Economy has declined, creating a crisis for the state and leading to loss of welfare system. In a society of scarce resources ICT plays an important role in individuals' everyday lives and is highly valued.

Trusted communities (explorative): Society is characterized by separation into local and digital communities. Life happens within the communities, where trust is high, while distrust flourishes with regard to "others".

Life online (explorative): Life is lived for the most part online, where all kinds of social interaction take place and any interests can be satisfied. There is low interest for material objects; money and stuff do not give status, which is now gained through online efforts.

Controlled convenience (explorative): Society with high living standard is driven by convenience and concern about the future of the planet is not in focus. People willingly share their personal data in exchange for a high-tech convenient life.

Valued environment (normative): Reaching environmental objectives is considered more important than targets about economic growth. The Swedish environmental quality objectives from mid-2010 have been fulfilled, mainly due to direct digitization and innovation of incentives and disincentives in various forms.

Paper V presents the environmental assessment of the scenarios. The scenarios were assessed using the following set of environmental aspects with a resource use perspective: water, land, minerals, chemicals, and energy use. In addition one emission-based aspect was included – greenhouse gas (GHG) emissions.

Certain issues, such as energy mixes and situation in the rest of the world, were not described in the scenarios, but were needed for the assessment, thus assumptions were made. It was decided to define two sets of assumptions – Business as usual development (BAU) and Improved performance (IP). BAU assumptions (inspired by Riahi et al. (2011); SEA (2014)) implied the development continued as now, i.e. with slight improvements, but no major changes in technology, energy mixes and environmental policy. IP assumptions (inspired by van Vuuren et al. (2011); Gustavsson et al. (2011)) implied significant improvement in technology, more sustainable energy mixes and strict environmental policies. Each scenario was assessed with both sets of assumptions. For more detail see Paper V, Appendix B.

The summary of the assessment results is presented in Table 3 and below. The summary presents overall risks and opportunities in the assessed scenarios compared to today, without going into details for all risks and opportunities. More details on the information from the scenarios used in the assessment and the intermediate (Characterization) results are presented in Paper V, appendix A and Supplementary material respectively.

Table 4 Risks and opportunities related to the different environmental aspects in the five scenarios (Source: Paper V)

	Main features	Overall outcome	ICT
Economic decline	Decreased consumption, more careful use of resources and less travel, more local food production, weak environmental regulation, low technological development.	Many opportunities for reduction of environmental pressures. Some risks related to increased internal water and land use, and possibly increased chemicals use for economic reasons.	The role of ICT is supporting the current life style, facilitation of more efficient use of goods and spaces, substituting or optimizing travel and transport.
Trusted communities	Slightly decreased consumption, decreased travel, slightly more local production, no change in eating pattern, weak environmental regulation.	Both risks and opportunities are limited due to limited changes in life styles. *BAU:* risks for an increase or no change in water, land, minerals and chemicals use; opportunities for reduced energy use and GHG emissions. *IP:* opportunities for decreased chemicals and energy use, and GHG emissions; overall water and minerals use may remain as today or decrease slightly.	Environmental benefits of ICT use are unintentional rather than planned. There is a potential for ICT to increase the automation and efficiency of processes and activities, however, the potential might not be realized due to low technological development and lack of incentives, such as e.g. environmental regulation.
Life online	Decreased overall consumption, transportation and travel, increased ICT use, weak environmental regulation, choice of inexpensive food.	*BAU:* many opportunities for reduction of the environmental pressures; risks for increased critical minerals use and increased chemicals use for ICT and food production. *IP:* opportunities for reduction of the environmental pressures in all aspects.	ICT is not used for the purpose of environmental benefits; however, environmental improvements can be a side-effect as more sustainable practices are the result of online activities replacing travel, products, transport and spaces. More efficient industrial processes are supported by ICT.

