

End-of-life implications of electronic textiles

Assessment of a converging technology

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Abstract

Contemporary innovation in the converging technology sectors of electronics and textile aims at augmenting functionality of textiles, making them “smart”. That is, integrating electronic functions such as sensing, data processing, and networking into wearable products. Embedding electronic devices into textiles results in a novel category of products: electronic textiles (e-textiles). Whereas researchers and innovators are pushing forward technological development little attention has been paid to the end-of-life implications of such future products.

E-textiles may not only entail promising business opportunities but also adverse environmental impacts. This study examines potential end-of-life implications, which could emerge once future e-textiles are disposed of. Using the methodological framework of technology assessment an overview of current innovation processes for e-textiles is established and an outlook on future applications areas is provided. Further, information on technologies and materials composition of e-textiles is mapped as a basis for assessing the prospective implications at the end of their useful life.

The findings suggest that widespread application of e-textiles could result in the emergence of a new waste stream. There are various parallels to electronic waste, which causes profound environmental problems nowadays. Risks include potential release of toxic substances during the disposal phase. And, loss of scarce materials is to be expected if no recycling takes place. This would accelerate the depletion of resources. Recycling of textile integrated electronic devices will be difficult. From the analysis it can be deduced that today’s schemes for take-back, recycling and disposal would not be sufficient to cope with waste e-textiles in an environmentally benign manner. Instead, discarded e-textiles would find their way into solid waste and increase the existing environmental problems of waste disposal.

The study concludes with recommendations for policy makers and technology developers on how a waste preventative technology design could be achieved.

Key-words: converging technology, electronic textiles, end-of-life, e-waste, environmental impacts, recycling, smart textiles, wearable computers, WEEE,

Zusammenfassung

Gegenwärtige Innovationen in den Technologiesektoren Elektronik und Textil resultieren in neuartigen high-tech Produkten mit erweiterter Funktionalität: intelligente Textilien. Für diesen Zweck werden elektronische Elemente wie z.B. Sensoren und Prozessoren in Textilien eingebettet. Mit der Verschmelzung elektronischer und textiler Materialien entsteht eine neuartige Kategorie technischer Artefakte. Die so genannten elektronischen Textilien (E-textilien) befinden sich gegenwärtig im Entwicklungsstadium und werden als viel versprechende Zukunftstechnologie mit hohem Marktpotenzial angesehen.

Dabei stellt aber sich die Frage nach den Umweltauswirkungen solcher zukünftigen Produkte. Es besteht ein Risiko, dass diese am Ende ihrer Gebrauchsphase zu Problemen bei der Entsorgung führen. Diese Studie untersucht die zukünftigen Auswirkungen von E-textilien auf Recycling und Entsorgung. Basierend auf der Methodik der Technologiefolgenabschätzung wird ein Überblick über gegenwärtige Innovationstrends und potentielle Anwendungsgebiete für E-textilien geschaffen. Ausserdem werden Informationen zu Grundlagentechnologien und Materialien zusammengestellt. Diese dienen als Basis für die Analyse der voraussichtlichen Auswirkungen auf Entsorgungsprozesse und die daraus resultierenden Umwelteffekte.

Die Ergebnisse der Studie zeigen, dass eine massenhafte Verwendung von E-textilien zur Entstehung neuer Abfallströme führen kann. Dabei bestehen Ähnlichkeiten zu Problemen mit der Entsorgung von heutigem Elektronikschrott. Umweltrisiken existieren in Zusammenhang mit der möglichen Freisetzung von Schadstoffen aus E-textilien, wenn diese nicht fachgerecht entsorgt werden. Ohne Recycling würden ausserdem wertvolle Sekundärrohstoffe verloren gehen und zur Verknappung natürlicher Ressourcen beitragen.

Das Recycling von textilintegrierten Elektronikkomponenten ist voraussichtlich schwierig. Heutige Sammel- und Recyclingsysteme für Elektronikschrott und Altkleider sind nicht auf die umweltgerechte Behandlung von E-textilien vorbereitet. Stattdessen würden verbrauchte E-textilien wahrscheinlich als Teil des Hausmülls entsorgt werden. Existierende Umweltprobleme der Abfallbeseitigung würden sich dadurch vergrössern.

Der Studie schliesst mit Empfehlungen an die verschiedenen Akteure im Innovationsprozess, darunter Innovationspolitiker, Technologieentwickler und innovative Unternehmen. Die Vorschläge zeigen Möglichkeiten auf wie das Prinzip der Abfallvermeidung bereits im Frühstadium der Technologieentwicklung berücksichtigt werden kann.

Executive Summary

Background and motivation for the research

During the last decade widespread use of electronic products has entailed rapid growth of the amount of electronic waste (e-waste) to be disposed of. Electronic products, which had once been considered high-tech, usually turn to e-waste after a short service life. Obsolete high-tech products pose immense issues at the end of their useful lives and environmental and societal problems have arisen worldwide. E-waste shows a variety of unique characteristics that differ from normal solid waste necessitating special end-of-life management: large quantities are generated, e-waste can contain hazardous substances, and there are valuable materials to be found in it. The e-waste problem has its origin in past innovation cycles of the electrical and electronic industry. Obviously, environmental and societal effects in the end-of-life phase of high-tech products have been overlooked at the time when they were developed. Thus, as a lesson learned from past mistakes, technological innovation should be accompanied by environmental assessment ex-ante to market pervasion.

This technology assessment study addresses the potential end-of-life problems of a novel generation of high-tech products: electronic textiles. E-textiles denote the concept of integrating electronic devices or materials into textiles. The products emerging from that converging technology are expected to enter mass markets in the future. That makes e-textiles a subject of scrutiny because the lessons learned from the e-waste problem suggest that mass application of high-tech products can cause problems in the end-of-life phase.

The ongoing innovation process in the converging sectors of electronics and textiles entails opportunities to prevent future disposal problems. Informed governance of innovation for e-textiles could achieve a more sustainable future. Evaluating the end-of-life implications of new technology at an early stage of development appears to be a prerequisite to embark into waste preventative innovation strategies.

Research objectives

The technology assessment conducted on e-textiles aims at raising awareness about the possible end-of-life implications of e-textiles. The purpose is to establish sufficient intelligence as necessary for adjusting innovation policies towards eco-innovation. A multidisciplinary perspective is taken combining knowledge from various domains including basic research, technology development, recycling, industry, and policy. The study attempts to find answers to the research questions below:

1. Are there similarities between today's e-waste and the properties of e-textiles?
2. Are established schemes for collection, recycling and disposal of wastes sufficient to process end-of-life e-textiles so as to mitigate environmental impacts?
3. How could mass application of e-textiles collide with the aims of European waste policies?
4. What adjustments in innovation policy could be taken in order to prevent e-textiles to become tomorrow's e-waste problem?

Target audiences of this study are actors of the innovation system of e-textiles including researchers, innovators, policy makers and stakeholders. Furthermore, experts and companies in textile and e-waste recycling may be interested to notice future change in the properties of post consumer waste streams.

The findings on the research

There are similarities between today's e-waste and the properties of e-textiles.

The relevance of electronic textiles, having the potential for generating end-of-life issues in the future was substantiated. This assertion is based on three-fold reasoning: (1) large mass flows of e-textiles can be expected if e-textiles experience break-through on mass markets, (2) there are potential issues with problematic materials, and (3) there is a risk of acceleration of resource depletion if no recovery of materials from waste e-textiles takes place.

Experiences drawn from past innovation cycles in electronics suggest that mass application can entail an e-waste problem. E-waste problems typically emerge with a delay of a couple of years after market introduction of new electronic products. There are also opportunities to avoid future problems related to e-textiles. The toxic load of waste e-textiles could be significantly lowered as compared with today's e-waste. Due to the European RoHS-Directive 'traditional' hazardous substances are to be phased out from use in future electronics. But, a risk does exist in regard to new materials and new combinations of them prospectively to be used in e-textiles. Moreover, textile embedded electronic components contain a variety of scarce materials, such as silver. There is a risk that they could not be recycled because they will be highly dispersed within a large mass flow of waste textiles. In future, there are opportunities for decreasing consumption of scarce resources if polymer electronics were to replace for silicon based electronics.

E stablished schemes for collection, recycling and disposal of wastes are hardly sufficient to process end-of-life e-textiles so as to mitigate adverse environmental impacts.

From the present day situation it can be assumed that the biggest fraction would enter solid waste disposal channels. That is because the end-users may be unmotivated or unable to separate old e-textiles from household waste because electronics will be embedded into textiles in unobtrusive ways. End-users were identified as the key junction for the end-of-life fate of old e-textiles as they decide in which recycling or disposal channel they discard them.

If e-textiles were to enter today's recycling schemes they would most likely be sorted out and disposed of. Recycling schemes in operation are not prepared to separately collect and process textiles with embedded or integrated electronics. The organization and financing of take-back and collection systems is hardly adjusted for this novel category of waste. Technically and economically, it appears hardly feasible to process such blended feedstock by means of existing recycling facilities for WEEE or textile products respectively. Thus, scarce materials would get lost in waste streams.

Mass application of e-textiles could collide with the aims of European waste policies.

From today's perspective environmentally benign management of waste e-textiles is not guaranteed. Disposing waste e-textiles together with municipal solid waste would thwart the goal of the WEEE-Directive to facilitate reuse and recycling of materials. Further, environmental policies could be violated by the risk of formation and release of toxic substances if e-textiles would be landfilled or incinerated.

Potential conflicts with the Basel Convention could emerge if e-textiles were to be exported towards foreign second hand markets as part of reusable clothes. Embedded electronic components may be considered waste, being subject of the Basel export ban for hazardous wastes. Co-shipment of waste e-textiles within reusable clothes could fuel the debate around illegal e-waste exports destined for backyard recycling in developing countries.

The research has found little evidence that a waste preventative approach is properly implemented in the innovation system for e-textiles. The same can be said in regard to the principle of Extended Producer Responsibility. Among researchers and innovators a generally low awareness on these policies seems to prevail in practice. Obviously, coherence is lacking between waste policies and innovation policies. If key actors within the innovation system of e-textiles lack awareness regarding waste policies then a risk exists that mistakes of past innovation cycles in electronics are repeated and future e-waste problems are programmed.

A adjustments in innovation policy that could be taken in order to prevent e-textiles to become tomorrow's e-waste problem.

The study puts forward recommendations for governance of innovation processes that could help pushing technology trajectories of e-textiles into more sustainable pathways:

- Improving the coherence between environmental/waste policies and innovation policies
- Adopting a proactive approach in implementation of waste policies in the innovation process.
- Raising awareness among key-actors in the innovation system in regard to the waste prevention principle.
- Fostering the implementation of the waste prevention principle in the goal definition of publicly funded R&D projects.
- Evaluating whether e-textiles need to be considered in the European WEEE-Directive.
- Informing actors in e-textiles innovation about the existing environmental/waste regulation concerning electronic products.
- Monitoring of discarded e-textiles arising and their occurrence in waste streams. Establishing adequate collection, recycling and disposal schemes for EoL products that contain embedded electronic components.
- Facilitating innovation in the recycling sector.
- Searching for ways to motivate and educate end-users to feed old e-textiles into recycling schemes.

Finally, possibilities are discussed on how design principles of green electronics could be adopted for development of e-textiles. It is recognised that, in the context of converging technologies, few of them would be applicable without revision. Thus, addressing the R&D community, recommendations are formulated to rethink the existing paradigms for eco-design and green electronics.

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1 Introduction

*"While we cannot predict the future, we need to prepare for it."
(Fadeel et al., 2007)*

1.1 Background

Technological innovation is held to be one of the most forceful drivers in modern societies. Public or private decision makers strongly believe in the beneficial outcome of progress in science and technology. The European Commission is convinced that *"Our future depends on innovation"* (EC, 2006) p.2). Innovation is by nature a multidisciplinary task. In the near future various technological disciplines are anticipated to converge (Anton, Silbergliitt, & Schneider, 2001). One does not need to go as far calling that process a new technology revolution but it seems evident that a fusion of formerly distinct domains of technology and industry can entail an emergent phenomenon.

One sector of innovation that has caused disruptive change in production and consumption patterns during the last few decades is information and communications technology (ICT). The so-called "information society" enjoys many benefits made possible by the use of ICT such as job creation, increased productivity, and new lifestyles. However, the flip side of the coin is an immense environmental footprint of ICT (Plepys, 2004). Accelerated depletion of natural resources and disposal of approximately 9.1 million tonnes electronic waste (e-waste; WEEE) per year in the EU are the most prominent ones among the adverse environmental effects of high-tech products (Huisman & et al, 2007). A good part of today's problems around e-waste roots in the fact that the end-of life phase had often been overlooked at the time when the ICT products were developed. Obviously, past innovation policies have missed to evaluate ex-ante the entire life cycle of new technology and to implement waste preventative strategies.

A recent innovation trend in ICT is about embedding of electronic devices in every day objects, making them smart. That technology, being still basic research today, is likely to constitute the base of tomorrow's society across many sectors of industry. If new generations of electronics are being developed today there are opportunities to do things better this time and to avoid the creation of the next e-waste problem. There is an urgent need *"to act wisely more often so as to achieve a better balance between the benefits of innovation and their hazards"* (EEA, 2001) p.5. Hence, the benefits and the potential risks need to be assessed and communicated simultaneously to the genesis of converging technologies (Anton et al., 2001).

Of course, it is not easy to anticipate possible consequences of novel technologies at an early stage of development. But that is not a reason to neglect risks or to postpone preventative measures that aim to avoid adverse side effects. On the contrary: this puts increasing responsibilities on key-actors in science, engineering, business, and government to make informed decisions. The increasing pace and complexity of innovation processes require that innovation policies foster environmentally conscious design. Governance of innovation processes can push technology trajectories into more sustainable pathways. The European innovation policy aims at proactive governance of innovation in order to achieve sustainable global competitiveness. The European Commission encourages eco-innovation aiming at increasing eco-efficiency of future technology generations (EC, 2005b).

This technology assessment study addresses the potential end-of-life problems of a novel generation of high-tech products: electronic textiles (e-textiles). The attention towards end-of-life aspects results from the proposition that they are to be considered a relevant environmental and societal issue and the assertion that they are able to be influenced at an early stage of innovation.

1.2 Innovation in e-textiles and environmental implications

Innovation in recent years has shown hype around textile products providing novel and advanced functionality, a concept, which is wrapped into the term “smart textiles”. Smart textiles denote the concept of integrating materials or devices from other domains of technology into textiles (making them smart). Among the various approaches towards smart textiles there is a trend to utilize textiles as a platform for ICT. The products of those converging technologies are electronic textiles (e-textiles). Textile integrated sensors and actuators, lightening elements and electronic devices constitute some of the enabling technologies for e-textiles (Tang & Stylios, 2006). Wearable computing indicates a far-reaching vision of computing devices embedded into garments being unobtrusive but ubiquitous in daily life (Hilty, Behrendt, Binswanger, & al, 2005). Hot spots of innovation in e-textiles are the market segments of consumer garments, health care, work wear, and military. Integration of electronic functions into garments is expected close to market entry and clothes with incorporated electronic devices (e.g. inbuilt mp3 player, solar cells) have already been commercialised (Mecheels, Schroth, & Breckenfelder, 2004). There is a potential that smart textiles will pervade the mass market within one decade (BCC Research, 2007).

E-textiles may not only entail promising business opportunities but also environmental impacts at the end of their useful life. Whereas innovators and companies are pushing forward with technological development there seems to prevail a lack of awareness on potential environmental impacts. As yet, no studies have been made publicly available examining possible end-of-life implications of e-textiles and neither research literature nor conference programmes reveal the existence of any discussion about their environmental implications.

Findings of a technology assessment study on pervasive computing¹ suggest that problems in end-of-life treatment are likely to emerge because established e-waste collection and recycling schemes seem to be unable to cope with miniaturised and embedded ICT (Hilty et al., 2005). Also increased demand for scarce raw materials and potential content of harmful materials needs to be taken into account (Köhler & Som, 2005). Mass application of electronic devices, which are embedded into commodities of daily use, could amplify consumption of scarce resources if no material recycling takes place.

Translated to the case of e-textiles one can assume similar effects. As two types of relatively short living mass applications, textiles and ICT, are about to converge there is a risk of increasing material and energy flows during the product life cycle. If existing recycling schemes were not sufficient to recover valuable materials from discarded e-textiles they would be lost within the mountains of textile waste. New risks may emerge due to the fact that textile embedded ICT is put into completely new context of production, use, and disposal. Particularly the dissipation of potentially hazardous materials in a large amount of textile products is of concern. While some traditional hazardous substances will be phased out soon new materials and combinations of them will be used for future electronics and little is known on their environmental and health effects.

Experiences drawn from past innovation cycles teach that risks have often been underestimated or neglected (EEA 2001). EEA illustrates at the example of polychlorinated biphenyls (PCBs) what can happen if generations of technologies are developed and up-scaled without taking risks into account (ibid p.64). PCBs are a group of chlorinated organic compounds showing superior technological properties. But there were early warnings about harmful effects for human health and environment. Nevertheless, PCBs had widespread use for tech-

¹ Pervasive computing provides an overall vision on a possible future of ICT where e-textiles would fit into [see 3.1.2].

nical applications until the eighties of the 20th century before they were banned eventually. PCBs are one of the reasons why Waste Electrical and Electronic Equipment (WEEE; e-waste) has evolved to be a big environmental and societal problem (Leung, Wei Cai, & Hung Wong, 2006). Electronic products, being once considered high-tech turned to hazardous waste due to the risk of PCB contamination (among other toxic substances found in it). EEA concludes that earlier control of PCBs would *“have resulted in a more manageable, less costly problem than we are faced with today”* (EEA 2001 p.71).

Contemporary problems with e-waste result from a couple of issues like that. They have often been neglected in the beginning and then accumulated over the years. While ICT has experienced tremendous growth due to break-through on the mass markets the problem of waste ICT has grown up to a large-scale issue worldwide (UNEP 2008).

From a policy perspective, it appears crucial to learn from such lessons of past innovations in ICT. They suggest that technological development needs foresight and governance in order to prevent future problems in the end-of-life phase of products. That means in the case of e-textiles: Environmental implications that could possibly emerge during the life cycle of future products need to be addressed already at an early stage of innovation process. As long as e-textiles have not yet pervaded mass market there is an opportunity to steer development towards environmentally benign trajectories. This would make it easier to meet the objectives of European environmental and waste policies in future.

Governance of the innovation for e-textiles appears necessary and possible in the light of normative frameworks such as European innovation policy and waste policy. The European Waste Framework Directive stipulates a waste preventative principle to be applied already during the development stage of technologies (EP, 2006). Looking at the innovation process in e-textiles against this backdrop the question arises as to how research institutes and innovative companies that are interested to place themselves in a strong position at future markets could implement design for recyclability already in the present stage of development.

1.3 Purpose of the study

The main objective of the study is to examine possible future end-of-life implications of electronic textiles. The research attempts to combine knowledge from various sectors including research, technology, recycling, industry, and policy. First, an overview over recent trends in technology development and application of e-textiles is provided. Further, the innovator's awareness of end-of-life aspects and their attitudes towards environmentally conscious technology design is explored. A closer look was taken at materials composition to be found in e-textiles. Further, recycling and disposal schemes for textiles and e-waste are studied and their ability to cope with end-of-life e-textiles is analysed. Finally, it is analysed whether objectives environmental and waste policies could be met in future. The study finishes with recommendations as to how waste prevention principle and design for recyclability could be implemented in the current innovation process.

The purpose of this report is two-fold: first to raise awareness about the possible end-of-life implications of e-textiles and second to provide relevant knowledge needed for informed decision making and policy setting. The results of this multidisciplinary perspective may be useful for adjustments of development in e-textiles towards eco-innovation.

Target audiences of this study are actors of the innovation system of e-textiles including researchers, innovators, policy makers and stakeholders. Furthermore, experts and companies in textile and e-waste recycling may be interested to notice future change in the properties of post consumer waste streams.

1.4 Research questions

The research questions are:

1. Are there similarities between today's e-waste and the properties of e-textiles?
2. Are established schemes for collection, recycling and disposal of wastes sufficient to process end-of-life e-textiles so as to mitigate environmental impacts?
3. How could mass application of e-textiles collide with the aims of European waste policies?
4. What adjustments in innovation policy could be taken in order to prevent e-textiles to become tomorrow's e-waste problem?

1.5 Scope, Definitions, and Limitations

Scope:

- The topic is on electronic textiles (e-textiles) forming a segment within the spectrum of smart textiles. E-textiles are seen as the result of converging technologies at the intersection of ICT and the textile industry.
- The focus of the study is on the end-of-life phase within the product life cycle of future e-textiles.
- The study takes a European perspective at innovation systems and environmental policies.
- A time horizon of one decade was applied in regard to the innovation perspective. The end-of-life effects of e-textiles can reach further ahead of course.

Definitions

For the purpose of this study the term electronic textiles (e-textiles) refers to electronic devices that are closely attached to, embedded in, or integrated in textiles. Electronic devices include conductive wiring, printed circuit boards (PWB), active and passive electronic components, light emitting elements, electrically powered mechanical and thermal active elements, and power sources such as batteries, solar cells (PV), or thermo generators. Textiles are mainly referred to as consumer textiles (e.g. garments) if not stated differently.

The term "e-waste" refers to electronic waste and is commonly used synonym to Waste Electrical and Electronic Equipment (WEEE). However, the term WEEE is tightly defined by European regulation (EC, 2003). Post-consumer e-textiles may not fall under the current definitions of that directive as listed in its Annex I B (ibid). Therefore, the term e-waste is used.

Limitations of the study

The scope of environmental assessment was limited to direct aspects (first order) while secondary and tertiary effects were not investigated. Legal implications were not analysed.

1.6 Methodology

1.6.1 Methodological background - Technology Assessment

Assessing the implications of a novel technology is very much a question of the perspective on it. Technology is a construct of society, which, in the first place, serves to satisfy societal or individual needs. Such needs can be of technical, economical, or existential nature. However, technology does, as a rule, not only interact with society but also with the environment; directly or indirectly through society. The interaction with the environment can be intended. Normally, technology also influences environment in an unintended (and often unknown) manner. The ways in which these interactions with the environment take place depends on the ways in which the technology is applied in society. Assessment of a technology from an environmental perspective needs to consider the ways in which society uses that technology and how society deals with its side effects. Environmental impacts caused by end-of-life e-textiles depend on waste policies and management procedures and are likely to differ widely among different countries. Therefore, this study examines technological features of e-textiles and analyses them in the light of innovation and waste policies.

The methodological framework of this study is technology assessment (TA). Among the various conceptual approaches towards TA a more recent definition was coined in the TAMI project (Europäische Akademie GmbH, 2004) p.4):

“Technology assessment (TA) is a scientific, interactive and communicative process which aims to contribute to the formation of public and political opinion on societal aspects of science and technology.”

According to this definition TA not only examines implications of technology but also puts the analysis into societal context. TA is seen as an instrument for scientific policy advisory deliberately placed at the interface between science and society (Decker, 2007b). It depends on the institutional tradition which purpose is emphasized in TA: support for societal opinion formation, for political decision-making or for the process of public participation in setting innovation policies. This study on e-textiles is to be placed within the second of the aforementioned approaches: advisory for decision-making within the innovation process. As such, the approach of this study is an inductive analytical one rather than a communicative / discourse-oriented one.

According to (Grunwald, 2007) TA utilizes prospective insights into future effects of technology for the support of society in opinion formation and decision-making. While TA is neither able nor legitimized to actually determine public opinion or to decide political issues in questions it is broadly acknowledged that TA is a constructive approach. TA aims to contribute to better-informed policy setting by early recognition of possible adverse effects. In contrast to science road mapping, technology forecast of futurology, which merely (try to) predict future, TA is build upon the assumption that it is possible to shape future in a proactive manner. Particularly in the context of sustainable development it has been argued that TA can introduce prospective insights into early stage of the innovation process. Early warnings could be used to govern innovation in order to avoid adverse trajectories (Paschen & Petermann, 1991).

The idea that the future can be proactively shaped so as to achieve more sustainable technological pathways is a basic proposition of this study on e-textiles. Its aim is not to predict possible futures of e-textiles but to identify critical trends in the upcoming technology that

could jeopardise a sustainable development. Moreover, the study is based on a constructive approach² for recommendations are proposed on how the innovation system of e-textiles could be adjusted in order to minimise future end-of-life issues.

As e-textiles will not become adopted by society over night but over a longer period of time so will their environmental impacts be changing over time too. In fact, new technologies emanating from an innovation process have a twofold lifecycle: First, the life cycle of the technology that spans from introduction/childhood, over growth/adolescence, saturation/maturity (Grübler, 2003) pp. 51-55). During their childhood novel technology usually undergo an innovation process prior to their introduction to the market. It includes basic research (frequently within academia), goes over to applied research, product development, and finally commercialization of products. Actually innovation processes often do not obey a pathway as linear as sketched above. It knows numerous feedback cycles and interactions among actors in research, industry and society. Nevertheless, if a technology is successful during its lifecycle then products will be released onto the market. Those products in turn have their own life cycle: from production, to use to disposal – from cradle to grave. Technology is interacting with society and the environment during all these stages of the product lifecycle.

When the environmental implications of a novel technology, such as e-textiles, are of interest a life cycle perspective is appropriate to look at them. However, this study is not a life cycle assessment (LCA) for that methodological framework is suitable only to be applied for assessing the product life cycle. LCA necessitates detailed information (life cycle inventory) on environmental impacts of materials and production processes, which are not available in the case of e-textiles. That is a principal lack of data due to the fact that the technology life cycle has not yet resulted in successful products at the market (apart from some prototypes). Since the future is open, it is not possible to predict in detail how the technology will evolve and how future e-textiles will look like beyond prototypes. Therefore, quantitative LCA of e-textiles appears not feasible at the moment. Instead, a qualitative life cycle approach is adopted using generic information that can be drawn from existing technologies such as ICT and traditional textiles.

1.6.2 Methodological approach of the study

The research was undertaken in the framework of a master thesis project in the period from June to September 2008 and carried out by the author. A qualitative inductive research design was chosen whereby (Creswell, 2002) served as a general guideline. The reason for use of qualitative methods was the principal absence of life cycle inventory data concerning the emerging technology under study. Direct empirical evidence is hard to establish for a technology that is still in a nascent phase of development. Thus, technology assessment (TA) was conducted as a scientifically grounded framework of research. TA structure was adopted from the setting that has been proposed by the TAMI project (Decker, 2007a). (see fig. 1-1). A TA-procedure in compliance to the TAMI guideline appeared to be a suitable approach for the following reasons: First, the project design needed to facilitate the creation of a knowledge base embracing the technological, social, and policy dimensions of e-textiles. Second, the TAMI approach is widely accepted in the European context. It has been outlined in a collective process including numerous TA institutions and is a TA approach recommended by EPTA (EPTA, 2008).

² Noteworthy to mention that this study did not perform a transdisciplinary approach and was therefore not in line with the methods of "Constructive Technology Assessment" as outlined by (Schot & Rip, 1997)

TA project design starts with a preparatory research phase called situation appreciation. That phase aims at establishing comprehensive enough insights as necessary to set realistic and correct project goals. It includes mapping of existing knowledge base and identification of knowledge gaps/needs. Next follows goal setting whereby the intended impact of the research is outlined in accordance with a typology of impacts spanning from “raising knowledge, “forming attitudes and opinions”, and “initialising actions”. (Decker, 2007a). In project design the scope of the research is defined and methods to be applied are chosen. Also quality criteria for the research shall be defined. Finally implementation of the main project takes place.

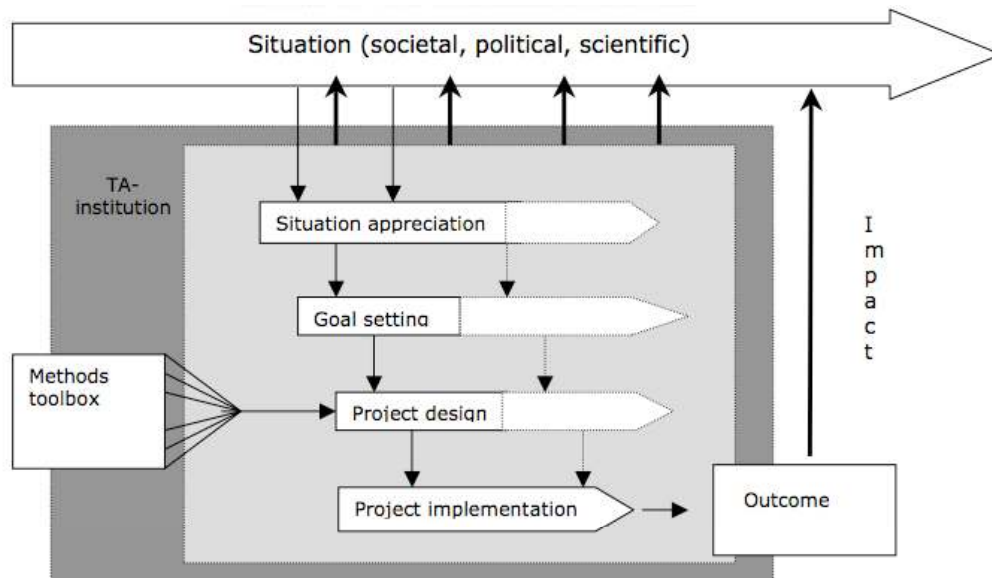


Figure 1-1 TA project design as proposed by the TAMI project. Source: (Bütschi et al., 2004)

1.6.2.1 Procedure during situation appreciation

Preparatory research was conducted in the framework of assignment work prior to the thesis period (Köhler, 2008). The purpose of this assignment was to explore the relevance of the topic and to establish field competence. The preparatory study focused on smart textiles as a preliminary scope of the technology under examination. As starting point, information regarding environmental impacts of smart textiles were sought after in science publications and the Internet.

