Prospective Impacts of Electronic Textiles on Recycling and Disposal

Andreas R. Köhler, Lorenz M. Hilty, and Conny Bakker

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:// Supporting information is available on the *JIE* Web site

Summary

Electronic textiles are a vanguard of an emerging generation of smart products. They consist of small electronic devices that are seamlessly embedded into clothing and technical textiles. E-textiles provide enhanced functions in a variety of unobtrusive and convenient ways. Like many high-tech products, e-textiles may evolve to become a mass market in the future. In this case, large amounts of difficult-to-recycle products will be discarded. That can result in new waste problems.

This article examines the possible end-of-life implications of textile-integrated electronic waste. As a basis for assessment, the innovation trends of e-textiles are reviewed, and an overview of their material composition is provided. Next, scenarios are developed to estimate the magnitude of future e-textile waste streams. On that base, established disposal and recycling routes for e-waste and old textiles are assessed in regard to their capabilities to process a blended feedstock of electronic and textile materials. The results suggest that recycling old e-textiles will be difficult because valuable materials are dispersed in large amounts of heterogeneous textile waste. Moreover, the electronic components can act as contaminants in the recycling of textile materials.

We recommend scrutinizing the innovation trend of technological convergence from the life cycle perspective. Technology developers and product designers should implement waste preventative measures at the early phases in the development process of the emerging technology.

Address Correspondence to:
Andreas R. Köhler
Delft University of Technology
Faculty of Industrial Design Engineering
Design for Sustainability Program
Landbergstraat 15
2628 CE Delft
The Netherlands
a.r.koehler@tudelft.nl
www.io.tudelft.nl/dfs

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Introduction

Electronic textiles (e-textiles) consist of clothing or technical textiles with electronic components integrated into them. Clothes provide a wearable platform for electronic gadgets, making the latter easily portable and more convenient to use in daily life. Interactive clothes with integrated lighting elements, dial pads, mp3 players, and solar cells have already been commercialized (Mecheels et al. 2004). The first generation of e-textiles has the potential to enter mass markets in the near future (Stork 2008). More advanced e-textiles, with unobtrusively embedded computing devices, are still at an immature development stage. They represent an example of "pervasive computing"—a technology vision of the integration of information and communication technology (ICT) into everyday objects (Hilty et al. 2004). Technology developers utilize textiles as a basis for pervasive computing products because many objects of the daily living environment are made of textile materials. E-textiles have a wide range of potential application areas, such as health care, sports and outdoor fashion, work wear, interior textiles, and safety and security products.

E-textile developers currently pursue design concepts that seek a deep and seamless integration of electronics and textiles. Both types of products represent relatively short-lived mass consumer goods. Combining them can intensify the reasons for product obsolescence and may lead to products that have even shorter service lives. That makes e-textiles a subject worthy of scrutiny from the perspective of industrial ecology. If the convergence of textile and electronic products leads to short-lived mass products, then it is likely that they will become a source of large waste streams in the future. Moreover, e-textiles will form a new type of waste, namely e-waste contaminated old textiles. Such materials can entail recycling and disposal problems.

Thus far, only a few studies have examined the possible end-of-life impacts of smart everyday objects that contain electronics components. Hilty and colleagues (2004) assessed the technology vision of pervasive computing and warned of quick premature obsolescence ("virtual wear-out") affecting such products due to short innovation cycles and software incompatibility. The expected consequences are increased resource consumption in production and increased waste generation. Scrapped wearable computers will be difficult to collect and recycle because these tiny devices will be scattered in general household waste streams (Köhler and Erdmann 2004; Kräuchi et al. 2005). Because of the computers' unobtrusiveness, their last owners will find it hard to separate them from residual waste. Thus, numerous small e-waste items can end up in normal household waste or find their way into recycling processes, where they act as contaminants. This creates a twofold risk: First, recycling processes of other materials may be disturbed by cross-contamination. Second, release of toxic substances is possible during unsophisticated disposal processes. Wäger and colleagues (2005) found that RFID tags[1] can cause problems in established recycling processes of non-electronic goods.

Experiences with the disposal of contemporary electronic waste (e-waste) give reason to expect severe environmental and social impacts worldwide (Hilty 2005; Kräuchi et al. 2005; Puckett et al. 2005; Widmer et al. 2005; Schluep et al. 2009). The e-waste problem consists of three key factors: (1) Large amounts of obsolete electronic products are arising[2] worldwide. (2) Electronics usually contain problematic substances that can cause harm to the environment and human health if they are released during disposal. (3) E-waste contains valuable materials that are difficult to recover. E-textiles are expected to fulfill all three factors of the e-waste problem (Köhler 2008).

Future waste problems can be mitigated by environmentally conscious design of e-textiles. Waste prevention by design can be successful at an early stage of technology development. This holds true as long as e-textiles have not pervaded the mass markets. That requires e-textile developers to make design decisions under conditions of uncertainty. In this situation, "it is important to understand where we have choices and where we do not" (Allenby 2009, 181). Allenby also notes that "identifying reasonable scenarios for emerging technologies and exploring their implications remains an important priority" (180) for industrial ecology. To this end, the objective of this article is to examine the prospective end-of-life implications of e-textiles before they become reality. The ex-ante assessment of future waste problems serves as a basis for outlining possible sustainable design choices that can be made at the early stage of the e-textiles' innovation process.

