Effects of Pervasive Computing on Sustainable Development

Illustration Works

ANDREAS KOEHLER AND CLAUDIA SOM

Since pervasive computing is expected to become ubiquitous in the coming years, the question arises whether it will support sustainable development or may counteract that aim. Based on the results of a technology assessment study we show that pervasive computing could amplify already existing problems related to the environment, human health, and society. Power consumption for digital networks, e-waste streams, and exposure to non-ionizing radiation may all increase. Furthermore, social sustainability could be threatened by the technology if it is applied in a way that restricts consumers' privacy and freedom of choice. We refer to the precautionary principle as an analytical framework for discussing the opportunities and risks of pervasive computing for sustainable development.

Visionary New Ways to Apply ICT

Pervasive computing refers to visionary new ways of applying information and communication technologies (ICT) to our daily lives. It involves the miniaturization and embedding of microelectronics in non-ICT objects and wireless networking, making computers ubiquitous in the world around us [1]. The miniaturization of semiconductor technology is bound to continue for about another 10 years without breaking the trend [2]. Further development of wireless communications by means of mobile phone networks and wireless local area networks (W-LAN) will play a decisive role. It is likely that the number of mobile ICT components per person will rise into the hundreds. Unlike most of today's ICT products, pervasive computing components will be equipped with sensors enabling them to collect data from their surroundings without the user's active intervention. On the software level, so-called agent technologies will gain in importance.

Pervasive computer refers to visionary new ways of applying information and communication technologies (ICT) to our daily lives.

If our life is to be pervaded in such ways by microelectronic components, running all the time with most of them wirelessly networked, one must ask whether these technologies might not have undesirable side effects that counteract the aim of a sustainable information society [3], [4]. In a sensible discussion about the effects of pervasive computing on sustainable development the expected benefits need to be weighed against the potential risks involved.

Our understanding of sustainable development is based on the so-called Brundtland definition: "A development is sustainable if it meets the needs of the present without compromising the ability of future generations to meet their own needs" [5]. This definition can be interpreted as an extension of the ethical principle of justice in space and time, leading to the principles of intra- and intergenerational fairness. It implies keeping as much space for future decisions open as possible, since we cannot anticipate today what the needs of future generations will be. This is the aim of the precautionary principle [6], [7], which is recognized as one framework for sustainable development. The precautionary principle is intended to anticipate and minimize potentially serious or irreversible risks under conditions of uncertainty [8], [9].

Technology assessment for pervasive computing that is oriented towards sustainable development should, therefore, pay attention to trends that may be socio-economically irreversible [10]. In a theoretical sense, the concept of irreversibility can only be based on natural science. However the impacts of a novel technology on society may cause a situation in which it is practically impossible to restore the status before the addressed effect of the technology has occurred.

Irreversibility based on cultural facts should not be underestimated. As the diffusion of pervasive computing is coupled with considerable investments, it will be very difficult to change at a later date.

In order to make precautionary measures effective, risk assessment has to be started as early as possible and is to be accomplished before such technologies have penetrated the market. This is especially true for pervasive computing, as the diffusion of this embedded and networked technology is practically irreversible due to costs of change and may therefore limit future development. Thus early precautionary measures could avert irreversible negative developments cost-effectively. In this way the precautionary principle can serve as a framework to constructively set the course for innovations [11]-[15].

The Swiss Centre for Technology Assessment (TA-SWISS) commissioned a study to display the opportunities and risks of pervasive computing, focusing on its impacts on human health and the environment. This article provides an overview of the most important results of that study [16].

Technology Assessment Study Approach

Pervasive computing comprises a broad and dynamic spectrum of technologies and applications. The assessment of long-term effects has to deal with uncertainty for two reasons. First, scientific knowledge – for example causal models of the long-term health effects of non-ionizing radiation (NIR) – is insufficient. Second, it is an open question as to how pervasive computing will develop in its various fields of application. We cannot predict how fast and to what extent the technology will be taken up and how it will be used.

Due to these uncertainties, quantitative methods to evaluate expected risks are inadequate. To cope with the second type of uncertainty, possible development trajectories have been taken into account and described in scenarios.

