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Smart labels in municipal solid waste — a case for the Precautionary Principle?

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Abstract

The Precautionary Principle aims at anticipating and minimizing potentially serious or irreversible risks under conditions of uncertainty. Although it has been incorporated into many international treaties and pieces of national legislation for environmental protection and sustainable development, the Precautionary Principle has rarely been applied to novel Information and Communication Technologies (ICT) and their potential environmental impacts. In this article we analyze the implications of the disposal and recycling of packaging materials containing so-called smart labels and discuss the results from the perspective of the Precautionary Principle. We argue that a broad application of smart labels bears some risk of dissipating both toxic and valuable substances, and of disrupting established recycling processes. However, these risks can be avoided by precautionary measures, mainly concerning the composition and the use of smart labels. These measures should be implemented as early as possible in order to avoid irreversible developments which are undesirable from the viewpoint of resource management and environmental protection.

Keywords: Precautionary Principle; Smart labels; RFID transponders; Recycling; Waste management; Sustainable development; Risk assessment

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1. Introduction

Novel technologies inspire in us the expectation of a better life, but simultaneously they bring about new risks. The increasing power of innovation makes it difficult to anticipate the implications of novel technologies in time (WBGU, 1998). There is "a growing tension between two aspects of science: its growing innovative powers are increasingly outrunning its capacity to anticipate the consequences" (EEA, 2001, p. 185).

This applies in particular to new applications of information and communication technologies (ICTs). Many factors have been determining the development of ICT for some decades now: the continuing miniaturization of components, the continually rising performance of processors, the availability of memory even in small places, higher telecommunication communication bandwidth and progress in materials sciences.

Against this background the term 'ubiquitous computing' has been coined, describing a vision of unobtrusive technology in which the computer as we know it today recedes into the background and smart objects communicate directly with one another.

In the area of business, the term 'pervasive computing' is used for this paradigm. It also describes the ever-present, pervasive processing and networking of information. However, "pervasive computing" emphasizes those solutions that are feasible in the near future more so than does ubiquitous computing.

The opportunities and risks of these potential ICT applications are manifold (Hilty et al., 2004, 2005; Oertel et al., 2005). This article focuses on one specific aspect, the risks related to waste treatment processes, of a forerunner technology of pervasive computing: radio frequency identification technology in the form of the so-called smart labels.

1.1. Smart labels

RFID systems (referring to Radio Frequency IDentification) comprise one important development track in the framework of ubiquitous or pervasive computing. RFID is a method of automatic identification and has been getting more and more public attention recently. An RFID system consists of two components: a transponder and a reader:

- The transponder acts as the data carrier. It is mounted on an object (for example on a product or packaging) or integrated into an object and can be read by radio technology without making contact and even updated depending on the technology. Basically the transponder consists of an integrated circuit and an RF module. An identification number and further data about the transponder itself and the object with which the transponder is connected are stored on the transponder.
- The reading device – typically called simply a reader, as it will be in the following remarks – consists of a read or read/write unit and an antenna depending on the technology used. The reader reads data from the transponder and in some case instructs the transponder to store more data. The reader also checks the quality of the data transmission. Readers are typically equipped with an additional interface (RS 232, RS 485, etc.), in order to pass on the data received to some other system (a PC, a machine control) and to process them there.

There is a broad discussion on security and privacy issues of RFID systems (Oertel et al., 2005). However, the end-of-life phase of RFID transponders and its impacts have rarely been addressed so far.

Smart labels are very thin and flexible self-adhesive tags with an integrated passive RFID transponder. Passive transponders do not need an internal energy source; they are supplied with energy by an electromagnetic field emitted by the reader during the query.

In the future, smart labels will replace or supplement barcode, Optical Character Recognition (OCR) and contact-bearing smart cards (Oertel et al., 2005). Due to the large numbers of smart labels that are expected to be produced (hundreds or thousands per capita and year), the question of how these small electronic components will be disposed of becomes relevant. In particular, potential environmental impacts of smart labels as a part of municipal solid waste should be assessed and minimized before irreversible damage occurs. We therefore investigate the end-of-life phase of smart labels from the perspective of the Precautionary Principle.

1.2. The Precautionary Principle

The Precautionary Principle (PP) provides a framework to anticipate and minimize the risks of novel technologies as well as to foster their positive potential. It aims to minimize risks that could be caused by human activities as early as possible and thus to keep a space open for future developments.

During the early stages of environmental protection, governments waited until full scientific certainty was available on risks before taking any action, an approach called prevention. Risks without complete scientific proof and long term risks were underestimated or even ignored, and as a consequence, environment and human health suffered serious consequences (Reich, 1989; EEA, 2001; Wiedemann and Brüggemann, 2001; Grundwald, 2004). Thereafter the PP gained importance in national regulations (Williamson and Hulpke, 2000; Cranor, 2004) and international treaties for environmental protection and sustainable development (Raffensperger, 1999; Sandin, 1999; EEA, 2001; Som et al., 2004). An important example is the formulation of Principle 15 of the so-called Rio declaration signed at the 1992 UN Summit on Environment and Development in Rio de Janeiro: "where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost-effective measures" (Rio Declaration on Environment and Development, 1992).

The core idea of this and many other articulations of the PP is to avoid potentially serious and irreversible damage under the condition of uncertainty (Wingspread Statement, 1998; EU, 2000; Lowell Statement, 2001; Renn et al., 2003; IDA Vorsorgeprinzip, 2003). The PP is regarded as one of the important tools needed to implement the concept of sustainability. Rausch (1985), Rehbinder (1991) and Norton (1992) recognize the sustainability concept and the PP as having the same intention: not just to delay the overexploitation of nature, but to prevent irreversible damage.

Thus, the irreversibility of an undesirable situation is an important criterion with which to assess risks qualitatively whenever a quantitative risk assessment is impossible due to uncertainty (Som et al., 2004).