Next, systematic literature review was conducted on technology and application of smart textiles to obtain an overview over the state of technological development. The survey of scientific literature databases included Lund University library service ELIN³ as well as TOGA textile database⁴. Also, Internet sources were screened for company communication, media coverage and tech-blogs related to smart textiles. Internet search yielded an abundance of hits, which were roughly screened and a number of articles were taken into account. The attempt to establish information on market perspectives in the smart textile area yielded no valid results since such studies, being matter of proprietary consulting, are too expensive to purchase. Thus, only abstracts or press coverage were accessible.

³ Electronic Library Information Navigator, Lund University

⁴ TOGA (c) FIZ Technik is an abstracting service for German and international literature in textile research and technology.

All papers and reports were screened using search function and information on materials, technology, and expected applications was extracted, aggregated and structured. A preliminary environmental assessment was carried out based on a life cycle perspective. In order to analyse the ascertained environmental implications of smart textiles, a conceptual framework was adopted from (EITO, 2002), which distinguished between two levels of impact, that were first order aspects and second order aspects⁵.

1.6.2.2 Goal setting

Findings from situation appreciation suggested that there seemed to be a prevailing lack of awareness and knowledge in regard to environmental implications at the end-of-life of e-textiles among innovators (in research as well as companies in the field). Review of research literature, conference schedules, and corporate communications did not reveal the existence of any discussion about that issue. It was further recognised that key actors putting innovation policies into practice may endure a lack of knowledge about the same issue. Concluding, it was found that current innovation process lacks a comprehensive view on relevant aspects of the technology created.

Thus, project goals were devised to generate basic knowledge necessary for:

- (1) raising awareness on possible end-of-life implications of e-textiles among actors in the innovation system and,
- (2) making informed decisions fostering environmentally benign innovation trajectories.

Quality criteria defined for this thesis work:

- scientific soundness: fulfilment of the academic requirements for thesis work in the Master of Science in Environmental Management and Policy programme at IIIIE; Adoption of good practice in TA,
- relevance: usefulness of the results for the audience groups,
- neutrality and independency from particular interests of actors in the innovation process,
- interdisciplinary: combining knowledge from various domains of technology and society.

1.6.2.3 Project design

Based on the insights gathered during the phase of situation appreciation a research proposal was drafted. The draft proposal was presented and discussed with members of the StEP⁶ initiative on the occasion of the initiative's general assembly 2008. The feedback given at that event helped to refine the research questions and the scope of this study as follows:

First, the scope was narrowed to e-textiles. It was recognized that the concept of smart textiles was too broad and heterogeneous to be dealt with in the framework of a thesis project. The reason to look at e-textiles as an example for converging technologies was also justified by the environmental relevance that both basic technologies (ICT and textiles) already exhibit. They form both a mass market and generate considerable material and energy flows worldwide. Also, both technologies (and the involved industries) are known to have immense environmental footprints. Finally, there are severe disposal issues related to each of them.

⁵ The framework knows also third order aspects e.g. rebound effects. But they were out of scope in this study.

⁶ Solving the E-waste Problem

Second, the life cycle perspective was focused on the end-of-life phase of e-textiles. This was necessary for reducing the complexity of the analysis within the short timeframe of the thesis project. The reason to focus on the end-of-life phase was: Results from situation appreciation suggested that converging product life cycles of ICT and textiles are likely to entail new environmental effects above all in the disposal phase.

Third, with the StEP initiative, one audience group was identified that considered the topic relevant and expressed their interest. Interactions with the StEP initiative also determined the purpose of the study: the selection of a constructive approach rather than a pure descriptive, analytic one.

1.6.2.4 Procedure during project implementation

Literature review was carried on to establish information on innovation processes, policies and stakeholder views. One drawback in information availability was due to the fact that neither fairs nor conferences could be visited during the project period. Within the innovation system of e-textiles expert communication mainly takes place at such events. Literature was also reviewed to yield a list of experts in e-textiles that came into question as interview partners. Finally, insights into recycling and disposal schemes of both products groups: ICT (e-waste/WEEE) and textile (post consumer garments) were established.

Expert interviews among researchers and firms in the field of e-textiles were conducted. The purpose of interviews was to validate and complement the findings from literature review. Furthermore, the expert's knowledge on and attitudes to environmental policies, regulations and environmental design principles were explored. The expert interviews did not aim at empirical robustness; instead they provided a snapshot of the present R&D priorities and the prevailing attitudes towards eco-innovation in the sector.

Data sampling: Potential interviewees were selected according to their authorship of scientific publications or reports as well as conference contributions. Moreover, contact persons mentioned in outreach materials of participating projects in publicly financed R&D clusters were approached. Some interviewees recommended additional experts. As for firms, contact persons were approached based on recommendations from key-managers within public-private research clusters of privately run innovation promoters. In total 63 researches and 25 companies were contacted and requested for an interview by email (followed by phone calls). The response rate was 44 %. 39 interviews were conducted (31 researches and 8 companies). A list of all interviewees is attached to the report (Annex I).

Data gathering: Most interviews were done by phone. Two interviews took place in a face-to-face setting; six respondents answered based on a questionnaire. 56% of the respondents came from Germany (see Annex I). The experts were asked open-ended questions based on questionnaire (see Appendix II). During the interviews the questions were adopted according to the expertise of the respective interviewees. Information provided by the interviewees were aggregated and saved in minutes, which were structured according to the same questionnaire. The explanations regarding terminology and technology were crosschecked with publications of the respective interviewees (whenever available).

A second batch of expert interviews was conducted to explore the end-of-life implications of e-textiles. This time, 6 experts in the field of recycling and disposal from research and industry were interviewed (see Appendix I). Experts were challenged with the previously obtained insights into prospective materials content and product design of e-textiles. The interviews mostly evolved around technical issues and followed a loose structure. Key statements and opinions were noted in minutes.

Analysis: Results from the interviews were anonymised and condensed whereby interviewee statements were interpreted and similar assertions were aligned (preserving the frequency of similar statements). Aggregated interview results on terminology and technology were compared with the findings from literature. Results on interviewee's opinions regarding policy were also aligned and categorized whereby minority opinions were preserved. Results of the analysis provide insights in present day trends and mainstreams within the R&D field.

Overall, analysis was grounded on abductive reasoning⁷. Anticipation of implications on recycling and disposal systems was approached by the means of foresight, trend extrapolation and projection. For this purpose, simple scenarios on technological development and market diffusion of e-textiles were set up and set into contrast to known issues in contemporary EoL treatment. Findings from foresight were compared to lessons learned from the e-waste problem, which served as a general yardstick for analysis. Moreover, statements from the second batch of interviewees were considered. Analysis was generally facilitated by the author's background knowledge on electronics and ICT as well as e-waste recycling⁸. Recommendations for eco-innovation were elaborated in discussion and exchange of ideas with experts being members of the StEP initiative.

1.7 Outline of the report

Chapter 2 introduces the phenomenon of e-waste as an environmental and societal problem having its roots in past innovation cycles of the high-tech sector. Furthermore, contemporary policy approaches to tackle the e-waste problem are briefly introduced.

Chapter 3 provides a review over the recent innovation system for e-textiles emanating from the converging sectors of technology in ICT and textile industry. Moreover, recent technological trends and visions on e-textiles are looked at as well as envisioned application areas and market perspectives of them.

Chapter 4 takes a look at actors involved in the innovation system and what attitudes and knowledge they have about end-of-life implications of e-textiles. The chapter is based on literature review and results from the expert survey.

Chapter 5 provides a background on the anticipated materials composition of future e-textiles, based on literature review and results of the expert survey.

Chapter 6 puts forward a discussion on possible environmental and societal problem of e-textiles at the end of their useful life. Further, the ability of recycling and disposal schemes to cope with old e-textiles is discussed.

Chapter 7 presents a wrap up of the findings of the study and summarises answers on the research questions. Addressing the fourth research question, recommendations are proposed on how current innovation processes in e-textiles may be adjusted so as to avoid e-textiles to become the e-waste problem of the future.

Chapter 8 critically reflects upon the methods applied in this study and outlines further research needs.

⁷ Also called the "inference to the best explanation".

⁸ The autor holds professional experience as technical auditor within the Swiss e-waste recycling scheme (SWICO) (ca. 30 audits in e-waste recycling companies between 2002 and 2007). During the same period he had been involved in TA-research concerning pervasive computing, RFID and nanotechnology.

2 The e-waste problem

2.1 Definitions of e-waste

Electric and electronic equipment (EEE) turns to e-waste at the end of its useful life. This is usually the case when the value on the marketplace becomes equal zero or negative. Various reasons can cause the market value to drop: malfunction, obsolescence or replacement by newer products. Some products undergo a second hand use phase before they are scrapped (reuse) but eventually all EEE enter the end-of-life (EOL) phase and thus become Waste Electrical and Electronic Equipment (WEEE) or e-waste respectively. OECD considers “A ny appliance using an electric power supply that has reached its end-of-life” as e-waste (OECD, 2001). While the term e-waste is a generic one that encompasses various forms of end-of-life electronic equipment the term WEEE is defined by European regulation. In Article 3 the WEEE Directive (EC, 2003) explains that: “WEEE means electrical or electronic equipment which is waste [], including all components, subassemblies and consumables which are part of the product at the time of discarding”. Annex 1 of the same directive specifies this definition by means of a list of 10 categories of electrical and electronic appliances that fall under the scope of the directive. Nearly 94% of the WEEE arising in Europe belongs to the following categories as listed in the WEEE-Directive (see fig. 2-1) (Huisman & et al, 2007):

| | |
|---------------------------------------|------------|
| 1 Large household appliances | ... 49 % |
| 2 Small household appliances | ... 7 % |
| 3 IT and telecommunications equipment | ... 16.3 % |
| 4 Consumer equipment | ... 21.1 % |

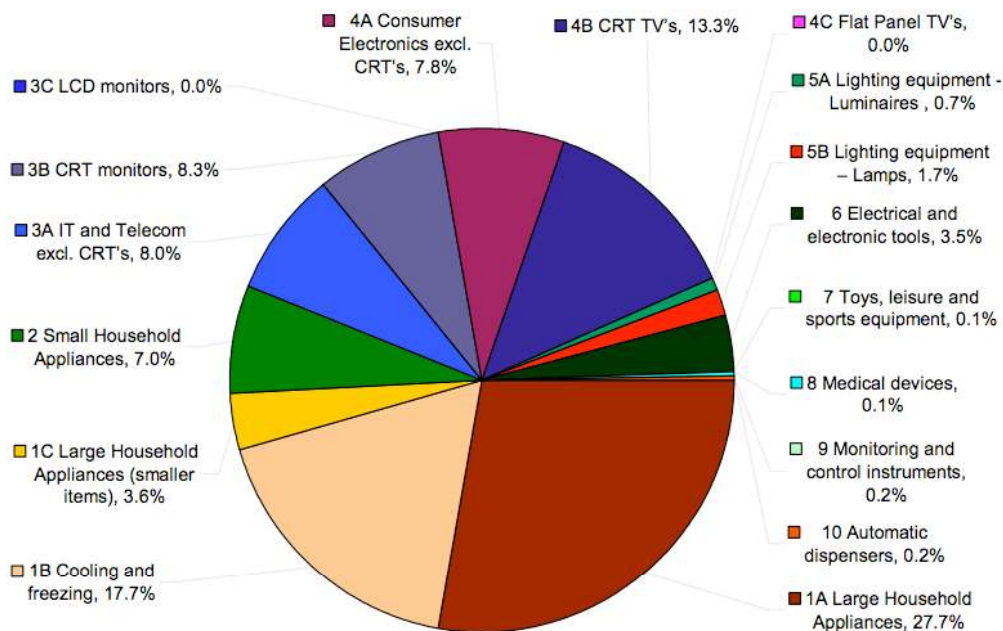


Figure 2-1 Categories of devices found in WEEE in Europe 2005
Source: (Huisman & et al, 2007)

2.2 E-waste: the dark side of high-tech

Globally, e-waste is subject of growing concern. Greenpeace warns: “A dangerous new waste stream is rapidly emerging.” (Cobbing, 2008) p.5., and Basel Action Network adds: “electronic waste, is growing up alongside the proliferation of electronic products” (Basu, 2008). The European Environmental Bureau (EEB) argues that the rapid growth of e-waste flows worldwide is of particular concern because technological innovation for new Electrical and Electronic Equipment (EEE) entails the fastest growing markets among the manufacturing industry (EEB, 2001). According to the OECD e-waste is one of the waste streams that grows fastest globally and UNEP considers e-waste being a priority waste stream (UNEP, 2008).

Electronic products, which had been considered high-tech at the time when they were produced, become obsolete very quickly and turn to e-waste. Computers have an average lifespan of only two to four years in developed countries (Greenpeace International, 2008). Mobile phones for instance have an average useful life of 18 months and are to be disposed of thereafter (The Environmental Literacy Council, 2007). Taking that into account one can assume that many of the 183 million computers and 674 million mobile phones that were sold globally in 2004 have already turned to e-waste by now (2008). It has been estimated that already by 2004 30 million tons of PCs and CRTs had been scraped and mostly landfilled (Plepys, 2004). Nevertheless, global sales numbers increase steadily as economies in transition (like China and India) now form new markets for EEE. In 2004 grow rates for computer sales were 11.6% and 30 % for mobile phones. It is predicted that by 2010 716 million new computers will be put on the global market (ibid). Fig. 2-2 shows the dynamic increase in PC sales and WEEE arising within the past decades.

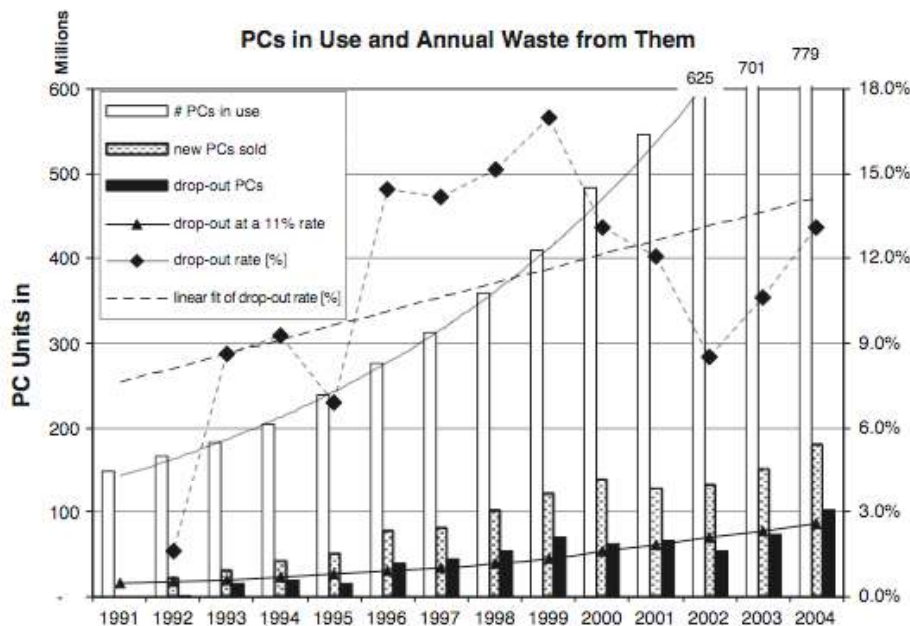


Figure 2-2 Global PCs in use and waste PC arising from 1991 to 2004
 Source: (Widmer, Oswald-Krapf, Sinha-Khetriwal, Schnellmann, & Boni, 2005) p.443)

Obsolete high-tech EEE have evolved to pose immense issues at the end of their useful lives as they entail many adverse environmental, social and economic distortions. E-waste shows a variety of unique characteristics that differ from normal municipal solid waste. There are three fundamental reasons why e-waste constitutes a special problem necessitating special end-of-life (EoL) management:

1. The e-waste mountains: worldwide a huge quantity of e-waste is generated each year and mass flow is growing rapidly.
2. The toxic load: content of hazardous substances in e-waste and the hazard of their generation in during improper disposal and recycling operations.
3. Resource depletion: The content of valuable and scarce materials results in exhaustion of natural resources if no recovery takes place.

2.2.1 The e-waste mountains

Since the early nineties of the 20th century the mass flows of obsolete electronic goods has seen tremendous increase. 20 to 50 million tonnes of e-waste is generated annually around the world (Greenpeace International, 2008). About 315 million personal computers were discarded only in 2004 after a useful life of less than 4 years in average (Plepyts, 2004; UNEP, 2006). Within the EU estimated 7 to 9.1 million tonnes e-waste (WEEE) are generated of per annum while only 2.1 million tonnes are separately collected and recycled (Huisman & et al, 2007). Yet more alarming is the steady increase in that mass flows and the prospect of further substantial growth (see figure 2-3). While in the EU the amount of e-waste generated is expected to increase by 3–5% each year developing countries will see a factor 3 increase until 2010 (UNEP, 2006). To illustrate: in the EU the WEEE generation has risen from estimated 14 kg per capita in 1998 to up to 20 kg per capita and year recently (Herten, 2008).

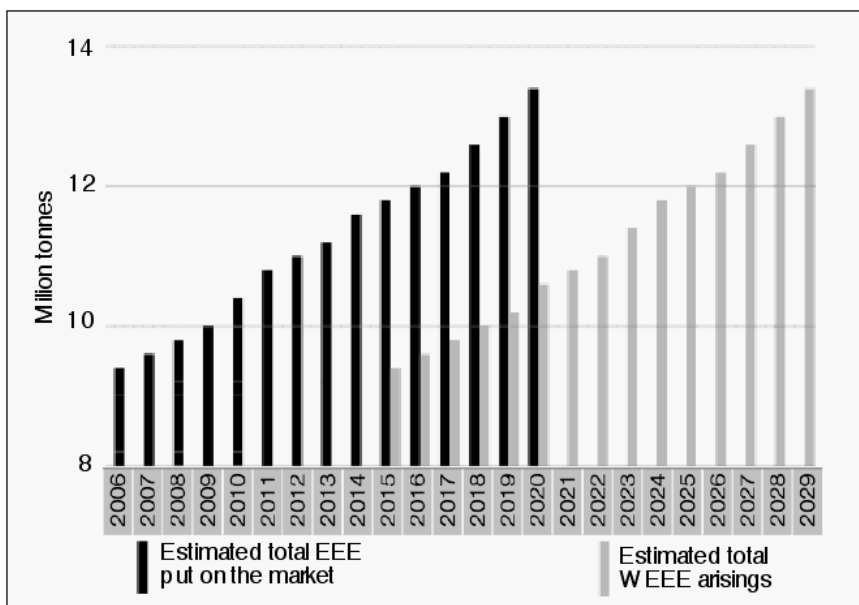


Figure 2-3 Estimation of future growth in total EEE market and future WEEE arising within EU27
Source: (Cobbing, 2008)

However, there is uncertainty about the exact amounts of e-waste created. The figures quoted above are rough estimations only. A considerable share of e-waste is escaping the statistics. A big fraction of outdated or scrap electronic devices is stockpiled at consumers homes and disposal is delayed (Nokia, 2008). This is true in particular for smaller electronic devices. Most likely, many of the 850 million mobile phones produced worldwide in 2005 already share the same fate.

E-waste is one of the fastest growing components in the municipal solid waste (MSW) stream. The fraction of e-waste that is not separately collected for recycling or export is usually

disposed of as part of MSW. The fate of this partial flow depends on the waste treatment schemes implemented in the respective countries. In many countries of the EU, MSW is simply landfilled and the e-waste contained in it shares the same fate. In some countries MSW is incinerated in municipal waste incinerators (MWI) of different technical sophistication. Co-incineration of e-waste is known to cause toxic fumes and dust to emerge. Only MWI that are equipped with state of the art flue gas purification may retain those pollutants.

2.2.2 The toxic load

EEE products are complex technologies containing a plethora of materials and substances with some of them are hazardous to human health and the environment. Appendix III shows the hazardous materials inventory of today's e-waste. Noteworthy to mention that other substances found in e-waste may also cause problems if disposed of improperly (e.g. non biodegradable plastics that are dumped in nature).

Several of the materials listed above have been phased out from use in EEE products already decades ago. Those are for instance asbestos insulation, PCBs in capacitors, CFCs, and mercury in switches. Nevertheless, there is still a risk that those materials are to be found in contemporary e-waste streams for historical e-waste is still stockpiled in consumer's attics. The time lag between end-of-use and actual disposal can be decades. This fact poses problems to future e-waste management: Even though several hazardous substances are now banned from use in EEE by the RoHS-Directive (see table 2-2) they will remain to be a risk for a long time.

Hazardous substances can also be formed when e-waste undergoes inappropriate disposal or recycling processes. Chemical and thermal reactions, for example open burning, cause a variety of pollutants to be created and emitted into air. Also unsound disposal practices (dumping) can result in formation and release of pollutants due to corrosion. This is particularly a problem in non-sanitary landfills and dumpsites, which are a frequent practice not only in developing countries but also in EU countries (Figure 2-4).



Figure 2-4 WEEE dumped in an informal landfill in Greece. Source: Köhler, 2008

As a consequence, e-waste is threatening the environment and human health due to hazardous materials contained in it as well as those, which are formed during unsound disposal and recycling. Table 2-1 lists examples for hazardous substances emanating from e-waste.

Table 2-1 Possible arising of hazardous substances from WEEE disposal

| Hazardous substances | Emanating from | Primary emission path |
|---|--|------------------------|
| Thermal processes (incineration, open burning) | | |
| hydrochloric acid HCl; HBr | PVC, flame retardants | Air |
| carbon monoxide CO | plastics | Air |
| polybrominated dioxins (PBDDs) and furans (PBDFs) | PVC, flame retardants, with Cu as catalyst | Air, recycled plastics |
| Fumes and dust containing heavy metals | unspecified | Air |
| residue ash | unspecified | Soil |
| Landfilling | | |
| toxic leachates containing oxides and salts of heavy metals (e.g. Cr6+) | PWBs and others | Soil, groundwater |
| dimethylene mercury | | Soil, Air |

Sources: (EMPA, 2008; UNEP, 2008)

2.2.3 Resource depletion

The production of EEE products entails immense consumption of natural resources (raw materials and primary energy). Crystalline silicon for instance, the basis of almost all contemporary electronics, is made out of quartz sand but the energy consumption for purification, refining and wafer production is immense. The total resource consumption of one 32 Mbit microchip of approx. 2 g weight has been calculated to amount 1.7 kg, including a consumption of 1.6 kg of fossil fuels (Williams & et al, 2002). Moreover, production has do deal with a multitude of problematic substances; the same study has shown that 27 g of various chemicals and 700 g of elemental gases are needed to produce a microchip. The total abiotic resource consumption to produce a complete PC including CRT has been estimated to amount up to 1,500 kg (Türk, 2003). Energy consumption for production of the same unit has been calculated with 430 KWh electricity and 3,300 MJ of fossil fuels (Williams, 2004). While the energy consumed during the production of EEE is spent once the final products are made they still contain a considerable degree of embodied energy in form of their materials content. Embodied energy refers to the cumulated energy that is necessary to extract, refine and produce the materials. At the end of the useful life scrap electronic products still contains those materials thus representing a huge resource potential in terms of both, valuable materials and embodied energy waiting to be recovered.

Electronic products consist of many complex components that contain a large variety of substances with some of them being valuable or scarce materials (Appendix IV). PWBs found in mobile phones network components for instance contain more than 32 different elements some of them in minute amounts (Scharnhorst, Althaus, Classen, Jolliet, & Hilty, 2005) (see Appendix VI).

Scarce materials such as gold, indium, or tantalum occur in very limited amounts on earth or are expensive to extract and cause serious environmental damage during mining and refining of the raw materials. Mining, refining and production of many of the materials from which EEE are made of demand large quantities of energy and auxiliary materials. Thus, materials found in e-waste have an enormous "ecological backpack", that is the accumulated material input (MI) of all non-renewable materials consumed for production of a final good. For instance the average MI for a notebook laptop has been calculated with 434 kg (hardware

only) (Geibler, Ritthoff, & Kuhndt, 2003). Many of the materials contained in EEE have an even higher “ecological backpack”: 1 kg steel has a backpack of 7 kg, PVC 8 kg, aluminium 85 kg, nickel 140 kg, copper 500 kg, and 1 kg gold causes a material flow of 540.000 kg (Türk, Alakeson, Kuhndt, & Ritthoff, 2003). Most mining and refining processes entail toxic emissions too.

Given the immense mass flow of up to 9 million tonnes of e-waste per annum in the EU even minute concentrations of scarce materials do result in depletion of non-renewable resources.

2.3 Regulations addressing the e-waste problem

The European Waste Framework Directive 2006/12/EC stipulates a waste preventative principle (EP, 2006). According to the consolidated draft for revision of the directive 2006/12/EC prevention of waste is prior to recycling and disposal. The objective is to “*minimise the negative effects of the generation and management of waste on human health and the environment*” (EP, 2008). Conservation of natural resources is a further objective. An important new provision of the consolidated draft is that an extended producer responsibility (EPR) is now laid on the developers of products (ibid):

Article 8: Extended producer responsibility

1. In order to strengthen the prevention, re-use, recycling and recovery of waste, Member States may take legislative or non-legislative measures to ensure that any natural or legal person who professionally develops, manufactures, processes, treats, sells or imports products (producer of the product) has extended producer responsibility.

Notwithstanding the rather soft stipulation (“Member States may”) of this aspect in the draft directive it is obvious that policy makers have recognized a need to govern innovation in order to prevent future waste issues. The European Commission is assigned to elaborate a product eco-design policy that goes beyond the hitherto existing ones (EC, 2005b).

The RoHS-Directive: In 2002, the EU issued the RoHS-Directive (European Union's Restriction of Hazardous substances 2002/95/EC) (EC, 2002). With the directive the EU encourages life cycle thinking and eco-design in the development process of new electronic products. Article 4 of the directive stimulates advances in environmentally sound product design through science and technology and Article 13 aims at finding alternatives to the use of hazardous substances in EEE. The main stipulation of the RoHS-Directive however is the ban of certain substances from usage in EEE from June 2006 onwards (see table 2-2).

Table 2-2 Substances banned from use in EEE by the European RoHS-Directive

| | |
|-------------|--|
| • Lead (Pb) | • Hexavalent chromium (Cr6+) |
| • Mercury | • Polybrominated biphenyls (PBB) |
| • Cadmium | • Polybrominated diphenyl ether (PBDE) containing flame retardants for plastic usage |

With the RoHS-Directive the EU puts responsibility on developers, producers and importers of EEE. Indeed, companies have perceived the directive being one of the most powerful drivers in the sector fostering innovation for waste reduction and recycling (Bogaert et al., 2008)

The WEEE-Directive: Complementing the RoHS-Directive the Directive 2002/96/EC on WEEE introduces the principle of extended producer responsibility to the manufacturers and importers of EEE. Before the European WEEE-Directive had been legislated there was almost no link between EEE manufactures and the recycling and disposal business. Due to the EU Directive on WEEE the situation has changed radically and EEE producers are now responsible for end-of-life treatment of their products.

The WEEE-Directive was legislated in 2002 by the European Parliament and set in power by the Council in 2003 (EC, 2003). The legal basis of the WEEE-Directive is Article 175(1) of the Treaty of the European Community aiming at creation of common environmental standards. Aiming at reducing the environmental impacts of WEEE the directive and has two main goals (Huisman & et al, 2007) p.9):

- “1. Ensuring a high level of recycling and reuse of materials,
2. Prevention and control of the release of potential toxic substances present in WEEE from entering the environment.”

To achieve that goal the WEEE-Directive sets the following provisions (Savage, Ogilvie, Slezak, & Artim, 2006):

- Reduction of the amount of WEEE disposed of in landfills;
- Creation of a free take-back scheme for post consumer WEEE;
- Encouraging a product design that prevents WEEE and facilitates reuse and recyclability of electronic goods;
- Setting recovery, reuse and recycling targets for WEEE of different classes;
- Establishment of collection systems and facilities for WEEE from private households;
- Setting up financing systems for recycling and sound disposal of WEEE.

According to the directive a sufficient percentage of post consumer WEEE has to be collected and recycled in accordance to dynamic targets. Producers and importers of EEE are made responsible to take back electronic waste, which is introduced into the European marketplace by them. The amounts of WEEE a certain company is responsible for depends on the market share of the respective company. In addition historical WEEE is to be taken back and recycled as well. The companies are allowed to delegate that business to specialised companies but are required to finance the recycling system and to report about quantities recycled. Most companies join one of the collective take-back systems such as European Recycling Platform (EPR) or the WEEE-forum.

EU member states have transposed that directive into national laws but not a few countries are still lacking behind in implementation. Hence, there are still some countries where environmentally sound end-of-life management of WEEE is not guaranteed.