The article is organized as follows: First, we outline the most relevant design concepts that influence the direction of innovations in the area of e-textiles. Next, we provide an overview of their materials composition. Finally, we describe and analyze application scenarios of three types of e-textiles as a basis for estimation of future waste streams and evaluate prospective consequences for recycling and disposal of these products.

Description of E-textiles

Current trends in innovation and market development were examined through review of the technical literature and an expert survey. The survey was conducted among 39 European researchers and enterprises by means of questionnaire-guided interviews. The survey addressed three thematic areas: (1) design concepts, (2) estimation of future market perspectives, and (3) material composition. The expert survey did not aim at empirical robustness; instead, it provided a synopsis of current priorities in the research and development process. The interviews were conducted between 2008 and 2010. A copy of the expert survey is provided in the supporting information S2 on the Journal's Web site.

Current Innovation Trends

Smart textiles represent an emerging technology that is being developed by innovators in both the electronics and the textile sectors. Technophile trendsetters, such as fashion artists and industrial designers, have inspired the innovation process by creating prototypes of high-tech textile products with advanced functionality. In the textile sector, the term "smart" has been used to describe functional textiles with engineered properties. They can contain a wide range of engineered materials and components (Mecheels et al. 2004; Tang and Stylios 2006; Cho et al. 2010). Phase change materials (PCM), for instance, create a cooling effect or store excess heat. Micro- or nano-encapsulated substances (e.g., insecticides, perfumes, drugs) can be attached to fabrics and released during the use phase in a controlled dosage.

The notion of product-smartness has recently shifted toward more active and "intelligent" functions (Centexbel 2011). Now, smartness is often interpreted as the products' ability to sense and respond to external stimuli. Shape memory materials that can adjust the texture of fabrics depending on temperature change are an example. Sophisticated smart textiles show interactive behavior, such as sensing, signal transmission, and data processing. These functions are established by means of textile-integrated electronic components. The term "e-textile" is specifically used for that technology.

Developers of e-textiles pursue different design strategies depending on their respective discipline (textiles or electronics). The two disciplines are only beginning to cooperate in the development of dedicated e-textile materials. Apparel designers usually start with traditional clothing and seek to make it smart by integrating commodity electronic components (Tang and Stylios 2006). Design concepts take advantage of classical textile qualities, such as comfort and fashion. Although the properties of textiles can be easily customized, they should not be compromised by integrated electronic components. For example, e-textiles should withstand laundering. Thus, a redesign of electronic components is needed to match their properties with those of textiles. Electronics must become resistant to water, detergents, and mechanical stress (Marculescu et al. 2003; Mecheels et al. 2004; Stylios 2007). Electronic engineers seek to develop electronic components that are soft, flexible, stretchable, and water resistant and that fit seamlessly into surrounding textiles. Microsystems technology, organic semiconductor materials, and nanotechnology are enabling technologies that facilitate the general innovation trend of seamless integration of electronics and textiles (Kind and Bovenschulte 2006).

Sophisticated e-textiles that host ICT devices and their peripheral equipment are currently in a laboratory stage of development. Some researchers pursue design concepts that aim at deep integration of wearable computing devices into clothing (Buechley 2006). Such integration will render separate ICT devices unneeded. Textile-embedded human-computer interfaces (e.g., switches, dials, keyboards, flexible displays) provide superior usability and comfort (Marculescu et al. 2003; Park and Jayaraman 2003). Other researchers comprehend wearable computers as detachable objects, such as headsets, glasses, buttons, and rings, that form a body-centered network that is mounted on clothing (Starner 2001).

Three successive steps of innovation can be delineated with regard to design concepts of integrating electronic components into textiles (figure 1; Mecheels et al. 2004; Cho et al. 2010):

1. Adoption: Distinct electronic devices are embedded into a textile platform (e.g., incorporated into pockets). Such products have been introduced into the market in the form of mobile phone periphery gadgets.
2. Seamless integration: Electronic devices are to be incorporated throughout textile materials (e.g., embroidered sensors, laminated circuit boards). This is the current stage of the innovation process.
3. Combination: Textile materials and structures with inherent electronic functionality (e.g., yarn transistor, fiber-based circuits, photovoltaic fibers).

Market Perspectives

For the time being, e-textiles exist in specialized niche markets (e.g., health care and work wear applications). This first generation of e-textiles is leading the innovation process. The proliferation of sophisticated e-textiles at consumer mass markets is expected to take more time. Observers of the innovation process expect that e-textiles will penetrate mass markets within the decade (McWilliams 2007; Stork 2008). In particular, the market segments of sports clothes, telemedicine, and lifestyle textiles hold potentials for mass application (Stork 2008). Results from our expert survey among e-textile developers indicate current hot spots of innovation (figure 2, left). The estimation of the possible market size varied depending on the respective application area (figure 2, right). For the near future, the interviewees expected the highest market potential in the area of ambulatory health monitoring.

Materials and Components Used in E-textiles

The first generation of e-textiles contain a similar range of materials as today's commodity electronic products. The latter usually contain considerable amounts of valuable materials, which reside mainly in the gadgets' printed wiring boards (PWBs; Huisman 2004; Chancerel et al. 2009; Schluep et al 2009). In addition, electronic products are known to contain hazardous substances or their precursor substances (Chancerel and Rotter 2009). Mobile phones, for instance, contain valuable metals, such as copper, silver, and gold, as well as problematic substances in batteries and plastic additives (e.g., flame retardants).