Controlled convenience	Increased consumption of goods and services, increased travel and transportation, high efficiency, electrification of transport in cities, locally focused environmental regulation, advanced technological development, and high ICT use.	*BAU:* risk for increased environmental pressure in all aspects. *IP:* risks for increased resource use, partly counteracted by high efficiency in combination with environmental regulation (in the rest of the world), leading to either limited risks or no change compared to today. Opportunity for decreased GHG emissions due to carbon neutral energy mixes.	Digitization is mainly for well-being. Environmental benefit is a result of optimization and automation introduced for economic and social reasons. ICT solutions only to a limited extent replace products, transport, travel and spaces.
Valued environment	Service and circular economy, strong environmental regulation, advanced technology, high ICT use, low consumption, transportation and travel.	The Swedish environmental objectives are per definition fulfilled (normative scenario). Substantial reduction of the environmental pressures in all aspects with some risks for increased land use for biofuels and renewable energy and for increased use of critical minerals, although used in a circular way.	ICT is used with the ambition of decreasing environmental impacts in all areas, e.g. travel, transport, consumption, production, spaces, communication, etc.

Valued environment is one scenario with significant environmental improvements, however, this was defined by scenario description (normative scenario), and thus the assessment results mainly present possible ways of how these improvements could have been achieved, and indicate the risks that may still occur.

Except for Valued environment, there are two more scenarios with significant opportunities for environmental improvements – Economic decline and Life online. In both cases the reasons lie in reduced consumption, transportation and travel. However, there are a number of risks in both scenarios. In Economic decline the consumption shifts to being more local, reducing imports and increasing own production, which would lead to increased (compared to today) use of land and water in Sweden. With the economic constraints and lack of environmental regulation that characterize the scenario this may lead to overuse and contamination of these resources. Another risk is related to chemicals use – driven by economic constraints the use of chemicals may increase in e.g. food production. As imports are low the main risks would be in Sweden. In Life online there are risks for increased critical minerals use (due to increased ICT use) and chemicals use (for food production) under BAU assumptions.

Trusted communities and Controlled convenience are two scenarios in which the risks and opportunities for environmental consequences are difficult to assess. The changes in life styles and society activities are small in the Trusted communities scenario which makes it difficult to say if the benefits of slightly reduced consumption and transportation would counteract the negative impact from increased population. Opportunities mainly occur under IP conditions, due to improvements in efficiency and energy mixes. In Controlled convenience, technological solutions are promising environmental improvements, however, increased population and increased consumption may counteract those. The only certain opportunity is related to reduction in GHG emissions under IP assumptions as even with increased consumption the use of carbon neutral energy mixes leads to improvements.

Based on the assessment of these five scenarios a number of key issues for environmental risks and opportunities were identified: energy mix, economic conditions and trade, environmental ambitions and regulation, technology, and life styles.

The importance of the energy mix for the outcomes of LCA results is well-known (Björklund and Finnveden 2005; Wenzel 2006). Energy mix is also pointed out as crucial by a number of studies looking at environmental impacts of ICT (e.g. Arushanyan et al. (2014); Malmodin et al. (2014)). In this assessment two alternative energy mixes – BAU and IP – for Sweden and for the rest of the world were used to reflect on the energy mix importance. The difference was especially noticeable for the scenario with high import levels – Controlled convenience – where even with high consumption a carbon free energy mix for the rest of the world (under IP assumptions) provided opportunities for improvement. The difference between BAU and IP mixes in Sweden was not large, thus the importance of the energy mix was not so visible. However, based on the risks and opportunities for energy use it can still be concluded that the energy mix is more crucial for environmental impacts in Controlled convenience (with intense economy and potentially same or increased energy use), than for e.g. Economic decline, where reduction in consumption and transportation led to reductions in energy use.

The economic conditions and trade were crucial for the resulting environmental consequences. Economic constraints in Economic decline scenario led to decreased consumption, transportation and travel, and to more careful use of resources, which result in large opportunities for environmental improvements. However, these unplanned economic limitations may lead to risks for environmental impacts due to choices based on costs rather than on environmental impacts. In contrast, in Valued environment economic limitations are used as an instrument guided by environmental regulation, which leads to environmental opportunities and allows avoiding environmental risks.

Another possible risk resulting from economic difficulties is the lack of technological development and potential inefficiency of processes, e.g. transportation, also leading to environmental risks, such as polluting technologies or high energy use due to inefficiency. On the other hand it was illustrated that the technological development by itself may not be the key to solving environmental problems. In Controlled convenience the technological development is intense and the efficiency gains are high, however, high materialism in society with high consumption and lack of environmental regulation risks counteracting the potential opportunities provided by technological improvements in this scenario. In this case trade plays an important role as well. With high consumption and high imports technological improvements within Sweden are not enough to reduce overall environmental impacts from consumption. Under BAU assumptions for the rest of the world there are risks for negative environmental impacts due to the high level of imports without efficiency gains and technological break-through.