This article assesses potential impacts of smart labels on municipal solid waste recycling and disposal with regard to implications for natural resources and environmental pollution. The uncertainty we face in this field can mainly be attributed to the difficulty of predicting technological and societal developments: we do not yet know whether the smart labels applied in a few years will still contain the same substances as today, nor can we predict which types of products and product packaging will be tagged with smart labels.

Viewed from the perspective of the PP, it seems nevertheless necessary to look for potential damage caused by the diffusion of smart labels on consumer products, and to qualify potential risks in terms of the irreversibility criterion. This makes it possible to find precautionary measures which can be applied to minimize risks at an early stage of development.

2. Small electronic components in non-electronic waste streams

In most industrialized countries, end-of-life electronic equipment is processed separately from other waste streams, which is both

- *necessary* because electronics typically contain hazardous and valuable materials and
- *possible* because most electronic appliances today are large enough to make them relatively easy to separate from other types of household waste.

However, as microelectronic components such as smart labels become increasingly embedded in commonly used non-ICT objects, it may become both ecologically and economically unfeasible to separate these embedded components for special treatment. Smart labels might even become the first application of ICT that is no longer recognized as "ICT" by most of its users.

The hope that the continued miniaturization of electronics, according to the so-called Moore's Law and related technological trends, will solve the problem in the long run is not supported by past experience. The miniaturization of devices is usually counteracted by the growing numbers of devices produced. For instance, the considerable reduction in the average physical mass of a mobile phone from over 350 g (1990) to about 80 g (2005), which corresponds to a reduction by a factor of 4.4, was accompanied by an increase in the number of subscribers, which in turn lead to a rise of the total mass flow by a factor of 8.0 (data for Switzerland, Hilty et al., 2005). In every case of miniaturization in digital electronics thus far the price per functional unit has always fallen and triggered greater demand, which compensates – or even over-compensates – for the miniaturization effect in terms of mass flow.

For small microelectronic components embedded in or attached to consumer packagings and products, the question arises as to whether their occurrence in traditionally non-electronic waste streams will be associated with mid- or long-term risks regarding resource management or pollution issues, calling for precautionary measures. In order to provide initial answers from the perspective of the Precautionary Principle, we present a case study based on the expected diffusion of smart labels introduced for item-level tracking in the retail sector in Switzerland.

3. Expected impacts of smart label diffusion on municipal solid waste processing: a case study from Switzerland

We have carried out a prospective study on the smart label diffusion in the Swiss retail sector and assessed the impacts on disposal and recycling processes at the level of chemical elements (Kräuchi et al., 2005). In the present paper, we refer to the results of that study. Methodology and results are summarized as far as they are relevant for the evaluation of the impacts from the perspective of the Precautionary Principle.

We focus on the first-order effects of smart labels, i.e. the effects of the physical existence of the labels, and do not consider potential second- and third-order effects in this article (for this classification of environmental effects see e.g. Köhler and Erdmann, 2004). In particular, we do not rule out that some future applications of smart labels may have positive effects on material efficiency and waste management, i.e. second-order effects that would counteract the negative first-order effects described here.

3.1. Methodology

In order to identify the impacts on disposal and recycling systems in Switzerland, the quantities of smart labels from the retail sector expected to reach waste streams in municipal solid waste incineration (MSWI) and waste streams in recycling processes were estimated. The following waste streams destined for recycling were identified as relevant for smart labels from the retail sector:

- aluminium cans, aluminium tubes and aluminium pet food containers;
- paper and cardboard packaging material;
- container glass;
- PET bottles;
- tin cans.

The quantities were estimated for the period between 2002 and 2012 based on market analysis data and waste statistics

(1) for a “conservative” scenario consisting of the application of smart labels to selected types of food packaging and (a negligible number of) durable goods, and
(2) for a “high-tech” scenario representing a full implementation of smart labels in the retail sector in the place of outdated bar code.

From the estimated smart label quantities, the element flows of aluminium, copper and silicon into disposal and recycling processes were calculated using information and data from expert interviews and smart label composition analysis.

Based on the calculated element flows, the first-order effects of smart labels on disposal and recycling processes, i.e. effects resulting from the physical existence of the smart labels, were identified. Second-order effects induced by the application of smart labels, e.g. for reducing losses in the supply chain or for the optimization of waste identification and sorting, were not taken into consideration.

The first-order effects were identified based on published data about recycling and disposal processes and interviews with experts in the field of recycling technology. Although the findings refer to the Swiss waste management system, they should be transferable to other countries with modern, industrial waste management systems.

3.2. Material and element flows

Smart labels on packaging materials from the retail sector will either enter disposal processes for municipal solid waste or existing recycling systems for packaging materials. Separate recycling of smart labels will hardly be an option: in the retail sector, low mass smart labels bundled with packaging materials will be highly dispersed. As a consequence, the costs, the resource consumption and the emissions induced by their separate collection and recycling would be immensely high. In addition to this, recycling of smart labels would be hampered by the high number of different materials and their amalgamation in a small volume. The recycling of smart labels separated in conditioning processes prior to recycling of the packaging materials, however, would be conceivable.

The entire market for food and non-food products for the Swiss retail sector can be estimated to have been approximately 17,000 million (17 billion) items in 2003 (Kräuchi et al., 2005). By far the most of these items are perishables. We therefore assume that the number of durable items contained in this totality can be neglected. In the conservative scenario, we assumed that only the food products with high requirements on food safety are tagged with smart labels (dairy, meat, fish and poultry) in 2012. However, due to the low quantity of *recyclable* packaging materials from this product group compared to other product categories in the retail sector, the input of this type of packagings into recycling processes has been neglected in both scenarios. Thus, approximately 4000 million smart labels from dairy, meat, fish and poultry packagings would enter the MSWI plants in the conservative scenario.

In the high-tech scenario we assumed that all products in the retail sector are tagged with smart labels. For simplification we assume that the recycling rate will not increase significantly in Switzerland for the waste streams investigated and the market volume in the retail sector remains stagnating. Thus, approximately 2672 million smart labels of the total estimated number of 17,000 million smart labels applied would enter the recycling processes for packaging materials. A remaining part of 14,328 million smart labels would potentially enter the MSWI in the high-tech scenario (Fig. 1; Kräuchi et al., 2005).