The electronic components in first-generation e-textiles are made of off-the-shelf technology—for example, arrays of small light-emitting diodes. These parts are spread out across the textile surface areas. Electronic circuits can be either sewn on fabrics directly or mounted on flexible PWBs, which must be compatible with classic textile properties (i.e., stretchable, elastic, and waterproof). Flexible PWBs often consist of polyamide foil coated with nickel/copper layers that are plated with thin gold layers to allow for good electrical contacts. Flexible PWB can be sewn, laminated, or glued onto fabrics. Casing and packaging of electronic components are made of fabric or plastic foil rather than of steel, aluminum, or bulky plastic parts. Thus, e-textiles contain smaller amounts of such construction metals, whereas certain specialty metals may gain in relative importance. Silver, for instance, is a candidate for more widespread usage.

If the design concepts of integration and combination (see figure 1) become reality, one can expect more significant changes in the materials composition. Then, textile electronics will consist of embroidered circuitry and organic electronic components, which can be printed directly onto the fabric surface. Electronic components will tend to become smaller and

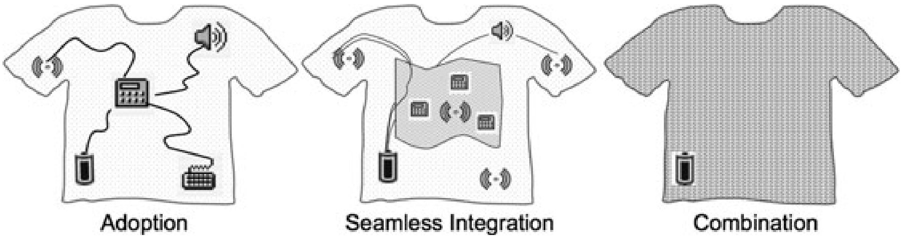

Figure 1 Design concepts of converging electronic and textile components (symbolic sketch).

more scattered across the textile. Moreover, electronic and textile materials will become more and more amalgamated. Polymer-metal composites and nano-materials may replace traditional electronic materials. Table 1 provides an overview of electrically active components of e-textiles that are currently in the focus of research and development. The following subsections provide a glimpse into the materials inventory of some enabling technologies of e-textiles (Köhler 2008).

Electrically Conductive Fibers and Interconnections

To establish electrical interconnections, developers of e-textiles normally use metalized fibers or yarns that contain silver, copper, or nickel (table 2; Meoli 2002; ; Berzowska and Bromley 2007; Mythili et al. 2007). The metal content of commercially available conductive yarns can be up to 40%$_{\mathrm{wt}}$. Solid metal strands and wires of stainless steel are used as well, but they are less flexible and less comfortable to wear. Alternatively, conductive fibers can be made of intrinsically conductive polymers, such as polyaniline (Kim et al. 2003; Kim and Lewis 2003). Some developers experiment with conductive composite fibers that contain metallic particles or carbon particles (Lübben 2005). Also, nano-composites with 0.5% to 20%$_{\mathrm{wt}}$ carbon nanotubes (CNTs) in the polymer matrix show sufficient electrical conductivity for certain applications of e-textiles (Köhler et al. 2008). Cotton yarn can be made

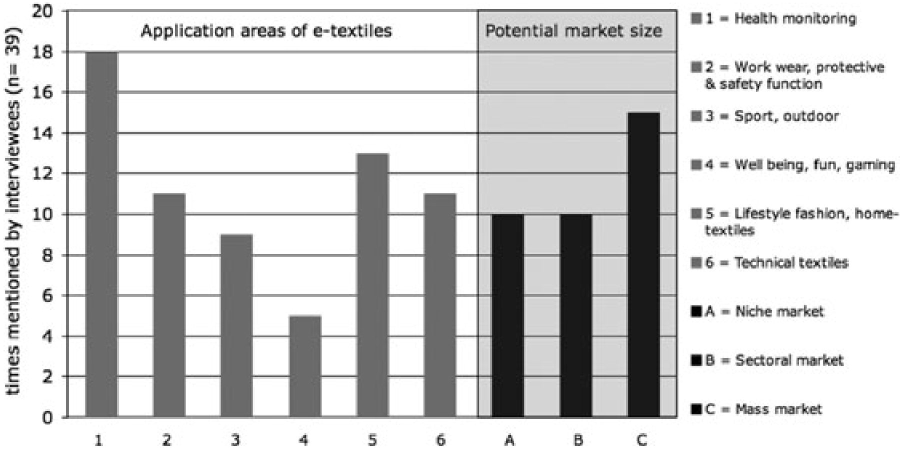

Figure 2 Expert expectations on application areas (left) and market size (right) of e-textiles. The time horizon is 1 decade. Niche market = high-value-added specialty products (e.g., firefighter suits); sectoral market = customized applications (e.g., telehealth monitoring); mass market = ubiquitous consumer applications (e.g., casual apparel).
Source: Authors' own data.

