

Expected Environmental Impacts of Pervasive Computing

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ABSTRACT

Pervasive Computing will bring about both additional loads on and benefits to the environment. The prevailing assessment of positive and negative effects will depend on how effectively energy and waste policy governs the development of ICT infrastructures and applications in the coming years. Although Pervasive Computing is not expected to change the impact of the technosphere on the environment radically, it may cause additional material and energy consumption due to the production and use of ICT as well as severe pollution risks that may come about as a result of the disposal of electronic waste. These first-order environmental impacts are to be set off against the second-order effects, such as higher eco-efficiency due to the possibility to optimize material and energy intensive processes or to replace them by pure signal processing (dematerialization). The potential environmental benefits from such second-order effects are considerable and can outweigh the first-order effects. But changes in demand for more efficient services (third-order effects) can counterbalance these savings. The experience gained thus far with ICT impacts has shown that such a rebound effect occurs in most cases of technological innovations.

Key Words: Pervasive Computing, environmental impact, energy use, electronic waste, dematerialization, rebound effect.

INTRODUCTION

Pervasive Computing is a vision of future applications of Information and Communication Technologies (ICT) in which highly miniaturized, embedded, networked microprocessors equipped with sensors pervade our daily lives: "A billion people interacting with a million e-businesses through a trillion interconnected intelligent

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devices" (Gerstner 2000). Pervasive Computing involves the miniaturization and embedding of microelectronics in non-ICT objects as well as wireless networking. Unlike most of today's ICT products, Pervasive Computing components will be equipped with sensors that will enable them to collect data from their surroundings without the user's active intervention.

Present ICT has already become a serious threat to the environment. Three types of environmental risks or hazards caused by ICT products and infrastructures can be discerned: global resource depletion, energy use, and the emission of toxic substances over the lifecycle (production, use, disposal).

The requirements of semiconductor production for natural resources are significant due to the highly organized structure of microelectronics. For example, the total resource consumption during the lifecycle of a single 32 MB DRAM memory chip of approximately 2 grams amounts to: 1.6 kg of fossil fuels, 27 g of various chemicals, 700 g of elemental gases, and 32 kg of freshwater. Furthermore, 41 MJ of energy per chip is needed in the production chain of silicon wafers (Williams *et al.* 2002). For a complete personal computer including CRT-monitor, the input of abiotic raw materials is up to 1500 kg (Türk 2003).

Since ICT has become a mass product, its share in electricity consumption in national economy scales has continuously increased during the past decades. In Germany the ICT-related consumption of electric energy has risen up to 38 TWh in 2001, which is 7.1% of total electricity consumption (Geiger and Wittke 2002). As the generation of electric energy is mainly based on fossil fuels and atomic energy (*e.g.*, 61% and 34%, respectively, of total electric energy in Germany), the emissions of climate relevant carbon dioxide and radioactive waste are the most important environmental impacts of the ICT use phase.

The rapidly growing amount of ICT equipment is causing increasing problems in the disposal (end-of-life) phase of the electronic waste. The annual amount of scrap from electronic equipment is estimated to be 68,000 metric tons in Switzerland and 2.1 metric megatons in the United States (EMPA 2004a; USEPA 2002). Recycling or disposal of computers and telecommunication hardware is problematical, because electrical and electronic equipment includes a multitude of components causing human and ecological risks, such as heavy metals and halogenated organic compounds. In case of inadequate disposal or recycling, the emission of toxic substances from electronic waste can pollute water, soil, and air, and harm human health. The technically complex problem of electronic waste disposal is not taken care of equally well in all parts of the world.

Will upcoming generations of ICT strengthen or weaken these environmental impacts? Initial technology assessment studies on the impact of ICT on environmental sustainability indicate that not only established ICT, but also Pervasive Computing applications, will have a significant impact on environmental sustainability in the European Union (Erdmann and Behrendt 2003; Goodman and Alakeson 2003; Hilty *et al.* 2004). A study commissioned by the Swiss Centre for Technology Assessment (TA-Swiss), pointed out potential opportunities and risks of Pervasive Computing in the context of the Precautionary Principle (Hilty *et al.* 2003). Based on the results of this study, we show here the expected effects of Pervasive Computing on the environment.

APPROACH OF THE STUDY

The assessment of the effects of a future technology such as Pervasive Computing has to deal with two types of uncertainty: First, it is an open question as to how Pervasive Computing will develop in the various fields of application (path uncertainty), and second, the knowledge base for the lifecycle assessment (LCA) of electronic products is incomplete (data uncertainty).

Pervasive Computing comprises a broad and dynamic spectrum of technologies and applications. Therefore a narrow definition of system boundaries, as required for practical reasons to conduct a lifecycle analysis (LCA), is inadequate to reflect the character of Pervasive Computing. In general the LCA methodology (ISO 14040) (ISO 1997) is difficult to apply to microelectronic products. For example, an inventory analysis of microchip production has to deal with more than 400 processes, vertical ranges of manufacture, and dynamically changing global supply chains (Nissen 2001).

The data uncertainty encountered in the “LCA for ICT” field can only be dealt with by taking into account the few existing LCA studies for ICT while considering the uncertainty of their results. Only simplified LCAs have been conducted so far in the ICT field (*e.g.*, Aebischer *et al.* 2000; Geibler *et al.* 2003; Goodman and Alakeson 2003; Stutz and Tobler 2000; Williams *et al.* 2002; ZVEI 2000). Because of the high overall uncertainty of the results, they are only used to identify priority areas for precautionary measures, not to make a quantitative forecast of environmental impacts.