We defined three scenarios concerning the future development and application of pervasive computing with a time horizon of 10 years:

- Moderate Scenario: Pervasive computing will only develop in areas that are already pervaded by networked programmable microprocessors (such as the car).
- Average Scenario: Fields of application and their markets develop according to the trends that can be observed today without being significantly pushed or counteracted.
- High-Tech Scenario: Computing will be highly ubiquitous (anywhere, anytime computing).

These scenarios differ mainly in the degree of diffusion of pervasive computing applications and in the extent of connectivity. Experience gained from ICT products and services show that user behavior has a great influence on the development and diffusion of a technology and that the uncertainties of user behavior are usually high [17]. In the case of pervasive computing, the knowledge of future usage patterns is extremely scarce, as the applications are just emerging.

The application areas chosen for the study were “housing,” “traffic,” “work,” and “health,” of which the most dynamic area was traffic. In addition, three cross-sectional technologies – future digital media, wearables, 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.

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 outcome of these expert consultations was a list of the potential opportunities and risks of pervasive computing. After an initial screening the risks were filtered in order to separate the wheat from the chaff and – as a beneficial side-effect of the filtering – to recognize which risks have similar characteristics and can be clustered for complexity reduction [18].

Environmental Impacts

Ecological sustainability will be influenced by pervasive computing in two ways: Pervasive computing will bring about additional loads on as well as benefits to the environment [19]. The environmental impact over the life cycle of single microelectronic components is not expected to change significantly with the trend to pervasive computing.

Resource Consumption

Intel expects that semiconductor technology will develop continuously towards a design geometry of 22 nanometers within the coming ten years without a general change in material composition [20]. Semiconductor miniaturization is accompanying the decrease in the power demand of single transistors, but this savings is being counteracted by a higher structural density and higher power leakage caused by quantum effects [2]. As the acceptable energy consumption of silicon chips (e.g., microcontrollers) for mobile devices is limited by the power supply of batteries or other portable energy sources, the power demand of a single device cannot increase very much.

Assuming that a pervasive computing device has a mobile phone like size and a similar battery capacity of 1500 mAh, it has to be significantly more energy efficient than a 2004 mainstream PC using about 210 W [21] and likewise a Pentium 4 Notebook (23 - 54 W) [22]. The functional requirement of low energy consumption provides a great opportunity to the environment on the macro level as pervasive computing could increasingly replace the PC for many applications (e.g., Internet access).

However, due to the increasing number of components that will be used, the total material and energy consumption caused by the production of electronic goods [23] is still expected to accelerate global resource depletion. The vision of pervasive computing implies that a large number of electronic components will be used in parallel (IBM estimates 1000 components per person [24]). Furthermore, the trend toward throwaway electronics caused by price reductions will shorten the average service life of electronic devices and components in general. For these reasons, a reduction of the total demand for raw materials by the ICT sector can be anticipated only in the moderate scenario.

As the number of components produced will increase dramatically in the Average and the High-Tech scenarios, a compensation or even over-compensation of the material efficiency gains brought about by continued miniaturization and integration is more likely. Fig. 1. shows the dependency between the weight per mobile phone and the total mass of all mobile phones sold in Switzerland as an example. Even though the miniaturization has led to a decrease in physical mass per device, the physical mass of all mobile phones sold has increased sharply [16]. Furthermore, no significant substitution effect occurred because the number of conventional telephones decreased only slightly. Thus the overall resource demand for the production of ICT is expected to grow if the vision of pervasive computing becomes real.

Fig. 1. Individual and cumulative weight of mobile phones sold on Swiss market [16].

Direct (primary) environmental effects of pervasive computing also occur during the use phase of electronics, mainly due to the energy consumption of network infrastructures, which is estimated to increase as a result of increasing data traffic generated by pervasive computing. Networked household appliances with embedded ICT, which draw energy from the mains, require additional power. The energy demand of the network infrastructure needed for pervasive computing might be as large as several percent of total power consumption [25]. Always-on devices in particular and devices in stand-by mode will also form a substantial part of the total electricity consumption. The energy efficiency of mains adaptors and power management technology will be important factors in the future as always-on devices become more ubiquitous.

On the other hand, there is a great potential for power savings due to the trend to mobile devices because the acceptable weight of mobile devices limits battery size. Energetically more efficient power supply technologies such as low temperature fuel cells are expected to enter the market in the coming years. In addition the optimization of energy management in buildings and facilities by using more intelligent controls represents a great potential for energy efficiency. However, the risk of additional energy consumption in total may predominate if incentives for rational energy use are missing [26].