Table 1 Examples of electronic components and materials that are integrated into textiles

Examples of electronic components in textiles	*Application*
Electrically conductive fibers and sheets	Electrostatic dissipation and electromagnetic shielding Electric interconnection and power distribution Sensor and actuator elements Heating resistors Transmission of analogue and digital signals Radio-frequency antennas
Optical fibers	Light dispersion, signal transmission
Soldering joints, bonding pads, mechanical contacts	Electric contacting and mechanical fixation
Flexible wiring boards and embroidered wiring	Mechanical fixation and electric interconnection of electronic components, protection against wear and tear
LEDs, OLEDs, laser diodes, and flexible displays	Lighting, photonic effects, user interaction
Digital devices, such as mp3 player, microcontroller, and networking units	Information and communication functions, interactivity and smartness
Embedded periphery: dial pad, speaker, microphone, radio-frequency antenna, RFID tags	User interaction, data input and output, wireless network connection
Solar cells, piezoelectric units, thermoelectric generators	Power generation (harvesting from ambient energy sources, e.g., light, heat, mechanical movements)
Rechargeable batteries	Power storage

Note: LED = light-emitting diode; OLED = organic light-emitting diode; RFID = radio-frequency identification.

electrically conductive when it is coated with polymer stabilized CNT (Avila and Hinestroza 2008; Shim et al. 2008).

Contacting and Bonding Elements

New technological solutions are being developed for mechanical fixation of electronic components and their interconnection within textile materials. Electrical contacts must withstand harsh external impacts during use phase (washing, drying, mechanical abrasion, humidity, chemicals and UV radiation, etc.). Those factors limit the useful lifetime of e-textiles (measured in washing cycles). The following list summarizes the state of the art for electrical contacting technologies.

- Soldering: based on lead-free solders (alloys of tin, silver, copper, antimony, bismuth).
- Mechanical connections: embroidery of conductive yarn. Metallic snap fasteners or metalized hook-and-loop fasteners are used for detachable connections.
- Conductive adhesives that contain metallic particles (typically silver) or carbon black dispersed in monomers or polymers (e.g., [poly]urethane) or bicomponent epoxy resins (Healy et al. 2003; Kolbe et al. 2005).

Power Supply

E-textiles are mostly powered by lithium-ion batteries. They can be recharged either by means of grid-connected chargers (requires user interaction) or by solar cells, thermo generators, or piezo elements that harvest ambient energy (Kim and Lewis 2003). Batteries are embedded into textiles in such a way that they can be detached before laundry. Some developers have created waterproof batteries, which can be seamlessly embedded into textiles (nondetachable).

Table 2 Overview of materials used to enhance conductivity of textiles

Material	*Integration in textiles*	*Percentage of conductive material*[a]	*Production technology*
Metals			
Cu/Ag /Au	Cu wire plated with Ag or Au single wire or strand 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/Ni	Coating of fiber or fabric surfaces	1% to 40% of fiber weight	Chemical deposition
Ag	Coating fabric surfaces	Metal content in the ink up to $70\%_{wt}$	Screen printing, ink-jet printing
Cu/Ag/Au/Al/Ti, etc.	Fiber of fabric coating	$< 0.5\%_{wt}$	Sputter deposition, plasma coating
Conductive polymers			
Polyaniline (PAni), polypyrrole, polythiophene	Conjugate polymer fibers or bicomponent (core/shell) fibers	Up to $100\%_{wt}$ PAni in the shell of coated polyester fibers	Solvent casting, melt spinning, conjugate spinning
Nano-particles			
Carbon nanotubes, single walled or multiwalled (in the future)	Pure CNT yarn, CNT-polymer composites coating of fiber, yarn coating of fabric surfaces	Approximately $100\%_{wt,}$ 0.1% to $0.5\%_{wt}$ CNT in polymer composites	Spinning, in situ polymerization, melt-spinning, and annealing of polymer-coated CNT; wet dying; ink-jet printing
Carbon black	Filler of polymer fibers, surface coating of cotton fibers	$50\%_{wt}$	Melt spinning, wet spinning, printing, wet coating
Nanoparticulate silver	Coating of fiber or fabric surfaces	n.a.	Plasma coating, sol-gel process
Other			
Optical glass or plastic	Optical fibers mechanically attached	n.a	Sewing, stitching

Note: Al = aluminum; Ag = silver; Au = gold; CNT = carbon nanotubes; Cu = copper; PAni = Polyaniline; Ti = titanium; n.a. = not available.

[a] Material content refers to the intermediate material (e.g., yarn, fabric). No data were available for final products.

Source: Köhler 2008.

Estimation of Future E-textile Waste Streams

E-textiles will inevitably turn to waste at the end of their useful lives. Contemporary electronic products usually have rather short service lives. There is no reason to assume that e-textiles will break with that trend. On the contrary, their obsolescence may even be accelerated due to fleeting fashion trends in the apparel sector. One can expect that old e-textiles will cause large waste streams similar to today's e-waste.

To estimate the order of magnitude of future waste streams, we extrapolated the possible market diffusion trend of e-textiles in scenarios.[3] We conceived a base scenario of market diffusion by projecting historic data on market diffusion of small high-tech gadgets, such as mobile phones, into the future. The scenario represents a case study of the national German market. We assumed that the market diffusion of e-textiles will follow a sigmoid growth curve similar to the mobile telecommunication market in the past. That market segment grew from 10% to 90% of the maximal market size (K) within a period of 9 years (for details, see Appendix S1 in the supporting information on the Web). With the base scenario in the background, three different application areas of e-textiles were considered. Table 3 gives an overview of the key parameters presumed for the application scenarios.