The element flows into the waste management processes have been quantified using composition data of a sample label. The sample label analyzed at Empa consists of a paper substrate with an aluminium antenna mounted on it. On the antenna an adhesive layer is applied. The entire tag surveyed has a weight of 790 mg. The antenna mass is 330 mg and the silicon chip has a mass of 2 mg. Figs. 2 and 3 show the aluminium and silicon flows into MSWI and into recycling processes.

In view of a discussion of the copper flows, the copper amount in smart labels with copper antennas has been calculated on the basis of the sample analyzed at Empa. The

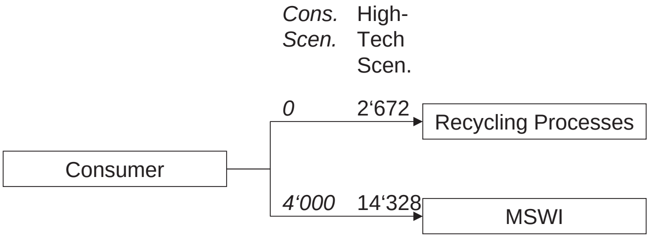

Fig. 1. Flows of smart labels into recycling processes and municipal solid waste incineration (MSWI) in both scenarios (conservative and high-tech). The figures are given in millions of pieces per year.

underlying assumption was that the dimensions of the copper antenna would not differ from those of the aluminium antenna. Under consideration of a density ratio of 3.3 between copper and aluminium, the share of copper in smart label was estimated to amount to roughly 1 g.

3.3. Impacts on disposal processes

To evaluate the significance of the smart label import into municipal solid waste incineration, the changes in aluminium and copper concentrations of municipal solid waste have been estimated. Silicon and combustible organic parts of smart labels (paper and plastics substrate) pose no problems when incinerated.

According to these estimates, smart labels from packaging materials would raise the actual concentrations of aluminium in municipal solid waste from 14 g/kg (SAEFL, 2003) up to 15.8 g/kg for the high-tech scenario, which corresponds to an increase of 13%. In

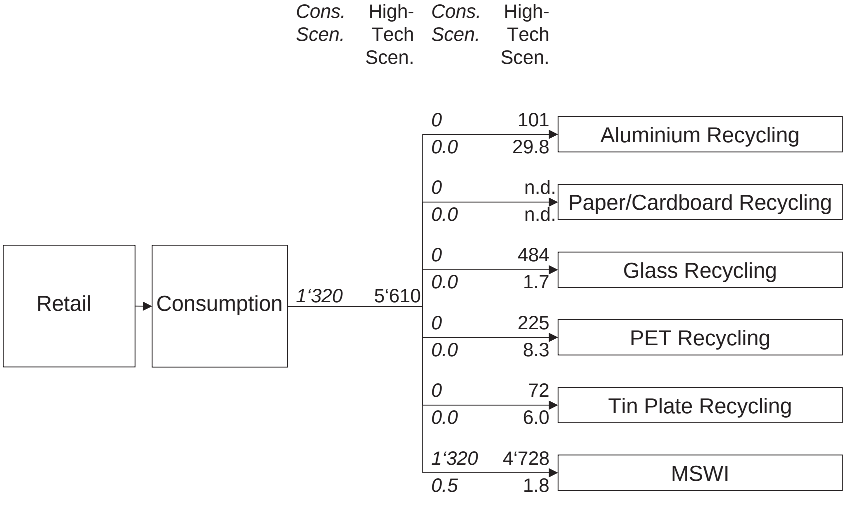

Fig. 2. Aluminium flows into recycling processes and municipal solid waste incineration (MSWI) induced by smart labels in both scenarios (conservative and high-tech). The figures above the arrows are given in tons per year [t/a], the figures below are given in grams of aluminium per kilogram input material [g/kg].

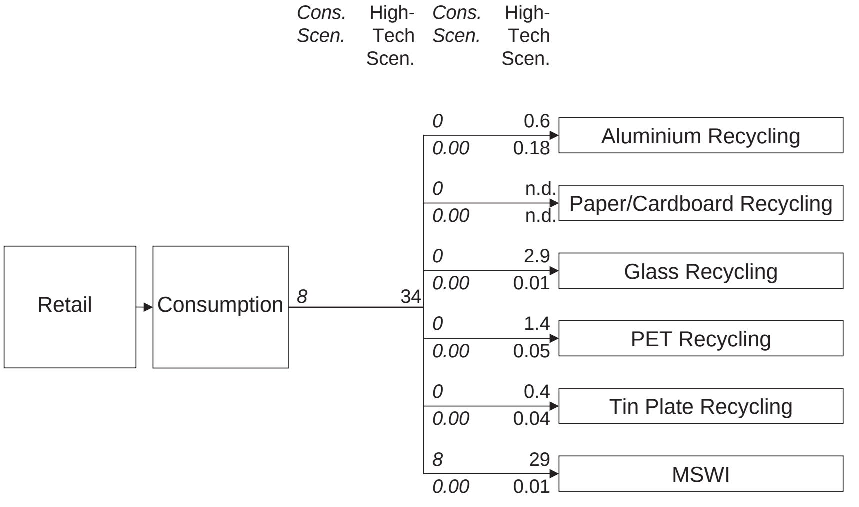

Fig. 3. Silicon flows into recycling processes and municipal solid waste incineration (MSWI) induced by smart labels in both scenarios (conservative and high-tech). The figures above the arrows are given in tons per year [t/a], the figures below are given in grams of silicon per kilogram input material [g/kg].

case smart labels with copper antennas are still used by 2012, the concentrations of copper in municipal solid waste would rise from currently 1.13 g/kg (SAEFL, 2003) up to 6.6 g/kg, which is an increase by almost a factor of 6.