The Basel Convention: On an international level the Basel Convention addresses the control of transboundary movements of hazardous wastes (The Basel Convention, 1989). Details of what is “hazardous waste” are elaborated in Annex VIII to the convention. “Waste electrical and electronic assemblies or scrap” is considered a hazardous waste (code A1180) as long as no removal of hazardous components has taken place. Particularly substances being listed in Annex I of the convention (e.g. Be, Cr⁶⁺, As, Se, Cd, Sb, Te, Hg, Pb, asbestos as well as CRT-glass and capacitors containing PCBs), which form common constituents of e-waste [see 2.2.2] turn the entire e-waste stream into hazardous waste. While at least lead is ubiquitous in e-waste (solder) other substances may be found in traces only. The risk of their occurrence in historical e-waste implies that e-waste is to be considered hazardous waste according to the precautionary principle. Hence, e-waste falls under the stipulations of the Basel Convention.

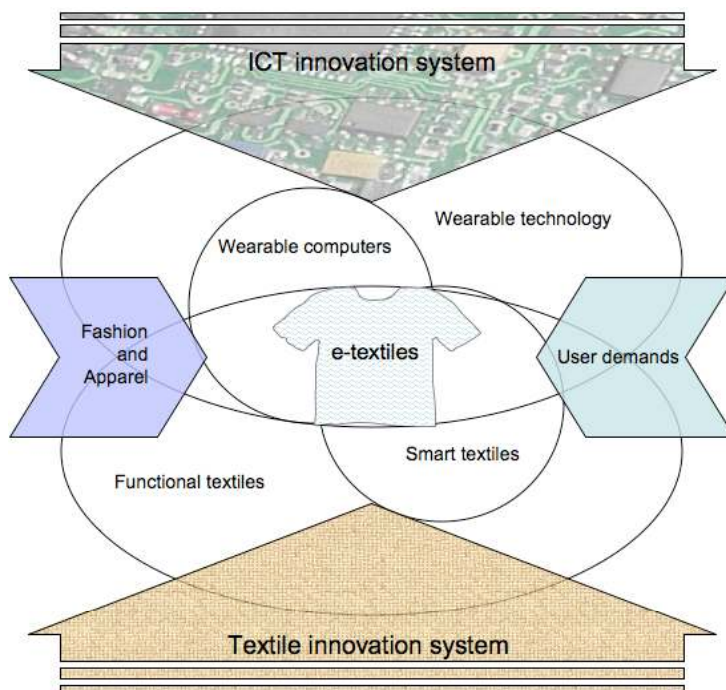
The Basel Convention requires the signatory parties to “ensure that the generation of hazardous wastes and other wastes within it is reduced to a minimum, taking into account social, technological and economic aspects” (The Basel Convention, 1989). Further stipulations require member states to build environmentally sound disposal facilities and to enact management mechanisms for pollution prevention. A central feature is the implementation of a system for regulating and monitoring of transboundary movements of waste (Article 4.2.b et seq). Exports of hazardous wastes are generally prohibited subject of permission. Illegal transboundary movement of waste is considered criminal conduct.

In practice, the Basel Convention has been far from being effective. In practice, exports take place even though transboundary movements of hazardous wastes to non-OECD countries are banned by EU legislation and the Basel Convention. Greenpeace contends that a hidden flow of e-waste is being exported towards developing economies in India, Asia and Africa (Cobbing, 2008). Developing countries are a final destination for about 70% of all e-waste arising. There it is dumped illegally or undergoes crude recycling processes according to the Basel Action Network (Basu, 2008). Particularly, used mobile phones are traded on the second hand market in developing countries. UNEP expects further significantly increase of transboundary movement of used EEE (UNEP, 2006).

3 E-textiles – future high-tech emerging in the labs

3.1 Trends and visions

In recent years various industrial sectors have seen convergent technological innovation. Among them, the electronic and the textile industry are two candidates to create a new generation of applications with mutually augmented functionality. There is a broad spectrum of future applications in the development pipeline that, to higher or lesser extent, entail fusion of electronic and textile functions or materials respectively. A typical situation in the early days of converging technologies is that two formerly distinct domains of technology need to grow together. In the case of e-textiles there are basically two roots out of which innovation evolve:



the textile sector and computing sciences. The intersection of future application areas where they are expected to meet is of highly multidisciplinary nature. Each sector utilises different technologies, methods, and logistics and has a different culture and means of communication. Consequently, the field of innovation in e-textiles is very heterogeneous and so is the terminology used. A rough categorisation of the converging innovation systems is shown in Figure 3-1.

Figure 3-1 E-textiles within the landscape of converging technologies in textiles and electronics. Source: adopted from (Dunne, Ashdown, & Smyth, 2005)

3.1.1 E-textiles in the context of textile innovation

Electronic textiles form a segment of innovation within the broader field of smart textiles. The term “smart” refers to an evolving innovation path in the textile sector. Visions on future textile products and applications anticipate that a wide range of new technologies and materials will enhance textiles. The concept of a smart material goes back to 1989 indicating engineered properties making materials capable responding to external stimuli in a controlled manner (Langenhove & Hertleer, 2003). Since the mid of the 1990ies the innovation trend has been adopted by the textile sector and one can recognise an increasing number of publications reporting smart textile-based applications. In the textile world the term “smart” was first applied to fibres showing shape memory that is they adjust their shape depending on temperature. Mostly the term smart is used to describe textile materials or products capable to sense and to respond (Tang & Stylios, 2006). Some authors consider textiles as smart if produced by nanotechnology or containing nano-materials. Next to the term “smart textile” a variety of synonymous terms can be found in literature including “intelligent textile”, “interactive textile” and so on.

Despite the rather inflationary use of the term smart in media and corporate communication there is as yet no common agreement on the exact meaning of “smartness” nor the minimum extent of additional functionality required to make a material smart. Some authors consider

smartness or intelligence in such a way that active sensing/responding capability is integrated into textiles (e.g. clothes) (Mecheels et al., 2004). Zhang and Tao (2001) quoted in (Langenhove & Hertleer, 2003)) proposed the following categorisation of smart textiles according to their functionality:

1. passive smart textiles: sensing only
2. active smart textiles: sensing and response
3. „very smart textiles“

This categorisation scheme may be of academic interest only and does not really reflect the full spectrum of developments. On the other hand, not all smart textiles of higher functionality are intended to exhibit active behaviour. In practice, most authors reporting developments in smart textiles miss to clearly indicate the degree of “smartness”. In the following a rough allocation of the various technological features as reported in literature is described in accordance to the abovementioned classification scheme.

It appears appropriate however, first to introduce so-called “functional textiles” since they already constitute a dynamic and successful sector of textile innovation. Smart textiles partly evolve from them. Functional textiles found on the market exhibit enhanced properties being waterproof, breathable or dirt repellent for instance. While conventional garments primarily serve twofold purpose, fashion and wellbeing, functional textiles impose enhanced or additional services such as safety, health protection, comfort, and sportive performance. The properties of functional textiles are optimised to provide constant protection under variable environmental conditions or to improve effectiveness of body function (e.g. transpiration). Phase change materials (PCM) have been applied in textile prototypes to store and release excess heat in a controllable manner (Mecheels et al., 2004). One example for functional textiles that are related to electronic textiles is EM-shielding. Protection against electromagnetic (EM) radiation from mobile phones is achieved by interwoven metallic threads or metalised fabric. Functional textiles are mostly based on passive technology while smart textiles are considered to respond actively. Yet, regarding industry involved and materials used there are many overlaps between functional and smart textiles.

The smartness of passive smart textiles (**group 1**) may go not much beyond those of functional textiles but embedded sensing elements in textiles provide augmented service to the user. Textile embedded sensors measure physical/chemical parameters as they change their electrical/optical properties in response to external stimuli (tension, pressure, temperature, gas concentration etc.). They may also capture surface currents or electrical fields and transform them into signals. Sensor signals are then transmitted electronically or optically to an external control unit. The spectrum of possible applications ranges from surveillance of physiological parameters (e.g. electrocardiogram, ECG) of the human body to technical applications (strain sensing). Textile embedded user interfaces (e.g. switches, dials or keyboard) can be considered a type of sensing elements. Prototypes of textile integrated flexible keyboards have been realised providing improved usability and comfort (Park & Jayaraman, 2003).

Actuator functions increase the degree of smartness (**group 2**). Intrinsic sensing and response capabilities create dynamic functionality that can be engineered to meet the required application purpose. Active sensing devices can be used in combination with electrically active materials (EAM) to adjust textile properties in response to mechanical, thermal, chemical, or other environmental parameters (Dunne et al., 2005). Adjustment of physical properties ranges from changing size, shape, colour and thermal insulation (e.g. by shrinking/expanding fabrics) (Tang & Stylios, 2006). Also electroluminescent textile surfaces or light emitting elements integrated into textiles have been realised in order to create context responsive functions of

garments. Lee and Kim report on active cooling fabrics utilising the Peltier effect (Lee & Kim, 2006).

The third group, “**very smart**” textiles, can be understood as a more sophisticated vision on future technology that is not only adaptive to environmental parameters but also actively controllable by users or computers. Integrating foreign technologies such as electronics into textiles can impart completely new functions, which are untypical in textile applications (Mecheels et al., 2004). One technological approach is microsystems technology (MST), comprising microelectronic, micromechanical or optical devices embedded into textiles. Another approach is embedding electronic devices of higher functionality into textile platforms such as clothing. Prototypes of garment embedded mp3 players or mobile phone periphery have already been realised. The smartness of those smart clothes goes hardly beyond those of the embedded electronic device, which provides traditional electronic functions in a more convenient (that is wearable) context.

Summing up: smart textiles are the result of a broad variety of basic technologies being applied to augment the functionality of textiles. They derive from chemistry, nanotechnology, microelectronics, and other domains of technology. As far as electronic components are deployed or electronic functions are accomplished e-textiles form a continuum with smart textiles. The term e-textiles encompass electronic garments as well as technical textiles and household textiles such as wall hangings or quilts (Buechley, 2006). In all cases however, there is a trend to blend textile materials with non-textile, mostly electronic, components.

3.1.2 E-textiles in the context of wearable computing

Frequently the terms “wearable computing” or “i-wear” are used to characterise an upcoming concept of mobile information and communication technology (ICT). Wearable computing originates from computing science and explores new concepts of human - computer interaction based on highly miniaturised, networked and body-mounted technology. As such, wearable computing constitutes a subarea of pervasive computing (PvC) (or ubiquitous computing respectively) that represents a comprehensive vision.

Excursion: pervasive computing

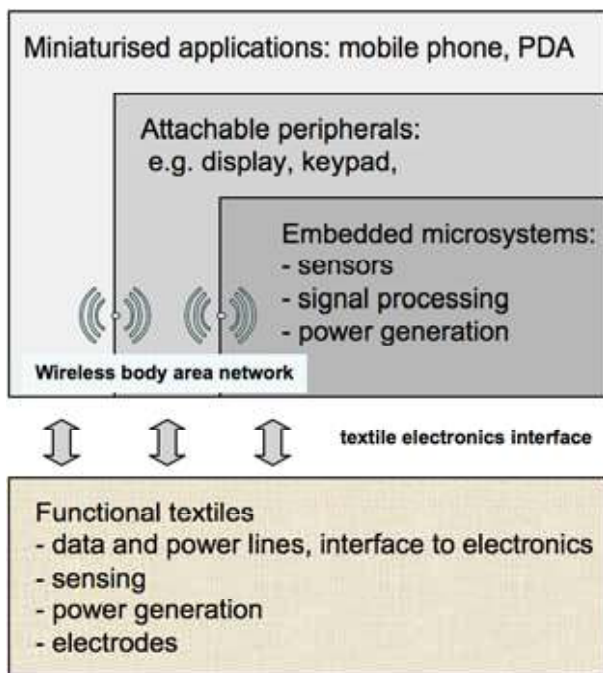
PvC denotes the idea of microelectronics that is unobtrusively embedded into every-day objects providing ubiquitous ICT services. PvC is characterised by the following features (Hilty et al., 2005):

- Ubiquity: ICT becomes omnipresent in daily life but also unapparent or even invisible.
- Miniaturisation: ICT devices will shrink and become more mobile as compared to today's computers.
- Embedding: ICT is to be embedded or integrated into objects of daily use (smart things).
- Networking: Wirelessly connected ICT components exchange data with surrounding networks.
- Context sensitivity: using integrated sensors the ICT components collect and process information about their surrounding and exchange them wirelessly.

Back to wearable computing: Most of the aforementioned characteristics of PvC apply to wearable computing as well. However, the focus of innovation is slightly different. Main emphasis is given to usability aspects that is the seamless integration of computing services into the user's the personal space. Enabled by miniaturisation of hardware components the usability of the human – computer interface is optimised. Steve Mann, one of the pioneers of

wearable computing, gives the following definition: A wearable computer is “a device that is always with the user, and into which the user can always enter commands and execute a set of such entered commands, and in which the user can do so while walking around or doing other activities. [...] The wearable computer is more than just a wristwatch [...] being a fully featured computer, it is also inextricably intertwined with the wearer.” (Mann, 1998).

The understanding of the shape of wearable computers depends on the respective research community. Some comprehend them as being distinct objects such as headsets, glasses, buttons, rings etc., which are networked thus forming a body area network. Others go a step further and strive to embed computing technology into clothes in order to create artefacts that are soft, flexible and comfortable (Buechley, 2006). Research in e-textile builds on the fact that textiles are worn in almost all situations of life making garments an ideal platform for wearable



technology. Proximity to the human body and ubiquity in daily life makes clothes capable to host additional functionality. Pragmatic perspectives on contemporary innovation in wearable computers rely on existing off-the-shelf technologies. A wearable system is build around a central hub of higher functionality such as a smart phone which is complemented by peripheral devices such as sensors, actuators, displays and power supply (see Figure 3-2). Those elements can be integrated into e-textiles while the smart phone remains a distinct device.

Figure 3-2 Example for the architecture of a wearable system.

Source: adopted from (Latwo, 2006)

3.2 The innovation system for e-textiles

3.2.1 Innovation paths in smart textiles

Presently, e-textiles are still in an infant stage of development. Innovation takes place above all in terms of selection, testing and evaluation of enabling technologies (VDI/VDE /IT, 2006). A good part of those enabling technologies does already exist but needs to be adapted to the new application context of wearable technology. As yet, innovation process still struggles with the integration of electronic materials into textiles while preserving the traditional textile properties (e.g. washability). Moreover, the costs remain to be the big challenge beside technical issues. If e-textiles are to conquer the market (and that is perceived preconditional for innovation) they must become cheaper to produce. In the consumer market for smart clothes the projected additional willingness to pay is between 10% and 30% (ibid). However, apart from technophile consumer groups there is no real demand for smart clothes at the moment.

For textile industry there is a big opportunity to push forward innovation and to create new markets for high-tech products. Innovation tends towards value-added products enhancing the consumer value of textiles (Langenhove & Hertleer, 2003). However, the break through on the market place is still missing. That situation can partly be explained with the fact that the innovation system of the whole sector of smart textiles is determined by the supply side (that are labs in R&D and industry). Innovation follows a technology push model (Brand et al.,

2007). The overall technological progress in the ICT sector (in particular fueled by Moore's Law) and micro systems technology are salient driving forces. Visions and promises about future applications of e-textiles may therefore emerge from engineer's inspirations rather than from actual needs of potential customers. There has been prevailing uncertainty among innovators about the demand side (Mecheels et al., 2004). At the moment there is still no big market pull even though some potential application areas have urgent needs for improved technology at lower costs (e.g. the health care sector).

With regard to the way how electronic components are to be embedded into textiles three steps of innovation can be road mapped (Mecheels et al., 2004):

1. Adoption: distinct electronic devices are embedded into a textile platform (e.g. pockets),
2. Integration: electronic devices are to be seamlessly incorporated (e.g. embroidered),
3. Combination: textile materials and structures with inherent electronic functionality (e.g. yarn transistor, fibre based circuits, photovoltaic fibres).

Adoption is certainly the starting point for contemporary innovation and closest to the market. Some innovative companies have already presented prototypical e-textiles on exhibitions and fairs (e.g. IFA Berlin 2007, CBIT Hanover 2007) (FIS, 2007; K., 2007a). Frequently, out-off-the-shelf electronic components are used. In order to adopt them into textile products electronics must be encapsulated into a flexible protective casing so as to increase their resistance against water and mechanical stress. Some developers also keep electronics detachable from the textile so that the consumers can remove sensible parts before laundering the clothes.

Seamless **Integration** requires more sophisticated materials and production technologies. If electronic components are to be merged with textile materials they must become soft, flexible, stretchable, and water persistent - quite the contrary to classical electronics. R&D labs around the world are developing such novel electronic materials and early attempts towards commercial application have been announced.

Combination is to be seen as long-term goal of innovation in e-textiles. Market readiness is expected to be still 10 to 15 years ahead (Mecheels et al., 2004). Inherent electronic functionality of textiles may come closest to the more visionary perceptions of wearable computing. The keyword computational clothing is closely related to further advances in nanotechnology. While in the domain of silicon based electronics 45nm structures are close to market now the creation of semi conductive structures on flexible substrata is still in the stage of fundamental research.

3.2.2 Innovation in ICT

Within the ICT sector innovation is a constant and priority process. Advances in microelectronics have been obeying the so-called 'Moore's Law' for decades. According to that rule of thumb (once proclaimed by Gordon Moore of Intel Corp.) the number of transistors on a circuit doubles every 18 months while the chip area remains +/- the same (Moore 1965). That rule has been interpreted as general roadmap for growing performance of ICT and is expected to remain applicable for within the present decade (Moore 2003). As a consequence, future generations of computers are expected to continue the trend of increasing performance. That development trajectory of ICT is overlaid by another trend: the multiplication in numbers of shrinking ICT devices, that is pervasive computing [see 3.1.2]. It has been predicted that after the age of personal computers (one computer per person) a time will come when each person utilises a large number of small computers (smart devices) simultaneously. IBM chairman Lou Gerstner expressed it in the following way: „A billion people interacting with a million e-businesses through a trillion interconnected intelligent devices...“ (quoted in (Mattern 2005)). Recent developments in the area of PDA and smart phones can be seen as a leap towards that direction.

Interestingly, those mobile electronic devices seem not to replace traditional PCs but supplement them. Hence, number of computing devices per person is growing.

On the European level there are several R&D clusters engaged in developing pervasive or wearable computing. The ARTEMIS⁹ European Technology Platform for Embedded Computing Systems is a joint undertaking that has set up a Strategic Research Agenda (Artemis, 2008). Artemis facilitates multidisciplinary and downstream-oriented research. Among the 8 sub-programmes there are several opportunities for development e-textiles. For instance safety-relevant embedded systems such as protective clothes (SP1); medical and health care applications using wearable sensor shirts (SP2), efficient industrial tools (e.g. interactive work wear) (SP4), and SP7 that are Embedded technology for sustainable urban life.

Another large F&E project dedicated to wearable computing is the European Commission funded “wearIT@work” with bundles the research of 36 institutional participants across Europe (wearIT@work, 2006). The 6th Framework Programme project focuses at development of wearable workwear in order to increase the productivity and flexibility of industrial working processes such as production, maintenance and medical care. The project has yielded a variety of demonstrators and prototypical applications.

On the national level several countries promote R&D in the context of smart textiles. In Germany for instance the governmental funded research cluster “MST textil” aims at advances of micro systems technology in the textile application context (VDI/VDE/IT, 2006). A roadmap for micro systems technology in the context of smart textiles was drawn by the German VDI/VDE (table 3-1):

Table 3-1 Innovation roadmap for smart textiles in Germany.

| | 2006 | 2010 | 2015 | future |
|-------------------------|---|---|----------------------------|----------------------|
| Range of application | First products ready for the market New markets for textile industry Automotive industry (car interior) Sensor clothes for health monitoring | Wellness & health & sport Safety Protective workwear with sensors | | Pervasive Computing |
| Hot spots of innovation | Embedding electronics in pockets Textile switches El. interconnections in textiles Technical textiles & clothes Integrated actuators | Textile integrated power supply Washable batteries Textile displays | Fully integrated solutions | Woven circuit boards |
| Enabling technologies | Miniaturisation Flexible materials (PWB) El. conductive fibres Polymer electronic Nanocoating RFID | Nanotechnology Improved textile sensors El. luminescent textiles | Yarn-transistor | Textile chip |

Source: (VDI/VDE/IT, 2006)

⁹ “Advanced Research and Technology for Embedded Intelligence and Systems”

3.2.3 Innovation in textile industry

The textile industry constitutes one of the large industrial sectors in Europe employing 2.6 million persons and having a total turnover of billions € 213 per year (Walter, 2005). Textile-clothing industry is a highly fragmented sector operating in a competitive globalised market situation. The main branches of textile industry are apparel 44%, interior and household 33%, and industrial and technical textiles 23% based on volume produced in 2002. Figure 3-3 illustrates the textile value chain.

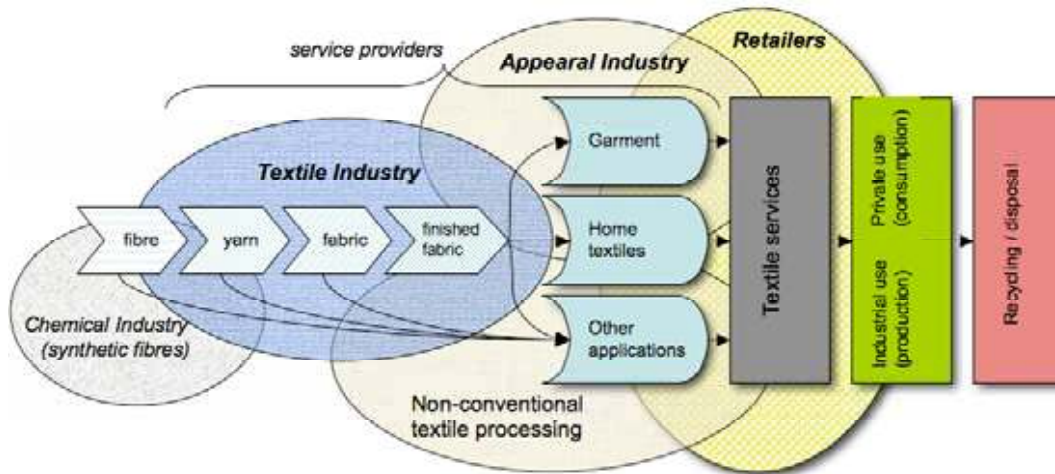


Figure 3-3 The world of textiles. Source: adopted from (Walter, 2005)

Fierce competition within global textile industry has resulted in relocation of resource-based textile mass-production during the last decades. Today manufacturing takes place in Asia and India mostly. Producing textile industry in Europe (and the US) has therefore suffered a decline and cannot compete in low cost segments of the textile market. Instead, textile companies operate in high-added value niche markets where they need to engage in constant innovation. Particularly start-up companies and spin-offs from research institutes have engaged in innovation in order to create high-added value products being superior in the textile market (Ohmatex ApS, 2007).

Public-private innovation clusters do exist on regional and national level and there are also a couple of R&D projects on the European level (e.g. FP6 and FP7) in which textile companies engage with university departments and national research centres. However, most SMEs do not employ permanent R&D personnel. Overall, the sector as a whole is not known to be particularly research oriented and has been lacking a strategic direction (Euratex, 2004). In order to improve industry's capability to engage in innovation Euratex has developed a long-term strategic vision. The strategy is build upon the assumption that research and innovation are keys for future success of the industry sector. According to that strategy there are 3 main success factors for textile industry in future (ibid p.3):

1. "A move from commodity fibres, filaments and fabrics towards specialty products from flexible high-tech processes,
2. The establishment and expansion of textiles as the raw material of choice in many industrial sectors and new application fields,
3. Ending the era of mass manufacture of textile products and moving towards a new paradigm of customisation, personalisation, intelligent production, logistics and distribution."

With their strategic research agenda Euratex has identified smart textiles as a priority area for necessary research and development (Euratex, 2006). Strategies for a more radical industrial

breakthrough aim at smart multi-functional properties of future textiles. To accomplish that goals textile industry seeks cross-sectoral alliances with other domains of industry. Several textile companies engage in EU-funded F&E clusters. Examples are the BIOTEX (bio-sensing textile for health management) project, the WEALTHY (Wearable Health Care System) project and MyHeart project (Coyle et al., 2007).

3.3 Envisioned outcome of innovation in e-textiles

3.3.1 Application areas

Research and innovation in e-textiles occurs in a very application oriented way. Most authors reporting on technological developments in materials and integration technologies do mention expected application areas. Particularly applied R&D within public private research clusters commonly aims at concrete applications or products to be developed. The following list provides an overview over application areas for e-textiles (and smart textiles in a broader sense) and gives examples for envisioned use situations¹⁰.

- **Health monitoring:**
wearable medical monitoring suits, ECG t-shirt, home care and rehabilitation, remote telemedicine, remote baby monitoring, vital signs monitoring blankets in hospitals,
- **Sport and outdoor:**
wearable monitoring for body functions (respiration rate, breathing frequency, body-temperature, ECG bra or shirt), mobile communication skiglove, GPS outdoor jacket, smart jogging shoes, kinesthetic monitoring for athlete training
- **Well-being & fun:**
active heating and cooling clothes, wearable gaming console; constant monitoring of vital signs for elderly persons,
- **Fashion & Lifestyle:**
mobile entertainment (mp3 jacket), touch-sensitive shirt, lightening and actuated decoration elements on clothes, status symbol,
- **Every day life:**
solar cell powered bags, garments, bags, textile switches,
- **Work: computer assisted working:**
work flow assistance and surveillance, hands-free human-computer interaction (e.g. wearable motion-capture or speech-controlled systems), location awareness, mobile information exchange,
- **Work: protective function & safety:**
fire fighter clothes, space suits, smart surgery suits,
- **Automotive and aviation industry:**
car upholstery (seats, car interior), textile aircraft structures (defect detection)
- **Furniture and interior textiles:**
curtains, wall hangings, carpets, pillows, decoration elements, carpet embedded guidance systems in buildings,

¹⁰ The list is a summary of applications as frequently reported in literature and does not claim comprehensiveness. The allocation of examples is non-exclusive (products are applicable across several application areas).

- **Technical textiles & civil engineering:**
mechanical stress monitoring in technical textiles (buildings), defect detection in textile concrete constructions,
- **Promotion and event industry:**
large size display (luminescent curtains), colour change event wardrobe,
- **Security and military.**

3.3.2 Market perspectives

Many authors in science and business media are optimistic that innovation in smart textiles will eventually result in successful products on the apparel market. There is a potential for mass application in the market segments of sports and outdoor clothes, health care, and work-wear (Stork, 2008). The approach of adoption (embedding electronic gadgets into clothes) is expected closest to market entry (Mecheels et al., 2004). Particularly the application segment of sportswear is pioneering development of e-textiles adopting distinct electronic devices (e.g. inbuilt mp3 player, solar cells). Such e-textiles have already been commercialised by several companies (Lukowicz et al., 2001). However, they have been failing break through at the consumer market thus far. Industry encounters barriers in up-scaling technological concepts as developed in the labs. Three main problems remain to be solved yet (ibid):

- Technological barriers to integrate electronics into textiles (e.g. maintaining washability),
- Design issues of textile embedded electronics (aspects of ergonomics and fashion),
- Functionality: acceptance of the comparable high price of e-textiles as compared to distinct electronic devices.

Therefore, consumers are still hesitant to buy textiles with embedded electronics. Despite of the hype in some media and corporate communication, really convincing application areas, justifying the higher price of such products, have still to be found.

One consultancy estimates the U.S. market for smart textiles in the segment of consumer products to account for \$71 million in 2006 and \$78.6 million in 2007. Further they predict an Annual Growth Rate (CAGR) of 37.9% until 2012 resulting in a market volume of \$391.7 million in 2012 (BCC Research, 2007). Another report contents the global market of smart fabrics and interactive textiles had a market volume of \$248 million in 2004 and will grow up to \$642 million by 2008 (table 3-2) ((VDC, 2006) reported in (Stylios, 2007). The same consultancy (VDC) estimates the total turnover in the sector of wearable technologies and smart clothes to be \$700 million by 2010 (Lohmann, 2008)

Table 3-2 Market expectations for interactive textiles.

| Segment | Year 2004 | Forecast 2008 | compound annual growth rate (%) 2004–2008 |
|-------------------------|-----------|---------------|---|
| Industrial | 9.9 | 51.4 | 51 |
| Military and government | 59.5 | 167.0 | 29 |
| Medical and health | 14.9 | 51.4 | 36 |
| Consumer and retail | 24.8 | 102.7 | 43 |
| Transportation | 136.4 | 263.3 | 18 |
| Other | 2.5 | 6.4 | 27 |
| Total | 248.0 | 642.1 | 27 |

Source: (Stylios, 2007)

Proprietary research needs to be taken carefully due to a lack of transparency regarding data-sources and methods. However, such predictions may raise high expectations of venture capitalists and industry thus influencing innovation and commercialisation process.

To sum up: smart textiles, including e-textiles, are expected to bear the potential for a wide-spread market penetration within the next decade. As a consequence an increasing mass flow of embedded non-textile materials is about to become a part of textile life cycle.