Environmental ambitions from general public, business and government play an important role for environmental risks and opportunities. It has been reasoned that even in scenarios with environmental opportunities due to decreased consumption, travel and transportation (Economic decline and Life online) the lack of environmental regulation leads to certain environmental risks. The lack of environmental regulation poses a risk for rebound effect from the increased efficiency in Controlled convenience. Environmental regulation and environmental engagement from population are the drivers for environmental improvements in Valued environment.

There is a clear correlation between the level of consumption, transportation and travel and environmental risks and opportunities in the assessed scenarios. Those are highly dependent on the life styles in different scenarios. The lifestyles are shaped by various factors, such as economic conditions, societal structure, values, environmental regulation, and ICT. General consumption patterns and importance of ICT in society influence the amount of ICT devices in use (and thus overall impacts from manufacturing), the average service life and use time of the devices. Life styles (like in Life online or Controlled convenience) and economic constraints (like in Economic decline) affect the intensity of ICT use. Energy mixes affect the environmental risks from the ICT use when the use in the society is intense (e.g. Life online and Controlled convenience). On the other hand these potential negative impacts may be compensated by environmental improvements in other activities due to ICT use. This is especially vivid in Life online scenario, where online life substitutes a lot of real life activities leading to significant environmental improvements due to decreased overall consumption, transportation, travel and need for spaces (offices, shopping centers and entertainment).

ICT plays an important role in increasing efficiency of processes, optimization and automation. However, this may not always have just a positive outcome. In Controlled convenience the increased efficiency and automation may potentially lead to rebound effects as nothing is constraining it. On the other hand in Life online and Valued environment the increased efficiency and automation is driven by other factors (life style preferences and regulation respectively), thus the rebound effect is either not likely or can be counteracted, and the increased efficiency and automation are likely lead to reduced environmental impacts. For example, in Life online the automation is driven by the strive to reduce working hours (as defined by scenario), thus with increased efficiency a rebound effect is not likely, instead, even less working hours would be preferred.

4.4 What are the challenges of environmental assessment of ICT on different levels?

Any assessment method has their benefits, drawbacks and challenges. These were reflected upon in Papers I, III, IV and V regarding application of LCA and SAFS for assessment of ICT and ICT societies. The challenges discussed can be grouped into a few categories: data and methodological choices, assumptions on user behavior, results, and assessment on different levels.

4.4.1 Data and methodological choices

Gathering relevant, comprehensive, up-to-date and good quality **data** is a challenge for many assessments. As presented in Paper I many of the LCA studies reviewed point out the lack of relevant data for the assessments of ICT products. According to some of the studies the reason is that ICT products are generally complex, this makes it hard to access data for all involved components. Moreover, ICT is a rather new and rapidly developing technology which means that the data available are not abundant and become outdated rather fast. Another issue, pointed out by e.g. Plepys (2002) and Herrmann (2008), is that ICT require very specific materials, e.g. high purity chemicals, which make the generic material data easily available in databases less useful. Lack of data for specific components often leads to extrapolations and scaling, increasing uncertainty and reliability of the results.

Using primary (measured for a specific study) or secondary (collected from reports and databases), specific (for a certain process and location) or generic (of technology) data is one of the methodological choices to be made when applying LCA (Finnveden et al. 2009; Curran 2015). As discussed in Paper III, both specific and generic data have their benefits and flaws. Specific data often give a better picture of the specific activity, while may be less comprehensive, i.e. not include all processes or emissions. Generic data are often more comprehensive, however, do not reflect the specific processes. Primary data are rarely available in case of ICT assessments and a lot of secondary data are used (Paper I); leading to increased risk of errors, which are difficult to identify as many studies use the same data.