End-of-Life Treatment

Another environmental risk of pervasive computing is the release of pollutants caused by the disposal of the resulting waste. Service life is an essential parameter of the waste generation by ICT products: halving service life means doubling the resource use for production and doubling the amount of waste disposed per service unit. As ICT products are often scrapped after a service life of only 10-50% of their technically possible lifetime, there is some risk that this problem will be extended to non-ICT goods with embedded ICT components ("smart objects"). By this effect, pervasive computing could indirectly contribute to an increasing demand for raw materials and an increasing amount of waste. The increasing quantities and shorter service lives of components that accompany pervasive computing will most probably counterbalance or even outweigh the benefits obtained from progressing miniaturization.

End-of-life treatment of pervasive computing will have to deal with large numbers of small electronic components that are embedded in other products. More and more microelectronic throwaway products, including rechargeable batteries, will be found in waste streams outside that of electronic waste (packaging, textiles). The content of hazardous substances might be uncritical in a single pervasive computing component, but in mass application a release of toxic substances into the environment is to be expected when the components are disposed of in an uncontrolled way or enter recycling streams for materials like paper, cardboard or glass. The invisibility of pervasive computing components in many products will make it more difficult for consumers to differentiate between electronics and non-electronics.

Therefore waste separation by the end-consumers will be almost impractical. As a consequence, the risk of uncontrolled disposal of toxic substances as a part of household waste could counteract the goals of the European WEEE directive [27]. 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 noxious pollutants emitted to the environment.

Indirect Effects

In contrast to these primary environmental impacts, there are also second-order effects of ICT, i.e., optimizing material and energy intensive processes as well as substituting pure signal processing for such processes. The potential environmental benefits from such effects are considerable and can even outweigh the negative primary effects if, for instance, the increasing independence of activities from defined locations reduces traffic [28]. In principle, some business travel can be replaced by telecommunication, which could save long-distance flights in particular [29].

However, using these potential environmental benefits requires that there will be enough incentives to manage natural resources more economically. Otherwise, the growth in demand will counterbalance the savings. These so-called rebound effects are likely to occur, as the history of ICT has shown so far [30]. Pervasive computing could even intensify individual traffic as it supports independence from fixed locations and creates incentives for personal or commercial relationships over longer distances [31].

Whether the positive or the negative effects of pervasive computing on the environment will dominate will depend on how effectively energy and waste policies govern the development of infrastructures and applications in the coming years.

One must ask whether these new technologies might have undesirable side efffects that counteract the aim of a sustainable information society.

Health-Related Aspects of Pervasive Computing

As we have shown in the preceding sections, impacts of pervasive computing can affect not only natural resources but also human health due to the emission of pollutants. Beyond that, human health will also be affected by technical characteristics of "smart objects" and the way they are used.

Exposure to Non-Ionizing Radiation

First, the ubiquitous use of miniaturized and embedded microelectronic components interconnected in wireless networks could have an influence on human health due to the additional exposure to non-ionizing radiation.

Unlike most of today's ICT products, pervasive computing components will be carried close to the human body. Additionally, a predominant part of mobile equipment will stay in an activated mode permanently for functional reasons. As a consequence, a great part of the emitted radiation will be absorbed by body tissue, so that even low-emission power can lead to comparably high local exposure over a longer period [32], although not to thermal effects.

It is undisputed that health damage results from thermal effects by high NIR-exposure. It is generally assumed that an intensity above 100 W/kg has a negative impact on body tissue. Such thermal effects should be prevented by having boundary values for the specific absorption rate of 2 W/kg applying to cell phones. New aspects, however, will arise in the context of pervasive computing, as carrier frequencies differ from application to application.

The current controversy over health risks of cellular phone networks refers to athermal effects of non-ionizing radiation, i.e., effects that occur at low exposure. The following facts are known from past studies:

- Non-thermal biological effects have been observed in electroencephalograms done with sleeping subjects [33];
- Those effects depend on signal modulation, i.e., they do not occur when a non-modulated carrier signal is used [34].