- Scenario A: niche market: fire-fighter suits with integrated sensors, data processing unit, navigation system, radio transceiver, and batteries.
- Scenario B: sectoral market: electrocardiograph (ECG) shirt with integrated sensor pads and radiofrequency antenna, used for constant heart monitoring (telehealth monitoring).
- Scenario C: mass market: outdoor jacket with integrated mp3-player, mobile phone, dial-pad, flexible solar cells, and batteries.

The amount of waste per year from each type of e-textile was extrapolated on the basis of the three application scenarios. Figure 3 shows the extrapolated waste stream of complete e-textiles (electronic components together with textile materials). Significant amounts of waste emerge approximately 5 to 7 years after the first introduction of e-textiles at the mass market. Figure 4 shows the extrapolated mass stream of electronic components only, as if they were separated from the textiles. In each scenario, an annual 2% decrease in weight of the electronic components was presumed as an approximation for miniaturization trends.

The case study shows that the extrapolated waste stream of old e-textiles in Germany can grow as much as 24 kilotonnes (ktonnes)[4] per year in Scenario B (ECG shirt) and 55 ktonnes in Scenario C (outdoor jacket). Textile materials contribute the biggest portion by weight within that waste stream. The e-textile waste stream in the mass-market Scenario C would constitute approximately 5% of weight among the 1.13 million tonnes of discarded clothes and home textiles in Germany (BVSE 2009). Although old e-textiles may not result in a massive increase of the domestic textile waste stream, they can change the material composition of the recyclable fraction of old textiles.

Electronic components may have a concentration between $7\%_{\mathrm{wt}}$ in Scenario B and $15\%_{\mathrm{wt}}$ in Scenario A (firefighter suit); the rest consists of textiles or plastic and metal parts (e.g., buttons). The e-waste fraction in the textile waste stream is estimated at 1,300 tonnes per year in Scenario B and 4,000 tonnes in Scenario C. The flow of textile-embedded e-waste does not appear significant when compared with the total textile waste flow. Nonetheless, it has the same order of magnitude as obsolete mobile phones have today in Germany (see the data in appendix S1 in the supporting information on the Web for comparison).

The prospective arising of old e-textiles on a global scale was estimated at 1 million tonnes per year as an order of magnitude. That waste stream would contain 50 to 150 ktonnes of embedded electronic components, depending on the type of e-textiles.

E-textiles can form a considerable waste stream provided that they evolve as mass applications. Scenario B illustrates that this is also possible in sectoral application areas, such as health care. We consider our market diffusion scenario a rather conservative estimate. There are several reasons to assume that the future market diffusion of e-textiles can be at least as rapid and widespread as the diffusion of mobile phones in the past.

First, the time span in which the market diffusion of e-textiles grows from 10% to 90% of the total market size can be briefer than it was with mobile phones. The diffusion of mobile communication technology was largely determined by

Table 3 Specifications of the application scenarios

Scenario name	*Scenario A: Firefighter suit*	*Scenario B: ECG shirt*	*Scenario C: Outdoor jacket*
Market type	Niche market	Sectoral market	Mass market
Application area	Protective wear	Health monitoring	Everyday life
Maximal no. users	$K = 300{,}000$[a]	$K = 27$ million[b]	$K = 82$ million[c]
No. units per user[d]	1	7 (one per day of week)	2 (one summer jacket/one winter coat)
Average product lifetime[d]	5 years	1 year (50 laundries)	3 years (three fashion seasons)
Weight per unit[d]	2,000 g	130 g	800 g/1,200 g
Weight of the electronic components at beginning[d]	250 g	10 g	50 g

Note: Demographic data are from Destatis (2010). ECG = eletrocardiograph; g = gram.
[a] Number of fire-warden offices times 10. [b] All citizens of age 55 and older. [c] Whole German population. [d] Parameters are based on our own assumptions.

cocreation of the backbone infrastructure (e.g., mobile telecommunication networks). E-textiles, in contrast, can take advantage of already existing wireless network infrastructure, and some types of e-textiles can be used as stand-alone devices.

Second, e-textiles are likely to coexist in multiple application areas. The technology vision of pervasive computing suggests that users possess numerous gadgets simultaneously. Different types of e-textiles can be used at the same time, given their broad variety of functions. Stand-alone devices (e.g., mp3 players) may be used in addition to networked gadgets (e.g., smart phones). Conversely, consumers may possess multiple pieces of clothing and use them infrequently (e.g.,

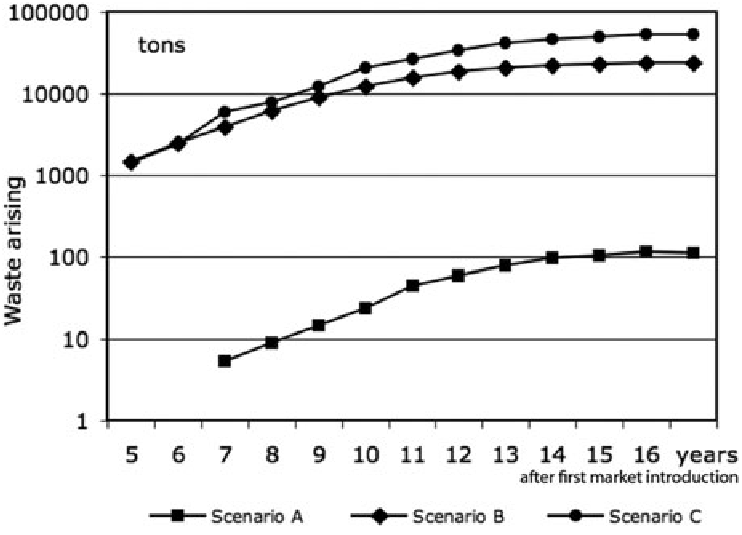

Figure 3 Extrapolated waste arising of obsolete e-textiles (whole product) for the three scenarios (Scenario A = firefighter suit; Scenario B = electrocardiograph shirt; Scenario C = outdoor jacket).