Being a framework for qualitative assessment SAFS does not require as much precise data for each specific process as LCA might (depending on the purpose). However, the data availability problem still arises in two ways: data available from scenario descriptions and data regarding current state of environmental aspects performance. Data about futures are inherently uncertain. Although it can be described in the scenarios as specific and precise as required if the assessment is done in collaboration with scenario development and there is a possibility of requesting data, this may still be challenging. As reflected in Paper IV, the futures studies and assessment practitioners may have different views on what and to which detail should be included in a scenario description. This may originate from different perception of aims of such studies. Futures studies are usually aimed at exploring possible, probable or desirable future developments (Börjeson et al. 2006), providing basis for discussion and learning in the process (Svenfelt 2010). Assessment studies are usually more result-oriented looking to find a specific answer to research questions. Learning from experience of combining the two approaches is that the high level of detail may not be needed in this type of assessment and that the knowledge produced in the processes may be as valuable as the end result.

Including consumption perspective in the assessment poses additional challenges. Considering a consumption perspective requires data on processes and their environmental impacts along the supply chain. This is rather complex even for current state assessments. In the case of assessing futures, this would require scenarios to include a lot of information on where specifically the goods come from and what are the conditions for technology development, environmental regulation, energy mixes, etc, in those locations. This may not always be feasible and/or not in line with the purpose of the scenarios assessed, if they were developed independently. As a way of considering a consumption perspective without data in the scenarios regarding this, assumptions can be made, as presented in Paper V and 4.3.

When assessing future scenarios using SAFS the data on current state performance regarding the chosen environmental aspects need to be gathered in order to be able to relate the environmental risks and opportunities of scenarios to today's situation. The data on current state with consumption perspective can be collected from trade statistics and input-output databases; however, those are usually presented in monetary values, providing information on only last port (not the actual country of origin). Another approach is using environmentally extended input-output databases as was done by e.g. SEPA (2011); Zeller and Degrez (2015), but those are also based on input-output tables and face problems of incompatibility of input-output databases from different countries, limited environmental data (usually GHG emissions and air pollutants), and data gaps regarding technology use. However, there has been significant development in this area in the past years (e.g. Wood et al. (2014)), which may provide better data sources for future assessments.

The choice of **functional unit** is important in LCA studies and especially in comparative ones. The role of the functional unit chosen should not be underestimated especially when comparing ICT solutions with their traditional counterparts. As was observed in Paper III the results of a comparison between environmental performance of an online and printed newspaper can be very different depending on the functional unit chosen. This is in line with other studies (e.g.

Reichart and Hischier (2002), Moberg et al. (2011), Ahmadi Achachlouei and Moberg (2015)). Figure 10 presents results of the comparison of the same online and printed newspapers (Paper II) with different functional units – per reader and week, and per reading hour.