3.4 Findings from the expert survey

Results from the expert survey confirmed the findings from literature review described above. A number of experts agreed that e-textiles were an example for converging technologies. The innovation system of e-textiles was perceived being very young and not yet established as a distinct sector within the industrial landscape. The different industrial sectors involved had not yet found a common language and not really established cross-sectoral strategies. Nevertheless, the majority of the experts interviewed were optimistic that the innovation process for e-textiles would result in useful applications in the medium term (that is about one decade). This optimism was certainly grounded on the fact that most experts were involved in applied R&D where they engaged with industry in the framework of public-private research clusters. A few interviewees were less optimistic in their expectations arguing that many technical issues were still in a stage of basic research and market ready solutions would require another five to ten years of R&D.

Most interviewees confirmed the overall aim of research to achieve deep integration of electronic functions into textiles. They named increased comfort and reduction of production costs as important drivers supporting this innovation trend. While today's e-textiles are based on the principle of adoption the experts anticipated that fully integrated e-textiles could be realised within the next five years. Combination was seen as a rather visionary concept and not expected to be relevant for products within the next decade. Some interviewees argued that, within an applied innovation system, the low hanging fruits (that is the concept of adoption) were prioritised. That incremental approach of innovation was held to prevail at the moment.

As a rule, the experts were pragmatic in this respect, stating that adoptive, integrative, and combined technology would co-exist in future, depending on the respective application context, target market and price segment. Several of the interviewees stressed that consumer added value were to be seen prior to technical sophistication. The idea of co-existing textile integration technologies was emphasised in particular by experts from the wearable computing community. They underpinned the necessity of usability and questioned as to whether fully textile integrated ICT were useful anyway, from the user's perspective. From that viewpoint only a minor part of electronic functions were to be integrated into or combined with the textile. Higher computing services would better remain to be separate gadgets, which can easily be recognised and dealt with as electronic device.

Asked for their appraisal regarding most promising application areas the interviewees, as a rule, named more than one. They were however very careful ranking them pointing at the uncertainty in respect to many influencing factors. Several experts explicitly stated their expertise was not in the field of commercialisation but limited to the scientific/technical sphere. Moreover, none of the experts felt able to answer that question in respect to the entire field of e-textiles or wearable computers. The following figure 3-4 summarises the relative frequency of statements as mentioned by the interviewees (number of experts interviewed was 39).

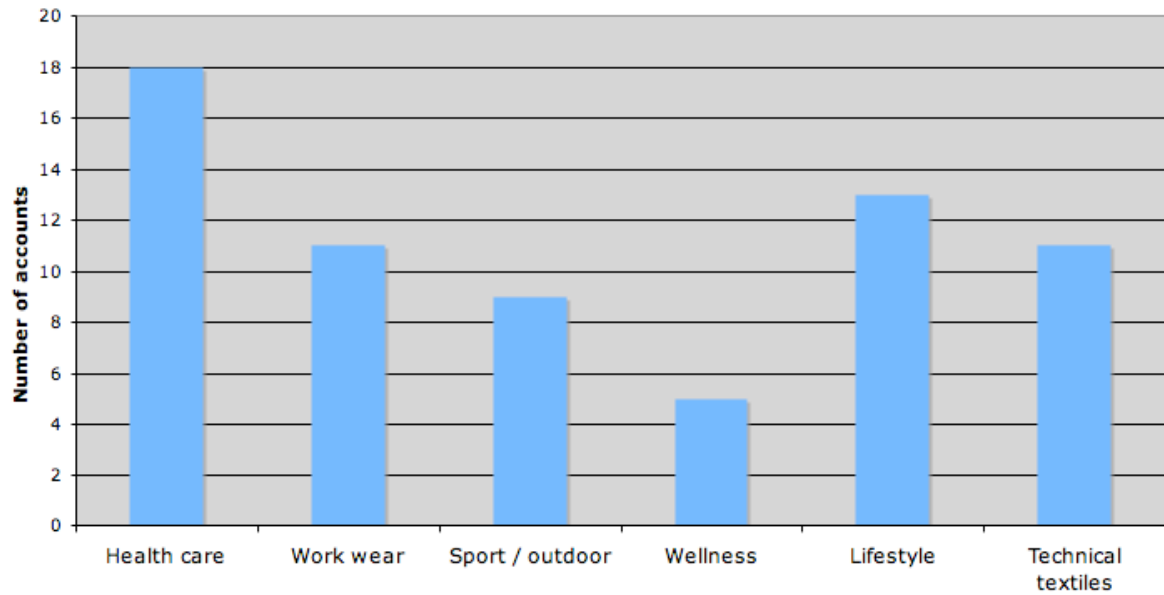


Figure 3-4 Relative numbers of statements for different application areas of e-textiles.

Similar to the findings from literature review, the expert's answers did not allow for an exclusive allocation of anticipated products to one or another application area. There were considerable overlaps across the categories. A number of experts also stated the application purpose intended during R&D might be complemented (or even outrun) by other application areas. It was argued that the achievements of R&D were often placed within expensive niche markets (mostly health care). Later away such technologies could be used for mass products such as lifestyle or wellness applications. Hence, figure 3-4 may be interpreted as a spotlight on contemporary mainstream of expectations rather than a prognosis on future market breakthroughs.

When asked for their estimation on future market penetration of e-textiles the interviewees were uncertain pointing at the large heterogeneity of potential target markets. The expectations ranged from e-textiles to form a specialised niche market (10 statements), a sectoral market (10 statements) to mass market (15 statements). While the majority of the respondents voted for more than one of these options 7 interviewees (researchers) felt not able to give estimation. As a tendency the interviewees expected e-textiles to form a niche market (e.g. in health care and workwear sector) in the near future. In the long term however the majority of the experts expected e-textiles evolving to mass applications (within one decade). Some argued that economy of scale, as prevailing in the ICT and textile sectors, would eventually entail low-cost mass applications, which would then enter the consumer market.

The experts were also asked for their expectations on the useful lifespan of future e-textiles. The majority of the interviewees supposed e-textiles to be found in the high price segment in the begin of market introduction. Valuable products would be rather long lasting. In a mass-market scenario, however, average lifespan could be lower. The expectations on product life span were closely related to the application type. Very long lasting e-textiles were expected in the area of technical textiles. As for consumer products washability was expected to be the most influencing factor on the service lifespan of a product. Increasing the e-textiles fastness to laundry was seen the foremost challenge for contemporary R&D.

4 The role of end-of life issues in the innovation system for e-textiles

4.1 Awareness for environmental aspects

Screening of literature databases and the Internet did not yield much information on environmental assessment studies considering the field of smart textiles, e-textiles or wearable computing. No evidence could be corroborated that environmental effects related to resource consumption, emissions and end-of-life treatment of e-textile have been matter of explicit assessment thus far. In the textile sector LCA have been conducted and basic life cycle inventory data¹¹ are available for many of the materials used. Moreover, technology assessment studies on pervasive computing (PvC) have been conducted (Köhler & Erdmann, 2004). Results of the latter suggest that waste disposal problems could arise if no adequate collection and recycling schemes are installed for post-consumer PvC items. An expert survey conducted among international researchers and innovators in PvC revealed that environmental issues and resource consumption were not considered important factors in the innovation process (BSI, 2006). However, a majority of experts consulted in that survey agreed to the importance of end-of-life issues. In their opinion recycling schemes need to be adjusted at future waste-PvC but there seemed to be no waste preventative attitude within the innovation system for PvC.

Subject to more intense attempts of information sourcing from conferences there is hardly any expert discussion on environmental effects of e-textiles. None of the scientific or journalistic articles on smart and e-textiles report about assessment of their environmental effects and one can assume that not much has been investigated in this respect thus far. Researchers mostly refer to environment as an external impact factor affecting function of e-textiles. In addition environmental influences on e-textiles are seen as input variables, which e-textiles are designed to sense and actively respond to by changing their properties. However, it would be misleading to assume that there was no awareness on end-of-life issues at all among researchers/developers and companies engaging in e-textile innovation. Such questions have been risen (Schroth, 2003) but seem to be unanswered as yet.

Within the textile sector integrated product policy is being discussed. Environmental aspects of the textile value chain are subject of concern and the main attention is paid to chemicals and waste during production chain. In the electronic sector environmental aspects have been discussed far and wide resulting in environmentally sound design approaches such as green electronics (Mueller et al., 2004). Recommendations for environmentally sound design of electronic products have been explored in the framework of the ECOLIFE II thematic network, (Ecolife II, 2006). Moreover, a system-focused approach has been suggested for sustainable technology development in ICT and micro systems technology. According to that approach *"Technologies should not be developed without a rough understanding of future applications"* (Schischke, 2003).

Hence, awareness on environmental aspects does exist and strategies to tackle these challenges have been developed within both industrial sectors out of which e-textiles emerge. There seems however to be a prevailing communicative gap between these sectors and the innovation system for e-textiles.

¹¹ For example EcoInvent life cycle inventory data. <http://www.ecoinvent.ch/>

4.2 Findings from the expert survey

In regard to their respective field of expertise the interviewees were asked to rank the relative importance of environmental aspects (and recyclability in particular) during design phase of e-textiles. They were also asked to compare them with technical/functional design criteria and to indicate other relevant criteria, which govern technology design.

All respondents to that question (25) prioritised technical/functional design criteria being the dominating ones beyond question. Also aspects concerning safety and health were deemed to be top priority according to some experts. Some indicated that costs ranked next in relevance. They said that there was always a trade-off to be dealt with between a variety of design criteria; costs were often the limiting factor for optimization. Only one respondent ranked recyclability being equally relevant as technical aspects while six opted for secondary importance. All other respondents (17) considered environmental aspects less relevant design criteria, *inter alia*.

The experts were also asked to what extent interests of stakeholders and recycling industry influenced the design specifications and how they were involved into the innovation process.

Most interviewees pointed at cooperation partners in industry and public R&D funds. Of course, researchers and engineers involved in the innovation process do influence design criteria. The design criteria mentioned here were technical/functional aspects for the most part. Some experts mentioned environmental aspects being design criteria in certain publicly funded research projects. None of the interviewees mentioned contacts to external stakeholders or recycling industry. There seem to be no direct interactions between the innovation system for e-textiles and actors in recycling and disposal sector.

When asked for internal and external environmental policies influencing the innovation process of e-textiles the responses were as follows:

The majority of interviewees indicated that they were not aware of such internal policies to exist in their respective research institutions or companies. Some few pointed at generic environmental policies targeting in-house waste separation etc. A minority however, stated a proactive approach was necessary during the whole development process. Some experts reported on systematic use of environmental assessment methods for supply chain evaluation. As examples were mentioned: eco-labels and eco-tex standards. Other interviewees reported on the use of science based assessment such as LCA or software tools¹². These examples were exceptions however and no default methods used in the innovation process.

Regarding national and international waste policies and regulations the knowledge was commonly rather low. While a few respondents seemed to be quite well informed other stated that legal aspects were beyond their expertise. In general, most interviewees were aware of the stipulations of the RoHS-directive (e.g lead-free soldering) but could not indicate further details. A few mentioned REACH-directive as potentially relevant for e-textiles innovation. Else, regulations and standards regarding product safety and health protection were mentioned as well as sector specific standards (e.g. geo-textiles or protective clothes).

Next the experts were asked to state whether they perceived a necessity to take action towards design for recyclability (DfR) during the design phase of technology for e-textiles.

¹² Examples mentioned here: SiDDatAS and ProdTect (for details see: (Herrmann & Luger, 2006)).

Five interviewees objected that idea and eight indicated to be not the responsible person for that aspect to evaluate. They maintained their research was not related to materials selection or design. One argued that R&D needed the freedom to explore a variety of technological options without restraining choice of materials or design. Before environmental aspects could be discussed a functioning technology had to be developed. Else there was a risk that promising technological opportunities were abandoned too early in R&D. Another expert stated that during the early stages of technology design only few alternatives were available and that the researcher's primary aim was to accomplish a functioning system at all.

The majority of respondents to that question agreed in principal that there was a need for eco-design. Overall, the majority was positive in their attitudes towards DfR but hesitant to point at concrete activities in their research area. Many of those agreeing to the question relativated their answer indicating that it was too early in their particular field of research as to consider recyclability in practice. Some were uncertain if they were at the right position within the innovation system so to influence environmental features of technology. They perceived the principal need to develop recyclable products but deemed other actors within the innovation system being responsible to pursue that objective.

A last question addressed the interviewee's opinions who among the various actors in the innovation system for e-textiles should implement DfR.

Only a few interviewees gave a straightforward response. There was a slight tendency among the respondents to consider product designers in companies (system integrators within the textile value chain) to be able best to implement DfR. Some researchers pointed at their cooperation partners in industry (textile industry in these cases). They argued that the producers responsibility were with the companies. Thus, industry should set appropriate design criteria for the R&D process. A couple of respondents showed a more holistic stance expressing the need to consider environmental aspects throughout the entire innovation chain, R&D included.

Experts in firms rather pointed at their suppliers or costumers respectively. One supplier of intermediate materials argued the knowledge on application purpose was solely with the costumer (system integrator). Thus, a supplier holds limited abilities to influence design of finished products. Another interviewee, working for a system integrator firm, argued that knowledge on intermediate materials used was with the suppliers. They used textile and electronic standard materials and had little information on materials content. Venture capitalists were seen in a good position to determine the general course of innovative companies. One interviewee argued that venture capitalists should engage more in innovation and that way also push corporate environmental responsibility.

Despite the fact that no direct interactions seem to exist many interviewees deemed the textile or e-waste recycling sector to be in charge to deal with waste e-textiles. The experts involved in e-textiles innovation were optimistic that recycling industry could adapt to these new types of products or emphasised a need for innovation in that sector. Some interviewees expressed rather vague technical ideas how to recover valuable materials from waste e-textiles. Interestingly, they did not seem to be aware of the costs entailed to recycling schemes (both textile and e-waste) if e-textiles would enter these waste streams. They did not appear to consider the consequences on financing those recycling schemes and the possible costs for producers of EEE under an EPR regime.

Finally, it was argued that public environmental and waste policies and regulations should be adjusted (if necessary) or at least clearly communicated among all parties involved in e-textiles innovation. One expert pointed out that environmental regulation must be implemented in order to stipulate equal chances on the market. Otherwise, firms adopting environmental sound product design would not be rewarded for their investments.

5 Technologies and materials for e-textiles

5.1 Converging materials and functions

Traditional electronics does not have much in common with textile materials. As they serve completely different purposes both classes of products are composed of different materials and build in different ways. Most obviously, electronic products are hard and stiff while textiles are normally soft and flexible. Moreover, texture of electronic devices is usually highly ordered and not meant to change shape during use phase. In contrast, textiles are foldable, stretchable, compressible etc. Figure 5-1 contrasts typical appearances of electronics as compared to textile materials. Table 5-1 compares traditional properties of both technologies.

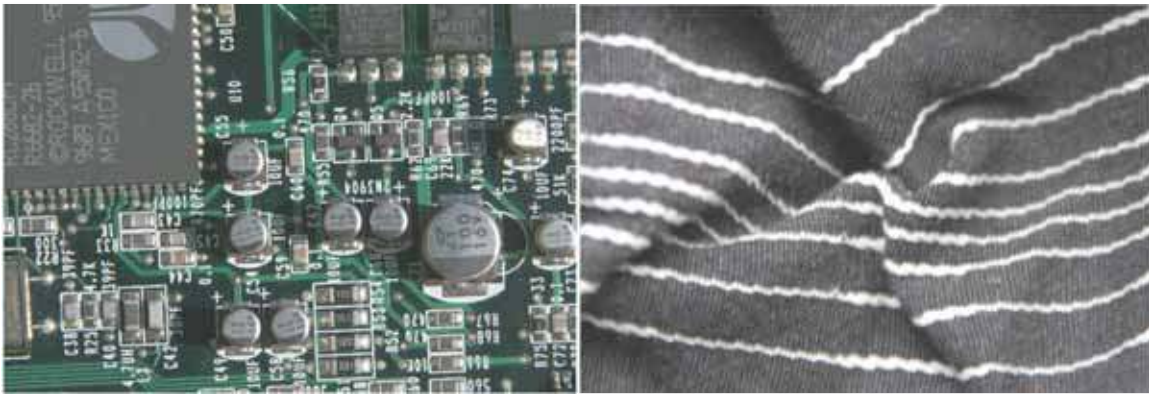


Figure 5-1 Comparison of the texture of a printed wiring board and a woven fabric. Source: Köhler, 2008

Table 5-1 Comparison of properties of typical electronics and textiles.

| Properties | Electronics | Textiles |
|-------------------------|---|--|
| mechanical | hard, stiff | soft, flexible |
| | not stretchable | stretchable |
| | low resistance against mechanical impact | medium to high resistance |
| | high structural complexity | low to medium structural complexity |
| weight per service unit | large range | low (clothes), medium (technical textiles) |
| chemical | huge materials inventory | few basis materials |
| | not water prove, not washable | can be wetted, washable |
| | do contain hazardous materials | can contain problematic materials |
| electrical | conductive, insulating, semi conductive | el. insulating, |
| | affected by static electricity | can generate static electricity |
| | storage of electrical energy (batteries) | no storage |
| thermal | gets hot, needs cooling | provide thermal insulation |
| | ignitable, (thus contains flame retardants) | ignitable, (can contain flame retardants) |
| logical | integrated into wider networks | integrated into fashion trends |
| | requires compatibility to data standards | compatibility to fashion trends |
| wear and tear | virtual wear and tear (obsolescence) | obsolescence depends on fashion |
| | casing protects against abrasion | prone to abrasion |
| | one defective part damages entire device | defects can be tolerated to certain degree |
| | often not reusable, repairable | easy reusable, repairable |

The creation of e-textiles means amalgamating electronic and textile materials posing new challenges for developers and designers. Development of a dual technology cutting across traditional technological domains requires a new design paradigm (Marculescu, Marculescu, & Khosla, 2002). Textile integrated electronic functionality makes necessary wholly new computational and architectural models and sets unique requirements to the materials composition and building structure. Hence, a range of enabling technologies and novel manufacturing technologies is prerequisite for successful implementation of the new type of products.

Looking at the desired properties of e-textiles it appears evident that modification of properties affects the electronic components in the first place. Textiles, being the platform of e-textiles (speaking about garments), should preserve their classic properties, which make them wearable, comfortable, fashionable, and washable. Embedding, integration or combination of electronics must not derogate those textile properties. Thus, electronics must become conformable with the properties of textiles including attributes such as soft, flexible, stretchable, and foldable. Apart from that, electronics must acquire resistance against mechanical and chemical impacts in order to withstand the stress textiles are usually exposed to during use phase. These constraints necessitate a water resistant and fault-tolerant type of ICT, which maintains low defect rate even if exposed to harsh wear and tear during application. In addition, textile embedded electronic can obtain novel properties which are not possible to realise in the traditional way. For example, fault tolerance can be achieved by covering large surface areas with spatially distributed computing nodes. Local defects in the textile can be compensated as they network spontaneously depending on their logical position.

While e-textiles or wearable computing systems require innovations in two fields: hardware and software, only the hardware components are of interest in this study. A precondition for development of e-textiles is the availability of various functional components and production technologies. Such enabling technologies include (Mecheels et al., 2004; Stylios, 2007):

- electrically conductive materials,
- contacting and bonding elements,
- embedded circuit boards,
- ICT devices and electronically active textile-materials,
- power supply.

Moreover, supporting technologies that fit into the whole system of e-textiles need to be developed such as sensors, data input devices and wireless data transmission technology.

There is no doubt that most of these technologies already exist and have resulted in applications. The big challenge remains to be the integration into textiles in such a way that consumer expectations on functionality are satisfied during a typical use phase. Requirements on operational capability are most demanding for clothes. Textiles are exposed to harsh external impacts during use phase that includes washing, drying, mechanical abrasion, humidity, chemicals and UV-radiation etc. Up to now producers of e-textiles are still challenged to develop functional components, withstanding all those impacts for a sufficient period of useful life. System integration at reasonable production costs seems to be the main difficulty.

In the following sections important enabling technologies and materials for e-textiles are summarized, based on literature review and information yielded by the expert survey.

5.2 Enabling technologies

5.2.1 Electrically conductive materials

Integration of electrically conductive structures into textile materials is a basic precondition for most types of e-textiles. The functions of conductive structures are listed below.

Electrostatic dissipation (ESD): Increasing the electrical conductivity of fibres helps to prevent electrostatic charging, which is one of the disadvantages of man-made textiles. Conductive textiles avoid charging as the electrostatic potential is dispersed and discharged immediately. Sufficient electrical conductivity for that purpose is around 10×10^3 ohm per cm (SWICOFIL, 2008), which is quite low. Antistatic properties are preferred in smart textile applications in order to prevent embedded electronic devices to be damaged by electric sparks.

Electromagnetic shielding: Protection against electromagnetic fields (or non-ionizing radiation respectively) is a function, which has seen increasing demand in the building sector and technical textiles but also has found application in the apparel market. Conductive fabrics can function as faraday cage if the conductive fibres are tightly interwoven showing a minimum mesh width of approx. $1/10$ of the electromagnetic wavelength. An example is a fabric of blended yarn with 8 threads per cm containing a 0.02 mm silver-plated copper wire (Elektrisola Feindraht AG, 2008). Required electrical conductivity is in the range of 10×10^3 ohm/cm. Electromagnetic interference control requires higher densities of conductive materials.

Signal transmission: Computing functions embedded into textiles require capability of signal propagation within textile structures. Data transmission between interwoven electrodes and ICT-devices necessitates low signal attenuation (Muth, Grant, Luthy, Mattos, & al, 2002). Therefore high electrical conductivity is necessary. Cables must be insulated to avoid shortcuts but bonding (making electrical interconnections) must remain possible. For low frequency signal transmission polymer coated metallised yarns can be used. Computing functions also require low impedance at high frequencies to allow for high data transfer rate. Up to now the electronic properties of textile wiring is not good enough for sophisticated computing applications. Optical fibres of about $120 \mu\text{m}$ in diameter are special cases in this context. These fibres consist of optical glass or plastic and are employed for high-speed data transfer. Application in smart textiles is difficult for glass fibres are rather stiff and brittle (Meoli, 2002b).

RF antennas: Wireless transmission of signals from embedded sensors to external electronic devices or vice-versa is typically based on inductive or RF coupling. For this purpose small antennas are integrated into textiles. They can be made of conductive yarn, thin metal wires, or conductive patterns that are printed or laminated on surface of flexible substrata. Most frequently this technology is used for RFID tags. Textile based RFID labels are commercially available and expected to be applied widespreadly in textile products in near future.

Power distribution: Distribution of electrical current from a power supply to textile-integrated electronic devices requires insulated conductive wiring. Conductivity should be high since devices operate at low voltage. Power distribution demands larger sized conductive wiring than signal transmission, depending on the electrical power demand of devices.

Heating: Electric resistance of conductive materials can be used for heating purpose in connexion with an external power source. Existing applications deploy metal wire blended yarns or conductive polymer fibres (Swicofil AG, 2008). Also CB coated polymeric fibres are used.

Materials applied

Polymers (e.g. PE and PES), the basic materials of which synthetic textiles are made, show low electric conductivity. They are perfect insulators. In order to increase electrical conductivity of textiles a couple of additional materials are introduced (see Appendix V). Information were obtained from literature review.

Manufacturing technologies for electrically conductive textiles

Electrical conductivity of fibres, yarns or fabrics can be increased by various technologies. Overviews over different types of conductive textile are given in (Berzowska & Bromley, 2007; Meoli, 2002b; Mythili, Gnanavivekanandhan, & Gopalakrishnan, 2007). Frequently, in e-textile research commercially available metallised yarns are used. Worldwide a number of firms offer a full spectrum of conductive fibres, yarns, and fabrics. These materials have been used in textile industry for a long time to increase electrostatic dissipation or for decorative purpose. Such out-of-the-shelf materials often have sub-optimal electronic or mechanical properties in terms of reliability and wear resistance. That makes necessary further R&D to meet the requirements of application in e-textiles. Several vendors of conductive yarns cooperate with e-textiles researchers to tailor-made conductive yarns for electronic application.

Metallic strand is made by spinning or twisting metal wires with diameters between 1 and 8 μm . Metallic strand shows high electrical conductivity and can be used for power distribution. Spinning process can be used to produce blended conductive yarn consisting of textile and metallic fibres. Coating of textile fibres with a metallic layer is another approach to produce conductive materials (they show lower conductivity than full-metallic fibres). Manufacturing methods are manifold. Usually surface of endless filaments is coated with thin metallic layers in the range of few μm . While galvanic plating is rarely used chemical coating is common practice in textile industry (Meoli, 2002a). Sputter deposition techniques or plasma coating are more recent approaches (Hegemann & Balazs, 2007; Qin, Wang, & Wang, 2008). These technologies produce very thin but stable coatings in the nanometer dimension. Other nanotechnological approaches include sol-gel processes and nano-particle coating using polymeric resins as binder (Brückmann, Koch, & Lutz, 2006). Across all these approaches, the most frequently used metal is silver but also copper or stainless steel are reported in literature.

Production of conductive fabrics is possible by surface coating by means of screen printing or ink-jet printing using conductive inks. These technologies result in good electrical properties (Kolbe et al., 2005). Spatial electronic patterns can be printed directly onto the fabric surface. In addition, spatial patterns of conductive materials can be incorporated into fabrics by means of embroidery. Here, conductive yarn is being embroidered into normal fabric (e.g. cotton or PA, PES, PS) resulting in mechanically hard-wearing structures. Advanced embroidery technologies are able to produce structures in the range of few 100 μm (line pitch). Finally, sewing or stitching metallised yarns into fabrics is a common way to produce conductive patterns. Weaving or knitting is used to integrate regularly arranged conductive structures in large area fabric. Density and spatial distribution of conductive threads within the fabric is adjustable within a wide range. So-called organza is made of metallic fibres or silk fibres that are wrapped into metal foil. These metallised fibres are interwoven in a very lightweight fabric.

Increasing intrinsic conductivity of synthetic fibres is another way to produce electrically conductive textiles. This is achieved either by application of conductive polymers such as polypyrrole or polyanniline (Devaux et al., 2007; H. K. Kim et al., 2003) or by dispersion of conductive additives (e.g. CNT, CB) into the polymer matrix (Hwang, Muth, & Ghosh, 2007; Lübben, 2005). Research groups around the world pursue to produce CNT/polymer composites by dispersing functionalised carbon-nanotubes in thermoplastic polymers (Kohler, Som, Helland, & Gottschalk, 2008). The amount of CNT used in experimental studies is in the

range between 0.5-20 %wt (ibid). Resulting masterbatches can be extruded and spun like other synthetic textile materials. However, spinning of such composites into fibres that meet requirements of textiles is still in the R&D phase and too expensive for mass application. Electrically conductive CNT-coatings on natural fibres (e.g. wool, cotton) can be produced by dyeing that is a traditional textile process (Panhuis, Wu, Ashraf, & Wallace, 2007).

Estimation of the metal content

Information regarding the metals content in e-textiles are hardly to be found in literature and at best authors report on electrical conductivity of materials used. Depending on the intermediate material used, production methods and application purpose metals content of fabrics varies in a wide range. Intermediate materials (e.g. yarn, fabric) are easier to characterise than fabric or final products.

Metallised conductive yarns exhibit coating thickness in the range from few nm to few μm (e.g. 2-3 μm). While metal content of nanocoatings seems to be negligible it can be up to 40 %wt if the thickness of the coating grows. Blended fabrics (with interwoven metallic or metallised fibres) contain up to 54 %wt metal. Also pure metallic strands and fabrics are available on the market (metal content 100%) (Elektrisola Feindraht AG, 2008). Some examples are listed in table 5-2.

Table 5-2: Example metals content of intermediate textiles.

| Material | Quantities | diameter and density of metal threads |
|--|------------------------|--|
| Blended yarn: PES/silver-plated copper | 80% PES / 20% CuAg | 20 μm , dtex* 31 |
| | 42% PES / 58% CuAg | 30 μm , dtex 70 |
| Blended yarn: PES/stainless steel fibres | 80% PES / 20% steel | dtex 200 |
| Silver coated cotton PA yarn | 90/95% cotton 10/5% Ag | dtex 1.8 |
| Blended fabric: PES/silver-plated copper | 46% PES / 54% CuAg | 27 μm , dtex 58 |
| | 80% PES / 20% CuAg | 20 μm , dtex 31 |
| | 93% PES / 7% CuAg | 71 μm , dtex 385 |
| Blended cotton/CuAg fabric | n.a. | 20 μm , 18 threads per cm warp and weft |
| Strand wire (twist) | 100 %wt CuAg | 50 μm , dtex 192 |
| Copper monofilament fabric | up to 100 %wt | |

* dtex = g/10 000m

Source: (Elektrisola Feindraht AG, 2008; Hermann Bühler AG, 2008; NV Bekaert SA, 2008)

Figures for intermediate materials say not much about the metal contents of finished e-textiles however. No information could be found in this regard.

Findings from the expert survey

Information established from the interviews confirmed the findings from literature review. Silver coated yarn was most frequently mentioned being the preferred material conductive textile structures are made of. High electrical conductivity, resistance to corrosion, and biocompatibility were highlighted being the most important advantages of silver. Copper and stainless steel were mentioned to be used for some prototypes of electronic garments in form of strands or blended fabric. However, those materials were considered less relevant than silver. Other metals mentioned were nickel and gold (in rare cases). Conductive polymers were

not regarded to be a useful substitute for metallised conductive materials at the moment. Some interviewees pointed at the lower conductivity and argued that such materials would not be used as long as silver was available at reasonable costs.