The following are still unknown [35]:

- A causal mechanism that could explain the observed biological effects;
- Whether those effects can cause health damage;
- Whether serious long-term effects of NIR exposure occur.

Furthermore, it is still unclear whether the sensitivity to electromagnetic fields that is observed in single cases is based on biological mechanisms or has a purely psychological explanation.

Besides the biological effects, attention must be given to the psychosomatic effects of NIR exposure. Anxious people can develop real symptoms if they are convinced that NIR threatens their health.

Only under far-reaching assumptions might pervasive computing make possible a stabilization of, or decrease in, our daily exposure to non-ionizing radiation. An increase is more probable, as wireless local area networks (W-LANs) are being built in addition to mobile phone networks. In spite of their lower transmission power, they will add to the total exposure, unless they are used as a substitute for existing networks. Considering the fact that pervasive computing involves wearing radiation sources on the body (wearables) and even inside the body (implants), there is a need for further research. Even sources of low transmitting power may cause high exposure to radiation if they are very close to body tissues. There is a conflict potential, as non-users of pervasive computing will see themselves exposed to impairments caused by others, such as in the case of “passive smoking.”

Physical Contact with the Human Body

Physical contact with microelectronics can cause health risks as well. With the growing number of devices worn closely to the human body, a more intensive dermal contact with the surface of these products (polymers with additives) is inevitable. Grit and effluvium can be reabsorbed or inhaled during longer periods. Due to the wide range of substances used for microelectronics the risk of allergic reactions or chronic poisoning increases. Of course, the level of risk depends on the substances used and the kind of encapsulation or other design measures taken to prevent abrasion or effluvium.

Active implants, i.e., microelectronic devices inside the human body, provide great therapeutic advantages. They can be used as a component of computer-controlled prostheses such as brain pacemakers or for artificial sense organs.

There are possible side effects of active implants that are still unexplored:

- Health reactions to substances that are dissolved from the implant surface;
- Influence on functionality and behavior of cells, which are in direct contact with the implant surface (protein adsorption or denaturation on the implant surface);
- Mechanical stress within the body tissues surrounding the implant;
- Disturbance of cell-cell interaction caused by electrical or optical activity [36];
- Effects of high local NIR exposure in very small areas within body tissue caused by active implants.

Those risks can be influenced by design engineering of implant wrapping and clinical tests. There is need for further research in this field.

As the diffusion of pervasive computing is coupled with

considerable investments, it will be very difficult to change at a later date.

Psychological Stress

Further health-relevant effects of pervasive computing can be caused indirectly by influences on user behavior and the social context encountered. In particular, pervasive computing could cause stress for various reasons, such as poor usability, disturbance and distraction, the feeling of being under surveillance (privacy issues), the possible misuse of technology for criminal purposes, as well as increased demands on individuals' productivity. Stress has a considerable impact on health.

Although there is a promising opportunity for better adaptation of pervasive computing to human needs [37], experience with established ICT shows that interfaces with poor ergonomic quality are widely accepted by consumers. There is a general trend to frequent distraction of human attention caused by technical devices. Such disturbances are likely to increase in future due to the diffusion of pervasive computing gadgets. The question is still open as to how such harassments can be effectively prevented.

Medical Applications

The most significant opportunities of pervasive computing are expected in the form of medical prevention, treatment and health care. In particular the quality of life for chronically ill or convalescent patients can be improved as their dependence on hospital facilities will be reduced by new remote methods of personal health monitoring and by active implants [38]. These medical opportunities will be accompanied by the risk that active implants might have unexpected side effects or that an "over-instrumented" medicine might have negative psychological impacts on patients subjected to close observation.

To sum up: Pervasive computing is expected to cause undesirable effects on human health that could counterbalance the opportunities in the health sector. From the viewpoint of sustainability, this suggests that the risks should be minimized by applying precautionary measures to early stages of technological development.

Social Implications

Social effects of pervasive computing have to be seen as relevant for sustainable development as ICT is expected to interact intensively with social practices, which may result in profound changes to social rules and structures in the near future. Compared to the environmental risks or direct health effects, an assessment of the socio-economic effects has to deal with even higher uncertainty because societal development trajectories are almost unpredictable.