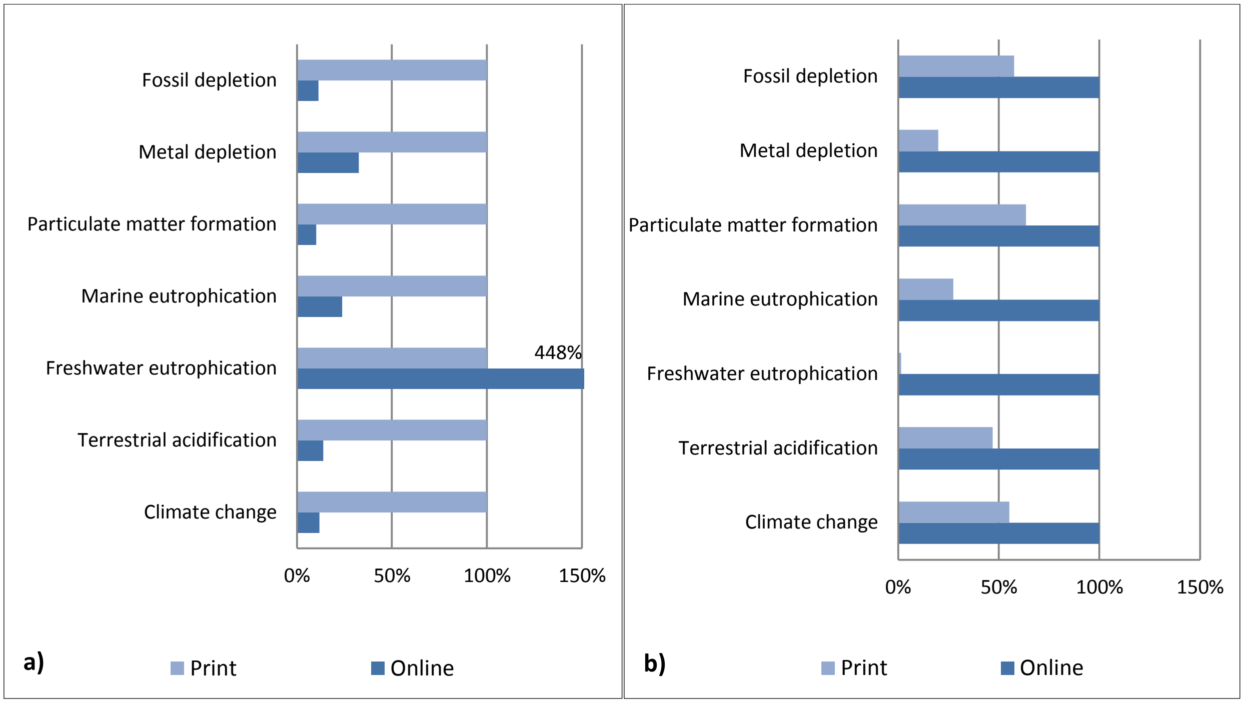

Figure 10 Environmental impact potential of Iltalehti.fi and printed Iltalehti. a) per reader and week, the printed version set to 100%. The total reading time per reader and week: 138 min (printed) and 9 min (online). Size of download for Iltalehti.fi: 100 MB per reader and week. b) per reading hour, the online version is set to 100%

This difference demonstrates that the conclusion on which newspaper – printed or online – has better environmental performance is not clear cut. The functional unit reflects the function of a product or service and in the case of online or printed media the function might not be exactly the same, making comparisons more complex. A way of reflecting this difficulty could be presenting results with several different functional units, which was done in Paper II in line with other studies (e.g. Reichart and Hischier (2002); Ahmadi Achachlouei and Moberg (2015)). This should be considered when discussing substitution of traditional products/services by ICT solutions.

Defining **scope** and system boundaries is another methodological decision to be made when starting an LCA. As discussed in Paper I the differences in system boundaries in LCAs of ICT makes it difficult to compare and relate the findings from different cases. Together with system boundaries a time scope needs to be defined. This includes defining the time period for accounting the emissions. As presented in Figure 11 one of the findings in Paper III was that including or excluding long-term emissions may have a significant effect on the results for some impact categories. This is in line with the findings of Moberg et al. (2014), confirming that considering and not considering long-term emissions when assessing ICT may lead to different results.