Experience with LCAs of ICT products and services has shown that the uncertainties of user behavior—which is a factor relevant to assessing the use phase—are usually higher than the uncertainties of knowledge about production processes (Reichart and Hirschler 2001). In the case of Pervasive Computing, knowledge about future usage patterns is almost nonexistent, as the applications are just emerging.

In order to cope with path uncertainty, scenario analysis was used to cover a spectrum of the possible paths of development. Three possible paths of future development were taken into account and described in scenarios. We defined three scenarios for Pervasive Computing with a time horizon of 10 years (until 2012):

- Cautious scenario: Pervasive Computing will only develop in areas that are already pervaded by networked microprocessors (such as the automotive sector).
- Average scenario: Applications fields and their markets develop according to the trends that can be observed today, without being pushed or counteracted significantly.
- High-tech scenario: Pervasive Computing will be ubiquitous (everywhere, any-time computing in all areas of daily life).

These scenarios differ mainly in the degree of diffusion of Pervasive Computing applications and in the extent of connectivity. The application areas chosen for applying the scenarios were “housing,” “traffic,” “work,” and “health,” of which the most dynamic one was traffic. In addition, three cross-sectional technologies—future digital media, wearable computers, and smart labels—were investigated, of which smart labels are expected to become the first type of application to form part of our

daily life. The reader is referred here to the original study for a detailed description of the scenarios and application areas (Hilty *et al.* 2003).

All defined scenarios and application areas were reviewed by an external interdisciplinary expert board set up by the client of the study (TA-Swiss). Based on the scenarios defined, we made rough quantitative assessments (case studies) for selected application areas in order to extrapolate trends into the future. Thirty-nine researchers and other experts from industry, NGOs, and public authorities were interviewed after being briefed about the preliminary findings. They were first asked to help identify potential applications of Pervasive Computing likely to be in place by 2012. Second, their appraisals of the consequences of technological developments on selected environmental topics were gathered in formal expert interview situations or discussed in expert workshops. Repeated consultations of the selected experts both from science and from politics contributed to the validation of the results and to the identification of priority areas for precautionary action.

The ascertained effects of Pervasive Computing on the environment were structured in a conceptual framework that distinguished among three levels of environmental impact of ICT (see, *e.g.*, EITO 2002; Fichter 2001; Schauer 2003; Türk *et al.* 2002):

1. First-order effects: Includes all environmental impacts resulting from ICT hardware during the product lifecycle, covering production, use, and disposal.
2. Second-order effects: The use of ICT causes effects to other processes such as traffic or industrial production and influences *their* environmental impacts indirectly.
3. Third-order effects: Owing to the assumed widespread use of ICT in daily life, economic structures and lifestyles can change, indirectly affecting the expression of first- and second-order effects.

In the following sections we shall discuss our specific findings according to this scheme. Because the task was to identify potential risks of Pervasive Computing and to suggest precautionary measures for Switzerland, the case studies reported in the following sections refer to the Swiss context.

ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF PERSVASIVE COMPUTING

First-Order Effects

The first-order environmental effects of Pervasive Computing include all environmental impacts caused by the physical existence of the technology over the entire lifecycle, covering production, distribution, use, and end-of-life phases. Key indicators for the environmental impacts are the lifecycle-wide energy and raw material consumption and the output of waste heat, solid waste, and the emission of substances into air, water, and soil. Basically, first-order environmental effects originate from the mass and energy flows needed for making Pervasive Computing possible. In the following text, two first-order aspects were given special attention, as they are presently widely discussed issues involving ICT.

Electricity consumption of pervasive computing

Electricity consumption is linked directly to environmental impacts by the supply infrastructure, for example, emissions from fossil fuel combustion or the radioactive waste problem. The ICT sector currently contributes 1840 GWh/a (3.59%) to Swiss electricity consumption (Brunner *et al.* 2001). According to Arthur D. Little (2001), electricity consumption of all commercial ICT will grow from 3% in 2001 to a maximum of 4% in 2010, or, on the other hand, might decrease to 2% if energy-efficient practices are pushed through. For Germany the share of electricity consumption related to ICT is expected to rise from 1% in 2000 to about 6% in 2010. If energy efficiency potentials were utilized, the share would stay around 1–3% (Langrock *et al.* 2001). Although the figures differ, those studies emphasize current ICT as a considerable factor for future electricity consumption.

Regarding power supply, the following categories of ICT can be distinguished from one another and classified by electricity demand:

- ICT devices connected to the mains,¹ such as today's stationary PCs. According to the vision of Pervasive Computing, these ICT devices will become less important in the future and thus represent a minor, energy-relevant factor.
- ICT devices powered through a mains adaptor and rechargeable batteries in a way similar to that for today's notebooks, PDAs, and mobile phones. As these kinds of devices are becoming more ubiquitous, the energy efficiency of mains adaptors and power management technology will be important factors in the future. Energetically more efficient power supply technologies such as low temperature fuel cells are expected to enter the market in the coming years. As a consequence electricity demand per unit will decrease as the demand for alternative fuels such as methanol or propane increases.
- Networked household appliances with embedded ICT ("smart home" concept), which draw energy from the mains, require additional power. Always-on devices in particular and devices in stand-by mode will cause significant total electricity demand.
- Semi-stationary infrastructure for wireless short-range communication. It must be assumed that a widespread application of W-LAN or radio frequency identification (RFID) readers will result in a growing stock of always-on radio transmitters whose transmitting power of up to 2 watts must be powered by mains adaptors. As a consequence, additional electricity consumption is to be expected.
- Stationary backbone infrastructures for the Internet and mobile phone networks. A more intensive use of network infrastructures is probable as automatically generated data transfer will definitely grow due to Pervasive Computing (Langheinrich and Mattern 2003). Extended server and network operation will result in additional electricity demand.
- Mobile and, in particular, wearable devices that will be smaller, lighter, and more common than today. As changing or recharging batteries repeatedly seems to be unacceptable to users, consumer acceptance and functional reasons will make new concepts of energy supply necessary. For this reason Pervasive Computing will provide additional incentives for the development of alternative energy

¹Editor's note: Mains refers to electrical power supplied by an electricity generating plant.

sources, for example, photovoltaics or piezo-elements as well as for minimizing the energy consumption of devices.