As social and environmental effects are tightly intertwined (social practices affect the environment, and vice versa), it seems advisable not to restrict the precautionary principle to environmental regulations, but anchor it also in other parts of legislation such as, e.g., consumer regulations. In the following section, sustainability-related opportunities and risks of pervasive computing for society are illustrated.

Digital Divide

New forms of human-computer interaction can lower physical and intellectual barriers against the use of ICT and facilitate participation to the information society. That could contribute to a reduction of the digital divide separating social groups [39]. According to the vision of pervasive computing users will be relieved from technical restrictions by better usability [40]. Handicapped and sick persons will benefit from applications that lower physical barriers, or even permit access for the first time. From the present point of view it is hard to anticipate whether pervasive computing will reach a higher degree of adaptation to the human.

Consumer Freedom of Choice

At the same time there is a risk that consumer freedom about which technology to use will be limited. As ICT dominates more and more activities (such as banking, learning, and shopping), alternatives to using ICT may disappear in certain cases. Persons who do not want or are not able to use ICT for certain reasons would be practically excluded from such services. The consumer can no longer decide freely for which activities he or she will use ICT, or not.

Moreover, a loss in competition among service providers may occur if proprietary de-facto standards continue to play a significant role in the computer economy. As a result the consumer may lose the power to decide which ICT products or ICT services he uses and what price he pays. This is true in the first instance on the software level. But as real world objects become equipped with microcomputers that make them smart, the problem may extend also to physical everyday objects. Smart objects will usually operate only with proprietary software and when the user holds the rights for using it. Technologies for digital rights management may be applied not only for digital content but also for the regulation of the functionality of physical objects. Auto-identification of objects by Radio Frequency Identification (RFID) may be utilized in this way for instance. Producers may use their enhanced influence on the functionality of “smart” objects for the purpose of market separation or forcing customer loyalty. Due to the loss of market forces in a monopolized market situation, the quality of ICT products and services may decrease.

Information Overload

Access to information and knowledge will work more efficiently under pervasive computing. Access will be possible everywhere and anytime (pervasiveness), and be dependent upon one’s location and local environment (context sensitivity). That will provide better opportunities for self-determined forms of learning and participation. Users will get easy access to context-based information (city map, timetable), enabling better orientation and decision-making. Furthermore, new forms of work (mobile teleworking) will be supported.

On the other hand, the user will be flooded with information even more than by the Internet today. In contrast to present ICT, pervasive computing will surround humans almost all the time (in particular if implemented as “wearable computing”) and makes them a target for uninterrupted influence. In a market situation the user’s conscious attention will become a scarce resource that will be hard fought after by commercial advertisers. It will become more and more difficult to relax mentally by merely turning away from the information flood. Even if the user has the ability to refuse the perception of information, in every case he has to make a decision how to handle a message or stimulus first. There is a risk of general increase of disturbance and interruption caused by pervasive computing.

Privacy

Pervasive technologies also pose a problem for privacy. In particular, RFID transponders in the form of "smart labels" will probably become the first and most widespread example of pervasive computing. With "smart labels" it will be much easier to protect goods from theft or imitation. In combination with new computer-supported authentication technologies (e.g., biometrics) there is an opportunity to protect buildings and facilities better from unauthorized access.

The same technology can also be used to intrude on the privacy of people. As RFID is intended to be used for unique identification of real-world objects (e.g., items sold in supermarkets), RFID systems can also be used for tracking the owner of the item as well as for object monitoring after the point of sale [41]. Accumulation of RFID transaction data by the regular RFID owner can threaten privacy more than eavesdropping of unsecured radio-frequency interfaces by a third party. Such data collection is already under discussion with the payback cards offered to customers by retailers. "Smart labels" will aggravate this problem, as a more extensive collection of personalized data is possible and the consumer is nearly unable to control access to the data. This applies to both the data stored on the RFID chips and those in centralized databases and associated with the unique IDs of the chips. Both data privacy and location privacy will be difficult to ensure in a world pervaded by RFID transponders.

Security Issues

New forms of computer crime may emerge due to the refined networking, embedding, and pervasiveness of ICT. Security can be undermined by the susceptibility to failure of a complex technology that is not well designed. Security vulnerability of software that promotes criminal abuse has already become a major economic problem in the use of Internet. In the case of pervasive computing, ICTs not only process information, but can also control physical processes. As a consequence, failure or criminal attacks in the virtual sphere can threaten physical inviolacy of persons and infrastructure.