A smaller increase in the aluminium and copper concentrations can also be seen in the conservative scenario. Whereas here the aluminium concentrations would only rise slightly, i.e. by about 4% to 14.5 g/kg, the copper concentration would more than double to 2.65 g/kg. However, it has to be considered that our assumption of 1 g of copper per smart label might be too high as, firstly, we did not consider the different functional properties of copper antennas compared to aluminium antennas in our above estimation of the copper content in smart labels (Section 3.2). Secondly, not every smart label would contain a copper antenna. Hence, our estimations of the copper concentrations in municipal solid waste reflect a worst case.

In MSWI plants, more than 90% of the aluminium and copper in the waste input is transferred to the slag (Baccini and Bader, 1996; Pilz et al., 2003), which in Switzerland is then landfilled. Long term emissions of aluminium and copper from landfilled slag may cause distinct impacts on terrestrial and aquatic ecosystems. However, there are still large uncertainties concerning the leaching mechanisms in landfills and open questions regarding adequate methodologies to assess future impacts (Hellweg et al., 2005).

Another effect to be considered is the formation of polychlorinated dibenzo-*p*-dioxins (PCDD) and -furans (PCDF) during municipal solid waste incineration, which is facilitated by the presence of copper as a catalyst. Without counter-measures such as flue-glass cleaning, increasing copper concentrations in municipal solid waste will lead to increased emissions of highly toxic dioxins and furans (SAEFL, 2004).

3.4. Impacts on recycling processes

The discussion of the impacts on recycling processes only refers to the high-tech scenario, as in the conservative scenario there are no relevant mass flows into recycling processes induced by smart labels.

3.4.1. Aluminium recycling

In Switzerland, used aluminium cans, aluminium tubes and aluminium pet food containers are collected at collection points distributed all over the country — aluminium cans in special can compactors, tubes and pet food containers often together with tin cans and steel panel covers in dumpsters. The collected aluminium scrap is transferred to regional conditioning facilities, where it is separated from other materials such as tin cans by magnetic separation, eddy current or flotation processes.

Depending on the separation process, smart labels will either be sorted out and subsequently incinerated in an MSWI plant or transferred to a specific recycling process, or they will enter the aluminium manufacturing process. In case they enter the manufacturing process, the organic parts of smart labels (adhesive plus paper or plastics substrate) will be transferred into the smelter together with the inorganic parts of the smart label (copper or aluminium antenna, silicon chip), unless they are separated in an upstream pyrolysis device. According to Willbold (2004), plastic negatively affects the smelting process.

Copper, zinc, silicon and some other elements, on the other hand, may have either positive or negative effects, depending on the alloy produced and its intended application. For the most common casting alloy 226, for example, a certain amount of copper and zinc is needed; in the production of aluminium for packaging foils, however, the same impurities are not tolerable (N.N., 2002; Willbold, 2004). According to Köhler and Erdmann (2004), the amounts of impurities in aluminium are typically on the magnitude of 0.001% to 5%. According to Koch (2004), copper amounts of up to 4% are tolerable, depending on the alloy.

3.4.2. Paper recycling

In Switzerland, used paper is collected by kerbside collection. For further processing, the collected paper is transferred to paper manufacturing companies. With the current processes in Switzerland, smart labels will enter the paper manufacturing process. In the pulper, smart labels with a silicon or polymer substrate will be removed from the paper, whereas smart labels with a paper substrate will be dissolved and their components, e.g. the aluminium or copper antenna, will be set free.

Colloidal and water soluble adhesives, very small plastics scrap and metal parts (with a maximum dimension on the order of 1 mm) will pass through the filter system and degrade paper quality. Non-soluble adhesives and plastics parts retained might congest the filtering system if critical loads are exceeded. For the smart labels' plastic substrate this critical load has been estimated to be roughly 1% of paper mass, but this value needs to be confirmed through further research (Gerber, 2004).

If only packaging materials are considered, it is expected that the critical load for plastics will be reached or exceeded. However, in practice the packaging materials will be mixed with e.g. newspapers and office documents, which could reduce the average mass share of smart labels considerably, unless they are also tagged with smart labels.

Smart labels' antenna entry might be more problematic if the antenna detaches from its support. In order to better understand this aspect, on-site experiments in recycling plants will have to be performed. In case they show any negative impact on paper manufacturing, smart labels might have to be sorted out before entering the process, which in turn would increase the recycling costs for paper and cardboard (STAR, 2004).

3.4.3. Glass recycling

In Switzerland, used glass is collected in about 12,000 glass containers located at collection points distributed all over the country. From the collection points, the glass is transferred to intermediate storage sites and from there to a central glass recycling plant in Switzerland.

It can be inferred from experience with conventional paper labels that a significant share of smart labels will enter the smelting process. There, the organic parts of the smart labels (paper or plastics substrate) will be burnt without causing any further problem.

The import of aluminium or copper from the smart labels' antennas, on the other hand, could lead to discolorations (copper) or to material defects by inclusion (aluminium) in new glass items (Stieglitz, 2004). For the case of aluminium antennas, assuming that 50% of the smart labels will enter the smelting process, the German limit of 5 g/t for non-ferrous metals allowed in glass (BVSE, 2004) would be exceeded by more than a factor of 150. If the smart labels were equipped with copper antennas, similar violations would result.

As a consequence, smart labels would have to be removed from the glass items prior to the melting process. This in turn would require major changes in the conditioning process preceding the smelting process. However, it seems likely that there will be feasible and efficient technical solutions, because – as opposed to paper and cardboard recycling – high temperatures can be used in glass treatment.

3.4.4. PET recycling

After collection and sorting, PET bottles are crushed to flakes and then recycled to bottles. With the current conditioning processes in Switzerland, smart labels will be separated from the PET bottles together with conventional paper labels by application of vapour. The separated labels will either be incinerated in an MSWI plant or transferred to a specific recycling process.

For low-tech processes where smart labels are not separated prior to the recycling process problems are expected for polymer-based smart label substrates, for antennas as well as for the solder used to join the chip with the antenna: The polymer might cause material inconsistencies, and the solder could e.g. set lead free during the smelting process. The latter would become critical if the maximum metal content of 100 ppm admitted by the EU packaging directive were exceeded (EU, 1994; Köhler and Erdmann, 2004).