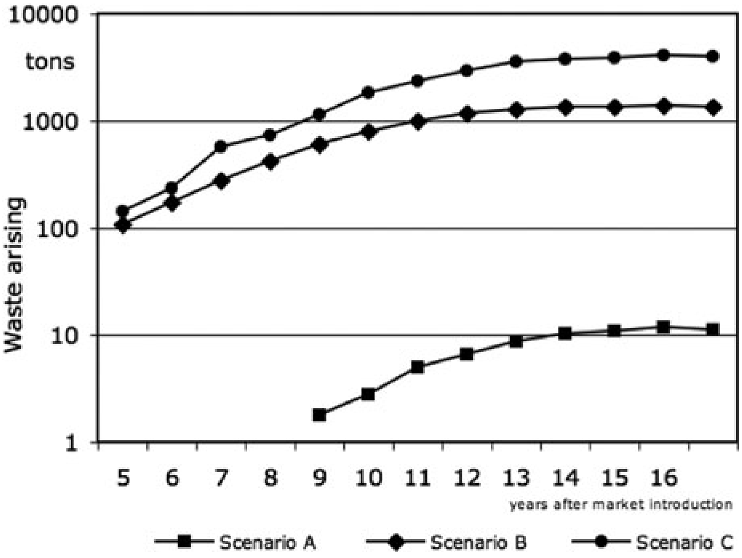

Figure 4 Extrapolated waste arising of textile-embedded electronic components for the three scenarios (Scenario A = firefighter suit; Scenario B = electrocardiograph shirt; Scenario C = outdoor jacket).

seasonal). That means users may own numerous e-textiles but not use these items all the time.

Third, we presumed a general miniaturization trend of single ICT devices. That trend has been observed throughout the history of the ICT sector—for instance, in the case of mobile phones. Miniaturization has almost always been outweighed by growing numbers of devices used, however. The effect has become known as the "miniaturization paradox" (Hilty 2008). There is no reason to expect that e-textiles will break with that trend. The results of our scenarios suggest that the waste flows of e-textiles will increase in spite of their miniaturization.

Recyclability of E-textiles

This section presents a brief discussion of the capability of recycling and disposal schemes to cope with old e-textiles.^{5} The fate of old e-textiles will depend on the waste management schemes that are established at the place of their disposal. They differ largely among countries (Schluep et al. 2009). Figure 5 summarizes principal recycling or disposal processes of e-textiles.

Currently established recycling schemes are inappropriate to collect and process textiles with integrated electronic components. From the present-day perspective, it can be assumed that the biggest fraction of discarded e-textiles would be disposed of together with municipal solid waste (MSW). In principle, MSW disposal is done either by incineration or by direct landfilling, depending on the country. If e-textiles are coincinerated with MSW, recovery of valuable materials is hardly possible with today's technology. Metal recovery from incinerator bottom ash is only possible for larger metal parts—roughly in the centimeter range (Morf et al. 2009). Metallic components found in e-textiles (e.g., silver-coated fibers) have a much smaller size. Therefore, co-incinerating e-textiles would disperse the valuable metals, such as silver, in the bottom ashes or in the filter dust. The latter is disposed of as hazardous waste. Hence, textiles will contribute to the contemporary environmental problems of disposing e-waste together with solid waste (Jang and Townsend 2003; Gullett and Linak 2007).

E-textiles Entering an E-waste Recycling Scheme

Discarded e-textiles may find their way into recycling schemes for e-waste (Waste Electrical and Electronic Equipment [WEEE]). With the WEEE Directive in effect since 2005, European