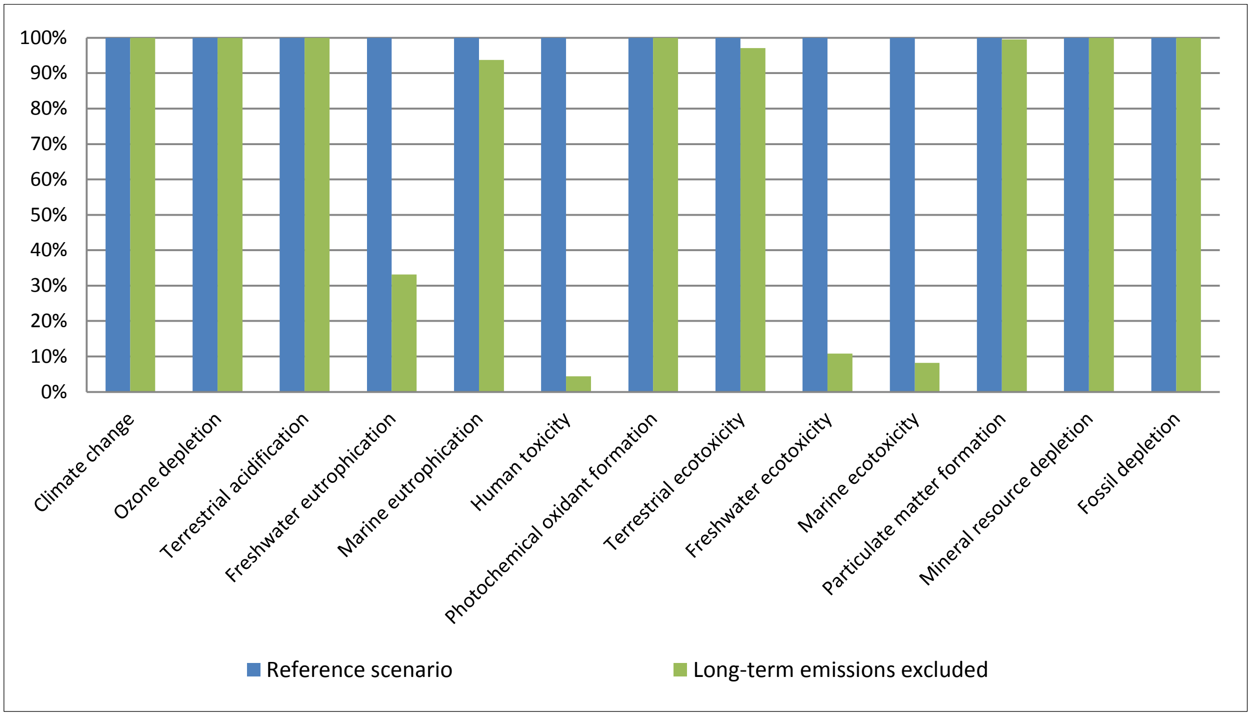

Figure 11 Sensitivity analysis including and excluding long-term emissions. Reference scenario (including long-term emissions) is set to 100% (Source: Paper III)

4.4.2 User behavior

As discussed above, assumptions on user behavior affect the resulting environmental impact of ICT products. In LCAs the information on user behavior need to be gathered or alternatively assumptions need to be made. As observed in Paper III there is lack of information on user behavior regarding ICT solutions, e.g. use of electronic media. Assumptions can be made based on statistics, presenting an average user. However, it can be argued that no one is an average user, and alternatively several types of users, e.g. heavy user, light user, sharing user, etc, can be addressed by defining a number of different assumptions. This is sometimes reflected by sensitivity analyses testing different assumptions on user behavior (e.g. Paper II and III, Ahmadi Achachlouei et al. (2015)).

In the assessment of future scenarios using SAFS the assumptions on user behavior are also important. Life styles are described in the scenarios, which makes it easier to make assumptions on user behavior for the assessment. However, different interpretations can still be made within the given scenario descriptions. For example, in Trusted communities, ICT is important and plays a significant role in the social life, partly substituting travel and providing a platform for social life and education. However, when interpreting this into number of devices and intensity of ICT use there may be different options, e.g. devices may be shared or not, the service life may be long or short, etc. In Controlled convenience the combination of materialistic society, economic growth and importance of ICT allows assuming that people have several devices per person and the service life is rather short. However, even within the defined scenario different people will have different patterns of behavior, which also leaves room for interpretation here.

4.4.3 Results presentation

The issues described above, affecting the assessment results, make it challenging to interpret and communicate the results in an easy and understandable but meaningful way. As observed in Papers III and V it may not be possible to give a straightforward answer neither from an LCA assessment of ICT nor from a SAFS assessment of future ICT societies.

However, both types of assessments provide a platform and means for learning. SAFS does not aim to provide a single answer, but rather focus on understanding of the reasons of potential environmental consequences and their drivers, and on illustrating the possibility of different future environmental alternatives. The involvement of stakeholders and actors in the assessment process is encouraged. It aims to provide learning and discussion platform for potential decision-makers in order to better understand the effects of various drivers and their combinations on the environmental consequences of future ICT societies and the role of ICT in planning for sustainability. LCAs also do not only aim for a single answer, but strive to identify and discuss hotspots in the life cycle of a product, making learning an important part of the process. Important factors and key issues affecting the results are presented and the variables can be tested in sensitivity analysis.

4.4.4 Different levels – product vs. society and present vs. future

LCA and SAFS are applicable for studies with different aims and objects in focus, and thus are useful for different purposes.

Product assessments help identifying hot spots for environmental impacts of specific products in order to address those for further product improvement. They also allow comparing different types of similar products or solutions in order to be able to choose a more environmentally preferable option. In order to consider how ICT solutions affect human activities and society overall it is important to consider environmental risks and opportunities related to ICT in a context of society. Product assessments can be used as a basis and information source for those broader, societal, assessments.