Interestingly, none of the interviewees was able to provide concrete data on metals contents, neither regarding the intermediate materials nor regarding the final e-textiles. Printed conductive structures were estimated to contain 2-10 %wt silver particles. Asked for an estimation of the metal contents of e-textile products some suggested rough calculations as shown below:

Estimation 1: electronic shirt with embroidered ECG electrodes:

- total textile area: approx. 3 000 cm² in cotton (200 g/m²) = 60 g cotton
- electrode area: approx. 300 cm² (3 patches 100 cm² each) = 6 g cotton
- electrode material: Ag coated yarn embroidered = 6 g yarn
- silver content yarn: approx. 40 %wt

Assuming dense embroidery of the electrode (50/50 ratio of cotton fabric and yarn) the silver content can be assumed with 3.6 g. Total silver concentration in the shirt would be approximately 6 %wt in this example.

Estimation 2: Jacket containing 500 cm² of conductive ribbons of silver blended PES fabric.

- total textile weight of the jacket: 1 000g
- ribbon material: 80% PES, 20% Ag;
- area weight PES: 300 g/m²

Approximately, the ribbon material would contain 60 g/m² silver equaling to 3 g silver per jacket. Silver concentration in the jacket would be approximately 0.3 %wt in this example.

Estimation 3: textile RFID transponder label integrated into a t-shirt

- total textile area: approx. 3 000 cm² in cotton (200 g/m²) = 60 g cotton
- label material: PE fabric, 4 cm²
- transponder antenna: 250 mm Ag plated copper wire, diameter of 40 µm, sinusoidal shape
- transponder chip: microchip (silicon) with 400 µm edge length,
- chip mounted on PES interposer.

The copper content of the transponder antenna is approx. 3.4 mg approximately. Copper concentration in the shirt would be approximately 5.6 permil in this example.

Noteworthy to mention that the examples above are not based on empirical data taken from real-world products but based on assumptions.

5.2.2 Contacting and bonding elements

E-textiles require new concepts of mounting and interconnecting electronic components that are embedded or integrated into textiles. In the first place mechanical fixation within the textile matrix needs to be established. Moreover, reliable electrical interconnection to sensors, other electronic devices, and power sources etc. is prerequisite to create electronic functions. A variety of contacting and bonding technologies are being developed for e-textiles as reported in literature. They include:

- Lead free soldering
- Conductive adhesives
- Mechanical connections

Solders

Traditional electronic components are held in place on printed wiring boards mechanically or by electric bonds, which are established by solders. These solders are based on metal alloys that show low melting temperature (approx. 183°C) so as to allow for precise and economic assembling methods. In the past eutectic tin-lead alloy was the most commonly deployed electronic solder (63 %wt tin and 37 %wt lead) (Kindesjö, 2002). Since 2006 those lead-based solders have been phased out because use of lead in electronics has been restricted by the RoHS Directive. Therefore, lead-based solders are being replaced by lead-free¹³ solders. However, these substitutes require a 10° C to 25° C higher processing temperature (see table 5-3). These processing temperatures are problematic when it comes to integration into textiles. Thermal stability of most textile materials (both, natural and synthetic ones) is limited to similar temperature levels. Consequently, direct soldering of e-textiles is challenging. Nevertheless, soldering is expected to be standard interconnection technology for e-textiles and embedded electronic devices. 'Flip chip on flex' is an example for soldering technology (Lukowicz, 2006).

Table 5-3: Examples for lead free solders. Source: (Kindesjö, 2002; Stannol GmbH, 2008)

| Alloy | Processing temperature |
|------------------------|------------------------|
| Sn63Pb37 | 183° C |
| Sn96/Ag4 | 221° C |
| Sn99/Cu1 | 227° C |
| Sn95.5/Ag3.8/Cu0.7 | 217° C |
| Sn95/Sb5 | 236° C |
| Sn42/Ag1/Bi57 | 218° C |
| Sn92.3/Ag3.4/Cu1/Bi3.3 | 213° C |

Conductive adhesives

An alternative to solders are conductive adhesives allowing for processing at low temperature. Adhesives consist of monomers/polymers (e.g. (poly)urethane) or bi-component epoxy resins, others are silicon based. Monomers typically need curing, that is thermal treatment while bi-component resins require hardener and some resins need thermal or UV curing in addition.

Vendors only know the exact recipe of their proprietary chemistry and details of materials content are hard to establish. Some adhesives can contain VOCs or other solvents. Conductive additives such as CB or metallic particles are usually added to achieve high electrical conductivity. Those would be nickel, copper or silver particles as a rule (Master Bond Inc., 2008). One vendor for instance quantifies the silver content of the hardened resin being higher than 81 %wt (Creative Materials Inc., 2008). Research on the use of CNT fillers is reported in literature. Heimann, Wirts-Ruetters, Boehme, & Wolter, (2008) for example prepared a conductive adhesive resin for electronic packaging, which was composed of cycloaliphatic epoxy resin (and anhydridic hardener) being filled with up to 10 %wt functionalized MWCNTs. Nanoparticle based conductive adhesives and resins may become a technology in future.

Mechanical connections

Classical textile technology, sewing (or embroidery respectively), can be adopted to create electrical interconnects in a solely mechanical manner (Linz, Kallmayer, Aschenbrenner, & Reichl, 2005). Flexible electronic modules can be attached to fabric using conductive yarn. The electronic modules are sewed through metallised contact points. Sewing entails a couple

¹³ Lead content must not exceed 0,1 %wt in electronic solders (apart from some exemptions) according to RoHS

of advantages: stable mechanical fixation, electrical interconnection without other materials introduced (avoiding solders) and application of standard textile manufacturing methods. In order to increase reliability the sewed contact points can be encapsulated within a drop of resin or moulded polymer substrate, the latter is to be cured at a certain temperature (typically 160° C to 185° C).

Removable connections can be made by mechanical means such as metallic snap fasteners or metallised hook-and-loop fastener. Also clamps can be applied (Laourine, Fritzsche, & Illing-Günther, 2005).

Findings from the expert survey

Interviews yielded little information on this topic. Most experts confirmed the use of lead-free solders and considered soldering a possible technology beside conductive adhesives. They could however not indicate details regarding quantities and composition of contacting materials used. Mechanical connections were regarded a promising innovation path, which could become a frequently applied interconnection technology for e-textiles.

5.2.3 Embedded circuit boards

In traditional electronics, active and passive electronic components are mounted and interconnected on solid printed wiring boards (PWB). These PWBs used to be stiff items made of a laminated fire retardant epoxy glass cloth (FR4) which is coated with copper layer(s), out of which at designated areas (using a screen printed photomask) the conductive patterns were created by an etching process. Nowadays, flexible laminate PWBs become more and more common, particularly in small electronic devices such as digital cameras. These laminates are made of a flexible polyimide film being coated with copper (up to 22 layers). Printed masks and etching is used to remove inverse patterns so that conductive patterns and contact bars remain in place (Healy et al., 2003).

Application in e-textiles makes necessary further developments in flexible PWB. The aim of developments is to create flexible, soft, stretchable, elastic but also rigid and watertight PWB. Flexible PBWs must acquire a degree of mechanical durability, which can compete with those of textile materials. Linz et al., (2005) report on development 25x25mm flexible PWB substrate for textile integration consisting of a 50 µm polyamide foil which is double sided coated with a 17 µm copper layer which is plated with 5 µm nickel layer, flash gold and a solder resist lacquer of 15 µm thickness (see figure 5-2).



Flexible PWB can be sewed onto fabrics using standard textile production techniques. For application in garments they may be sealed by plastic films or laminated into plastic foils.

Figure 5-2 Embroidered flexible PWB on textile substrate

Source: © Volker Döring/ Fraunhofer IZM

Brosteaux, Axisa, Gonzalez, & Vanfleteren, (2007) report about an elastic electronic circuit board with integrated interconnections. The substrate consists of a biocompatible silicon elastomer (Polydimethylsiloxan (PDMS)) with embedded gold plated copper patterns. Those conductive patterns are etched out of a copper layer (using photomask technique) and exhibit a horseshoe shape pattern so as to allow for high elastic stretchability. Electronic components, even a CPU, can be embedded into flexible silicon skins (Katragadda & Xu, 2005).

Electronic structures can also be laminated on fabric surfaces directly using an “iron-on” technique based on heat-activated adhesives (Buechley, 2006). The same technique is also suitable to establish electrical interconnections in one process step if conductive adhesives are used (Healy et al., 2003). Ink-jet printing of conductive inks makes possible producing electronic interconnections directly onto textile surfaces. The density of printable patterns (line pitch) is limited by the texture of the fabric rather than by the ink-jet print technology, which is applicable to resolutions as small as 200 μm (Kolbe et al., 2005). These examples can be seen as steps towards deep integration of electronics into textiles rendering PWBs obsolete at all. Presently those technologies are still under development.

Assembly and bonding of tiny microelectronic components such as microchips or SMD-elements directly onto textile surfaces are not easy. Therefore it is common practice to use interposer that widen the size of bonding pads from the micrometer dimension on silicon chips to the millimetre dimension on textile substrate. These interposers are typically plastic items.

No information could be established on the presence or absence of flame-retardants in flexible PWB, neither in literature nor during the expert interviews. However, as flame-retardants are usually to be found in conventional PWBs, so they may be used in the flexible ones too.

5.2.4 ICT devices and electronically active textile-materials

Seamless integration of electronic functionality into textiles is an overreaching goal of developments in e-textiles, in particular wearable computing. Textiles become smart and electronics become more ergonomically to use (speaking of garments in that case).

One basic precondition for convergence of electronics and textiles is miniaturisation of electronic components and structures. Another one is compatibility of such miniaturised devices with surrounding ICT infrastructure. Networking capability is regarded an essential feature of smartness. Therefore, active or passive data exchange is a necessity in the most cases. Moreover, electronic functionality must meet the up-to-date user expectations regarding performance of ICT service.

E-textiles compete, to a certain degree, with distinct electronic devices such as smart phones. Being highly miniaturised already such gadgets provide quite sophisticated ICT service. Further miniaturisation of high-tech devices is limited to the respective state-of-the-art in microelectronics. The frontier of miniaturisation is closely bound to technological progress in general, which in turn obeys Moore's law. There is no special microelectronics for e-textiles outpacing Moore's law. On the other hand, extreme miniaturisation meets limits of usability because tiny electronic gadgets are difficult to handle (risk of losing them physically; losing overview over functions etc.). Hence, attempts towards miniaturisation of textile embedded electronics need to cope with trade-offs in terms of usability versus ICT service power.

One approach towards miniaturisation is segmentation of functional electronic components (e.g. sensing units, user interface, processing units, networking devices and power supply) and their distribution among larger areas. Textiles usually exhibit large enough surface areas providing space for embedded electronic components in a spatially dissolved arrangement. That way, miniaturised ICT can be embedded into a macroscopic platform (maintaining usability). While the trend towards miniaturisation is determined by the general course of innovation the roadmap for textile integration is aligned to the three stages of technological development (First generation: adoption; Second generation: integration; Third generation: combination) [see 3.2.1]. In the following, these stages are explained in further detail.

A doption

The main attention in literature is paid to developments in the area of garments but also personal clothing accessory like caps, gloves, belts, shoes, handbags, backpacks, etc are mentioned. Technical textiles are also subject of R&D but less frequently reported. The first generation of e-textiles, already existing in form of prototypes and some products on the market, merely hosts than integrates electronic components within textiles. Adopted electronic components remain to be non-textile elements that can be attached onto or tightly embedded into clothes (Langenhove & Hertleer, 2003). Small and lightweight electronic components can be hidden behind a disguise of traditional textile attachments such as buttons, clasp, jewellery etc. Below is a list of embedded electronic devices, which are frequently mentioned in literature:

- Mp3 player including periphery (earphones, volume control),
- Mobile phones (in pockets) with embedded periphery (dial pads, microphone, earphone),
- Guidance systems in buildings (embedded into carpet),
- Wireless data exchange transceivers: RF-LAN, body area network (BAN), Bluetooth, IR, RFID labels,
- Control units (e.g. for electrically heated or cooled vests) and USB ports,
- display on the sleeve.

More sophisticated developments encompass:

- Garment mounted computational units integrated into buttons or belts. Electrical connections can be established by sewing with conductive yarn or wirelessly using RF technology (e.g. via Bluetooth). Hännikäinen, Mikkonen, & Vanhala (2005) describe a 2.5 cm sized circuit button made of solid PWB and other standard electronic components. Those items are suitable for mass-production and can be embedded into every-day clothing.
- GPS devices and antenna, wearable indoor location awareness system,
- Wearable computing apparatuses comprising a main board, inclusive processor, RAM, A/D converter, power supply, speaker, coin-cell pager motor, light sensor, LED (Buechley & Eisenberg, 2008).

Embedded electronic devices are usually complemented by external gadgets of higher functionality with whom they are networked. Mp3 players for instance, always need an external computer or DVD player to temporarily download audio files. Sensor equipped wearables are usually connected to external control units such as smart phones or notebook computers. Data exchange with external devices and networking functions are frequently realised using wireless technology (inductive coupling, Bluetooth). Wireless data transmission renders cables and connectors obsolete but requires additional electronics and power supply to be embedded into the textiles (Zięba & Frydrysiak, 2006).

As a rule, adopted electronics is made from out-of-the-shelf electronic components. There are no big differences in composition of components and materials as compared to distinct EEE. The main dissimilarities are with the way of electrical interconnection (conductive fibres), packaging (segmented, flexible PWB), and assembly (sewed into textile). Appendix VI lists the mixtures of materials found in mobile phones (tables A-1 and A-2) as a proxy for the materials inventory of textile embedded electronic devices.

Future e-textiles will show significantly reduced contents of bromine, cadmium, chromium, lead and mercury due to the RoHS-Directive [see chapter 2.3]. However, the total amount of hazardous substances within electronic could increase due mass application, even at low concentrations per product. For instance opto-electronic components (e.g. LED or laser diodes) contain minute amounts of GaAs (Schischke, 2003). These components may be incorporated in huge numbers into large area textiles. Moreover, new problematic substances could be introduced into e-textiles.

Integration

The next generation of e-textiles will be characterised by high degree of segmentation and integration of flexible electronic PWBs. The electronic components will be mounted on flexible PWB (see above) or embedded into polyimide, silicon, glass, ceramic laminates (Multi Chip Module - Deposited' technology) (Lukowicz, 2006). That development would require departure from classical shape of electronic items. Instead, electronics would be integrated into fashion elements such as collar, cuff, wristband, ornamentation, pockets or plain textile areas.

Recent R&D aims to alter the construction of active and passive electronic components themselves. Printed film electronic and polymer electronic is expected to replace for silicon and ceramic-based components in some application areas. While these types of electronics is not expected to achieve comparable computing power as compared to silicon-based microprocessors new application purposes for polymer electronic may be found in addition to silicon chips. Also optical electronics may become more important. In 2002 a prototype of the "Georgia Tech Wearable Motherboard" was developed using electrically conductive fibres (e.g. stainless steel, copper or doped nylon fibre) and plastic optic fibres. The fibres were coated with PVC and polyethylene respectively for insulation purpose. It also included sensors and processing units (Nørstebø, 2003).

As a rule, textile integrated electronics is anticipated to contain a much higher percentage of electronically active (that are intrinsically conductive or semiconductive) polymers and composites than today's electronic. According to Griese, Muller, Hagelucken, Reichl, & Zuber, (2001) future 'polytronic' will contain a large variety of polymers such as polyarylethers, SiLK-polymers, parylenes, and special PURs, BCBs, LCPs, polysulfone, PPV and derivatives. Moreover, nanocomposites are expected to be applied for future polymer electronics.

Combination

The third generation of textile incorporated electronics will, according to visionaries, look considerable different as compared to traditional ICT. Basic research on enabling technologies is being conducted in the R&D labs today. Combination will bring about electronic components, which are themselves fully transformed into textile materials (Langenhove & Hertleer, 2003). Interwoven yarn transistors might form active logic fabric or even integrated textile circuits. Hamedi, Forchheimer, & Inganäs (2007) for instance report on a wire electrochemical transistors (WECTs) consisting of 10–100µm textile monofilaments being coated with thin film conductive poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonic acid) (PEDOT/PSS). R&D on yarn based cylindrical organic field effect transistors is reported by (Maccioni, Orgiu,

Cosseddu, Locci, & Bonfiglio, 2006). They used 45µm metal fibers (probably silver) coated with 1 µm thin uniform layer of polyimide. The surface of these fibres were then covered with pentacene and electrode layers of gold or thin layers of PEDOT/PSS respectively. Another example is described by (Healy et al., 2003): They aimed at integration of computing power into textile fibres when they developed 'flexible intelligent fibres'. They deployed a technology called silicon on insulator material (SOI) that is based on a chemical wet etch process to produce active fibre circuits. They are confident that *"This technique has the potential to provide a planar technology that can manufacture extremely powerful circuits and systems in long narrow fibres, which can be woven into Fabrics"* (ibid p. 2).

Whether or not such visions will ever turn to real world products is not yet predictable of course. For sure, such technology would not substitute for traditional ICT but would coexist and, more likely, augment functions of ICT devices, which might undergo radical change in appearance as well. Pervasive computing has been anticipated to become ubiquitous in the technosphere around us within one decade (Hilty et al., 2005). The material composition of such type of ICT remains uncertain and can hardly be evaluated based on today's knowledge.

Findings from the expert survey

In their answers the interviewees referred mainly to embedded type of electronic components (adoption) and less frequently to integrated electronics. The concept of combination was held far away from today's practical relevance. The general trends of miniaturisation, segmentation and integration were agreed to but opinions differed regarding the way of integration. Some experts opted for deeper integration of electronics into textiles in order to increase usability and comfort. Others considered that idea problematic for two reasons: limited washability of electronics and user acceptance (consumers are not accustomed to embedded computing devices and may want to keep them detachable).

Development of novel materials takes place above all in terms of textile-integrated sensors. Many experts conducted research on fibre or foil shaped sensors based on polymeric materials, which are mostly coated with metallic layers. They indicated to utilise capacitive, piezoelectric, optical, or mechanical mechanisms in order to modulate sensor output signals. A few experts reported materials research in terms of electroluminescent, thermochromic, or colour-change textile materials. First generation of such products is already on the market. These products consist of textile embedded LED inclusive electronic controller and batteries. Future developments aim at intrinsically luminescent fabrics, foils or fibres. No details regarding materials content were mentioned but it appears that a variety of substances are tested, for instance copper doped zinc-oxide and other combinations of pigments.

None of the interviewees could provide details on materials inventory of the electronic components they used. Asked for possible content of problematic substances in textile embedded electronics the majority of experts, responding to that question, were confident that no hazardous materials were additionally introduced into e-textiles. They argued that innovation in the first generation of e-textiles relied on out-of-the-shelf electronic components while next generations would include higher percentage of polymeric and composite materials. Therefore they were optimistic that content of potentially problematic components would rather decrease than increase in future. With respect to flame-retardants some interviewees guessed that they probably would be used in e-textiles. However, no reliable information on this topic could be established during interviews.

5.2.5 Power supply

Electronic devices always need a electrical power source and this fact is not going to change with e-textiles. However, there may come novel powering technologies in future, which can be seamlessly integrated into textiles allowing for mobile operation of e-textiles. While today's mobile devices are normally powered by rechargeable batteries they will be complemented by other technologies in future. Presently, R&D in the field of energy-interactive textiles (EITXs) is manifold and cluster around two strategies: energy conversion and energy storage. Developments in specialty materials are seen a precondition for successful innovation in EITXs (Kim & Lewis, 2003). In the following some examples are briefly introduced.

5.2.5.1 Energy storage

Batteries

Rechargeable batteries are supposed being the most important powering technology adopted by the first generation of e-textiles. Most frequently mentioned in literature and by the interviewees, lithium-ion Li-ion batteries are seen as state of the art technology for mobile power sources. They come as coin-cells or cylindrical battery packs and are to be embedded into textiles in such a way that they can be exchanged or detached before laundry. Some developers try to create waterproof concepts of embedding batteries into textiles. They would be non detachable. The aim of deep embedding is increased usability and unobtrusiveness. Lithium polymer batteries offer interesting properties to meet these requirements. They can be cast into rectangular or irregular modules or even as film-shaped modules. Moreover, they can be made flexible and can thus better be embedded into clothes. The material content of commercially available rechargeable batteries is matter of proprietary know-how and few details could be established in the framework of this study. Generally spoken, Li-ion batteries consist of electrodes containing lithium/metal oxides (e.g. LiCoO_2 , LiNiO_2 and LiMn_2O_4) and graphite. Moreover they contain toxic and flammable electrolytes that contain dissolved substances such as LiClO_4 , LiBF_4 and LiPF_6 (Bernardes, Espinosa, & Tenorio, 2004).

A lot of research is being conducted on batteries based on nanotechnology. There is a variety of candidate technologies based on nanoparticles such as carbon nanotubes (CNT) (Köhler, Som, Helland, & Gottschalk, 2008). Future generations of e-textiles will most likely adopt state-of-the-art battery technology inclusive their respective charging auxiliary. Complementary, so-called 'super' capacitors can be used to store electricity like batteries. Prototypes of super capacitors deploy nanotechnology (e.g. CNT) and are expected to gain importance in future.

5.2.5.2 Energy conversion

RF and inductive powering

If embedded devices do not need constant power supply (e.g. sporadic data request from textile embedded sensors) RF or inductive coupling can be used for temporary powering. These techniques allow for energy transmission in close proximity (few cm) between an active device (powered e.g. by batteries) and a passive device (e.g. embedded sensors). Energy transfer takes place using magnetic or electromagnetic fields. The embedded passive device needs not more than a small antenna, which can be embroidered or printed onto fabric using conductive yarn or ink respectively. That technique is used for powering RFID transponders.

Ambient energy harvesting

One aim of innovation is to increase the e-textiles' autonomy from external power supply or respectively the necessity to periodically recharge batteries by using ambient energy sources. That necessitates new materials and technologies to be developed. R&D is conducted on harnessing ambient energy potentials around the human body (Kim & Lewis, 2003). In principle the following energy sources can be exploited by adequate technologies:

- photovoltaic energy: solar cells; photoadaptive polymers,
- temperature differences: thermoelectric generators,
- mechanical energy (motion, friction): piezoelectric materials,

Below, three generations of energy-interactive textiles (EITXs) are briefly illustrated as examples for the variety of technologies being developed at the moment.

Embedded solar cells: Silicon based solar cells (PV) have been used for decades to power mobile electronic devices and textile products with embedded PV-cells are to be found on the market already (e.g. solar backpacks, jackets, swimsuit) (K., 2007b; Strecker, 2007). Textile embedded solar cells need to be flexible and research is presently conducted on polymeric thin film solar cells which are based on conductive polymers such as Polyaniline (PANi) (Coyle et al., 2007). Beside the PV-cells solar powered textile products usually contain electronic power control and storage (e.g. batteries, capacitors).

Integrated solar cells: While the above mentioned flexible PV-cells are attached to textiles by sewing them onto the fabric surface the next generation of them is expected to be integrated into textile material. Currently there is basic research on the way to develop appropriate technologies (VDI/VDE IT, 2007). According to one interviewee such PV-cells would be coated onto textile substrate containing silver coated electrode patterns. The textile surface would be coated with a semi conductive zinc-oxide (ZnO) layer that is doped with photoactive pigments or dyes. Transparent electrodes would be laminated at the surface to seal the PV-cell. That PV concept would allow for application on large surface area textile products. Other materials combinations including nanotechnology are under R&D as well (Brand et al., 2007).

Combination - textile nanogenerators: a combined approach for textile powering devices has been reported by (Wang, Wang, Song, Liu, & Gao, 2008). They coated a forest of single standing piezoelectric ZnO nanowires radially around textile fibres thus creating a nanogenerator suitable to harvest energy from mechanical vibration (Qin et al., 2008). The textile basis material was Kevlar, which was first coated with tetraethoxysilane (TEOS) layer on which the nanorods were grown. Electrical charge was collected by a gold layer coated on the surface of every second of the nanorod-coated fibres. Such concepts are still basic research. Practical application would require larger textile areas to be coated that way in order to harvest enough energy to power electronic devices.

6 Discussion of possible end-of-life implications

6.1 E-textiles – the next e-waste problem?

From the literature review and the expert survey it has become evident that e-textiles constitute a dynamic sector of contemporary innovation. Important drivers for developments in that converging sector of technology are the overall technological trends in the ICT sector and the demand for innovation within the textile sector [see chapter 3]. European and national innovation policies foster R&D and encourage industry to invest in commercialisation of e-textiles. Many actors involved in the innovation system are optimistic that e-textiles can become a commercially successful generation of high-tech products. These arguments could be taken as profound indicators according to which e-textiles have the potential to pervade the market place within one decade.

There are some parallels between innovation in e-textiles and past innovations in ICT, such as mobile phones, from which lessons can be learned. First, the innovation process in ICT obeys similar drivers as in the case of mobile phones (e.g. Moore's law, miniaturisation, economy of scale, technology push). Second, innovation policies encourage growth of the high-tech sector and third, e-textiles have found early application areas in some market segments (work-wear, health care). While current R&D in e-textiles mainly aims at high added-value target markets it appears likely that later away the technology will be up scaled and introduced into mass-market sectors such as sport, well-being, fashion and lifestyle [see 3.3.1].

Experiences from past developments in ICT suggest that high-tech products can conquer mass markets very quickly. The success story of mobile phones may serve as an example for such an unexpected market break-through. In many countries the number of people using a mobile phone had been growing from a few percent of the population up to more than 60 % within less than one decade. Figure 6-1 shows the increase in usage of mobile phone in European countries during the 1990ies. Nowadays, mobile phones are more ubiquitous in daily live than fixed net phones have ever been. Moreover, newer models replace for mobile phones much more frequently than fixed net phones have been replaced.

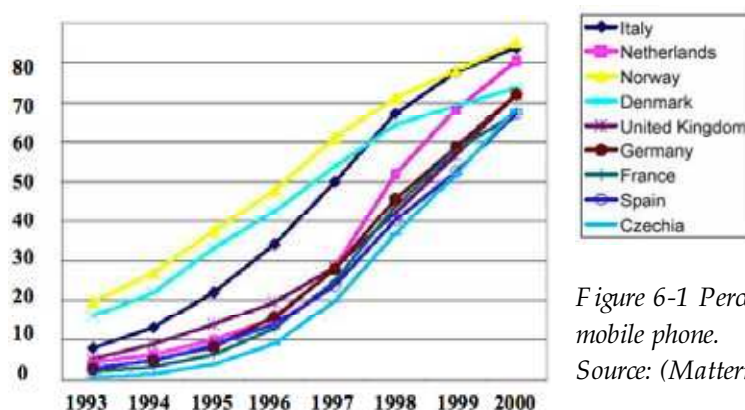


Figure 6-1 Percentage of people who have ever used a mobile phone.

Source: (Mattern, 2005) quoting E urescom

Hence, it is not an unreasonable proposition to infer that e-textiles, within some market segments, may experience break-through as mass application. That makes e-textiles being subject of scrutiny because the lessons learned from mobile phones (and other ICT devices) suggest that mass application of high-tech products can entail problems in the end-of-life phase. Discarded mobile phones constitute a prominent part of today's e-waste problem. 16 years after the first mass produced GSM phone was sold in 1992 collection for recycling of waste mobile phones is still an unsolved issue (Smith, 2007) (Nokia, 2008). If e-textiles were to

experience similar mass application then there is a risk that they could result in similar disposal problems in future.

In the following, e-textiles are analysed whether they would contribute to the e-waste problem in a mass application scenario. The analysis takes place in the context of the three main constituents of the e-waste problem [compare chapter 2]:

1. The e-waste mountains,
2. The toxic load,
3. Resource depletion.

6.1.1 E-textiles and the e-waste mountains

It is inevitable that e-textiles will turn to waste at the end of their useful lives. In a mass-application scenario e-textiles would be used in large quantities thus forming a considerable waste stream when disposed of. On the other hand, wearable electronics is expected to be highly miniaturised and lightweight. Could miniaturisation of textile embedded electronics counteract growth of the e-waste mountain due to substitution effects?

Upon first glance there is an opportunity indeed. A reduction in the overall e-waste stream could be achieved if highly miniaturised devices would substitute for larger ICT devices providing the same services. There are opportunities in some application areas such as hospitals and industry in which bulky, heavy-weight EEE appliances may be rendered obsolete by wearable electronics. For instance, stationary ECG-monitoring equipment could be replaced by wearable sensor shirts that are connected to small external ICT devices (smart phone).

However, one lesson that can be learned from the history of the ICT sector is: Growing numbers of electronic devices and more frequent replaces by newer ones have outweighed the benefits of miniaturisation by far. Substitution potentials have been utilised but they have hardly resulted in a decrease of e-waste streams. It can be presumed that e-textiles will not reverse that phenomenon. More likely, e-textiles will develop in line with the trend towards pervasive computing, that is growing numbers of items to be used in parallel for shorter usage periods. The chances of wearable computers to replace for laptops or smart phones are low according to experts in that research area. Rather, they will augment functionality of discrete ICT components that means e-textiles will be used in addition to them. Instead of substitution there is an addition potential. Hence, the amount of waste is likely to rise if e-textiles were about to become mass applications.