Opportunities and Risks

Within the context of the scenarios of the study [16] we have identified areas in which pervasive computing may both collide with or support the aim of a sustainable information society.

It is difficult to forecast the relative dominance of opportunities or risks due to the openness of the development, i.e. the highly dynamic character in technological and social development processes. It is to be expected that pervasive computing will amplify already existing trends such as growing e-waste streams, increasing power consumption for digital networks or increasing exposure to non-ionizing radiation. Pervasive computing can also generate stress for various reasons, such as poor usability, disturbance and distraction, the feeling of being under surveillance (privacy issues) or the well-founded fear of misuse of the technology for criminal purposes. Therefore pervasive computing has the potential to influence social practices and to lead to social conflicts.

What would be an adequate reaction to the risks identified by the study? In environmental policy, the precautionary principle has been established as an appropriate concept for action in face of technology caused risks to the nature and human health. In the context of sustainable development, an expansion of precautionary principle for social implications should be discussed.

To make pervasive computing sustainable, precautionary measures have to be initiated at the earliest possible time. First of all, national strategies towards sustainability, such as the Swiss Sustainable Development Strategy [42] are to be seen as a paradigm for the technological innovation process. Without a clear strategy to promote the social and ecological compatibility of new technologies, the innovation process would be purely technology-driven and might cause severe conflicts and high external costs in the future.

Application of the precautionary principle would also require more product stewardship from leading ICT producers. It is essential that development trajectories be adjusted towards sustainability before pervasive computing components become mass products because of the socioeconomic irreversibility of technology diffusion: after launch it will be difficult to correct any resulting disadvantageous effects. Adequate measures to manage product stewardship in the field of environmental aspects are eco-design, the inclusion of Life Cycle Assessment (LCA) in the decision process, and Life Cycle Costing (LCC) [43]. Furthermore the precautionary principle motivates developers and users to explore technological alternatives [44].

Foresight and monitoring activities are appropriate methods to generate early warnings about risks caused by novel technologies. Scientific minority opinions may serve as early warnings [45]. The German Advisory Council on Global Change (WBGU) even promotes broad participation by civil society in the discussion of new technologies in order to create knowledge about uncertain risks and deal with them adequately [46]. The Swiss Centre for Technology Assessment (TA-SWISS) organizes citizens' participation panels ("Public-Forum"), which is a promising approach in this context [47].

Pervasive computing becomes interesting for business and consumers when opportunities outweigh the risks – not only for the individual user, but also for society and the environment. The principle of sustainability is therefore an appropriate concept in order to achieve acceptability for this evolving technology.

Acknowledgment

This work was initiated and financed by the Swiss Centre for Technology Assessment (TA-SWISS).

The authors wish to thank Thomas Ruddy, Webster University, and Deepali-Rathin Sinha, University of St. Gallen, for revising this article.

Author Information

The authors are with the Swiss Federal Laboratories for Materials Testing and Research (EMPA), St.Gallen, Switzerland; Email addresses: Andreas.Koehler@empa.ch and Claudia.Som@empa.ch.