Life cycle assessment is traditionally an assessment method for products, thus naturally is applied for assessments of individual ICT solutions. However, LCA can also be applied on a more overarching societal level and for assessment of scenarios (e.g. Finnveden et al. (2013); Dandres et al. (2012); Singh and Strømman (2013)), although it is not common to assess scenarios for a whole society using LCA. The quantification of all the parameters of a scenario needed for an LCA model may be too complex. Possibilities for combinations of futures studies with environmental system analysis tools were explored by Höjer et al. (2008). The authors observe that analytical tools for environmental system analysis, such as e.g. LCA, usually require quantification of data, which is mainly possible for scenarios with short-term scope and no large trend changes. This makes the use of futures studies in combination with environmental system analysis problematic. However, recent development in Multi-regional Input-Output Analysis (e.g. De Koning et al. (2015)) may make it possible to explore scenarios of society in a quantitative way. Another way of addressing this problem could be using a framework like SAFS, adopting a qualitative approach. SAFS utilizes the principles of environmental system analysis tools, such as LCA, complemented with principles of Sustainability assessment, and does not require quantification of data and high level of detail, which makes it possible to use scenarios of any type and time frame.

Some future assessments are made using LCA (e.g. Dandres et al. (2012); Ljunggren Söderman et al. (2016)) with the help of economic modeling/simulations providing data for the LCA modeling. This way of assessing future impacts has its pros and cons. On the one hand the economic modeling provides a quantified image of the future and the assessment becomes more straightforward. On the other hand the results of simulations and therewith LCA are still uncertain, which may be more difficult to comprehend and to communicate with specific numbers presented for resulting impacts. Another issue of concern is that the models are usually based on the knowledge and structure of the present society, which may be problematic when aiming to consider more transformative changes. Another approach could be quantifying qualitative scenario descriptions based on literature, stakeholder participation and research group discussions as was done in e.g. Björklund (2012). In this way the quantitative assessment relies on several assumptions, which makes transparency of the assessment especially important in order to avoid misinterpretation of results.

Alternatively, SAFS suggests qualitative assessment of future scenarios with a life cycle and consumption perspective. The major difference here is that there is no quantitative modeling, the assessment is qualitative and the results are presented as qualitative descriptions of potential risks and opportunities for environmental impacts. This of course also has its pros and cons. As discussed in Paper V, the uncertainty is still high, which is inherent for futures studies. As discussed in Svenfelt (2010) uncertainty in futures studies is always present due to the impossibility to know the future, however, it is also common for any social and ecological system (even in the present) due to high complexity and dynamics (Berkes 2007). The purpose of futures studies is not to provide certainty about what will happen and how, but exploring different possibilities and learning about today and possible outcomes of current actions (ibid.). This could be used as a way of addressing inherent uncertainty and could assist decision-makers in making strategic decisions about an uncertain future with a long term perspective (Münster et al. 2013).

Although the assessment relies on several assumptions in the same way as in the examples described above, the results of an assessment with SAFS are presented in reasoning and discussing way. This indicates the uncertain nature and emphasizes the importance of the intermediate learning rather than final result and highlights the factors affecting the possible environmental risks and opportunities rather than actual impacts. The process of assessment is also suggested to be participatory, involving various actors and providing an opportunity for learning in the process of assessment. Although the process of performing an LCA differs, learning may also be an important outcome from an LCA.

Assessments on both levels – product and society – are important as a basis for planning for sustainability with support of ICT. Societal assessment provides a bigger picture and considers ICT in a context of society, assessing its role and potential environmental effects of different types. However, the societal assessments still need to be supported by assessments of individual solutions to provide knowledge on environmental impacts of specific products.

5 Conclusions

5.1 Impacts

Based on the overview of existing studies and supported by the case study of online newspapers it was concluded that the manufacturing and use phase of the ICT solutions play a crucial role in their environmental performance. The use phase is becoming of higher concern as the manufacturing is getting more efficient and more environmentally sound. In a similar way, energy efficiency improvements may lead to higher importance of the manufacturing for the overall environmental impact, especially in small devices. Longer service life of a device would decrease the environmental impact of manufacturing over the life cycle.