3.4.5. Tin plate recycling

In Switzerland, used tin cans and steel plate covers are collected together with aluminium in more than 4000 dumpsters located at collection points distributed all over the country. The consumers are urged to remove the paper labels from the cans prior to throwing them into the containers (Ferro Recycling, 2005).

From the collection points the containers are transferred to regional conditioning facilities, where the steel plate is separated from the aluminium. The steel plate fraction is then transferred to a blast furnace.

With the current collection and conditioning processes, smart labels on tin cans either will be sorted out prior to the steel manufacturing process and incinerated in an MSWI plant, or they will enter the blast furnace. In case they enter the blast furnace, their organic parts (adhesives, paper and polymer) will be completely burnt and will not pose any problem. The latter is also true for aluminium and silicon, which is transferred into the slag (Köhler and Erdmann, 2004).

Chlorine, zinc, lead and non-ferrous metals such as copper, chromium, nickel and vanadium, on the other hand, will either negatively affect the process or accumulate in the crude steel, from which they cannot be removed, or only to a limited extent (Buchwalder et al., 2003). This is the reason why in steel plate scrap, the amounts of copper and the sum of chromium, molybdenum and nickel have been limited to 0.15% and 0.10%, respectively (Swiss Steel, 2004). If smart labels with copper antennas were still used by 2012, their maximum share should not exceed 8% in order to comply with the limit value for copper in steel plate. This estimate is based on the assumption that every recycled tin can is tagged with a smart label (high-tech scenario) and every smart label contains 1 g of copper. The inherent copper content of tin cans, which amounts to 0.02% according to SAEFL (1998), has not been considered.

3.4.6. Synopsis of impacts

From the above discussion of the impacts on recycling processes, two aspects emerge which seem to be particularly relevant for an evaluation from a precautionary perspective: First, the negative impacts on the quantity and quality of secondary raw materials generated by the recycling process, and, second, the economic and ecological costs of counter-measures.

In Table 1, the impacts of smart labels on recycling processes are summarized with respect to these two aspects. The rough estimates given in Table 1 refer to the high-tech scenario. For the conservative scenario, there are no negative impacts on secondary raw material availability, as all smart labels provided in this scenario are incinerated in the MSWI plant and do not enter recycling processes.

Table 1
Impacts of smart label diffusion in the retail sector on recycling processes (high-tech scenario)

	Negative impacts on secondary material output		Cost of counter-measures (improved recycling processes)
	Quantity	Quality	
Aluminium recycling	low	medium	medium
Paper recycling	medium	medium	medium to high
Container glass recycling	low	medium to high	medium
PET bottle recycling	low	low	–
Tin plate recycling	low	low to medium	medium

With regard to the *quantity* of the secondary raw materials generated in the recycling processes, the impacts range from low to medium:

- For aluminium recycling, container glass recycling, PET bottle recycling and tin plate recycling no significant decrease in the output is expected.
- The paper output in paper recycling might be significantly reduced by congestion of the filtering system and paper tearing.

The latter presumption has to be confirmed by further research.

The impacts on the *quality* of the secondary raw materials range from low to high:

- No measurable effect is expected for PET bottle recycling, where the smart labels are separated prior to processing, together with the conventional paper labels.
- Negative impacts on the quality of the recycling process output are expected for paper recycling and for aluminium and tin plate recycling, if smart labels with copper antennas are still used by 2012.
- Significant negative impacts are expected for container glass recycling, where the import of aluminium or copper could lead to discolorations or to material defects by inclusion.

The costs of implementing technical counter-measures vary widely. We define "medium" costs as those permitting operation covering costs after the necessary capital expenditures have been made (under conditions otherwise kept the same), including the cost of capital. On the other hand, "high" costs are defined as ones making recycling prohibitively expensive:

- For PET bottle recycling, where no significant impacts on the output of secondary raw materials are expected, we assume that no counter-measures are necessary and the costs are zero.
- For aluminium recycling, container glass recycling and tin plate recycling, established technical pre-separation measures should be sufficient to avoid negative impacts on secondary raw materials (medium costs).
- For paper recycling, disturbing foreign matter has to be pre-separated manually or innovative changes in the main processes will be necessary, which both cause high costs. Even today in industrial environments, manual pre-separation is practiced to eliminate some foreign matter in paper waste.

We can conclude that smart labels could compromise, in the first instance, established paper recycling systems, if the tagging of paper packaging and printed matter becomes prevalent.

4. Discussion of the results from the perspective of the Precautionary Principle

The above impacts of smart labels are not known in exact quantitative terms. We have estimated the mass flows expected and the possible paths that the labels and their contents could take during their life cycle (Fig. 4). The resulting uncertainty as to the actual quantities of emitted hazardous substances or dissipated rare materials makes this example a case for the Precautionary Principle.

That means in the first instance that we must focus on the irreversible impacts and look for possible ways to avoid them. Whether the precautionary minimization of the mid- and long-term risks identified only imprecisely outweighs the possible disadvantages associated with these measures is a decision that ultimately has to be taken politically, and thus one outside the subject of our article.

We distinguish between two types of irreversibility:

- Physical irreversibility, which is connected to the second law of thermodynamics (entropy law).
- Socio-economic irreversibility, which is connected to the practical difficulty of reversing societal developments, i.e. to do without a technology after huge investments have been made by many people and they have adapted their behaviour to the availability of the technology.