- Components with passive energy supply (*e.g.*, RFID transponders). Such components with negligible energy demand do not contribute to electricity consumption itself, but in the case of passive RFID technology transponders must be powered by local inductive supply fields, the efficiency factor of which is low.

Pervasive Computing will evolve on the basis of existing ICT and will therefore spread over most of these categories. Which power supply technologies will be developed will depend on the purpose of the particular application. For mobile, location-independent use, there are strong incentives for producers to minimize power consumption or to utilize alternative energy sources, whereas stationary devices may develop in a less energy-efficient manner than they have thus far. How Pervasive Computing will change the patterns of electricity use is uncertain, as technical parameters and application patterns cannot be forecast.

The risk of increasing energy consumption is illustrated for two case studies, home networks subsumed under the term “smart home” and mobile network infrastructure for mobile phone technology.

Electricity Consumption in Highly Networked Private Households. The term “smart home” refers to the concept of a private home, equipped with many Pervasive Computing functions (Futurelife 2004; Smarthome 2004). To analyze the electricity consumption caused by smart homes, we take as a starting point the results of a study done by Aebischer and Huser (2000) and apply them to our scenarios. Electricity consumption resulting from networking in private households will reach an annual growth rate of 1.3% and will therefore be the most important factor of growing electricity consumption in the domestic sector in industrialized countries. We have assumed that technological efficiency gains will be compensated for by an increased demand for services.

The following considerations are a conservative assessment of the impact of Pervasive Computing on household electricity consumption. The results for single household types have been extrapolated to the macro-level, considering one- and multi-family houses, diffusion rates, saturation rates and diffusion times. Additional electricity demand can be calculated for the three scenarios, given the assumption that electricity consumption will be mainly caused by hardware used in a supplementary fashion, and a shift in use patterns.

The data in Table 1 show significant additional electricity consumption for all scenarios. In the average scenario, the additional demand is almost equivalent to the electricity consumption of all computer and network installations in Switzerland

Table 1. Additional electricity consumption for networking in 4 million private households in Switzerland (Hilty *et al.* 2003).

	Cautious scenario	Average scenario	High-tech scenario
Diffusion single- and multi-family houses	10%	30%	90%
Additional electricity demand	250 GWh	1000 GWh	3000 GWh

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today (Brunner *et al.* 2001). According to Aebischer and Huser (2000) the increase in electricity consumption due to networking in private households overcompensates the potential energy savings by ICT use (*e.g.*, e-commerce and teleworking) by a magnitude of at least one. Similar effects must be expected to result from Pervasive Computing.

If we assume, in compliance with Cremer *et al.* (2003), that about half of ICT electricity consumption is caused by households and the other half is consumed in offices and infrastructure, and that these sectors will develop similarly, we can extrapolate for both sectors an annual additional electricity consumption of 2000 GWh in the average scenario and 6000 GWh in the high-tech scenario. In the latter case, electricity consumption would rise by 7% due to the networking of ICT devices in private households alone.

Electricity Consumption for Mobile Network Infrastructure. The number of mobile phone subscribers has grown almost exponentially between 1998 and 2000. Now saturation tendencies can be observed. Parallel to the European GSM standard, third generation mobile phone infrastructure (UMTS) is being set up. An increasing number of mobile devices also support ad-hoc network standards, such as Bluetooth, USB, and W-LAN.

Ninety percent of the energy demand of a GSM network is due to stationary infrastructure and 10% is caused by end devices (Schaefer and Weber 2000). The energy consumption of UMTS will depend largely on the number and performance of its Base Transceiver Stations (BTS). BTS for UMTS have a reduced transmitting power compared to BTS for GSM, but the set-up of an enlarged infrastructure and the increasing data transfer caused by the growing stock of Pervasive Computing devices will outweigh the net effect.

As UMTS networks are still under construction, there are potentials for energy-efficient design. One key factor for BTS is having the design of their cooling systems modified for energy efficiency. The energy reduction potential has been estimated at 400 GWh per year for Germany (Stobbe *et al.* 2004).

Conclusions for electricity consumption

Pervasive Computing will probably increase electricity consumption due to accruing stocks of ICT and network infrastructure and extending power-on periods in an “always on—anywhere and anytime” culture.

Although the power demand of new ICT devices will be lower than the average of the ones currently in stock, the trends toward higher availability (always on, anytime) and higher stocks will counteract that positive potential. A key parameter that will affect electricity consumption in an era of Pervasive Computing will be the energy efficiency of stationary and semi-stationary devices. This is mainly determined by their power supply and cooling systems. There is a risk that inefficient energy schemes will prevail, as no strong incentives for energy-efficient design are given in the international economy. On the other hand, in the case of mobile equipment, functional reasons require high-energy efficiency, so that alternative energy supplies must be developed for them.