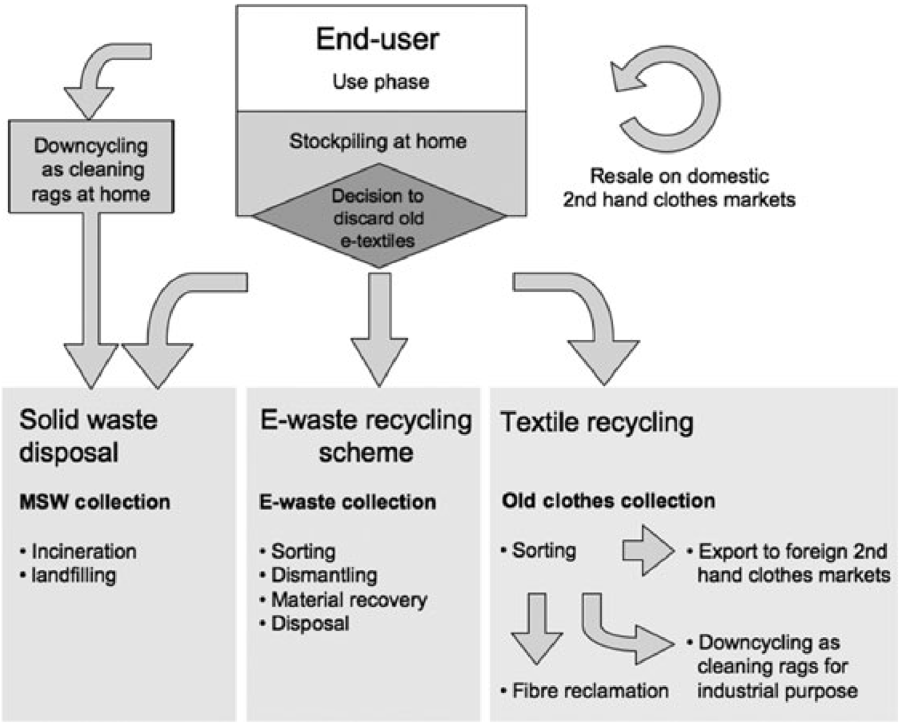

Figure 5 Possible recycling and disposal channels for e-textiles. MSW = municipal solid waste. Source: Köhler 2008.

countries are supposed to implement schemes for separate take-back and recycling of WEEE (EC 2003). E-textiles, however, because they are not explicitly addressed by that regulation, would be rejected at the collection points or sorted out by recycling companies. That holds true unless the legislature includes e-textiles in the regulation or material recovery from e-textiles emerges as a profitable business (the latter appears possible in developing countries, similar to today's informal e-waste recycling; Puckett et al. 2005). Sorted-out items are usually disposed of as solid waste. From the technical perspective, the established WEEE take-back and recycling systems are not designed to deal with this novel type of waste. In general, they exhibit very poor performance for e-waste items below 1 kilogram (Huisman et al. 2007). The recycling experts interviewed deemed it difficult to recycle e-textiles. They expected various technical problems. Textiles could jam shredders and crushers such as currently used in WEEE recycling. Automated separators were seen as inadequate to separate fluffy, lightweight materials, such as metalized plastic foils and textile fibers. From current WEEE recycling technology, we know that mechanical shredding results in great losses of precious metals. A large part of these materials are transferred into output fractions, from which they cannot be recovered (Chancerel et al. 2009). Likewise, shredding e-textiles would transfer the precious metals (e.g., silver) into the dust fraction.

The experts deemed manual sorting and processing of e-textile waste possible, although difficult. The processing costs were estimated to be prohibitively high because the valuable metals are not concentrated in PWBs as in traditional WEEE. The interviewees pointed to the serious challenge of taking into account the heterogeneity of textile products as well as the specific design features of e-textiles (unobtrusiveness). Personnel at collection points and recycling workshops would need to be trained to recognize miniaturized electronic devices that are seamlessly integrated in textiles. Moreover, investments would be necessary in regard to storage, transportation, and appropriate tools to process old e-textiles.

E-textiles Entering a Recycling Channel for Old Textiles

The last owners of old e-textiles are assumed to dispose of the old e-textiles together with ordinary old clothes rather than as e-waste because the electronic parts are unobtrusive. Collection of postconsumer textiles is often performed by charities or recycling firms. Collection rates of old textiles are usually low (e.g., 17% in the United Kingdom [UK]; Morley et al. 2006). The larger share of the collected old textiles is exported to developing countries, where they are reused and eventually disposed of (Waste Watch 2006). Shipments of old textiles to foreign markets are 54% in the UK and 41% in Germany (BVSE 2009). One third of old textiles in Germany (233,000 tonnes per year) consists of inputs to fiber reclamation processes to produce felt or fabric for industrial purpose.

The extrapolated arising of old e-textiles would constitute a minor fraction of the whole old textile stream—approximately 5%, as for Scenario C. In Germany, discarded clothes and home textiles form an annual waste stream of 1.13 million tonnes (BVSE 2009). Old e-textiles are likely to appear at the second-hand clothing market, for they may still provide textile functions after the smart function has ceased to be useful. In this case, the larger part of old e-textiles would be exported overseas as part of normal second-hand clothes. Before shipment, the textiles are baled by mechanical force. Batteries contained in old e-textiles could cause a fire hazard if not removed before baling. The end-of-life fate of e-textiles reused in developing countries is hardly predictable. One can assume, however, that the content of precious metals (e.g., silver) may trigger a backyard recycling under similar poor environmental and occupational health conditions as known from e-waste recycling.

E-textiles could also enter sophisticated fiber reclamation processes based on mechanical shredding. Waste electronic materials can be regarded as contaminants in the textile waste stream, as they are widely dispersed within discarded clothes. There is a risk that e-textiles could disturb these processes or contaminate the secondary fibers produced. Cross-contamination of other recycled materials (e.g., synthetic fibers) lowers the market value of the latter. Moreover, coprocessing of old e-textiles in fiber recycling could pose unexpected emissions of dust containing heavy metals. It could cause occupational health and environmental problems, like the dust released from e-waste shredding (Hanke et al. 2000). Removal of components containing hazardous substances would be necessary prior to fiber reclamation. The interviewees from textile recycling businesses deemed that additional step difficult and costly.