An example of a socio-economically irreversible development is the popularization of the car in the 20th century. The propagation of a widely used technology is reversible in theory, but irreversible in practice. Once a technology has been propagated, the costs to the national economy of adjusting the course of the trend would be very high, if the legal

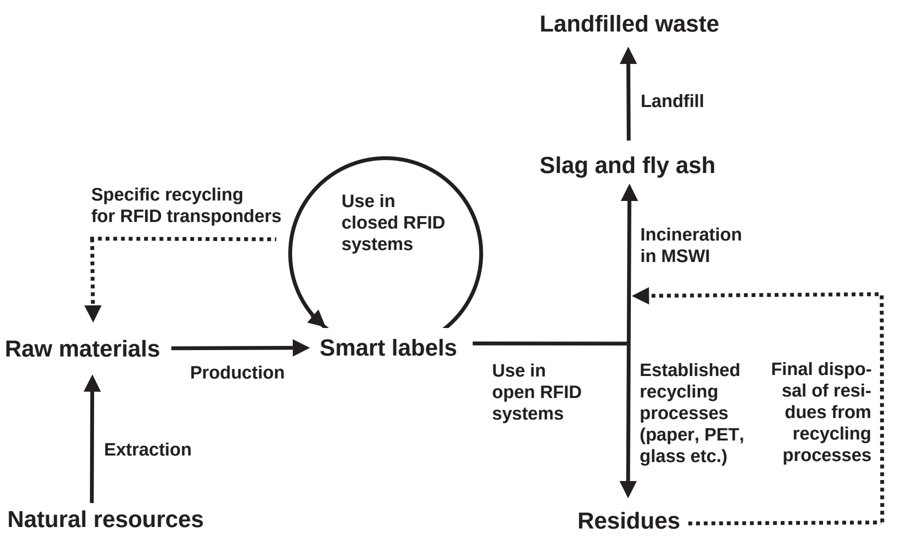

Fig. 4. Possible paths of the material content of smart labels. Closed RFID systems are systems where transponders (such as smart labels) are only used to tag objects that remain in the system for a long time (such as reusable containers). Smart labels used in open RFID systems will find their way either to municipal solid waste incinerators (MSWI) or to established recycling systems for packaging, where they become part of the residues. The residues are then incinerated, too. After incineration, most of the material content of the smart labels is found in the slag or in the fly ash from the MSWI, which are ultimately landfilled.

requirements for such an adjustment are satisfied at all. This should also be taken into account for the trend towards pervasive computing (Hilty et al., 2005).

4.1. Physical irreversibility

The spread of the substances contained in smart labels which are part of an open RFID system is physically irreversible, since the amount of natural resources that would be necessary to collect these labels after they have left the system and recycle their materials would be higher than the resources recovered by this process. According to our scenarios, all paths that the labels – or the main part of their materials – take finally end up in landfill (via incineration). A specific recycling process for the smart labels that would recover the materials has been assumed to be unrealistic (dotted line in the left part of Fig. 4).

The dissipation of substances is problematical only if they are either toxic or valuable. With regard to the first aspect (toxicity), there is a high uncertainty in the case of smart labels because long-term emissions of landfilled non-ferrous metals to soil are discussed controversially. However, the dissipation of copper or aluminium should also be avoided because of the value of these metals, which have been extracted from nature at considerable ecological and economic expense. Their "ecological Rucksack" is usually not fully accounted for by their market prices because of the externalities of extraction, processing and transport. However, despite of these externalities, metal prices are increasing and metal scrap is sought after on the world market, which shows that the scarcity of these resources is recognized today.

It follows that there are three basic precautionary measures to avoid the dissipation of toxic or valuable materials:

- Closed systems: use smart labels in closed RFID systems wherever possible. Closed RFID systems are systems where transponders are only used to tag objects that are used in the system for a long time, such as reusable containers. Only those labels which unintentionally drop out of the system will be disposed of in an uncontrolled way, which can be assumed to be irrelevant in terms of mass flow. Furthermore, when the whole RFID system is to be scrapped e.g. due to a technological renewal, it will be feasible to feed the old labels into a specific recycling process which recovers the metals.
- No tagging of perishables: if smart labels are only used to tag objects which have a longer service life than e.g. food products, the mass flow resulting from our high-tech scenario would be reduced dramatically. Although the labels used to tag non-perishable goods would still be part of an open system and, therefore, separate collection for specific recycling would still be unfeasible, their potential impact would be decreased due to the smaller throughput of the system.
- Ecodesign: avoid the use of both toxic and valuable materials in smart labels. Polymer electronics would be a promising candidate for future smart labels. However it is unlikely that one will be able to do without metal for the antenna. An alternative is to use much higher frequencies than today, which would make it possible to use smaller antennas. On the other hand, the worst thing to do would be to use active transponders

in open systems, because the batteries needed in these transponders, however small they might be, would be another major source of toxic substances.

- Selecting adapted materials: adapting the materials used in the tags to the materials and the designated recycling and disposal paths of the tagged object. For example, it is highly preferable to use tags with aluminium antennas to tag aluminium objects (as opposed to copper antennas).

Each single measure could be sufficient to avoid a significant irreversible dissipation of toxic or valuable materials by the use of this technology. However, implementing only the third measure (ecodesign) could induce the risk of a rebound effect. Smart labels containing less valuable materials would be cheaper and therefore used in much greater numbers, which could compensate for the improvements achieved at the level of the single label. As long as they still contain some amount of non-ferrous metals, the total impact might not be reduced by ecodesign. We therefore recommend using the proposed measures in combination.

4.2. Socio-economic irreversibility

Investments in RFID systems are often justified with the argument that this will create a new type of infrastructure: an infrastructure for synchronizing the virtual world (the world of data) with the real world (the world of physical objects). If this infrastructure becomes ubiquitous, people will adapt their behaviours, taking the services provided by that infrastructure for granted. Most people will also make smaller or bigger investments in complementary products that make use of the infrastructure. Society as a whole will become increasingly dependent on the availability of RFID systems.

For this reason, the broad application of RFID labels might be a significant step toward a situation which is socio-economically irreversible. If this situation has effects we usually consider undesirable, we should try to minimize these effects in a sustainable way or avoid entering the irreversible situation at all.

In Section 4.1 above we have discussed such an undesirable effect: the dissipation of toxic or valuable materials, which is in itself irreversible for physical reasons. To depict a worst-case scenario, we could find ourselves in a situation in which we depend on a technology that forces us to irreversibly dissipate rare materials. We would be unable to stop this dissipation even if and when the scarcity of the materials becomes critical and prices increase dramatically.