The increase in the data transfer of short-range networks caused by Pervasive Computing will require additional capacities in the long-range networks. This will cause an increase in the energy consumption of network server farms, as they need active cooling.

Pervasive computing and the risk of cross-contamination

The end-of-life phase of present-day ICT is accompanied by a considerable risk potential for health and the environment, as ICT components contain a multitude of harmful substances such as heavy metals and halogenated organic compounds (Behrendt *et al.* 1998). In cases of insufficient disposal or recycling practices, the emission of toxic substances from electronic waste can pollute water, soil, and air and harm human health (EMPA 2004b). In addition, the material loss caused by the disposal of these substances instead of recycling them has to be compensated for by extracting additional primary raw materials (*e.g.*, gold and copper mining), which is associated with severe burdens for human health and the environment.

Therefore, an increase in the amount of electronic waste (PCs, entertainment electronics, mobile phones, PDAs, *etc.*) is to be expected. It will add to the pressure currently on the disposal streams of electronic waste. Miniaturization and embedding in other goods will constitute a considerable part of the Pervasive Computing waste that will be found in residual waste (*i.e.*, not separable using conventional means). However, the mass flows of Pervasive Computing components in municipal solid waste remain relatively small and are not expected to pose a significant problem to incinerators. However, taken together, the loss of valuable raw materials such as copper is considerable and has to be compensated for by extracting correspondingly more primary raw material.

Moreover, Pervasive Computing has an impact on non-electronic waste. For example, electrical household appliances and vehicles will be equipped with printed circuit boards, LCD displays, and power supplies or batteries. Packaging will be “enriched” with small microchips (RFID). The presence of electronic components in objects that were formerly non-electrical will give rise to quality issues in the recycling processes used for those materials.

As the increase of electronic waste in general and the problem of ICT components in vehicles have currently been addressed by the WEEE and RoHS directives of the European Union (European Parliament 2003a,b), we want to emphasize the impact of Pervasive Computing on other waste streams and highlight the risk of cross-contamination. In the following we illustrate this effect, giving two case studies as examples. A case study on “i-wear” will take a closer view of the embedding of ICT in clothes, which may counteract reuse of them. In a second case study, we will discuss the effect of “smart labels” on the recycling of packaging, which may violate the quality requirements common in material recycling processes.

Case Study on the “End of Life Aspects of i-wear”. The term “i-wear” refers to a concept of wearable computing, which means that garments are equipped with embedded electronic devices (microprocessors, sensors, batteries). Pioneers of the concept define i-wear as the combination of mobile multimedia technology with wireless communication and portable computers integrated into clothing. Recent developments

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have attempted to incorporate electronic systems into the constituent fibers and fabrics of clothing, or even to incorporate them into a print applied to the garment. I-wear can be powered by integrated dry batteries, and in the future will be powered by fossil fuel cells. Alternative power supplies using body or ambient energy are under development, but rechargeable buffer batteries may be necessary in any case.

Even though the European RoHS directive (European Parliament 2003a) has prohibited the use of certain toxic or environmental risky substances in electronics since August 2004, from the standpoint of the Precautionary Principle, one cannot be sure that no pollutants are present, particularly in imported i-wear.

Therefore, embedded electronic devices and batteries will give rise to new end-of-life issues for garments.

What consequence will it have on waste streams if some worn out garments are i-wear? We assessed this by taking Switzerland as an example: Some 18 kg of textiles per capita are sold annually, about 10 kg of which are clothes.

Every year roughly 7 kg per capita are fed directly into municipal solid waste streams and 4.4 kg per capita are collected separately for reuse or recycling (BUWAL 2002).

If we assume that a typical consumer buys a 2 kg jacket every 2 years, which is used for an average of 2 years, and take into account a Swiss population of currently 7.3 million, the following waste flows would be expected for the three scenarios (Table 2).

In the cautious scenario annually 0.01 kg of i-wear per capita would be an insignificant amount, taking an annual total of 4.4 kg textiles collected separately per person and year as a reference. However, in the average and high-tech scenarios significant amounts would be achieved.

Used clothes are typically collected for charitable purposes, but we doubt whether second-hand i-wear could be remarketed in this way while retaining its original functionality. A restoration of the functionality is improbable and removal of electronic components from textiles would require a lot of work and might damage the cloth beyond usability. Exporting such garments to developing countries would—quite apart from the question of acceptance—merely shift the end-of-life problems of electronic waste geographically.

Table 2. Expected annual waste flows for “i-wear” (Switzerland).

	Cautious scenario	Average scenario	High-tech scenario
Assumed diffusion	1%	20%	80%
Waste (“i-wear”)	73 t	1,500 t	6,000 t
Waste (energy supply)	0.01 kg/cap. 36,500 batteries	0.21 kg/cap. 730,000 batteries or solar/fuel cells	0.82 kg/cap. 3 million batteries, solar/fuel cells or body energy devices
Max. mass of batteries disposed of	1.1 t	25 t	100 t

I-wear in municipal solid waste would be an additional source of pollutants in incinerators and landfills. Consider this: the annual amount of electronic waste in Switzerland is 68,000 t (EMPA 2004a), which corresponds to 9.3 kg per capita annually. I-wear would be responsible for an additional annual 0.82 kg of electronic-like waste per capita in the high-tech scenario.

Batteries found in i-wear would need to be removed and disposed of separately for environmental and safety reasons (fire danger). Dry one-way and rechargeable batteries for electronic equipment contain hazardous substances such as corrosive alkali electrolyte or volatile organic compounds. Also heavy metals, for example, cadmium and nickel, have been found in these components. NiCd rechargeable batteries will disappear from the European market in the near future; however, new types of rechargeable batteries (*e.g.*, Li-ion or Li-polymer) have to be treated likewise with caution.