User behavior and location proved to significantly affect the resulting environmental impact of certain ICT solutions and thus define the potential contribution of those to environmental sustainability. Overall use time of a device, location (and thus electricity mix), service life of a device, and end-of-life treatment affect the significance of use or manufacturing phase as well in the overall environmental impact of an ICT product. User behavior is also important when comparing ICT solutions with their traditional counterparts.

A number of components important for environmental impacts of ICT were identified in the literature review and in the case study. Manufacturing of Integrated circuits (IC) used in ICT devices causes high impacts due to energy use, wafer production, and gold mining and processing. This contributes significantly to most of the impact categories and especially to climate change and human toxicity. ICs were found among the main contributors to the environmental impacts of desktops, laptops, servers and mobile phones. Other important components pointed out by the studies overviewed were CRT tubes and glass in CRT screens; LCD module, glass and coatings in LCD screens; power supply for computers and chargers for mobile phones; metals and plastic in computer cases.

The importance of addressing impacts other than climate change when assessing ICT was discussed based on the results of the case study and the literature review. These more comprehensive assessments are largely lacking, many studies still focusing only on energy use and climate change.

The environmental risks and opportunities for future ICT societies are closely related to a number of key issues, such as energy mix, economic conditions, life styles, technology and environmental ambition, incentives and regulation. Various combinations of those key issues may lead to different environmental consequences. Although ICT plays an important role in all the assessed scenarios, its role in contributing to sustainability is defined by the key issues listed above. It has been shown that the potential of ICT for sustainability may not be fully realized without incentives or environmental regulation. Scenario assessment illustrated that even when

ICT contribution to technology improvements and efficiency gains is high, high materialism in combination with lack of incentives and environmental regulation may lead to rebound effects counteracting the positive effects of ICT.

ICT can play different roles in a society – it may support current trends and trend changes, or drive the transformation of life styles, or support transformations driven and lead by other factors, such as e.g. economic conditions and regulation. ICT can play an important role in sustainable development, leading to decreased consumption, improvements in technology and efficiency, and support environmental incentives and regulation. However, for realizing the full potential of ICT and avoiding the risks, active policy-making is required, based on scientific knowledge on environmental impacts of ICT solutions and ICT societies.

5.2 Methods

In order to assess the future environmental impacts of ICT societies a new Sustainability assessment framework for scenarios (SAFS) was developed. Based on the principles of LCA and Sustainability assessment, SAFS allows for qualitative assessment of future scenarios with consumption and life cycle perspective. Creating and testing SAFS contributed to methodological development of assessment methods. SAFS aims to assess sustainability consequences in future in the context of a whole society and to provide knowledge and basis for discussions for ICT community and decision-makers.

In this thesis LCA was used to assess current environmental impacts of ICT and SAFS was applied for assessment of future ICT societies. Both types of assessments have their benefits, drawbacks and challenges and can be best suited for an assessment depending on the purpose of a study.

In both cases data availability is one of the challenges of assessment. ICT is a rapidly developing technology with a limited availability of data for assessment. Large variety of components and use of specific materials (e.g. high purity chemicals) in combination with small pool of data in commercial databases makes it challenging to get relevant data of good quality for LCAs of ICT. Data availability is a challenge for SAFS as well. Using a consumption perspective requires data on a large number of processes, which are currently not available in sufficient amount and detail. The inherent uncertainty of futures studies is another issue making the analysis more challenging.

LCAs require a number of methodological choices, some of which can be especially challenging when assessing ICT, such as e.g. defining functional unit, scope and system boundaries, allocation procedures, and assumptions on user behavior. These may not be a problem when making an assessment on a societal level. Although LCA may be applied in an environmental assessment of a whole society, SAFS may be better suited when there is no aim or possibility of making an assessment with high level of detail. LCAs usually require quantified data, which makes it difficult to apply for future scenarios, especially long-term explorative ones. SAFS is designed to handle those.

It can be concluded that both types of assessments – on product level and on societal level – are important to carry out. LCAs of individual ICT solutions are needed to understand the environmental impacts of ICT products and services, which can further be used as a basis for broader assessments of future impacts on a societal level, taking into account broader application of ICT and considering its potential contribution to sustainability.

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