References

[1] F. Mattern, "Vom Handy zum allgegenwärtigen Computer - Ubiquitous Computing: Szenarien einer informatisierten Welt," in *Analysen der Friedrich-Ebert-Stiftung zur Informationsgesellschaft*. Bonn, Germany: Friedrich-Ebert-Stiftung, 2002, p. 17.
[2] G.E. Moore, "No exponential is forever: But "Forever" can be delayed! [semiconductor industry]," in *Dig. Tech. Papers IEEE Solid-State Circuits Conf. (ISSCC) 2003*, 2003, vol. 1, pp. 20-23.
[3] L.M. Hilty and T.F. Ruddy, "Towards a sustainable information society, *Informatik/Informatique*, vol. 4, pp. 2-7, 2000.
[4] L.M. Hilty and P.W. Gilgen, Eds., *Sustainability in the Information Society, Proc 15th Int. Symp. Informatics for Environmental Protection*, Zurich, Switzerland, Oct. 2001, vol. 1. Marburg: Metropolis, 2001.
[5] WCED (World Commission on Environment and Development), *Our Common Future.* Oxford, U.K.: WCED, 1987.
[6] D. Koechlin, "Das Vorsorgeprinzip im Umweltschutzgesetz, Unter besonderer Berücksichtigung der Emissions- und Immissionsgrenzwerte," *Neue Literatur zum Recht.* Basel, Switzerland: Hebling & Lichtenhahn, 1989, p. 143.
[7] H.M. Beyer, "Das Vorsorgeprinzip in der Umweltpolitik," *Schriftenreihe Wirtschafts- und Sozialwissenschaften*, vol. 10. Ludwigsburg/Berlin: Wissenschaft & Praxis, 1992.
[8] F.C. Cranor, "Learning from the law to address uncertainty in the precautionary principle," *Science and Engineering Ethics,* vol. 7, pp. 313-326, 2001.
[9] Rehbinder and Eckhard, "Das Vorsorgeprinzip im internationalen Vergleich," in *Umweltrechtliche Studien, Technik, Umwelt, Energie, Recht,* U. Battis, E. Rehbinder, G., Eds, vol. 12, 1991.
[10] C. Som, L.M. Hilty, and T.F. Ruddy, "The precautionary principle in the information society," *Human and Ecological Risk Assessment,* vol. 10, 2004.
[11] N.A. Ashford, "A conceptual framework for the use of the precautionary principle in law," in *Protecting Public Health, Implementing the Precautionary Principle,* C. Raffensperger and J.A. Tickner, Eds. Washington, DC: Island Press, 1999, pp. 198-206.
[12] D. Santillo and P. Johnston, "Is there a role for risk assessment within the Precautionary Legislation," *Human Ecol. Risk Assess.,* vol. 5, pp. 923-932, 1999.
[13] J.D. Graham, "Perspectives on the Precautionary Principle," *Human Ecol. Risk Assess.*, vol. 6, pp. 383-385, 2000.
[14] Kriebel *et al*., "The precautionary principle in environmental science," *Environmental Health Perspectives*, vol. 109, pp. 871-876, 2001.