In Switzerland currently 2332 t or 67% of the dry batteries sold annually are collected separately and recycled (BUWAL 2002). Assuming an average dry battery weight of 30 g (calculated from UBA 2001) in the average scenario, an additional maximum of 25 t of batteries and in the high-tech scenario an additional maximum of 100 t of batteries would have to be separated from i-wear annually. Compared to the total mass flow of exhausted dry batteries, these amounts are not dramatic, but i-wear is only one segment of Pervasive Computing.

Case Study on "Smart Labels on Packages". "Smart labels" are thin labels containing a transponder, that is, a microchip used to store data that can be read wirelessly. They use Radio Frequency Identification (RFID) technology.

Smart labels are usually based on flexible substrate materials, such as polyimide or polyester. The antennas are made of thin copper or aluminum layers and most of the commercially available chips use silicon technology. However, there has been progress in metal-free polymer electronics, which allows for the application of electronic circuits using printing technology. Currently it is unclear whether smart labels can be built without metal. The typical smart labels used in retail, transport/logistics, libraries, parcel services, and airlines' baggage traffic have dimensions of 50 × 50 mm and weigh about 0.1 g each (GEMPLUS 2002). The miniaturization of smart labels is limited by the space needed by the antenna for power generation and the frequencies used.

For present applications of smart labels only an estimation of total numbers is possible. From Germany we know that about 200 billion units of sales packaging are sold annually (Reichl 2003). Given a diffusion rate of 100% (complete replacement of barcodes by smart labels) and taking into account an estimated weight of 0.1 g per unit, the total mass of marketed smart labels would contribute to a waste stream of 20,000 t/a within this bottom-up assessment. Taking into account other applications, such as production, postal services, renting, public transport, and so on, might make the total amounts in all scenarios a magnitude higher.

In order to identify the impacts that smart labels may have on recycling, we looked at food packaging recycling as an example. One can distinguish glass, paper and cardboard, plastics, aluminum, and tin foil as the main material types involved. If a high percentage of food packaging is equipped with smart labels, recycling problems might emerge, as smart labels add impurities to otherwise recyclable materials.

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For glass-to-glass recycling, paper labels do not have to be removed, as they burn completely in the melting process. If the substrate of a smart label consists of organic materials, they would also burn without any problem, but copper could be introduced into the glass melt. In Germany the standard for impurities in end-of-life glass is max. 5 g/t for non-ferrous metals (Habel 2001). Assuming a smart label weighing 0.1 g on an average glass of 200 g, the share comprised by the smart label would be 500 g/t. If all glass for packaging were equipped with smart labels—as assumed in the high-tech scenario—a conflict with these quality standards is likely to arise. In the Average Scenario the share of smart labels amounts to 50 g/t, a level that would still have to be taken seriously. As a consequence smart labels might have to be removed before glass recycling.

In paper and cardboard recycling, impurities are removed in the pulper. Copper-containing paperclips are a type of impurity that often has to be dealt with. The silicon or polymer substrate of smart labels will be separated in the pulper as well. Therefore the expected amount of smart labels will probably not pose a disadvantage for paper and cardboard recycling.

In tin can recycling, compounds and residual adhesives, for example, from paper labels, usually do not cause any problems (IZW 2002). Smart labels based on polymers will burn in the blast furnace, silicon substrate would enter the slag. On the other hand the input of copper into steel is not desired, but the accumulation of copper in steel is a problem that is not specific for Pervasive Computing. Taking the high materials flows of shredder scrap and related copper loads into account, the impact of smart labels is negligible.

In aluminum recycling impurities such as paper labels are burned in the smelting process. Copper is especially critical to aluminum recycling. The amounts of other heavy metals and silicon also have to be limited, varying from alloy to alloy. Allowed impurities are on magnitudes between 0.001 to 5 percent by weight. Smart labels based on silicon might cause conflicts with quality standards. An aluminum package of 50 g with a “smart label” weighing 0.1 g has an impurity content of 0.2-percent by weight. The copper content may reduce the market prices of smart-labeled aluminum scrap, which might thwart recycling solutions for aluminum beverage cans.

Thermoplastics such as PET bottles are smelted at 150–300°C in plastics recycling. Smart labels based on polymers might cause material inconsistencies, whereas silicon substrates are removed by sieves. One problem could be the melting of solders, if, for example, lead is transferred into the plastic and collides with the maximum metal content admitted under the EU packaging directive. In high-tech PET recycling solutions all labels were separated in an automatic presorting process and are therefore not problematic.

The impact of future smart labels on recycling processes has to be assessed depending on their composition. Metal-free smart labels based on polymer electronic technology would facilitate recycling of metals, but would influence the quality of recycled plastics.

Conclusions for cross-contamination caused by pervasive computing

Pervasive Computing will cause a high diffusion of a growing number of miniaturized ICT components. Miniaturization and new technologies reduce the content of

valuable substances per device. But it is not realistic to assume that miniaturization will cause significant reductions in total material demand on the macro-level (Nissen 2001; Hilty *et al.* 2003; Behrendt and Erdmann 2004). Growing stocks of hardware may compensate or even over-compensate the effects of miniaturization.

The case studies underpin that the embedding of ICT in previously non-electric objects entails the risk to change waste streams adversely. The large diversity and high distribution of Pervasive Computing entail the risk of cross-contamination. It is likely that pollutants and impurities will cause problems in recycling other materials, for example, the recycling of packaging.