An exemplified calculation may illustrate a mass application scenario:

Assuming that the vision of pervasive computing will come true, an average consumer would possess more than one wearable computing device at the same time. That could be 7 sensor t-shirts for ECG monitoring (one per day of week) for instance. They may have an average lifespan of one year (equals approx. 50 laundries until wear and tear renders them unreliable). Assuming further that every second citizen older than 50 years in the EU25, about 100 million persons, (data from (EC, 2005a) use such devices in daily life (in particular elderly people could take advantage of every day usage). The resulting waste flow would be 7 waste t-shirts per user and year. That makes in total 700 million discarded sensor shirts per year to be disposed of in the EU. Assuming a weight of 60g per shirt the annual waste flow would be approximately 42 000 tonnes in that simplified example [compare estimation 1 in 5.2.1].

6.1.2 E-textiles and the toxic load

As shown in chapter [5] the first generation of e-textiles is expected to consist of miniaturised standard electronic components that are embedded into textiles. There is no reason to assume that textile embedded electronics would contain a different inventory of substances as compared to today's electronics. An opportunity exists that future electronics will contain a smaller amount of known hazardous substances. A number of them have been banned from use in electronics due to the RoHS-Directive (see table 2-2). Therefore, if compared to the composition of WEEE being found in the recycling and disposal channel today, waste e-textiles are likely to be less problematic in terms of toxic materials.

On the other hand, electronic components still contain a multitude of substances with some of them being problematic. The large-scale dissipation of minute amounts of toxic substances among textile bulk materials represents an emerging risk.

In e-textiles textile and electronic materials will be blended in the same product. Textiles themselves can contain a variety of chemicals such as dyestuff, flame-retardants, functionalisation and in future also nanomaterials (e.g. nano-silver). Future generations of e-textiles with integrated or combined electronic components will probably contain 'exotic' combinations of materials that are deeply integrated into textiles [compare chapter 5]. LEDs for instance contain minute amounts of GaAs. If it would come to mass application of light emitting textiles LED could be embedded into textile products in immense numbers (in order to illuminate large surface areas). As a result, total content of GaAs in textile materials could become an issue. Integrated power supply elements such as solar cells, thermo generators, piezoelectric elements and batteries can contain a problematic blend of substances, which would likely to be released during disposal of e-textiles. Textile integrated solders alloys and conductive adhesives are another potential source of heavy metals in waste e-textiles.

Another risk needs to be considered in this context. Formation and release of hazardous substances can occur if materials in e-textiles undergo chemical reaction. That could happen during use phase, e.g. while laundering or ironing. During disposal processes e-textiles may be treated by means of rough processes such as chemical leaching or open burning. Thereby pollutants could be released. Similar issues are documented to occur in many countries where e-waste is recycled and disposed of improperly (Puckett et al., 2002; Puckett, Westervelt, Gutierrez, & Takamyia, 2005). The risk of toxic substances formation is even higher since new combinations of materials are to be found in e-textiles. Some materials could act as precursor for hazardous substances to emerge. In particular the combination of plastics, halogenated organic compounds and metals (copper acting as catalyst) is known to result in formation of dioxins and furans if products undergo thermal decomposition.

In general, future electronic is expected to consist of plastics to a much higher percentage than today's ICT. Polymer electronic creates opportunities to replace a variety of metals and semiconductors that are used in silicon-based electronics. Polymeric or composite materials may replace for chemicals, which are to be found in traditional electronics in higher concentrations. However, plastics and elastomers typically contain a number of additives including plasticizers, softeners, colorants, fillers etc. Flame-retardants could gain importance in textile integrated polymeric electronic and despite the ban of brominated flame-retardants, the substitutes (that could be for instance phosphorus substances or nanoclay) may also cause adverse effects in disposal phase.

Application of novel materials could result in new risks. For instance, quantum dots, that are a family of nanoparticles, may substitute for GaAs in light emitting elements once. Little knowledge is available at the moment on toxicity of novel materials such as nanoparticles and quan-

tum dots. Conductive polymers can contain metallic or carbonous fillers in form of micro or nanosized particles. Carbon nanotubes are frequently mentioned in literature as one of the enabling materials that could be used in e-textiles in form of additives in fibres and conductive coatings (Köhler et al., 2008). Early warnings on potentially adverse environmental and health effects have been voiced in case of CNT (Helland, Wick, Koehler, Schmid, & Som, 2006). CNT are chemically and thermally much more stable than textile materials. Therefore they could be released from e-textiles in case of incineration or due to wear and tear.

In summary, there are opportunities that future e-textiles could contain significantly lower amounts of 'traditional' hazardous substances as compared to traditional electronics. At the same time there is a risk that new types of problematic materials are introduced into products and enter the waste stream at the end of their use phases. Moreover, new combinations of substances in and new application context of e-textiles could result in formation of toxic substances during disposal phase. Finally, there is a prevailing uncertainty around these risks since knowledge and practical experiences in EoL-treatment are still lacking.

6.1.3 E-textiles and resource depletion

There is little reason to assume that miniaturisation of electronics could result in an overall reduction of material flows in the ICT sector in future. Therefore, the high consumption rate of resources used for electronic devices will be an issue in the area of e-textiles as well. In the first generation of e-textiles (adoption) one can expect the full spectrum of valuable and specialty materials being typical constituents of ICT. This assertion is grounded on the information that textile embedded electronics will be composed of standard components. However, there may be shifts in combinations and concentration of certain materials used. For instance, iron and aluminium can be expected to lose importance. These metals have been used for computer cases but are too heavy and stiff for usage in textile embedded electronics. Plastics or textile materials will replace them.

Other materials may gain importance. Most prominently, silver is a candidate for usage in much higher quantities in e-textiles. Silver will, to a certain extent, replace for copper as the predominant material for electric wiring due to its higher electrical conductivity. Electronic components of the first generation of e-textiles (embedded) are probably not changed themselves but interconnected by silver coated conductive yarns. In contrast, future integrated e-textiles would require more expanded conductive structures due to spatial segmentation of electronic devices within the textiles. Combined technology would be made of conductive fibres for the most part (e.g. woven circuit board). It implies a more intense use of silver as compared to traditional electronic components. Whether, in turn, conductive polymers could substitute for silver in future is still uncertain, as technical performance of these materials cannot (yet) compete with silver.

Thus, consumption of silver for e-textiles production would increase sharply. In a mass application scenario silver demand would most likely overshoot the supply of silver by far. In the example on ECG-shirts presented in [6.2.1] the total silver content of those sensor shirts would be as high as 2 520 tonnes per annum. A silver consumption like this, for that application area of e-textiles only, would exceed economic feasibility. Consumption of 2 520 tonnes would constitute more than 12 percent of annual silver supply on the world market (in 2007 world mine production of silver was 20 500 t (Brooks, 2008)).

A second example may illustrate the perspective of a textile company producing smart jackets:

Based on estimation 2 in section [5.2.1] that product would contain 3 g silver per item. Assuming annual sales of 100 000 smart jackets the silver consumption would be 300 kg. Given an average silver price of 363 € per kg silver in 2008 (Jan-Aug) the company's costs for silver purchase would be 108 900 €. The silver price per jacket would be 1.09 €.

In that example the silver consumption does not a priori appear prohibitive to the company. However, assumed again a mass application scenario, the silver demand of that particular company would add to the increasing demand on the global metal markets giving raise to silver price. Within the last 4 years the silver price has already doubled while supply was almost constant. Mass application of silver based e-textiles is at conflict with resource availability. As a consequence, increase in silver price could render further developments of silver based e-textiles economically unfeasible.

Silver is only one example for a scarce material that could be depleted more quickly. Indium and tantalum are other essential materials used for modern ICT, which could run short in near future (Wäger & Classen, 2006). Indium is used in form of ITO for transparent electrodes in flat screen displays and solar cells. Tantalum is used for capacitors that are applied in mobile phones. Demand for these components is likely to increase as miniaturised ICT devices become ubiquitous in daily life according to the vision of wearable computing.

Design of future generations of e-textiles (integration; combination) may offer opportunities to avoid increase in consumption of scarce resources. Despite the demand for conductive fibres and other textile components increase in consumption of silver could be avoided by use of conductive polymers or composites, which could become available in future. In general, polymer electronic could contribute to a reduction of resource consumption in terms of speciality metals. Polymers are made of mineral oil. This is a limited resource too but e-textiles would (even in a mass market) not much increase the relative demand for mineral oil (as compared to fossil fuel combustion). Yet, there is too little information available in regard to materials inventory and architecture of combined textile electronics. Therefore, the assertion above remains to be subject of uncertainty.

Across all three generations of e-textiles a trend can be observed towards increasing dispersion of scarce materials within a large quantity of textile materials. While in embedded electronics valuable materials are mainly to be found in spatially segmented electronic devices these materials will be more dispersed within textile substrate in future e-textiles. Furthermore, e-textiles would be scattered within a huge amount of relatively short living textile mass products (garments). As a consequence, there is a risk that valuable and in particular scarce materials would be diluted within an immense waste stream. Dispersion of scarce materials within textiles and dilution in a waste stream could render recycling and recovery of them impossible. If materials recovery were beyond technical and economical feasibility these materials would not be reintegrated into production cycles. Hence, resource depletion would be accelerated.

6.2 Environmental and societal impacts of waste e-textiles

In the context of e-textiles there are opportunities for a reduced toxic load and consequently some environmental and societal problems could decline in relevance as compared to e-waste. In particular, environmental pollution and adverse effects on workers health during recycling and disposal could be lowered. On the other hand, lessons learned from the e-waste problem suggest that adverse impacts for the environment and society can arise if high-tech products are disposed of in large quantities. Several issues related to e-waste can be anticipated to become relevant for e-textiles too.

- **increase in waste flows:** increasing societal costs for waste treatment and disposal, exhaustion of landfill capacities, illegal waste dumping and transboundary movements of waste, environmental pollution by non-toxic materials (e.g. plastics),
- **disposal of hazardous components:** adverse effects on human health and workers safety, environmental pollution, displacement of pollution towards developing countries,
- **depletion of resources:** increase in scarcities, resulting increase in material costs, intensified mining for some substances and resulting environmental impacts, reduced resource availability for future generations.

Further risks to human health and the environment can emerge if textile-embedded waste electronics is put into the context of textiles recycling and disposal. Discarded e-textiles would be scattered within a large waste stream of old garments. That way hazardous and valuable substances would be diluted. This could result in health threats and environmental pollution at places where such problems are not being expected. Disposal of waste textiles is typically not a matter of special attention in waste management, for instance in developing countries where large second hand markets for garments do exist.

It appears questionable whether actors involved in the textile recycling businesses are prepared to cope with embedded electronic components in an environmentally sound manner. Experiences from e-waste recycling suggest that problems with cross-contamination can emerge if valuable materials (such as precious metals) are mingled with hazardous substances in the same product. Attempts to recover valuable materials usually cause occupational health problems and environmental pollution, particularly in case of improper technology is used. This often happens in developing countries where backyard recycling is performed as part of informal recycling business.

EoL e-textiles can also give rise to novel risks because novel materials and substances (e.g. nanoparticles) will be introduced into textile products. Adverse environmental and health effects could emerge from nanoparticles, if they are released from e-textiles during recycling processes. They could turn out problematic even at low concentrations. But their effects on human health and the environment are not thoroughly studied as yet and remain uncertain.

6.3 Anticipation of the fate of e-textiles at the end of their useful life

From the considerations made in the previous section it can be deduced that, in a mass application scenario, waste e-textiles could increase the e-waste problem: (1) they would contribute to increase the waste streams, (2) there is a risk of hazardous or problematic substances to be found in them and (3) they will accelerate depletion of resources if no recycling takes place. Lessons learned from the e-waste problem suggest that environmental and human health problems can emerge in the disposal phase of high-tech products. If old e-textiles exhibit similarities to the e-waste problem then there is a need to pay attention to their fate at the end of their product life cycle. Acknowledging that a large part of future waste e-textiles will emanate from B2B sector (e.g. health care, work-wear) the following discussion considers only waste e-textiles in the post-consumer waste channel.

Like other products at the end of their useful lives e-textiles will be discarded eventually. By then, their use-phase may have included reuse and refurbishment or second hand use. There may be a delay between the end of the practical use-phase and the user's eventual decision to discard the e-textiles. It has been found that consumers tend to stockpile high-tech gadgets at home instead of feeding them into a recycling scheme. A recent survey from Nokia suggests that 44% of old mobile phones are stored at consumers home (Nokia, 2008). Likewise, consumers keep old garments in their wardrobes for an indefinite period of time before discarding them eventually (Morley, Slater, Russell, Tipper, & Ward, 2006). Within this study no empirical data could be established in regard of the time delay but it can be reckoned that old

clothes are often stored for years or even decades. It can be reasoned that consumer's awareness and knowledge on e-textiles ceases during this period of time. Hence, consumer's decision how to dispose of such products would hardly be determined by knowledge. Rather they are likely to choose the disposal channel in accordance to the appearance of e-textiles.

As converging technology e-textiles will form a novel category of products combining properties from electronic and textile sectors (compare table 5-1). A foremost aim of contemporary innovation is seamless integration of electronics into textiles. That means, the electronic part will be unobtrusive or even invisible to the consumer's eye. E-textiles will look unlike traditional e-waste and not be identifiable as such. Instead, they may look like normal garments. Figure 6-2 illustrates the differences in appearance of e-waste as compared to old textiles (note: no e-textiles are displayed).



Figure 6-2 Typical appearance of e-waste (left side) and old clothes (right side)

Findings from the expert survey support the assumption that end-consumers may not easily recognise e-textile. If no electronic components or other obvious signs are displayed these products would be considered as old textiles rather than as e-waste. Here, the question arises what would happen to e-textiles at the end of their useful life.

The fate of post consumer e-textiles is difficult to anticipate. It will depend from the application area of e-textiles and how they look like. Moreover, consumer's awareness on and attitudes to waste separation are developed unevenly from country to country and not everyone has access to developed recycling and disposal schemes. Many aspects influencing the fate of future products are subject of uncertainty (e.g. innovations in the recycling industry, future regulation). From today's perspective, end-consumer have got three principal options into which disposal channel they can feed their discarded e-textiles (figure 6-3). The figure highlights that the consumer's decision is a critical junction for the end-of-life fate of e-textiles. In this respect there is little difference to existing recycling schemes for post consumer waste (such as e-waste).

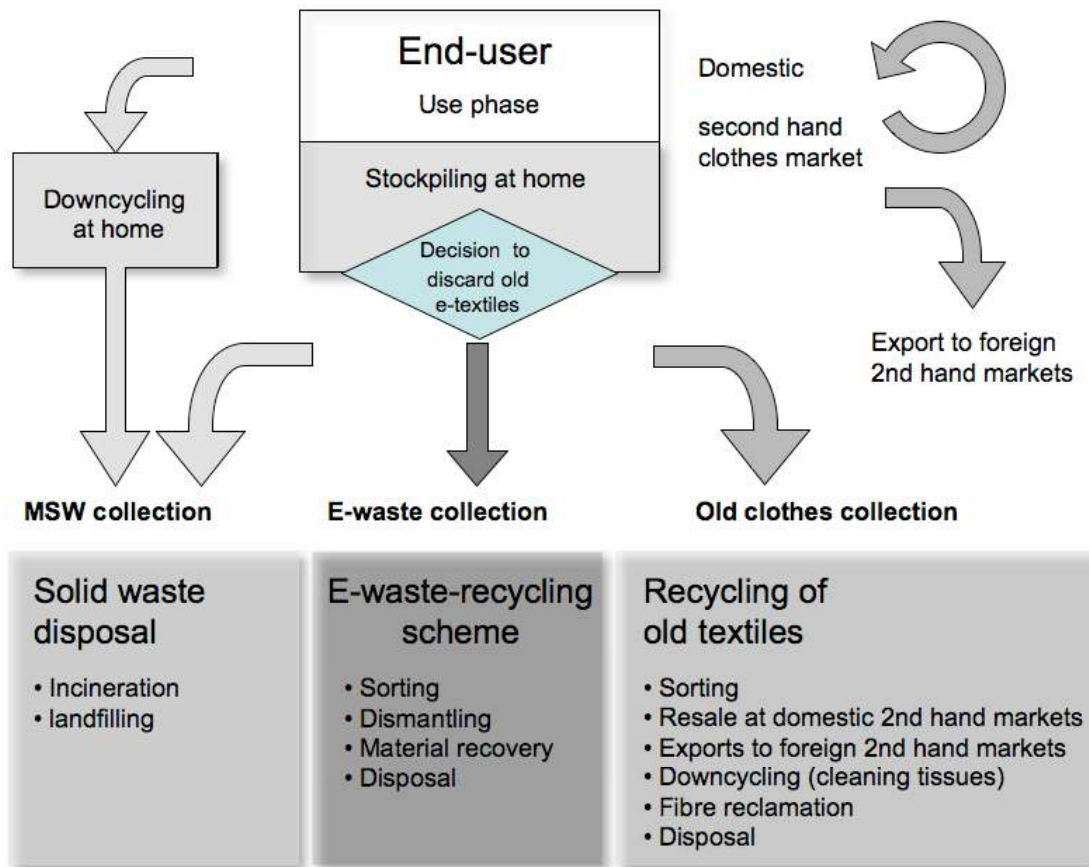


Figure 6-3 Possible recycling and disposal channels for e-textiles

6.3.1 E-textiles as part of the municipal solid waste (MSW) stream

Consumers could use the old e-textiles (or parts of them) as cleaning rags (e.g. wipers), similar to normal discarded textiles. This application could be seen as an open-loop recycling or down-cycling respectively (Morley 2006). After one-time use for that purpose the e-textiles would most likely be disposed of as part of normal MSW according to the local way of MSW disposal. End-consumer can also feed e-textiles directly into the MSW without down-cycling. In both cases the e-textiles will become part of the normal MSW treatment and disposal scheme as established in the respective country. In principal disposal schemes of MSW can be incineration or direct disposal in sanitary or non-sanitary landfills or even dumping.

Disposal of discarded textiles is common practice in many countries. In the UK for example, textiles constitute approx. 3% of the domestic MSW stream. 70% out of the approximately one million tons of discarded textiles are disposed of (Madsen, Hartlin, Perumalpillai, Selby, & Aumonier, 2007). Of this amount 14% is incinerated and the rest directly sent to landfill. In Switzerland, where all MSW is incinerated, textiles account for approx. 3% of the MSW as well. That makes 5.5 kg per inhabitant and year (Steiger, 2003). In Germany, 1.2 million tons of textiles are incinerated or landfilled annually (62% of all discarded textiles) (BVSE, 2001).

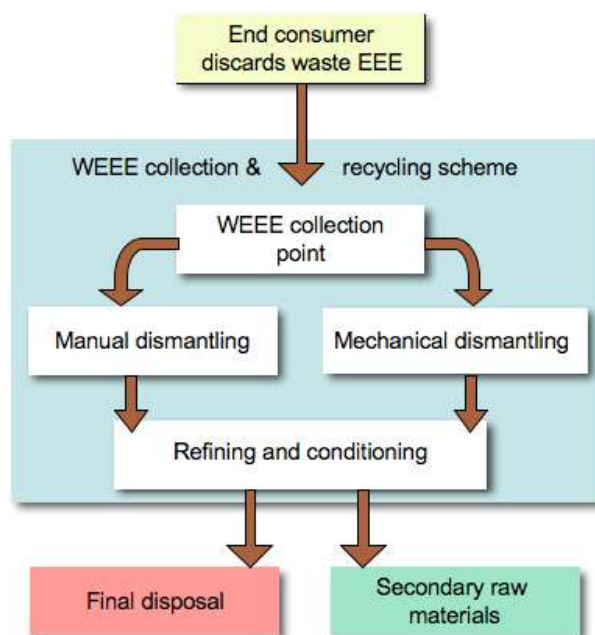
E-textiles, which enter the MSW-stream will be co-processed. While modern MSW incinerator plants and sanitary landfills are equipped with pollution control technology this is not state of the art in all countries. Thus, release of hazardous substances potentially to be found in e-textiles could occur. Released pollutants would add on to the overall environmental issues of MSW disposal. Nevertheless, there is also a risk that new types of pollutants could be formed when e-textiles are co-incinerated. While intrinsically conductive polymers will burn like other plastics the fate of nano-composites in an incineration process is still uncertain. For instance incineration of CNT-polymer composites would dislodge the nanotubes, which may survive the incineration and become airborne as a consequence.

No recovery of valuable materials is to be expected if e-textiles are co-processed with MSW. Even though some modern MSW incinerators in Europe are equipped with metal recovery from the slag, that technology is suitable to recover solid metal parts larger than a certain minimum size only (roughly in the centimetre range). The size of metal parts as used in e-textiles (in particular silver coated fibres) seems to be far below the capabilities of these technologies to recover metals. Thus silver, copper and other metals would be dispersed within the slag or would find their ways into the filter dust (being disposed of as hazardous waste). Upon dispersion within low-grade wastes valuable materials would be at loss.

6.3.2 E-textiles entering an e-waste recycling scheme

Waste e-textiles may find their way into recycling schemes for WEEE. With the WEEE-Directive in effect since 2005, European countries are supposed to implement schemes for separate take-back and recycling of e-waste (WEEE). The directive sets a collection target of annually 4 kg per year per citizen for WEEE from households (EC, 2003). The performance of WEEE collection schemes is still insufficient in some countries of the EU (Huisman & et al, 2007). In the years to come the compliance of national WEEE collection schemes may improve. By the time when e-textiles will first appear in the e-waste stream one can optimistically expect WEEE take-back and recycling schemes to be in operation in all European countries.

6.3.2.1 Background: recycling and disposal schemes for WEEE



In the following section a brief review of WEEE collection and recycling schemes is presented (figure 6-4) as a basis to evaluate the technical ability to handle e-textiles.

Figure 6-4 Generic WEEE-recycling processes in an European context Source: (EMPA, 2005)

Collection and pre-sorting: This first step aims to separate waste EEE products from MSW. As a rule, separation of WEEE from MSW has to be initiated and performed by the end-consumers. It is their responsibility to identify waste items as WEEE and to feed them separately into the respective WEEE collection scheme in place. In most cases they are supposed to convey the WEEE to managed collection points. Consumer's motivation to undertake these efforts can be facilitated by economic incentives or educational campaigns. Most WEEE recycling schemes employ collection points, which are contracted to retailers, municipalities or charities. This service can be organised by manufacturers or retailers of EEE or, in a delegated manner, by a collective organisation. At the collection points trained personnel would normally survey the items and classify them as being WEEE or not, accord-

ing to appendix 1 of the WEEE-Directive. Non-compliant items are rejected. At the collection point also rough pre-sorting is usually carried out, e.g. separating washing machines, refrigerators and electronics. From the collection points the WEEE is shipped to recycling centres for further processing by authorised transporters.

Dismantling: There are two ways to dismantle WEEE: manual or mechanical processes.

- Manual dismantling relies on simple work done by hand and the use of manually operated tools (e.g. screwdrivers, hammers and tongs). Training of working personnel is a crucial success factor for economically and environmentally sound recycling. Manual dismantling roughly deploys the following process steps:
 - sorting of incoming WEEE into various categories,
 - separation of components that contain hazardous materials,
 - separation and sorting of parts that contain recyclable materials,
 - separation and conditioning of non-recyclable components.
- Mechanical dismantling is mainly based on machinery such as shredders, crushers and automated separators. Still there may be a need to manually dismantle hazardous components (e.g. capacitors, large batteries or toner cartridges) in order to avoid cross-contamination. Recyclable materials are separated by shredding the WEEE into small pieces followed by a series of automated sorting processes. They rely on various physical principles and separate the various materials according to their magnetic/electric properties as well as weight, density, shape, etc. Specialised recycling companies apply a large variety of proprietary mechanical dismantling processes. Roughly, they comprise the following steps:
 - categorisation of incoming WEEE by manual pre-sorting,
 - separation of components that contain hazardous materials,
 - mechanical break down into small pieces based on shredding, crushing, milling etc.,
 - mechanical sorting and separating based on physical properties of the materials,
 - conditioning of recyclable and non recyclable materials (volume reduction).

Refining and conditioning: The recyclable output fractions of dismantling processes, that is secondary raw material, are feed into industrial material cycles as s. Refining processes include mechanical, thermal and chemical treatment and do not differ much from the production of raw materials. Secondary raw materials such as iron, copper, and lead are usually co-processed together with raw-materials in the refining plants. Special components such as CRT or batteries may enter special processes. Printed circuit boards (PWB) for example can be co-processed in copper smelters whereby also silver, gold and other precious metals are recovered. Plastics could be recycled as well. In practice however, recycling of plastics is complicated due to the fact that plastics in WEEE typically contain brominated flame-retardants that pose a toxic risk.

Some fractions such as normal solid waste and special waste undergo conditioning in order to reduce the volume and the reactivity of such components. Separating hazardous substances from non-recyclable components can be done to reduce their toxic load and thus reducing disposal costs.

Final disposal: Non-recyclable materials that are sorted out during all dismantling steps as well as waste from refining processes are finally to be disposed of in landfills. Slag and ashes are created by incineration of which at least the filter ash needs to be disposed of as hazardous waste. For example deep underground disposal sites are used. Some incineration plants possess over metal recovery from slag but this is not standard in all countries. In some countries poorly conditioned materials are landfilled or dumped.

6.3.2.2 Implications if e-textiles enter the WEEE recycling scheme

From the present day perspective e-textiles would not be recycled within the existing WEEE recycling schemes. The reasons are twofold: first, administrative barriers and second, technical problems. While the latter could be overcome by technological innovation the administrative hurdles could turn out to be more difficult. The reasons are as follows:

Definition of WEEE: It is not yet generally agreed whether or not post consumer e-textiles are to be defined e-waste. WEEE-Directive from 2003 does not explicitly mention such products in its appendix 1 (EC, 2003). The closest proxy to these type of embedded electronic devices could be the phrase "other products and equipment" in category 3 (IT and telecommunications equipment) and category 4 (consumer equipment). Also "sports equipment with electric or electronic components" from category 7 (toys, leisure and sports equipment) and "other appliances" from category 8 (medical devices) may describe e-textiles. There is much space for interpretation. For instance, German Federal Administrative Court decided that chip equipped sports shoes are not to be considered electronic devices (EEE) according to German ElektroG¹⁴ ("BVerwG 7 C 43.07," 2008). However, ongoing revision of the WEEE Directive may include mobile electronic devices more explicitly into the legislation. All the same, if e-textiles would experience break-through at the mass markets in future a need would emerge to include them into the WEEE-Directive.

At the moment, being not explicitly defined as EEE, waste e-textiles would probably be rejected at the WEEE collection points or sorted out by recycling companies during pre-sorting. Sorted out items may be disposed of as solid waste.

Responsibility and financing: WEEE-Directive stipulates extended producer responsibility of manufacturers or importers of EEE requiring them to install take-back and recycling schemes for WEEE. Usually the costs of WEEE collection and recycling exceed the revenues from recovery of valuable materials. In particular the collection of WEEE from private households is costly. The administrative costs of the take back system can comprise 50% of the total recycling costs (Lymberidi, 2001). Hence, take-back of waste e-textiles would entail additional costs.

As long as e-textiles are not explicitly considered EEE it appears doubtful whether any producer of e-textiles would voluntarily undertake that efforts or participate in a collective take-back scheme. Experiences from WEEE recycling show that many companies are rather reluctant to join collective take-back schemes (the so called free-rider problem). That means, financing of collection and recycling operations is not guaranteed for waste e-textiles. As a consequence, no recycling will take place as long as e-textiles are no product category according to the WEEE-Directive.

Technical issues: From the viewpoint of recycling technology waste e-textiles will pose many challenges. They are unlike traditional WEEE and would not easily fit into established handling and processing of WEEE. Especially handling of highly miniaturised and embedded electronic devices appears problematic. They would probably drop out of the collection containers or otherwise "disappear" during transport. Huisman & et al, (2007) conclude that performance of existing WEEE take-back and recycling schemes is low for devices below 1 kg. The fate of tiny devices such as flash-memory chips and mp3-players etc. is uncertain. They are hardly to be seen in typical WEEE even though they are sold in huge numbers.

¹⁴ The European WEEE directive is transposed into national law by the ElektroG

Manual operations (collection, manual sorting and dismantling) could probably be adjusted to handle soft, flexible materials. Adjustments would be necessary in terms of storage¹⁵, transportation, handling and choice of appropriate tools. Moreover, education and training of the personnel at collection points and recycling workshops seems necessary. Taking into account the heterogeneity of textile products it appears challenging to recognise miniaturised electronic devices that are embedded or integrated in textiles. Thus, separation of valuable materials and removal of components that contain hazardous substances would be difficult.

Mechanical processing of waste e-textiles would require new machinery. Shredders and crushers as used to process WEEE would not be able to cope with textile materials. Subject of experimental study one can assume that e-textiles would jam those machines. Also automated separators would fail to separate fluffy lightweight materials such as metallised plastic foils and textile fibres.