A second undesirable effect of a socio-economically irreversible adoption of RFID technology could be its impact on established recycling systems. We will elaborate on this aspect in the light of the estimates presented in Section 3 above.

Based on the assumptions underlying our high-tech scenario, we have shown how the use of smart labels on packaging could affect established recycling processes for aluminium, paper and cardboard, container glass, PET bottles and tin cans.

As can be deduced from Table 1, only the impact on paper and cardboard recycling must be considered as a potential threat. Extensive use of smart labels to tag paper packaging, newspapers and other paper or cardboard products could make existing recycling systems so inefficient that they would become prohibitively expensive. Although it would be possible to stop this type of application of smart labels later and re-establish the paper and cardboard recycling systems, this is unlikely to happen, once infrastructure and habits are adapted to contactless data carriers on paper documents and packages. There could be a huge market for complementary products such as devices for document management based on RFID readers.

Although there is some uncertainty concerning the impact on paper recycling processes, from the perspective of the Precautionary Principle it seems advisable to minimize the risk of compromising the established recycling systems. By stating this, we are presupposing that industrial societies have 'good reasons' to do paper and cardboard recycling.[1] Based on this assumption, we propose the following precautionary measures:

- No tagging of extremely short-lived paper products: if smart labels are only used to tag paper or cardboard products which have been used for weeks or months when disposed of (such as books or office documents) instead of hours or days (such as newspapers), the mass flow resulting from our high-tech scenario would be dramatically reduced and no threat would occur for the paper recycling systems. This measure is a special case of the second measure mentioned in Section 4.1 above, but is proposed here for a different reason, namely the protection of an established recycling system.
- It might have a mitigating effect to use *polymer* substrates for smart labels and not *paper* substrates (which would be the case e.g. if the label should be invisibly integrated in a paper product) from the perspective of paper recycling, because a polymer label is not resolved in the pulper. This would keep small parts from passing through the filter systems.

It is not clear from the present perspective whether the second measure alone would be sufficient to avoid the risk of compromising established paper and cardboard recycling systems by the extensive use of smart labels on paper products.

Our assessment of the impacts of smart labels on established recycling systems is valid for smart labels of today's size, as they were taken as a basis by Kräuchi et al. (2005). In case a considerable miniaturization becomes possible in the future, the negative impacts on recycling processes could increase, because smaller components are more difficult to separate and tend to pass through filter systems. The estimates presented in Section 3 and their implications would then have to be reconsidered. This aspect should also be taken into account when measures for ecodesign are concretized.

Finally, we want to recommend to expand the perspective to cover other auto-identification technologies as well besides RFID, both existing and emerging technologies, in order to find ecologically sustainable solutions. Seen from the viewpoint of a few years from now, a perspective focusing on RFID technology for auto-identification might appear unnecessarily narrow. A systematic assessment of alternatives, a generic precautionary measure proposed by Tickner and Geiser (2004), could help to find alternatives that might be interesting in both environmental and economic terms.

[1] This assumption might well be questioned in countries where the electricity mix used for the recycling processes contains a high share of fossil energy. In Switzerland, the share of fossil energy in the electricity mix is lower than 2.7% (BfE, 2004), so that paper recycling pays off in ecological terms (Reichart et al., 2002).

5. Conclusion and outlook

We have analyzed the potential impacts of the broad application of RFID labels in the waste area. There are two potential impacts emanating from the end-of-life phase of smart labels that are in conflict with the usual goals of waste management:

- dissipation of toxic and/or valuable substances
- potential disruption of established recycling systems

These impacts can be avoided if a number of measures are taken in a suitable combination. These measures are not only *feasible* but also *indicated* from the standpoint of the Precautionary Principle because irreversible developments are otherwise to be expected: firstly, establishing smart labels as a new type of infrastructure may become socio-economically irreversible, and secondly dissipation of the substances contained in them is irreversible for physical reasons.

The measures we propose are aimed mainly at the composition of the smart labels and at reducing the quantity of smart labels, in that one does not use them to tag objects with extremely short lives. Specific recycling processes for smart labels are *not* considered feasible, except in the case of closed RFID systems when the whole system is to be scrapped.

One important additional measure is the continuing observation and prospective analysis of the impacts in order to reduce the uncertainty still present in the impact assessment, as well as seeking for alternatives that may emerge from the rapid technological progress.

To the degree that one is successful in avoiding the risks early on, the opportunities that smart labels hold for waste management – or for resource management more generally – can actually be used. The opportunities lie primarily in the affinity of smart labels to a closed loop economy, consisting e.g. in a more efficient, electronic identification of recyclable materials (e.g. plastics), which in turn would support increasing recycling quotes.

Smart labels create no disposal problems as long as they are used in closed RFID systems, which means that they circulate in closed loops. Furthermore, they can facilitate guiding the *objects* to which they are attached into closed loops. A great opportunity lies in this insight which deserves to be considered in the future: reusable packaging systems and the re-use of products and parts could then experience a renaissance on a higher level of sophistication, enabled by RFID. This shows that we only have treated one aspect of RFID tags and waste management in this article, namely the first-order effects of smart labels. Including the second- and third-order effects, it seems worth considering that a symbiosis between RFID systems and closed loop logistics could emerge. It is an open question if this symbiosis could then outweigh their negative impacts both economically and ecologically.

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References

Baccini P, Bader HP. Regionaler Stoffhaushalt. Heidelberg: Spektrum Akademischer Verlag; 1996.

BfE. Schweizerische Elektrizitätsstatistik 2003. Ittigen: Bundesamt für Energie; 2004.

Buchwalder J, Grosspietsch K-H, Hartig W, Janz J, Lüngen HB, Schmöle P. Anforderungen an Reststoffe für das Einblasen in den Hochofen. Stahl und Eisen 2003;123(1):29–37.

BVSE. Sekundärrohstoffe: Altglas; 2004. Available at: www.bvse.de/home.html; accessed April 21, 2005.

Cranor CF. Toward understanding aspects of the Precautionary Principle. J Med Philos 2004;29(3):259–79.