However, a separate collection of single components, such as microchips and batteries for recycling, would require tremendous logistic and technical efforts, entailing the risk of high-energy demand for itself. It has to be checked for which waste fractions a separate treatment makes sense and logistic and separation capacities have to be adjusted or set-up. As a part of large waste flows, no high-level recycling, but only a down cycling seems feasible economically. The small size and ubiquity of Pervasive Computing components will result in a definite loss of valuable materials.

Finally it must be clarified under which conditions embedded electronics can be treated together with residual waste.

Second- and Third-Order Effects

The use of ICT has caused structural changes in economics and a decoupling of economic growth from investment in energy and material-intensive sectors (Fichter 2001). Today value is being created increasingly in the immaterial sphere of ideas and information, which have little direct impact on the environment.

ICT use may contribute to relieving environmental impacts. Terms as “dematerialization” and “demobilization” reflect the high expectations being placed on ICT to substitute pure data processing for material and energy intensive processes. Replacing physical goods or processes by virtual services can contribute substantially to increasing resource productivity. This way of saving energetic or material resources (second-order effects) can go far beyond the environmentally harmful processes generated by the production and disposal of ICTs, making it possible, for instance, to avoid traffic by substituting telecommunication for trips.

But this potential to relieve environmental impact can only be realized if economic and regulatory frameworks favor the sustainable management of natural resources. Otherwise, a surge in demand can neutralize or even outweigh the possible savings. In almost every case in which ICT use could have made possible an environmental benefit, it turned out that some related or otherwise environmentally harmful activities increased simultaneously. These rebound effects (third-order effects) counteract the environmental benefit expected from dematerialization and are thus to be regarded as a serious risk for the environment (Radermacher 1997).

Considering the uncertainty surrounding the forms and ways in which Pervasive Computing will develop, it is not possible to make a reliable prediction or to present evidence of second- and third-order effects on the environment. Instead it is expected that the conceptual characteristics of Pervasive Computing will intensify or accelerate the same effects that we know from existing ICT. On the other hand, there is no evidence that the use of Pervasive Computing will inevitably entail ecological

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consequences other than those we know from ICT. Hence, specific environmental effects expected of Pervasive Computing can be evaluated on the basis of the findings made thus far on ICT.

In the description that follows, three environmentally significant cross-sectional aspects are taken as examples, while bearing in mind that these ecological impacts are not determined by Pervasive Computing alone, but also by a concurring series of further technical and socioeconomic factors.

Influence on fuel consumption in facilities

Building insulation has become a high-priority action field for climate protection in Switzerland because 42% of Swiss total fossil energy demand is used for heating purposes (BFE 2003). Similar priorities would apply to many industrial countries. Active measuring and control systems supplement energy-efficient heating systems. Computer-assisted facility technologies are equipped with sensors to take inside and outside measurements such as temperature, penetrating sun radiation and wind force. This makes it possible to reduce the loss of heat energy by adapting heating and ventilation to keep operating conditions optimal. Remote control of heat installations per telephone has been part of present-day technology for a while now, and the Internet has more recently been added as an option (Bohn *et al.* 2003). Although it is not possible to quantify the benefit of ICTs for building insulation, these measures have on the whole been successful. In spite of the increasing number of buildings, it has been possible to avoid an increase in the amount of energy consumed for heating purposes in Switzerland (BFE 2003). The use of ICT in installations for generation of regenerative thermal energy provides additional advantages for climatic protection. The optimal utilization of solar or geothermal energy requires sophisticated control technologies (Koner 1995). Programmable electronic control units with sensor networks can make it more economical, and thus more attractive, to use renewable energy sources for heating (Hastings 2004).

Electronic facility technologies will represent an attractive field of application for Pervasive Computing. Innovative functions of Pervasive Computing such as presence detection and voice or gesture recognition interfaces are predicted to enter the home automation market (Smarthome 2004; Jedamzik 1996). Compared with today's state of the art, such control systems in buildings will integrate considerably more networked components (*e.g.*, sensors, actuators), functions (*e.g.*, remote control, thermal control for individual rooms), and be also connected to external networks. Pervasive Computing components spread throughout a "smart home" will provide both real-time data on usage in individual rooms and, in ideal cases, information on the intentions and living habits of the residents. Such concepts will make possible intelligent heat requirement planning on the basis of prevailing weather forecasts and utilization profiles of the residents (Fleisch *et al.* 2002). Automated and adaptive energy management will make it possible to make buildings' energy management more efficient (Schrott *et al.* 2000). Another advantage of using Pervasive Computing consists of avoiding heat losses caused by incorrect manual operation or inadvertence of the users—a great potential of this technology, as user conditioned heat losses also occur in energetically optimized buildings (Spasokukotskiy *et al.* 2001).

Quantitative estimates of the energy savings that can be obtained with automatic heat control in buildings vary between 15 and 35% of today's total heating energy use. That yields a net benefit for the purposes of energy saving, although to a lesser extent if the performance factor of electricity generation is taken into account (Cremer *et al.* 2003).

However, it would be wrong to think that Pervasive Computing automatically results in the saving of energy. The opportunities have to be seen in opposition to a number of risks due, on the one hand, to the functionality of technology and, on the other hand, to human interaction with technology. From the standpoint of energy policy, the use of Pervasive Computing for the energetic optimization of buildings must be considered critically. Energy-efficient architecture is also feasible and economically attractive without using "smart" electronics (Jakob *et al.* 2002; see also Aebischer and Huser 2000). If one overestimates the advantages of electronic control systems, one runs the risk of neglecting the fact that passive heat protection concepts have proven to be energy saving and economical. On new buildings, they clearly represent the better alternative, while Pervasive Computing assisted control systems have to be seen, at best, as a useful supplement. Systematically applied to existing buildings, they have the potential to save 3–6% of total energy consumption under West-European conditions (Arnfolk *et al.* 2004).