Conclusions and Recommendations

We have portrayed e-textiles as an example of pervasive computing technologies. These products can cause end-of-life problems in the future due to the following reasons:

- E-textiles will likely be used as mass appliances and can result in large waste streams.
- It will be difficult to collect and recycle old e-textiles by means of contemporary collection and recycling schemes.
- Valuable materials contained in e-textiles are dispersed within textile bulk materials, which makes e-textiles a low-grade feedstock for metal recycling. Fiber recycling, in turn, is seriously compromised by e-waste contaminating the textile materials.
- The possible content of problematic substances (or their precursors) in e-textiles poses environmental and health risks in recycling and disposal processes.

At present, not even contemporary e-waste, which has a relatively high content of valuable metals, is recycled at sufficient rates. There is no reason to expect sufficient recycling rates with low-grade waste, such as old e-textiles. Hence, the industrial ecology community is confronted with the prospect of a new generation of high-tech products undermining one of the core ideas of industrial ecology: closing material loops (Ehrenfeld 2008).

From this background, we regard it crucial to implement waste-preventative measures (i.e., design for recyclability) integrated in the innovation process of e-textiles. Later on, opportunities for fundamental solutions wane, and technical "quick fix" solutions are applied at best, which cure only the symptoms of the problems. This is because corrective action, such as redesign, becomes too difficult and expensive once a technology reaches a large market penetration (Collingridge 1980).

Accordingly, researchers face a challenge to launch waste-preventative measures before adverse end-of-life impacts become obvious at a large scale. E-textile developers should therefore scrutinize the design concept of seamless integration. The technology should not be used to produce short-lived consumer products. Moreover, technology developers and product designers of e-textiles should not simply delegate responsibility for the end-of-life phase of their inventions to the recycling sector.

Ehrenfeld (2008) suggests turning the problems into opportunities by designing technical artifacts in such ways that they yield supreme sustainability benefits over their whole product life cycle. ICT can, like no other technology, be part of the solutions that we need to reduce the material intensity of the economy (Hilty 2008; Hilty and Ruddy 2010). We believe that e-textiles bear a great potential in this regard. Because they offer radical new ways of human-technology interaction, they can be designed to persuade their users to commit to a more sustainable behavior. These possibilities are unlikely to unfold in a business-as-usual mode of innovation, however. Sustainability benefits must be searched for and proactively put into practice.

Industrial designers can play a vital role here, because they can create showcases of sustainable e-textiles. That way, they can inspire consumers and decision makers in industry to turn their attention toward sustainable alternatives. It remains to be demonstrated that e-textiles can indeed fulfill sustainable functions while keeping the end-of-life and other sustainability risks in check. We recommend that industrial designers adopt the principles of green engineering as a modus operandi of taking responsibility for the life-cycle-wide environmental impacts of e-textiles (Anastas and Zimmerman 2003).

To prompt sustainable innovation of emerging technologies, the legislature should send clear signals to research institutions and industry. The revised European Ecodesign directive (EC 2009) could serve as a model; it mandates eco-design requirements for the development of energy-related products. Likewise, waste prevention should be made an explicit goal of innovation strategies. The U.S. Environmental Protection Agency (EPA) has outlined possible ways to move forward with sustainable management of materials by incorporating life cycle thinking into the design process of future products (EPA 2009). In addition, recyclability targets should be mandated in the framework of innovation funding schemes that support the developers of e-textiles.

Notes

1. RFID tags refer to radio-frequency identification (RFID) transponders in the form of labels.
2. In some countries, the term "waste generation" is used in lieu of "arising."
3. The prospective waste stream of e-textiles was estimated by means of trend extrapolation and analogy. For this purpose, a base scenario of market diffusion was set up in the form of a sigmoid market growth model (Boretos 2007). That base scenario was calibrated with data derived from a case study on the market diffusion of mobile phones in Germany. On top of the base scenario, three application scenarios of e-textiles were developed that characterized their technical properties and useful lives. Lessons learned from the contemporary e-waste problem served as a general yardstick for analysis. This information was obtained from literature. Further details of the scenario development are explained in the supporting information on the Web.
4. One kilotonne (kt) = 10^3 tonnes (t) = 10^3 megagrams (Mg, SI) $\approx 1.102 \times 10^3$ short tons.
5. We undertook a broad review of scientific literature and contributions at conferences and industry fairs regarding expected end-of-life implications of e-textiles. No such information could be found by literature review, however. Therefore, a second batch of interviews was conducted with six experts from recycling firms of both sectors, e-waste recycling and textile recycling. The interviewees were presented the properties and materials of e-textiles

and then asked open-ended questions. These interviews were meant to explore the experts' opinions about the recyclability of e-textiles.

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About the Authors

Andreas R. Köhler is a Ph.D. researcher in the Design for Sustainability section at Technical University Delft, in the Netherlands. **Lorenz M. Hilty** is head of the Technology and Society Lab at Empa, the Swiss Federal Laboratories for Materials Science and Technology, in St. Gallen, Switzerland, and professor of informatics and sustainability at the University of Zürich, Switzerland. **Conny Bakker** is assistant professor in the Design for Sustainability section at Technical University Delft, in the Netherlands.

Supporting Information

Additional supporting information may be found in the online version of this article:

S1: This appendix contains a description of a model for the diffusion of e-textiles in Germany based on past mobile phone diffusion statistics.

S2: This appendix contains a copy of the expert survey of e-textile developers in Europe.