Refining of recycled materials from e-textiles could be challenged by the fact that metal content in textiles is much lower as compared to solid PWB. Moreover, metals being highly dispersed in combustible bulk materials would probably not melt in metal smelters but ignite and become airborne in the flue gas stream or enter the slag. No information on experimental studies on these matters could be found.

In summary: From today's perspective it appears unlikely that future e-textiles will be feed into the WEEE take-back schemes. Separate collection could fail because consumers will not recognize e-textiles as e-waste. Established WEEE recycling systems are not suitable to process waste e-textiles so as to recover valuable materials and to reduce risk of environmental pollution. Moreover, unclear regulation would entail a lack of financing for e-textiles recycling.

6.3.3 E-textiles entering a recycling channel for old textiles

A certain fraction of e-textiles is likely to be feed into a recycling channel for old textiles. This assertion can be derived from the proposition that e-textiles will be designed in such ways that the electronic component appears unobtrusive or even invisible. From the consumer's perspective they will appear as textile product. As discussed above, end-users may have already forgotten about the electronic function at the time when they decide to discard the old product. For the same reason it seems unlikely that end-users would undertake much effort in pre-sorting or removal of electronic components from e-textiles.

6.3.3.1 Background: recycling and disposal schemes for textiles

Fate and quantities of textile waste flows are badly documented in most countries. Since waste textiles are not defined special waste they are not subject of governmental monitoring. Data available from the textile recycling businesses suggest that approximately one third of all old textiles is separately collected and recycled. Data reported in literature are often quite outdated or incomplete; sometimes contradicting each other.

¹⁵ Waste e-textiles could start to rot under humid storage conditions.

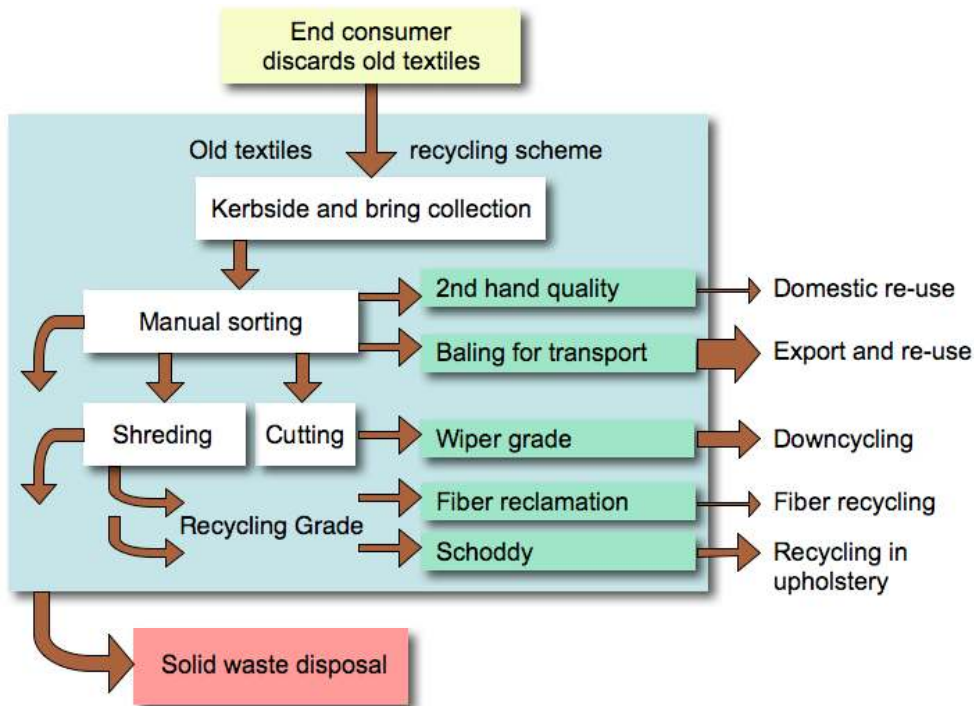


Figure 6-5 Generic processes of old textiles recycling in an European context

As for traditional garments, some typically enter the second hand market and a large fraction is exported to developing countries where they are re-used (Waste Watch, 2006). In the UK, ca. 30% (170 000 tonnes per year) of old clothing and other textiles are collected for reuse or recycling according to (Madsen et al., 2007). Much lower rates of separate textile collection (17%) but larger quantities (303 000 tonnes per year) are reported by (Morley et al 2006). Clothing collection is undertaken by second-hand businesses such as 'clothes banks', charities or for 'jumble sales'. The fate of post-consumer household textiles is believed to be as follows:

Madsen et al (2007)

- 13% enter the domestic 2nd-hand market in the UK (that means a delay of disposal),
- 54% are baled and exported to 2nd-hand markets abroad (overseas),
- the rest is downcycled into low-grade products (flocking or shoddy).

Morley et al (2006)

- Re-use in UK: 3%
- Re-use abroad: 60%
- Wiper Grade: 12%
- Recycling Grade: 19%
- MSW: 6%

In Germany, estimations from 2001 suggest that annually 716 000 tons out of the 1.9 million tons of discarded post-consumer household textiles are feed into textile recycling schemes (BVSE, 2001). According to that source the following textile categories are recycled and transferred into recycling products:

- | | | |
|--|---|--|
| <ul style="list-style-type: none"> - apparels textiles: 580 000 tons - household textiles: 52 000 tons - home textiles: 84 000 tons | } | <ul style="list-style-type: none"> - 50% sales to 2nd-hand markets for re-use (domestic 5%; abroad 95%) - 17% downcycling to cleaning rags, - 21% flocking or shoddy, - 12% MSW. |
|--|---|--|

The largest part of re-usable garments arising in European countries is exported abroad with target markets in Eastern Europe (declining amounts) and Africa.

Technically, textile-recycling processes rely on manual work during collection and sorting steps. Incoming old textiles are sorted by trained personnel and classified into a number of qualities (depending on customer demands, market situation and season). Reusable garments are resold without further processing (as a rule no laundering or repair is done). Second-hand clothes destined for export are normally baled (pressed to tight bundles) to reduce the volume.

Non-reusable qualities are sorted according to various properties (material blend, density, colour etc.). Qualities for production of cleaning rags are stripped from buttons, zippers etc. and mechanically cut into pieces, which are baled and sold to the industry. Cleaning rags undergo an open-loop recycling (downcycling) as they are mostly used one time only then disposed of as part of industrial mixed waste (Müller, 2005).

Fibre reclamation starts with mechanical shredding of the textiles. The machinery used here comprises various types (up to six in a line) of mechanical cutters, shredders, and slicers (however different ones as used in WEEE processing) (BAuA, 2007). After shredding, metallic parts larger than 1 mm are removed by means of magnetic/inductive separators or mass screening while non-metallic parts can be removed by air-classifiers for example. The content of metallic parts in textiles (typically copper and nickel plated ferrous metals, brass, or aluminium) is in the range of 5 %wt. The secondary fibres are then screened according to their length and blended with other fibres.

The recycled fibres can be agglomerated to flocks or manufactured into non-woven fabrics. Application areas of recycled fibres are mattress/upholstery (66%) and carpet underlay (11%), as well as use in the pulp & paper (5%), and automotive industry (8.7%) (Morley et al 2006).

6.3.3.2 Implications if e-textiles enter recycling schemes for old textiles

Considering the fate of post-consumer e-textiles one can suppose that a certain fraction of them would be feed into recycling schemes together with other household textiles. That may be true in particular for such e-textiles having similar appearance as other textile products of daily use: e.g. garments, working and protective clothes, curtains, pillows, sheets and shoes. Based on that assertion one can recon with approximately 30% of the old e-textiles entering textile recycling.

No information could be found whether it would be possible to maintain the “smartness” of e-textiles for re-use. It can be deduced that repair will hardly be possible during textile recycling neither from a technical nor from an economic perspective. Restoring the electronic functions would at least require functional test. Even if they were still intact the risk of defects occurring in the second life phase is high. Therefore, medical applications could not rely on second-hand e-textiles. Lack of reliability will render smart functions obsolete. Moreover, hard- and software upgrade may be necessary. ICT components suffer from virtual wear and tear, that is obsolescence, due to relatively quick ageing as compared to surrounding computing networks. Typically, ICT devices (e.g. laptops, smart phones) lose compatibility within few years and the same phenomenon may affect e-textiles more rapidly. That is due to the fact that they will often come as peripheral components of wearable network systems. Once that single components of a networked system are discarded (and particularly after some years of stockpiling), it seems impossible to restore the smart functionality.

However, old e-textiles may still provide classical textile functions. Therefore, a large part of them is likely to be categorised as 2nd hand clothes. They would be exported as usual towards overseas together with normal clothes. The fate of that large fraction in the recipient countries is unknown. Some interviewees assumed the e-textiles would be worn down and eventually dumped.

Whether e-textiles would enter fibre reclamation processes depends on the sorting step over which a recycling company holds good control. There is a risk that e-textiles could disturb fibre reclamation processes or contaminate the secondary fibres produced.

Results from chapter [5] suggest that future e-textiles will contain a variety of materials and components, which are not typical constituents of textiles. E-textiles can contain solder alloys such as Sn, Bi, Sb and other components such as batteries, solar cells etc. Embedded or integrated electronic devices would introduce metals, polymers, composites and other chemicals into mechanical shredding processes if not manually removed beforehand. It is well known that shredding of e-waste causes emissions of dust, which contains heavy metals and other harmful substances (Hanke, Ihrig, & Ihrig, 2000). They pose occupational health and environmental problems. In contrast, textile shredding is considered rather safe from the viewpoint of occupational health (BAuA, 2007). That situation could change if e-textiles were to be co-processed with normal waste textiles in fibre reclamation processes. Apart from dust emissions, materials of shredded electronics could end up in the recycled fibres and lower their quality. That issue may turn out very sensitive for recycling companies from the economic viewpoint.

From the economic perspective, textile recycling could become more expensive because new sorting and processing steps (e.g. removal of hazardous components) would be necessary. There is a risk that textile recycling becomes less profitable in general and suffers further decline as a consequence.

For technical reasons it appears hardly feasible to recover blended textile fibres and precious metals from e-textiles at the same time. However, recovery of valuable metals from e-textiles could be an attractive business alternative for textile recycling companies. For that purpose, investments into new recycling technology would be necessary. Large mass-flows of relatively high-grade materials are precondition for these investments to pay back. However, the trend towards high dispersion of minute amounts of metals within textile materials results in low-grade feedstock for recycling. While conductive fibres that contain metal wires represent distinct structures the degree of material dispersion is much higher in case of metal-coated fibres. In particular, the application of plasmathechnology and nanotechnology yield ultra thin conductive layers whereby metal content is below 1 %wt of fibre weight.

It is uncertain whether any technology would be able to recover highly dispersed metals from waste e-textiles at reasonable costs. For instance recovery of silver from coated fibres appears possible in theory. But in practice, large investments would be necessary to install appropriate screening apparatus. The same applies for other metals such as copper, which could be more abundant in waste textiles but less attractive to recover. The example of textile RFID labels [see 5.2.1. estimation 3] illustrates that the metal content per item can be very low (e.g. 3.4 mg copper per shirt). In a future scenario where RFIDs are embedded into every textile item sold globally, the total quantity of metals dispersed in textiles would be considerable. From today's perspective, the revenues from recovered metals would probably not pay back the investments into recycling technology.

Hence, dispersion of metals in e-textiles and their scattering within large streams of waste textiles do pose a recycling problem. Dispersion of metals within textile materials implies that they would be lost at the end of product life cycle. If e-textiles become mass-applications resource scarcity will be significantly amplified.

7 Conclusions and recommendations

7.1 Wrap up: the main findings of the study

Upon inception of this study a hypothesis was raised implicitly. It said that a more sustainable future could be achieved by governance of the ongoing innovation process in the converging sectors of ICT and textiles. It was further assumed that some lessons could be learned from the e-waste problem so as to avoid repetition of past mistakes. In that sense, the research conducted on end-of-life implications of e-textiles aimed at establishing sufficient intelligence as necessary for adjusting innovation policies. The findings on the research questions are presented below.

7.1.1 Addressing the research questions

1. Are there similarities between today's e-waste and the properties of e-textiles?

The relevance of electronic textiles, having the potential to generate end-of-life issues in the future, has been substantiated. This assertion is based on three-fold reasoning: (1) large mass flows of e-textiles can be expected if e-textiles experience break-through on mass markets, (2) some of the materials used can turn out to be problematic for the environment, and (3) there is a risk of acceleration of resource depletion if no recovery of materials from waste e-textiles takes place.

The first reason was inferred from the observation of some important drivers: It has been shown that innovation follows a technology-push model, which is in line with overarching development trends in the ICT sector. Innovation policies encourage technological progress in the converging technology sectors of ICT and textiles. Moreover, important actors within the innovation system believe that e-textiles will successfully pervade markets within the next couple of years, and they act into that direction. A couple of market segments (forming mass application areas themselves) are envisioned application areas of e-textiles [see 3.3.1]. Experiences drawn from past innovation cycles in ICT suggest that mass application can entail an e-waste problem subsequently [chapter 2]. It was deduced that high-tech products have the potential to conquer mass consumer markets in a disruptive manner (as illustrated at the example of mobile phones in [6.1]). It was further explained that e-waste problems typically emerge with a delay of a couple of years after market introduction of new electronic products.

The second reason was derived from the expected material composition of e-textiles. Opportunities to avoid future problems do exist since a number of 'traditional' hazardous substances are banned from use in future ICT. Therefore, the toxic load of waste e-textiles could be significantly lower as compared to today's e-waste. However, it was argued [chapter 6.1.2] that a risk does exist in regard to new materials, i.e. nanomaterials, and new combinations of textile and electronic materials. The risk results from the lack of knowledge regarding toxicity of novel materials. There is also a lack of experiences on how they could be released from e-textiles during product life cycle. Taking again into account lessons learned from the past (see the example on PCBs in [1.2]), one should be careful dispersing such materials within mass applications.

A third similarity is to be seen with view on scarce materials that will be used in e-textiles. It has been shown in chapter [5] that textile embedded electronic components contain a similar inventory of scarce materials as normally used in ICT. Moreover, silver is abundantly used for e-textiles. If it comes to widespread application a considerable amount of silver could be dispersed within a large waste flow. In future, there are opportunities for decreasing consumption of scarce resources if polymer electronic were to replace for silicon based electronics.

Gains in resource are made possible by the trend towards lightweight embedded ICT-devices. Positive net effects in resource efficiency could be realised if miniaturised wearable electronics would substitute for heavier ICT devices in a one-to-one ratio. But in reality it seems more likely that wearable electronics will be supplemented to existing ICT systems rather than substituting them. Moreover, shrinking mass per device could be overcompensated due to multiplication in numbers of devices being used per consumer. There is a risk of rebound effects to occur in case of mass application of e-textiles. However, the research conducted did not allow for calculating a bottom line between gains in resource efficiency due to miniaturisation and substitution and the counteracting trend due to mass application.

2. Are established schemes for collection, recycling and disposal of wastes sufficient to process end-of-life e-textiles so as to mitigate environmental impacts?

From chapter [6.3] can be concluded that existing recycling schemes, neither those for WEEE nor those for old clothes, would be able to cope with EoL-e-textiles.

End-users were identified to be key for the EoL-fate of old e-textiles: They decide in which recycling or disposal channel old e-textiles are feed into. From the present day situation it can be assumed that the biggest fraction would enter the solid waste disposal channel. That is because end-users may be unmotivated or unable to distinguish old e-textiles from other old textiles. The later reason can be inferred from the fact that electronics will be unobtrusively embedded into textiles.

As far as recycling schemes are in operation at all they are not prepared to separately collect and process textiles with embedded or integrated electronics. If e-textiles were to enter today's recycling schemes they would be most likely sorted out and disposed of. The reasons are of organisational and technical nature. Organization and financing of take-back and collection systems is hardly adjusted for this novel category of waste. Technically, it appears unfeasible to process such blended feedstock by means of existing recycling facilities for WEEE or textile products respectively. An essential feature of e-textiles is dispersion of valuable materials within large mass flows of textile products. The resulting low-grade concentrations of valuable materials are difficult to recycle by means of existing recycling technologies.

Thus, scarce materials would get lost in waste streams. However, growing flows of waste e-textiles could trigger innovations in recycling technologies.

3. How could mass application of e-textiles collide with the aims of European waste policies?

The findings from the study lead to the conclusion that contemporary innovation trajectories in e-textiles could result in conflicts with environmental and waste policies.

European and international regulations addressing the existing e-waste problem aim at mitigating the adverse environmental and societal effects that stem from the big amount of e-waste generated. As discussed above, increasing mass flows of waste e-textiles could amplify the e-waste problem in future. From today's perspective proper EoL management of waste e-textiles is not guaranteed since established recycling schemes are not designed to cope with that novel type of waste. Co-processing of waste e-textiles with municipal solid waste would thwart the goal of the WEEE-Directive to facilitate reuse and recycling of materials. Further, environmental pollution could not be ruled out because landfilling or thermal disposal of e-textiles could potentially entail formation and release of toxic substances.

Potential conflicts with the Basel Convention could emerge if e-textiles were to be exported towards foreign second-hand markets as part of reusable clothes. While the toxic load of e-textiles may be lower as compared to contemporary e-waste, the Basel Convention may be applicable nevertheless. The purpose of exports would be reuse of the textile components.

Embedded electronic components may still be considered waste, being subject of the Basel export ban for hazardous wastes. In any case, the fate of exported textiles is basically uncertain. Therefore a risk exists that reused e-textiles finally end up in unsanitary landfills or undergo inadequate recycling processes. The latter could become an issue if the silver content in waste e-textiles gave rise to new informal recycling businesses. E-waste exports destined for backyard recycling in developing countries are currently one of the most contentious issues of the Basel Convention. Co-exports of waste e-textiles as part of second-hand clothes could fuel that debate in future. In particular, the enforcement of the export ban of the Basel Convention could become difficult because waste electronic components are embedded in clothes unobtrusively.

European waste policies are founded on a waste preventative strategy so as to avoid arising of future problems. For that purpose they stipulate the principle of extended producer responsibility (EPR). The RoHS-Directive and the consolidated draft for a revised waste framework directive, both broaden the understanding of EPR as they lay responsibility on developers of future products. The research has found no evidence that the waste preventative approach is properly implemented in the innovation system for e-textiles. The same can be said in regard on EPR. While the majority of the experts interviewed expressed positive attitudes towards waste prevention in principal, awareness on these policies seems to be low in practice. Apart from few exceptions there were prevailing information gaps and lack of awareness among the interviewees. Few revealed detailed knowledge on the stipulations of the RoHS and the WEEE-Directive. In particular the experts from companies were hardly aware of the implications EPR entails for companies in the sector of EEE.

Obviously, coherence is lacking between waste policies and innovation policies. If key actors within the innovation system of e-textiles are lacking awareness regarding waste policies then a risk exists that mistakes of past innovation cycles in ICT are repeated. This conclusion leads to the fourth research question, which is discussed in the chapter below.

7.2 Recommendations

The fourth research question addressed possibilities for governance of innovation processes that help pushing technology trajectories of e-textiles into more sustainable pathways:

4. What adjustments in innovation policy could be taken in order to prevent e-textiles to become tomorrow's e-waste problem?

Below, this question is discussed from two perspectives, first from the perspective of innovation policy [7.2.1] and second from a merely technical perspective [7.2.2] taking a look into eco-design principles for development of green ICT.

7.2.1 Recommendations for innovation process

As a basis for discussion of possible policy interventions the goals of European innovation policies shall be brought back into mind: The European Commission encourages eco-innovation as a salient strategy to increase eco-efficiency of future generations of technology (EC, 2006). For that purpose, governance of innovation is an accepted instrument aiming at increasing sustainable global competitiveness. The European Commission has recognised that governance structure for innovation needs improvements, that is, inter alia, better coherence of policies as well as knowledge transfer among the actors involved in innovation.

Coherence is lacking between waste policies and innovation policies in the case of e-textiles. Despite the strong synergies between goals of both policies a gap seems to prevail between them. Whereas increase in energy efficiency appears to be a focal area of eco-innovation waste

prevention is not explicitly targeted at in innovation policies as yet. More than this: eco-innovation targets primarily on developments in environmental technologies. Other domains of technological innovation, such as ICT and textile sector, seem to be out of focus in European strategies for eco-innovation. That is an unsatisfactory situation because both sectors have got potentials for waste prevention and increased resource efficiency. Moreover, initiatives for eco-innovation have been developed in both sectors [see 3.2.3 and 4.1]. These observations lead to recommendations R1 and R2:

R1: Improving the coherence between environmental/ waste policies and innovation policies at both levels, the European and national ones.

R2: Adopting a proactive approach in implementing waste policies in the innovation process: extending the concept of eco-innovation beyond the scope of environmental technology.

These recommendations may apply in general in the context of innovation policies. In terms of e-textiles, however, harmonisation of policy targets from different contexts appears of foremost importance since formerly distinct sectors of technology are about to converge. The converging innovation system of e-textiles is still in an embryonic state but the formation of a new industrial sector could accelerate rapidly in case of market break through (compare (Grübler, 2003). Once the technology life cycle of e-textiles enters in an exponential grow phase (adolescence) the possibilities of preventative policies will wane. Hence, embarking into an environmentally benign innovation path for e-textiles requires policy intervention at an early stage of technology development. Harmonisation of policies could be a first step in order to avoid future waste problems to inflate.

A further finding of this study was that awareness of actors within the innovation system of e-textiles is low in regard to the goals of environmental and waste policies. While researchers and innovators seem to pay attention to a number of requirements such as safety and usability, environmental and EoL aspects ranked relatively low in their attention. Lacking knowledge on these matters could be an explanation for that situation. Moreover, it turned out that waste preventative design criteria were hardly considered in calls for research proposals nor were they seen a conditional aspect in public research funding. If these aspects were considered at all then they were mentioned among others but hardly emphasised. From this finding derive recommendations R3 and R4:

R3: Raising awareness of key-actors in the innovation system in regard to the waste prevention principle and improving communication about these issues among researchers and innovators.

R4: Fostering the implementation of the waste prevention principle in the goal setting for publicly funded R&D projects.

Implementing these recommendations would encourage researchers and innovators of e-textiles to intensify scientific communication and knowledge exchange about environmentally relevant aspects of e-textiles (such as resource efficiency, toxic waste prevention etc.). An important source of relevant knowledge can be drawn from research institutes and companies engaging in green electronics design for long. Also the textiles sector can contribute with relevant experiences regarding environmentally and socially sound textiles. It matters to combine and propagate these sectoral sources of green innovation, feeding them into the process of technology convergence. Policy incentives towards green innovation could most efficiently be set in the framework of public research funding. Furthermore, best practice competition, such as design awards, could facilitate a green design process to evolve form innovative companies in the sector of smart apparel.

Drawing from the expert survey it can be concluded that a clear regulatory environment is precondition for eco-innovation to unfold. Legislated policies such as the RoHS/WEEE Directives were seen essential drivers for progress in green electronics. The RoHS-directive and the principle of extended producers responsibility (EPR) were acknowledged as driving forces in the electronic sector. But these policies were hardly known to innovators that have their tradition in the textile sector. There is a risk that such policies are overlooked or neglected as long as legislation remains unclear and debatable in terms of e-textiles.

R5: Embedded electronics, such as e-textiles, should be taken up into the range of products considered as E E E by the W E E E-Directive.

R6: Increasing knowledge among actors in e-textiles innovation about the existing environmental/ waste regulation concerning electronic products.

This appears important for innovative companies in the market segments of e-textiles and smart apparel. They may be not aware of the chances that e-textiles may become subject of EPR in future. This may happen sooner or later when e-textiles start to enter the waste streams in large amounts. EPR would entail a new situation for these companies, seriously influencing their business strategies. It appears recommendable to them to prepare for that situation by adopting a waste preventative innovation strategy early in technology development. Proactive design for recyclability could put them into a stronger competitive position under an EPR regime. However, regulatory certainty is considered requisite for eco-innovation to take place in practice. Else, firms engaging and investing in eco-innovation would suffer competitive disadvantage. Sending clear signals to industry is seen an essential success factor of policies for eco-innovation (Hayes, 2007).

Apart from implementation of waste preventative design principles it appears requisite to pay attention to the end-of-life treatment of e-textiles. An important finding of this study was that established schemes for collection, recycling and disposal of e-waste and textiles would be inadequate to cope with waste e-textiles. The recommendations below aim at preparing the recycling and disposal sector for the arrival of large amounts of discarded e-textiles as part of the waste stream.

R7: Monitoring arising of discarded e-textiles and their occurrence in waste streams. Establishing adequate collection, recycling and disposal schemes for EoL-products that contain embedded electronic components.

R8: Facilitating innovation in the recycling sector.

A lesson that can be learned from the e-waste problem is the necessity to strive for a closed-loop economy. It matters to reduce the life-cycle-wide consumption of non-renewable resources and to lower adverse environmental and societal impacts of high-tech products. That implies a high rate of re-use and refurbishment in order to extend the service life of products. Additionally, recycling of waste products is needed, that is recovering materials and reintegrating them into production of new products. From the environmental perspective, not only precious metals deserve to be recovered but also other materials carrying heavy ecological backpacks. Thus, recovery of metals, polymers and textile fibres from waste e-textiles should be approached. For that purpose development of new recycling technologies seems necessary.

Finally, it was recognised that consumer's attitudes and knowledge concerning waste separation are crucial success factors for recycling of e-textiles. Since such behavioural change needs time to develop, R9 should accompany the commercialisation of e-textiles from the beginning:

R9: Searching for ways to motivate and educate end-users to feed old e-textiles into recycling schemes.

7.2.2 Recommendations for eco-design of e-textiles

The recommendations R1 and R2 from the previous section [7.2.1] advocate for proactive implementation of the waste preventative principle in the innovation process. A move towards eco-design of e-textiles could help to avoid future EoL problems. However, from a holistic perspective it appears important to optimise the environmental performance not only regarding the EoL phase but also for the entire product life cycle. How could eco-design be adopted in development of future technology?

As introduced in section [4.1] the ICT sector has already brought about a spectrum of environmentally sound design approaches, commonly referred to as Green Electronics. Between 1998 and 2006 the Ecolife (I and II) thematic network has undertaken joined research to establish comprehensive know-how on life-cycle oriented eco-design aiming at improvements in e-waste management (Ecolife, 2002a, 2002b). Eco-design principles, also known as Design for Environment (DfE), provide assistance for technology designers to reduce life cycle wide environmental impacts. The international ECMA-standard 341 provides a basis for eco-design encouraging ICT-manufacturer to assume life-cycle thinking in product design (ECMA International, 2008). In an European context, the Framework Directive 2005/32/EC on Ecodesign of energy using products (EuP) (EC, 2005c) stipulates an Integrated Product Policy (IPP) in the design stage of EEE products (Nissen, Stobbe, Schischke, Müller, & Reichl, 2007). Presently the EuP implementation process is underway and will result in definition of eco-design requirements. They will address improvements in energy efficiency, resource efficiency and end-of-life impacts among other environmentally relevant aspects during product life cycle.

Life-cycle screening tools have been developed to support environmentally sound decision making during product design (e.g. Griese, Schischke, Reichl, Suga, & Stobbe, 2003; Müller et al., 2004). Design principles and assessment methods specifically addressing the end-of-life phase of electronic products have been developed e.g. (Hesselbach, Herrmann, & Kim, 1999; Huisman, Ansems, Feenstra, & Stevels, 2001; Hesselbach, Herrmann, & Luger, 2007). Pioneers in green electronics design have noted that each new product development requires tailored life-cycle analysis. Popular eco-design principles include: design for {reuse, upgrade, repair, disassembly, recycling}. The list below picks up generic DfE principles relevant for EoL-optimisation of electronics (adopted from Huisman, 2008):

Design for recyclability of materials (DfR):

- decrease overall weight and volume of the electronic parts,
- limit use of materials, which could be considered problematic in future,
- avoid blend of valuable materials and polymers (composites),
- consider materials compatibility rules (e.g. plastics),
- limit materials with surface coating,
- build components, containing hazardous substances, easily accessible,
- decrease total number of parts,
- label polymer type of plastic components.

Design for reuse and repair:

- modular construction: exchangeable and easy access to...
 - parts that are prone to wear & tear (also virtual w&t): batteries, memory,
 - parts which are prone to early obsolescence (trendy parts),
- enable upgrade of parts which determine compatibility,
- reusable subassemblies should be separable without damage,
- pass along information for easy repair (e.g. about components and functions).

Design for disassembly (DfD):

- limit number of fixtures and joints,
- prefer fixtures which can be unfastened by use of simple tools
- consider the following order of preference (best first): click joints, screws, adhesives, solder.

In theory, developers of e-textiles could adopt the eco-design principles listed above. However, locking at them in detail and contrasting them against the properties of e-textiles leads to the belief that few of them would be applicable at once. Many of the existing eco-design principles do not match with the properties of the converging technology (textile embedded electronics).

While DfE paradigms say that components should be separable and blended material may be avoided the overarching innovation trend towards deep integration and unobtrusiveness conflicts with them. Screws or click joints for instance will hardly be used for e-textiles, instead embedded electronics is fastened by sewing, embroidery or laminated. These junctions can hardly be unfastened without damaging the textile material. Moreover, the widespread use of metal-coated fibres and fabrics clearly conflicts the DfR principle to limit materials with surface coating. As discussed in [6.3] recovery of highly dispersed metals appears hardly feasible. But, textile technology may allow for other design options, which have not been considered for ICT as yet, such as buttons, hook-and-loop fastener, and pockets etc. Textile technology may also provide new packaging materials that render traditional ones obsolete (such as aluminum).