Quite particularly the increased complexity of electronic control systems incorporating Pervasive Computing makes high demands on thorough planning, calibration, and maintenance. In cases of inexpert or omitted planning and practice, there is a high probability that air conditioning will be insufficiently optimized or that Pervasive Computing-assisted systems will malfunction. As a consequence of the complex interaction of their various hardware and software components, it will be harder to detect energetically unfavorable operating situations with these systems, or to even remedy obvious malfunctions. Should a large portion of systems develop such technical problems, they might in total cause a considerable loss of energy.

Whether these technical problems will cause an increase in total energy consumption depends mainly on the area's energy policy. If there are no external incentives for optimizing energy efficiency, energy losses will be accepted, as usual, for reasons such as comfort. It will depend mainly on whether energy efficiency is financially profitable. As a personalized accounting system for heat, warm water, and power (micro-billing), the use of Pervasive Computing offers great potential for energy saving, especially in the rental flat sector. An equitable "pay as you consume" breakdown of expenses is known to motivate individual users to save energy (Diekmann 1994). If the use of Pervasive Computing makes it possible to influence consumers' behavior by improving the link between cost and consumption, this indirect way of saving fossil fuel could contribute noticeably to protection of the global climate.

Influence on the traffic system

Transport processes rank as some of the ecologically most relevant economic processes that exist: goods and passenger traffic add to the pollution of the environment due to the surface sealing needed for roads, the consumption of resources (fuels), and the emissions they cause (greenhouse gases, air pollutants, noise). However, the different means of transportation differ considerably with regard to their

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performance per environmental load unit. As compared with the car, the railway needs on average a third of the primary energy per passenger kilometer, and compared with short-haul flights, only a fourth (Westenberger 2004). Just how environmentally relevant a given means of transportation is does not depend, in the first place, on how much ICT equipment it has. Nonetheless ICTs do have the potential to influence the environmental efficiency of passenger and goods transport. Within the mobility sector, selection of the means of transportation can be influenced by ICT, and for goods environmental efficiency can be improved by avoiding unnecessary trips. The essential environmental effects of present-day and future ICTs within the mobility sector can be listed as follows and illustrated with examples:

- Improvement of the eco-efficiency of engines and exhaust gas filters or catalytic converters by using electronic control systems in the vehicle.
- Optimization of mobility by better planning itineraries and better utilizing vehicles and infrastructure.
- Substitution of telecommunication for traffic processes.
- Induction of additional traffic processes over longer distances as a consequence of telecommunication.

Improvement of Technical Eco-Efficiency. Electronics has been the main basis for progress in prime mover technologies in recent years. The use of electronic control systems has made train control energetically more efficient (UIC 2003; Ahman 2001). Modern high-speed trains such as the German ICE3 consume merely the equivalent of 2 liters of gasoline per passenger on 100 km when carrying an average load (Köser 2003). The trend of using ICTs has grown even more intensively in cars: nowadays a top-of-the-line-model car is equipped with more than 30 microprocessors (Burkhardt *et al.* 2001). On-board computers make possible a more uniform operation of engines, thus lessening considerably the frequency of starting and braking. Such “motronic” systems improve engine operating performance and simultaneously make it possible to save fuel and reduce the amount of pollutants emitted with the exhaust gas. Due to the increased overall number of cars, however, the improvement of technical efficiency has not been enough to reduce the total consumption of fuel (BFE 2003).

Optimization of Mobility Services. Pervasive Computing can make traffic-related information available faster and just when it is needed most. That leads simultaneously to increased efficiency of individual mobility and of the whole traffic system. In addition, navigation computers can plot one’s optimal itinerary, avoiding unnecessary detours and relieving the impact on the environment (Hartmann *et al.* 2003). In the high-tech scenario developed in the study by Hilty *et al.* (2003), traffic information (time-tables, *etc.*) is available for pedestrians as well as for motorists by means of wearable computers offering individual mobility logistics independent of their location. Travelers may ask for logistical answers to their mobility requirements at any time by means of a Personal Travel Assistant (PTA). As the need to plan is one of the handicaps of public transport in opposition to taking the car, such individual logistic assistance would indeed contribute to the attractiveness of busses and railways. But also in this case, rebound effects must be expected to set in, just as

rebound effects have compensated for past ICT optimization potentials in passenger traffic. In spite of the attractive public transportation available in Switzerland, the upward trend in motorized individual traffic is continuing (Arendt and Achermann 2002). We are therefore forced to conclude that the additional optimization potential offered by Pervasive Computing will not noticeably reduce the environmental impact of traffic on a macro level, as long as the business and regulatory environment of low energy costs and externalization of environmental costs remains unchanged.

Substitution of Telecommunications for Traffic Processes. Progress in telecommunications has been expected to make trips for persons superfluous for some time now, and thus to help save time, energy, and emissions. Trips are often intended to make contacts and exchange information. The same can be achieved with information technology without requiring any physical movement of the communicating partners. The lifecycle assessment (LCA) of an international conference in Zurich illustrates clearly this potential for substituting telecommunications for traffic processes: The effective environmental impact of the trips of 500 international participants (with 35% flights) was calculated with 4207 Ecoindicator Points (EIP). In the hypothetical case of a video conference, feasible with today's ICTs, such a meeting would have merely caused 10 EIP. Although such a totally dematerialized scenario does not have much relevance in practice, the more realistic scenario of a virtually connected conference at three conference sites (Zurich/Dallas/Tokyo) would still represent an ecological gain of about 50% as compared with a single central conference venue (Hischier and Hilty 2002).