[15] A. Stirling *et al.*, "On science and precaution in the management of technological risk," ESTO Project Rep., prepared for the European Commission – JRC Institute Prospective Technological Studies, Seville, Spain, 2001.
[16] L.M. Hilty *et al.* "Das Vorsorgeprinzip in der Informationsgesellschaft: Auswirkungen des Pervasive Computing auf Gesundheit und Umwelt," Swiss Centre for Technology Assessment (TA-SWISS), Rep. TA 46/2003, 2003.
[17] R. Hischier and I. Reichart, "Multifunctional electronic media – Traditional media - The problem of an adequate functional unit," *Int. J. LCA*, vol. 8, no. 4, pp. 201–208, 2003.
[18] L.M. Hilty *et al.*, "Assessing the human, Social and Environmental Risks of Pervasive Computing," *Human and Ecological Risk Assessment*, vol. 10, 2004.
[19] J. Goodman and V. Alakeson, "The future impact of ICT on environmental sustainability. Scenarios," commissioned by Institute for Prospective Technological Studies (IPTS), Seville, Spain, 2003, available: http://fiste.jrc.es/Pages/mobility.htm
[20] R. Sietmann, "Intel: Kein Ende für Silizium," *heise online news,* May 1, 2003*,* Available: http://www.heise.de/newsticker/meldung/36531.
[21] O. Mann, "IT-Stromfresser im PC: Komponenten im Überblick," *CHIP-online*, p. 1, Sept. 2004, available: http://www.chip.de/artikel/c_artikel_12200523.html?tid1=&tid2=
[22] R. Mösl, Computer - Notebook Stromverbrauch, Sept. 2004, available: http://notebook.pege.org/benchmarks/warten-stromverbrauch.htm.
[23] E.D. Williams *et al.,* "The 1.7 kilogram microchip, energy and material use in the production of semiconductor devices," *Environmental Science & Technology*, vol. 36, no. 24, pp. 5504 - 5510, Dec. 15. 2002.
[24] L.V. Gerstner, IBM, 2000, p.1, available: http://www-5.ibm.com/de/entwicklung/produkte/pervasive.html.
[25] B. Aebischer and A. Huser, "Vernetzung im Haushalt. Auswirkungen auf den Stromverbrauch," commissioned by Bundesamt für Energie (Swiss Federal Office of Energy), Bern, Switzerland, 2000.
[26] V. Türk, M. Ritthoff, J. Geibler, and M. von Kuhndt, "Internet: virtuell = umweltfreundlich? [Internet: virtual = environmentally sound?]," in: *Jahrbuch Ökologie*, G.Altner, B. Mettler-von Meibom, U. Simonis, and E.U. Weizsäcker von Ed., München, Germany, 2003, pp. 110-123.
[27] European Parliament, DIRECTIVE 2002/96/EC on waste electrical and electronic equipment (WEEE), 2003.
[28] A. Koehler and L. Erdmann, "Expected environmental impacts of pervasive computing," *Human and Ecological Risk Assessment*, vol. 10, 2004.
[29] P. Zoche, S. Kimpeler *et al*., *Virtuelle Mobilität: Ein Phänomen mit physischen Konsequenzen? Zur Wirkung der Nutzung von Chat, Online-Banking und Online-Reiseangeboten auf das physische Mobilitätsverhalten.* Berlin: Springer, 2002.
[30] F.J. Radermacher, "Globale Herausforderungen: Nachhaltige Entwicklung und Informationsgesellschaft," *OR News*, pp. 15-17, Aug. 1997.
[31] S. Rangosch, "Videokonferenzen als Ersatz oder Ergänzung von Geschäftsreisen," *Wirtschaftsgeografie und Raumplanung*, Universität Zürich: 223, Zürich, 1997.
[32] J. Fröhlich and N. Kuster, "Expected exposure from pervasive computing," in Hilty *et al*., Rep. TA 46/2003, Swiss Centre for Technology Assessment (TA-SWISS), 2003.
[33] R. Huber *et al.,* "Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG," *Neuroreport,* vol. 11, pp. 3321-3325, 2000.
[34] Independent Expert Group on Mobile Phones, "Mobile phones and health." *The Stewart Report*, U.K., 2000, available: http://www.iegmp.org.uk/report/text.htm
[35] F. Würtenberger and S. Behrendt, "Electromagnetic field exposure from Pervasive Computing," *Human and Ecological Risk Assessment*, vol. 10, 2004.
[36] F. A. Popp and J. Chang, "Photon sucking and the basis of biological organization," International Institute of Biophysics, Oct. 23, 1999, available: http://www.datadiwan.de/iib/ib0201e4.htm; http://www.bion.si/research/Biophotons.htm
[37] M. Weiser, "The world is not a desktop," *Interactions*, pp. 7-8, Jan. 1994.
[38] A. Grote, "Gesundheits-Check durch körpernahe Sensorik," *Heisse online*, Aug. 2001, available: http://www.heise.de/newsticker/data/jk-08.08.01-003
[39] T.F. Ruddy "A European perspective on the global digital divide," in *Proc. 15th Environmental Informatics Symposium*, Zurich, Switzerland, 2001.
[40] M. Weiser, "The computer for the 21st century," *Scientific Amer.,* vol. 265, no. 3, pp. 94-104, 1991.
[41] S.A.Weiss *et al*., "Security and privacy in radio-frequency identification devices," M.I.T., Cambridge, MA, July 2004, available: http://theory.lcs.mit.edu/~sweis
[42] Bundesrat, "Strategie Nachhaltige Entwicklung 2002," Interdepartementaler Ausschuss Rio (IDARio): 44, *Bericht des Schweizerischen Bundesrates*, Bern, Switzerland, 2002.
[43] European Commission, "Green paper on integrated product policy," COM, Brussels, 2001, p. 68.
[44] C. Raffensberger and J. Tickner, Eds., "Protecting public health and the environment: Implementing the Precautionary Principle." Washington, DC: Island Press, 1999.
[45] European Environmental Agency (EEA), "Late lessons from early warnings: The Precautionary Principle 1896-2000," Copenhagen, 2001, available: http://reports.eea.eu.int/environmental_issue_report_2001_22/en
[46] Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), *Welt im Wandel, Strategien zur Bewältigung globaler Umweltrisiken*, Berlin – Heidelberg: Springer, 1998.
[47] S. Joss and S. Bellucci, "Participatory technology assessment, European perspectives," Centre for the Study of Democracy, University Westminster and Swiss Centre for Technology Assessment, 2002.