Evidently, the innovation trend towards converging technologies raises new challenges to eco-design. **DfE guidelines and standards (such as ECMA-341) need to be rethought.** They should be complemented by design principles that apply for merged materials and integrated electronics. Adjusting existing principles of green electronic at a new type of ICT (that is pervasive computing in a broader sense) requires **research, experiments, and pilot study.** Joint action of eco-design experts and e-textiles researchers within the innovation process appears requisite. Moreover: for environmental optimisation of technology design it appears necessary to **revise life-cycle screening tools and EoL-assessment methods.** Existing software tools may suffer a lack of appropriate inventory data regarding textile materials and production methods. In addition, data may be lacking in regard to: disassembly methods; transfer factors of recycling processes, and formation of occupational health relevant emissions (e.g. dust).

Noteworthy to mention that e-textiles are to be seen as “energy using products” since they are powered by electricity. Thus, they would be subject of the EuP-Directive and necessitate application of eco-design mechanisms in design process. The EuP-process provides opportunities for proliferation of innovations in e-textiles: for instance transfer of power supply technologies using ambient energy sources to other sectors of ICT.

Finally, redefining eco-design paradigms in the context of converging technologies should be commenced at an early stage in the innovation process. It seems relevant to extend the scope of eco-design beyond the meaning of product design. At an early stage of innovation process technology is usually not yet ready to be applied in products. Thus, the attention of eco-design should be re-directed to **environmental optimisation of emerging technology already during R&D stage.** A “*system focused approach for sustainable technology development*” as recommended by (Schischke, 2003) could serve as a starting point further discourse.

To that end, **adopting a participative approach of technology assessment,** can help to identify societal needs and concerns in an early stage of development where there is still space for adjustments. Participative TA is involving not only experts but also future customers and stakeholders into the innovation process.

8 Outlook

8.1 Reflection upon the adequacy of the methods applied

In this study a methodological framework of technology assessment was applied in order to examine EoL implications of e-textiles in an early stage of technological innovation. Below, a brief discussion is developed whether the methods applied were adequate to establish scientifically sound answers on the research questions. The quality criteria as defined in [1.6.2.2] were used as a yardstick for those reflections.

The design of this research was inspired by the guideline of the TAMI project – an approach towards scientifically grounded TA being widely accepted in the European context. The project design starting with situation appreciation facilitated adjusting the objectives of the study on relevant issues. The focus on e-textiles as a relevant sector of technological innovation and the attention given to EoL issues of them were endorsed by most of the interviewees and the StEP initiative.

Out of the toolbox suggested by TAMI two tools (literature review and expert interviews) were chosen. Were they appropriate to be applied and sufficient to generate scientifically sound and relevant findings? Several drawbacks of practical nature limited the appositeness of these methods: literature review faced some obstacles due to lacking accessibility of literature databases. Many relevant research papers and conference proceedings were not available online or via library. The expert survey suffered from difficulties to contact an internationally balanced selection of experts in the European innovation system. Moreover, attending conferences and industry fairs, both relevant arenas for expert discourse, was not possible.

The barriers were mainly a consequence of the short project duration (3 months) and unsuitable season (summertime). The intended balance of the expert survey was not equally accomplished due to the fact that the response rate was above average in the German speaking countries. Nevertheless, it can be maintained that the aforementioned limitations did not affect the fulfilment of the research objectives because both methods yielded an abundance of information. They were sufficient to establish a proper level of evidence and the findings were indicative for the whole context. However, the results of the survey, solely relying on expert knowledge, were limited in their relevance for the fact that they may have missed to capture important insights into knowledge and attitudes of stakeholders and potential end-users of e-textiles.

For analysis the technique of abductive reasoning was applied taking the lessons learned from the e-waste problem as a background. That technique, being a pragmatic approach, yielded satisfactory explanations on the research questions. However, soundness of abductive reasoning would be strengthened by equally intensive efforts to disprove the preferred explanation. That is, testing alternative explanations for the phenomenon observed. This was not fully accomplished during the research due to the limited project duration. As a consequence, possible opportunities of e-textiles in regard to solutions of the e-waste problem were maybe systematically underestimated.

Another systematic bias in abductive conclusions stems from the chosen approach to learn lessons from the e-waste problem, which roots in the past. Learning from past experiences is a powerful heuristic in order to avoid repeating mistakes in future. But it is an insufficient instrument to recognise emergent phenomenon. Moreover, several of the drivers for the past e-waste problem have become obsolete by now. Hence, the conclusions of this study may be incomplete on the one hand and over-concerned on the other hand.

Finally, a generic point of view on e-textile and the innovation system was chosen for practical reasons. Many generalizations were made in regard to technology, products, materials etc. Therefore, the findings of the study were highly aggregated disregarding features of individual products. It remains subject of further research to go deeper into such details.

Conclusion: Considering the strengths and limitations of the methods applied and taking into account the limited resources available within the project it can be maintained that the findings of this study fulfil the quality criteria defined in [1.6.2.2]. This study provides a multidisciplinary overview over relevant EoL issues of e-textiles, which remain to be subject by further research.

8.2 Recommendations for further technology assessment

In this study a first multidisciplinary technology assessment was undertaken on a highly aggregated level. Details of future products remained uncertain due to the yet nascent state of the innovation system. Moreover, innovation of e-textiles progresses constantly and may bring about surprises (so called wildcards in innovation processes) resulting in EoL implications, which could not be recognised here.

Thus, **monitoring** of future developments in the converging technology sectors is recommendable in order to assure that future implications of e-textiles do not escape timely attention of policy makers. Monitoring should also include periodic review of knowledge base for early warnings arising from other domains of science, concerning adverse effects of novel materials used in e-textiles.

It matters to recognise such **early warnings** in time so as to avoid widespread market introduction of products containing potentially problematic materials. In particular, toxicological and ecological effects of nanomaterials need to be studied in a broader context. Applied research should also include study of mechanisms by which nanoparticles could be set free from textile products. Occupational health research should address human exposure to free nano particles being released during use phase and during recycling/disposal operations.

While the EoL-phase has been emphasised in this study, the environmental impacts of e-textiles should be studied over the whole product life cycle. From a life cycle perspective, manufacturing of ICT is typically of foremost importance since resource consumption during production is immense. Energy and material intensive production methods of high-tech products result in a large ecological backpack. **Life cycle assessment** (LCA) can be used to identify the hot-spots of environmental impact during the life cycle and can help to develop better alternatives. Establishing life cycle inventory data for materials and production processes applied in e-textiles would be the first necessary step. These data should be made available for LCA conducted in parallel to the development of real products.

Yet, it may be too early a stage in innovation at the moment to conduct LCA. Therefore, **foresight** should be undertaken before up-scaling of technologies to mass applications. Companies would do better anticipating future availability of materials before investing into development of technologies which could become unfeasible due to future resource scarcities.

More **detailed assessments** of recycling and disposal issues of e-textiles should run in parallel to the development of technology. Further research on recyclability may also deploy experimental methods so to generate knowledge on design options that facilitate refurbishment, repair and disassembly of e-textiles. It appears recommendable to take advantage of a broader base of expertise. That means bringing together experts from different domains of the innovation system, green electronics, eco-textiles and also the recycling sector.

8.3 Further research

During the research for this study some aspects were recognised which could be subject of further study.

- (1) The fate of old textiles shipped to foreign 2nd hand markets is hardly explored from an environmental perspective. Stakeholders, such as social charity organisations, have raised concern regarding shipments of textiles for re-use towards developing countries. That supply could distort local economies in the recipient countries. The further lifecycle of reused clothes in these countries is uncertain; they are probably disposed of eventually. The environmental effects of these disposal operations are uncertain. It should be explored whether waste electronic components that are embedded in textiles could pose problems in these countries if disposed of together with waste textiles.
- (2) Resource scarcity: the effects of dispersion of minute amounts of scarce materials in large amounts of bulk materials such as textiles.
- (3) Calculation of net-effects in resource consumption. The comparison of opportunities due to miniaturisation versus risks due to mass application.
- (4) It seems worthwhile to reconsider the meaning of **extended producer responsibility** (EPR) in the context of technology genesis. The environmental performance of future products is determined already in the development phase of novel technology. Hence, the responsibility of developers and designers for future environmental impacts should be reevaluated.

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Abbreviations

| | |
|-----------|--|
| CRT | cathode ray tube |
| EAM | electrically active materials |
| ECG | electrocardiogram |
| EEB | European Environmental Bureau |
| EEE | Electrical and Electronic Equipment |
| EM | electromagnetic radiation |
| EOl | end-of-life |
| EU | European Union |
| e-textile | electronic textile |
| e-waste | electronic waste |
| GPS | Global Positioning System |
| GSM | Global System for Mobile communications |
| ICT | Information and Communication Technology |
| LCA | Life Cycle Assessment |
| LED | Light Emitting Diode |
| MST | microsystems technology |
| MSW | municipal solid waste |
| MWI | municipal waste incinerators |
| OECD | Organisation for Economic Co-operation and Development |
| PC | personal computer |
| PV | photovoltaic |
| PvC | pervasive computing |
| PWB | printed wiring board |
| R&D | research and development |
| RFID | Radio-frequency identification |
| RoHS | Restriction of Hazardous Substances Directive |
| UHMW | Ultra-high-molecular-weight |
| UNEP | United Nations Environment Programme |
| WEEE | Waste Electrical and Electronic Equipment |
| %wt | percent by weight |

Abbreviations for Substances

| | | | |
|-------|-------------------------------|-----------|--|
| Ag | silver | PANI | polyaniline |
| Al | aluminium | Pb | lead |
| Am | americium | PBDE | polybrominated diphenyl ethers |
| As | arsenic | PBT | polybutyleneterephthalate |
| Au | gold | PCBs | polychlorinated biphenyls |
| Ba | barium | Pd | palladium |
| Be | beryllium | PE | polyethylene |
| CB | carbon black | PES | polyester |
| Cd | cadmium | PET | polyethylene terephthalate |
| CFC | chlorofluorocarbons | PCM | phase change materials |
| CNT | carbon nanotubes | PP | polypropylene |
| Co | cobalt | PS | polystyrene |
| Cr | chromium | Pt | platinum |
| Cu | copper | PVC | polyvinyl chloride |
| EAP | electroactive polymers | Rh | rhodium |
| Eu | europium | Ru | ruthenium |
| Fe | iron | Sb | antimony |
| Ga | gallium | Se | selenium |
| Ge | germanium | Si | silicon |
| Hg | mercury | Sn | tin |
| ITO | indium tin oxide | Ta | tantalum |
| Li | lithium | Tb | terbium |
| MWCNT | multi-walled carbon nanotubes | TBBA | tetrabromobisphenol |
| Nb | niobium | VOCs | volatile organic compounds |
| Ni | nickel | Y | yttrium |
| NiCd | nickel-cadmium | Zn | zinc |
| NP | nanoparticles | PEDOT/PSS | poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonic acid) |
| PA | polyamide | | |
| PAN | polyacrylonitrile | | |
| ZnS | zinc sulphide | | |

Appendix I: List of interviewees

Interviewees from research and development

| | |
|---------------------------------------|--|
| Astrid Böger, Prof. | Brandenburgische Universität Cottbus, Germany; Questionnaire July 2008 |
| Christof Breckenfelder, Dipl.-Ing. | Universität Bremen, Technologie-Zentrum Informatik (TZI), Germany; Phone interview 2. July 2008 |
| Simone Corbellini, Phd. | Politecnico di Torino, Dipartimento di Elettronica, Italy; Phone interview 4. July 2008 |
| André Decker, Dipl.-Ing. | Universität Bremen, Institut für integrierte Produktentwicklung (BIK), Germany Phone interview 8. July 2008 |
| Christian Dils, Dipl.-Ing. | Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (IZM), Germany Phone interview 25. June 2008 |
| Tilak Dias, Dr. | Universität Manchester, William Lee Innovation Centre (WLIC), UK; Phone interview 30. June 2008 |
| Sabine Gimpel, Dipl.-Ing. | Textilforschungsinstitut Thüringen-Vogtland (TITV), Greiz, Germany; Questionnaire June 2008 |
| Hansjürgen Horter, Dipl.-Ing. | Institut für Textil- und Verfahrenstechnik Denkendorf, Germany; Phone interview 26. June 2008 |
| Nader Jalili, Prof. | Clemson University, Smart Structures and Nanoelectromechanical Systems Lab U.S.A. South Carolina; Phone interview 1. July |
| Tünde Kirstein, Dr. | Schweizerische Textilfachschule STF, Zürich, Switzerland; Phone interview 1. July 2008 |
| Dierk Knittel, Dr. | Deutsches Textilforschungszentrum Nord-West, Germany; Phone interview 25. June 2008 |
| Michael Lawo, Prof. Dr. | Universität Bremen, Technologie-Zentrum Informatik (TZI), Germany; Questionnaire June 2008 |
| Lieva Van Langenhove, Prof. | University Gent, Belgium; Phone interview 3. July 2008 |
| Jean Léonard, Dr. | Centre Scientifique et Technique de l'industrie Textile belg, Belgium; Questionnaire July 2008 |
| Paul Lukowicz, Prof. Dr. | University Passau, Embedded Systems Lab, Austria; Phone interview 1. July 2008 |
| Corinne Esther Mattmann, Phd. Stud | ETH Zürich, Institut f. Elektronik, Switzerland; Questionnaire July 2008 |
| Jan Meyer, Phd. Stud. | ETH Zürich, Institut f. Elektronik, Switzerland; Phone interview 23. June 2008 |
| Andreas Neudeck, Dr. | Textilforschungsinstitut Thüringen-Vogtland (TITV), Greiz, Germany; Phone interview 8. July 2008 |
| Thomas Pusch, Dr. Ing. | TU Dresden, Institut für Textil- und Bekleidungstechnik ; Germany Phone interview 18. June 2008 |
| Markus Rothmaier, Dr. | EMPA St.Gallen, Switzerland; Phone interview 23. June 2008 |
| Martin Rupp, Dipl.-Ing | Hohensteiner Institute, Germany; Phone interview 11. July 2008 |
| Derck Schlettwein, Prof. Dr. | Institut für Angewandte Physik, Giessen, Germany; Phone interview 26. June 2008 |
| Elke Thiele, Dipl.-Ing. | TU Chemnitz, Sächsisches Textilforschungsinstitut, Germany; Phone interview 23. June 2008 |
| Alessandro Tognetti, Phd. | University of Pisa, Interdepartmental Research Centre 'E. Piaggio', Italy; Phone interview 2. July 2008 |
| Gerhard Tröster, Prof. | ETH Zürich, Institut f. Elektronik, Switzerland; Face-to-face interview 11. June 2008 |

Jan Vanfleteren, Dr. Universiteit Gent (Ugent), Electronics and Information Systems department
Belgium; Phone interview 11. July 2008

Christian Vogel, Dipl.-Ing. TU Chemnitz, Sächsisches Textilforschungsinstitut, Germany;
Questionnaire June 2008

Nadine Zimmermann, Dipl.-Ing. RWTH Aachen, Institut für Textiltechnik, Germany;
Phone interview 1. July 2008

Dirk Zschenderlein, Dipl.-Ing. Textilforschungsinstitut Thüringen-Vogtland (TITV), Greiz, Germany;
Questionnaire June 2008

One interviewee preferred to stay anonymous.

Interviewees from companies

Tanja Haiss, Statex Produktions & Vetriebs GmbH, Bremen, Germany;
Phone interview 26. June 2008

Isa Hofmann, Dr., IHOFMANN International, Germany;
Phone interview 4. July 2008

Mr. Kremer, Therm-ic, Germany;
Phone interview 30. June 2008

Axel Steinhage, Dr. Futureshape, Germany;
Questionnaire July 2008.

Sabine Seymour, MBA, MPS. Moondial, Austria
Phone interview 24. June 2008

Francisco Speich, Dipl.-Ing. Jakob Müller Technologie AG, Switzerland;
Phone interview 26. June 2008

Oliver Stollbrock, Industriekaufmann FIS Fashion Innovation Service GmbH, Germany;
Phone interview 25. June 2008

Dirk Wehner, Thorey Textilveredlung GmbH, Gera, Germany;
Phone interview 11. July 2008

Interviewees from research and companies in textile recycling

Bernd Gulich, Dipl.-Ing. TU Chemnitz, Sächsisches Textilforschungsinstitut, Germany;
Phone interview 14. July 2008

Jörg Julius, Dr.-Ing, RWTH Aachen, Institut und Lehrstuhl für Aufbereitung und Recycling
fester Abfallstoffe (IAR), Germany; Phone interview 18. July 2008

Günther Voetz, Vöko Textil-Recycling GmbH, Germany;
Phone interview 16. July 2008

Claudia Gräfen, Dipl.-Betriebsw. Bvse, committee Textilrecycling Germany;
Phone interview 17. July 2008

Alexander Gläser, R.A. Fachverband TEXTIL-RECYCLING e.V.,
Phone interview 11. July 2008

Mr. Wolf, SOEX Alttextilien,
Phone interview 17. July 2008

Experts from the StEP initiative meet in the course of the research

Jaco Huisman, PhD. M.Sc. TU Delft, IDE, Design for Sustainability, The Netherlands;

Rüdiger Kühr, PhD United Nations University, Zero Emissions Forum, Bonn, Germany;

Tobias Luger, Dipl.-Wi.-Ing. University Braunschweig, Institut für Werkzeugmaschinen und Fertigungstechnik
Germany; Face-to-face interview 29. July 2008,

Karsten Schischke, Dipl.-Ing. Fraunhofer Institut Zuverlässigkeit und Mikrointegration (IZM), Germany;

Appendix II: Questionnaire for the expert survey on electronic textiles

Project: Environmental implications of Electronic Textiles

Interviewee:

Research Area:

Institution:

Interviewer: Andreas Köhler

Date:

please return this questionnaire to: a.koehler@mymail.ch

Background

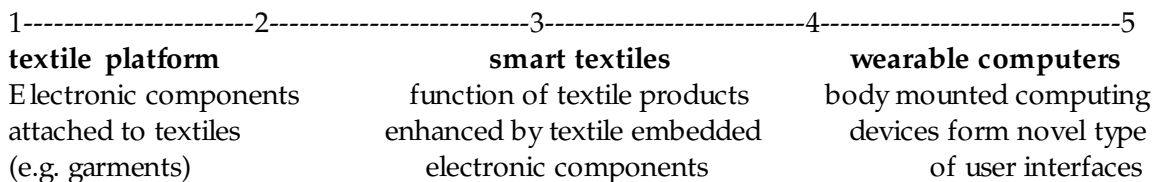
The main objective of this technology assessment study is to examine possible environmental implications of electronic textiles during an early stage of the innovation process. Carrying on previous work (Hilty et al 2005) an overview over recent trends in technology development and future application areas of smart textiles / wearable computers will be elaborated. A closer look will be taken at materials composition and ways of embedding electronic components into textile products. Based on this information it will be analysed how objectives of environmental and waste policies can be met in future. A time horizon of one decade will be applied.

Questions

(Please answer based on today's state of knowledge and note if there is uncertainty. Please also indicate if you expect a different situation in future.)

1. Terminology

Concerning the envisioned main function, how would you describe the category of products that may emerge from your research? Please indicate a place within the following spectrum or suggest another definition:



.....

2. Visions

Please provide a short description of the products, which will be made possible due to your research.

.....

- Expected application areas:
.....
- Expected time to market readiness:
.....
- Expected application volume (please choose):
(1 specialised niche market; 2 sectoral market; 3 mass application/everyday use)
- Expected product life span (please choose):
(1 single-serving; 2 reusable several times; 3 long-lasting equipment)
- Do you think an average user would easily recognise such a product as being an electronic device? (Yes / No)
.....

3. Materials used

3.A Which materials and devices are to be integrated into textiles in order to provide the smart functions (e.g. metals, conductive polymers, electronic components, batteries etc)?

.....

3.B. How are those materials and devices embedded into textiles (e.g. woven, embroidered, attached etc.)? Can the end consumer easily remove them from the textile?

.....

4. Policies

4.A: Do you know of any policies (internal / external), which do, or potentially could, influence the design of electronic textiles in terms of their environmentally relevant properties (such as materials used, energy consumption, recyclability)? Please consider:

- internal policies
.....
- costumer specifications
.....
- stakeholder demands
.....
- national regulation
.....

4.B: Are environmental aspects (such as recyclability) criteria of relevance in proposals for publicly founded research programmes? (Y/N)

.....

5. Design Priorities

5.A. Which aspects (technical, functional, environmental, safety etc.) govern the design specifications of electronic textiles during research and development phase?

Please prioritise them (1 = low 2 = medium 3 = high)

.....

5.B. Do you see any necessity to consider environmental aspects and recyclability during design phase of electronic textiles?

.....

5.C. Which actor within the innovation process for electronic textiles would be in the best position to implement design for recyclability? (e.g. F&E, designers, fashion companies, public innovation programmes)

.....

5.D. Which parties (e.g. engineers, costumers, authorities, stakeholders, future end user groups) take part in establishing design specifications during the R&D process? How are they involved?

.....

Do you agree to mention you name in a list of all interviewees of this survey? (Y/N)

Do you wish for anonymisation of your answers? (Y/N)

Are you interested to get informed about the results of this study? (Y/N)

Thank you very much for your participation in this survey!

Appendix III: Possible contents of hazardous substances to be found in WEEE

| Substances | Content in %wt of EEE* | Electronic components containing them (examples) |
|---|------------------------|---|
| Halogenated organic compounds | | |
| polyvinyl chloride (PVC) | n.a. | Cable insulation, plastic casing, |
| polychlorinated biphenyls (PCBs) | n.a. | Capacitors, large transformers |
| polybrominated biphenyls (TBBA) polybrominated diphenyl ethers (PBDE) | n.a. | Flame retardants in PWBs, plastic casing, cable insulation |
| Chlorofluorocarbons (CFC) | n.a. | Cooling aggregates, insulation foam |
| Heavy metals and other problematic metals or their components | | |
| Antimony Sb, antimony oxide | 0.0094 | Solder, plastics additives, flame retardants |
| Arsenic As | 0.0013 | Gallium arsenide in LED |
| Barium Ba | 0.0315 | Cathode ray tubes (CRTs): front glass, getters, plastic pigments |
| Beryllium Be | 0.0157 | Power supply boxes, x-ray lenses, PWB, Cu-alloys |
| Cadmium Cd | 0.0094 | CRTs: phosphorescent layer, PWBs, older copier drums, rechargeable batteries (NiCd), plastics additives |
| Chromium | 0.0036 | Data tapes, floppy-disks |
| Lithium Li or Lithium oxide | n.a. | Rechargeable batteries |
| Mercury Hg | 0.0022 | Flat screen monitors (backlight), batteries, old switches |
| Lead Pb | 6.3 | Solder, CRTs: cone glass, |
| Selenium Se | 0.0016 | Older copier drums, Rectifiers |
| Zinc Zn Zincsulphide ZnS | 2.2 n.a. | Batteries CRTs: phosphorescent layer, |
| Radio-active isotopes | | |
| Americium Am | n.a. | Smoke detectors, medical appliances |
| Others | | |
| Ultra fine particles (e.g. carbon black) Nanoparticles (e.g. carbon nanotubes) | n.a. | Toner cartridges Composites, batteries, capacitors (in future) |
| Asbestos | n.a. | Thermal insulation in old electrical devices |
| Phthalates and other VOCs Phosphorous organic compounds | n.a. | Plastics additives: softeners and stabilizers Flame retardants |

* Figures represent the order of magnitude of materials content but vary largely depending on the composition of e-waste.

Sources: (Crowe, 2003; EMPA, 2008; Puckett et al., 2002; UNEP, 2008)

Appendix IV: Valuable and other materials found in e-waste

| Material | Content in e-waste (in %wt)* | Electronic components containing them (examples) |
|---|------------------------------|---|
| Metals, Semiconductors and Alloys | | |
| Aluminum Al | 14.2 | Casing and mechanical parts, PWB, |
| Bismuth Bi | 0.0063 | Solder |
| Brass CuZn | n.a. | Casing and mechanical parts |
| Bronze CuSn | n.a. | Casing and mechanical parts |
| Cobalt Co | 0.0157 | Batteries |
| Copper Cu | 6.9 | Wiring, PWB, cabling, plastic casing |
| Germanium Ge | 0.0016 | Circuits, PWB solar cells |
| Gallium Ga | 0.0013 | Circuits, PWB |
| Gold Au | 0.0016 | Contact material on PWB, switches, connectors |
| Indium In (ITO) | 0.0016 | Transparent electrodes in flat screen displays, solar cells, transistors, PWB |
| Iron / Steel Fe | 20.5 | Casing and mechanical parts |
| Nickel Ni | 0.85 | Plating material, CRT, Rechargeable batteries (NiCd) |
| Palladium Pd; platinum Pt | 0.0003; < 0 | PWBs |
| Silicon Si | n.a. | Circuits, solar cells |
| Silver Ag | 0.0189 | Lead free solder |
| Stainless steel FeCr | n.a. | Casing and mechanical parts |
| Tantalum Ta | 0.0157 | Capacitors |
| Tin Sn | 1.0 | Solder |
| Other rare metals: Eu, Y, Ru, Tb, Nb, Rh | > 0.0001 | CRTs and flat screen monitors, PWBs |

* Figures represent the order of magnitude of materials content but vary largely depending on the composition of e-waste.

Sources: (Hageliken & Kerckhoven, 2007; Puckett et al., 2002)

Appendix V: Materials used to enhance conductivity of textiles

| Material | Integration in textiles | Quantities* | Production technology |
|---|---|--|--|
| Metals | | | |
| Cu / Ag / Au | - pure metal wires - Cu wire plated with Ag or Au - single wires or threads - blended/wrapped yarn or fabric | up to 100 % wt | Spinning, interweaving, Stitching, sewing |
| Stainless steel | - single wires or threads - spun into yarn | up to 100 % wt | Spinning, interweaving, Stitching, sewing |
| Ag / Cu / Au | - coating of fibre or fabric surfaces. | 1 ... 40 % of fibre weight | Chemical deposition |
| Ag / Cu / Au | - coating fabric surfaces. | metal content in the ink up to 70 % wt | Screen printing, Ink-jet printing |
| Cu / Ag / Au / Al / Ti etc. | - fibre of fabric coating | < 0.5 % wt | sputter deposition plasma coating |
| Conductive polymers | | | |
| Polyaniline (PAni) Polypyrrole, Polythiophene | Conjugate polymer or Bi-component fibres | e.g. core: PES sheath: PANI | solvent casting, melt spinning Conjugate spinning |
| Nano-particles | | | |
| MWCNT (in future) | - pure CNT yarn - CNT-polymer composites - coating of fibre or fabric surfaces. | approx. 100 % wt 0.1 ... 0.5 % wt in composites | Spinning In situ polymerisation melt-spinning and annealing of polymer coated CNT Dying, ink-jet printing |
| Carbon black (CB) | - as additive in polymers - coating of cotton | 50% wt | Melt spinning Wet spinning Printing, wet coating |
| Ag NP | - coating of fibre or fabric surfaces. | n.a. | Plasma coating Sol gel process |
| Others | | | |
| optical glass or plastic | - optical fibres - mechanically attached | n.a | sewing, stitching |

* Metal content of the intermediate material (e.g. yarn, fabric)

Appendix VI: Material composition of mobile phones

Table A-1: Material composition of mobile phones produced around 1999 according to: (Griese, Muller, Hagelucken, Reichl, & Zuber, 2001)

| Material content | %wt of the whole product |
|------------------------------|--------------------------|
| ABS-PC | 29% |
| Ceramics | 16% |
| Cu and compounds | 15% |
| Silicon Plastics | 10% |
| Epoxy | 9% |
| Other Plastics | 8% |
| Iron | 3% |
| PPS | 2% |
| Flame retardant | 1% |
| Nickel and compounds | 1% |
| Zinc and compounds | 1% |
| Silver and compounds | 1% |
| Al, Sn, Pb, Au, Pd, Mn, etc. | < 1% |

Table A-2: Material composition of mobile phones produced around 2003 according to: (Huisman, 2004)

| Material | g per kg | Material | g per kg |
|----------|----------|-----------------|----------|
| Ag | 1.4157 | Hg | 0.0000 |
| Al | 18.9633 | Liquid Crystals | 2.0000 |
| As | 0.0068 | Ni | 8.7567 |
| Au | 0.3261 | Other | 0.0000 |
| Be | 0.0219 | Pb | 3.4952 |
| Bi | 0.0489 | Pd | 0.1178 |
| Br | 9.4099 | Plastics | 634.4918 |
| Cd | 0.0004 | Plastics FR | 0.0000 |
| Ceramics | 0.0000 | Pt/ Ta | 0.0542 |
| Cl | 0.1253 | PVC | 0.0000 |
| Cr | 6.2697 | Sb | 0.7703 |
| Cu | 116.2145 | Silic.plast. | 0.0000 |
| Epoxy | 0.0000 | Sn | 5.3234 |
| Fe | 82.8234 | Zn | 3.4275 |
| Glass | 105.9372 | | |