Induction of Traffic by Telecommunication. There are nevertheless serious doubts about whether such examples represent ways to really take impact off the environment by using telecommunications. Virtual communication cannot totally be substituted for personal contact (Rangosch 2000). On the contrary, the number of business contacts and the distance between them have increased sharply with the spread of telecommunications. As a consequence, both business travel and virtual communication have definitely increased (Rangosch 1997).

Such rebound effects must also be expected to limit progress as virtual communication by Pervasive Computing becomes more attractive. Similar impacts are also certain to arise with an increase in leisure time. The popularization of the Internet has also boosted considerably the number of long distance contacts in business and private life (in the form of Internet chatting, for instance). Over three-fourths of these contacts made virtually entail repeated personal meetings and consequently involve travel by the participants (Zoche *et al.* 2002).

In addition to stationary applications, wearable computers and other mobile Pervasive Computing components (Web pads, e-paper) will make possible virtual communication and consumption of information and entertainment media independently of one's location. Present-day Internet users spend an average of 17 hours per week on the Internet (Hahn *et al.* 2000) and thus stay at one place for that time. Stationary online activities have lower negative impacts on the environment than other leisure activities. If Pervasive Computing makes it possible to use media services over a mobile connection as well, the user will no longer be bound to the

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location by a wired Internet connection. That will contribute to the transfer of at least a part of his/her daily online time to secondary activities on a mobile basis, for example, surfing the Internet while driving a car. Then the frequent leisure traffic we see today (BFS 2002) will grow further. Considering how things have developed thus far, we assess that the risk of an increase in environmental stress from changes in consumer behavior caused by Pervasive Computing and additional traffic may well overcompensate any potential for mobility optimization.

Influence on the service life duration of everyday objects

One environmentally unfavorable property of ICT products is their service life, which averages from 2 to 5 years. That time is short in relation to the amount of resources consumed for ICTs' production. There is a trend toward low-cost electronics, which is leading to even shorter service lives and one-way products (*e.g.*, mobile phones, cameras). As a consequence, the quantities of electronic waste that need to be disposed of are increasing in spite of continuing miniaturization.

The defining characteristic of Pervasive Computing is a miniaturization and embedding of ICT components into everyday objects, so as to make the latter "smart." With regard to the shorter and shorter service lives of ICT, short-lived smart functionality may devalue the objects in which ICT is embedded much sooner than without. Such "virtually worn" smart objects may be replaced and scrapped long before they become worn out physically. Thus, Pervasive Computing can intensify resource use and the waste problems encountered with goods other than electronic ones.

Smart objects will not necessarily be easily identifiable from the outside as containing electronic components (Weiser 1991). At the end of their service lives, the problem may therefore arise that the consumer will not identify them as electronic waste, which will make it difficult to collect electronic waste for material recycling separately.

Even with a financial motivation like the advanced recycling and disposal fee in Switzerland (BUWAL 2000), it is already obvious that the system presently relying on waste separation by the consumer will not be suitable for Pervasive Computing. Worse still, it must be added that today's collection logistics and most recycling processes are not economical for the recycling of highly miniaturized, single electronic components. The ecologically desirable reintegration of valuable materials and adequate disposal of harmful substances are both important matters of environmental concern in Pervasive Computing. However, it is uncertain whether either of them can be accomplished with the recycling technologies currently available. Therefore it is probable that the share of electronic waste in municipal waste will grow again in the future and may cause problems in waste treatment as well as further the dissipation of precious materials.

CONCLUSIONS

As Pervasive Computing encroaches upon more and more segments of our daily life, leading to an ever-higher dissipation of ICT components, environmental effects occur over the whole lifecycle of the products affected.

As we have shown, a quantification of the net opportunities and risks to the environment do not appear possible due to the highly dynamic character of technological development processes and uncertainties in their application and diffusion. In the range of our scenarios we have identified areas in which Pervasive Computing may collide with environmental goals and thus have to be judged as risks.

While Pervasive Computing is not expected to cause totally new types of impacts on the environment, it is likely to add to the well-known environmental impacts of today's ICT. Consumption of scarce raw materials for the production of electronics and the energy consumption of stationary infrastructure may increase. Furthermore, Pervasive Computing will change electronic waste streams in their amount and quality. If no adequate solution is found for the end-of-life treatment of the electronic waste generated by millions of very small components, precious raw materials will be lost and pollutants will be emitted to the environment. In OECD countries the expected amounts of microelectronics in residual waste are controllable in terms of environmental and health risk. Greater challenges may arise, however, in countries without well-developed systems of waste treatment and recycling. An increasing concentration of electronic waste in household waste streams will aggravate waste-related impacts on environment and health, for example, in the case of illegal landfill or open burning.

On the other hand the intensified use of ICT in the era of Pervasive Computing might result in certain advantages to the environment. Intensified use of information services instead of physical goods can contribute to higher ecological efficiency in economics and consumption. Although Pervasive Computing could bring a potential for dematerialization, it has to be expected that energy and resource savings will not be realizable in every case due to a growth in demand that will overcompensate for the savings (rebound effects).

There is a need for policies that exploit the environmental opportunities of Pervasive Computing while avoiding the risks at an early stage of technological and market development.

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