EEA. Late lessons from early warnings: the Precautionary Principle 1896–2000. Copenhagen: EEA; 2001. [January 10, 2002, available at: http://reports.eea.eu.int/environmental_issue_report_2001_22/en; accessed April 21, 2005].

EU. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, 31994L0062, 1994. Available at: http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber & lg=en & type_doc=Directive & an_doc=1994 & nu_doc=62; accessed April 21, 2005.

EU. Communication from the Commission on the Precautionary Principle. COM/2000/0001 final, Brussels, February 2, 2000, available at: http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber & lg=en & type_doc=COMfinal & an_doc=2000 & nu_doc=1; accessed April 21, 2005.

Ferro Recycling. Richtiges Entsorgen: Was passiert mit der leeren Dose? available at: http://www.ferrorecycling.ch/deu/kreislauf/richtigesEntsorgen.php; accessed April 21, 2005.

Gerber K. Papierfabrik Utzenstorf. Private communication; September 2004.

Grundwald A. The case of nanobiotechnology. EMBO Rep 2004;5:32–6.

Hellweg S, Hofstetter TB, Hungerbühler K. Time-dependent life-cycle assessment of slag landfills with the help of scenario-analysis: the example of Cd and Cu. J Clean Prod 2005;13:301–20.

Hilty LM, Som C, Köhler A. Assessing the human, social, and environmental risks of pervasive computing. Hum Ecol Risk Assess 2004;10(5):853–74.

Hilty LM, Behrendt S, Binswanger M, Bruinink A, Erdmann L, Froehlich J, et al. The Precautionary Principle in the Information Society — Effects of Pervasive Computing on Health and Environment. Second Revised Edition. Edited by the Swiss Center for Technology Assessment (TA-SWISS), Bern, Switzerland (TA46e/2005) and the Scientific Technology Options Assessment at the European Parliament (STOA 125 EN). Available at: www.ta-swiss.ch; accessed April 18, 2005; 2005.

IDA Vorsorgeprinzip. Das Vorsorgeprinzip aus schweizerischer und internationaler Sicht. Synthesepapier der interdepartementalen Arbeitsgruppe "Vorsorgeprinzip"; 2003. August.

Koch H. Aluminium Rheinfelden. Private communication; September 2004.

Köhler A, Erdmann L. Expected environmental impacts of pervasive computing. Hum Ecol Risk Assess 2004;10:831–52.

Kräuchi P, Wäger PA, Eugster M, Grossmann G, Hilty L. End-of-life impacts of pervasive computing. IEEE Technol Soc Mag 2005;24(1):45–53.

Lowell Statement. http://www.biotech-info.net/final_statement.html; March 2004; 2001.

NN. Aluminium - zum recycling besonders geeignet. Recycl-Mag 2002;17:1–6.

Norton BG. Sustainability, human welfare and ecosystem health. Environ Values 1992;1:97–112.

Oertel B, Wölk M, Hilty LM, Köhler A. Risks and opportunities of the use of RFID systems Bonn: Bundesamt für Sicherheit in der Informationstechnik. Available at: www.bsi de; 2005.

Pilz H, Kletzer E, Neubacher F. Beitrag der Abfallwirtschaft zum Aluminiumhaushalt Österreichs, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien, December 2003, available at: www.umweltnet.at/filemanager/download/9394/; accessed April 21, 2005; 2003.

Raffensperger C. Uses of the Precautionary Principle in International Treaties and Agreements, October 1999, available at: www.biotech-info.net/treaties_and_agreements.html; accessed April 21, 2005; 1999.

Rausch H. Kommentar zum Umweltschutzgesetz. Zürich: Schulthess Polygraphischer Verlag; 1985.

Rehbinder E. Das Vorsorgeprinzip im internationalen Vergleich. Umweltrechtliche Studien Band 12, Technik und Umwelt, Energie, Recht, Hrsg. Battis U., Rehbinder E., W. Gerd, Werner Verlag GmbH, Düsseldorf; 1991.

Reich A. Gefahr-Risiko-Restrisiko; das Vorsorgeprinzip am Beispiel des Immissionsschutzrechts. Umweltrechtliche Studien 5. Munich, Germany: Werner Verlag; 1989.

Reichart I, Hischier R, Werner F. LCA and decision making — conclusions from a review and a case study about paper recycling. SETAC Annual Meeting, Vienna, May 13–16; 2002.

Renn O, Dreyer M, Fisher E, Klinke A, Müller-Herold U, Morosini M, et al. The application of the Precautionary Principle in the European Union, final document of the EU-project: regulatory strategies and research needs to compose and specify a European policy on the application of the Precautionary Principle (PrecauPri); 2003.

Rio Declaration on Environment and Development. Principle 15, 1992. Available at: www.unep.org/Documents/Default.asp?DocumentID=78 & ArticleID=1163; accessed April 21, 2005.

SAEFL. Life cycle inventories for packagings. Environmental Series No. 250 (II). Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL); 1998.

SAEFL. Erhebung der Kehrichtzusammensetzung, Schriftenreihe Umwelt, Nr 356. Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL); 2003. Available at: http://www.poweron.ch/upload/cms/user/65AbfallBUWAL.pdf; accessed April 21, 2005.

SAEFL. Dioxin-und PAK-Emissionen der privaten Abfallverbrennung, Umwelt-Materialien Nr 172. Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL); 2004. Available at: http://www.umwelt-schweiz.ch/buwal/shop/files/pdf/phpmuGUCb.pdf; accessed April 21, 2005.

Sandin P. Dimensions of the precautionary principle. Human Ecol Risk Assess 1999;5:889–907.

Som C, Hilty L, Ruddy T. The precautionary principle in the information society. Human Ecol Risk Assess 2004;10:787–99.

STAR. http://www.altpapier.ch/AKTUELL.HTM; September 2004.

Stieglitz M. Vetropack. Private communication; October 2004.

Swiss Steel. Schrottnomenklatur Swiss Steel; 2004. Available at: www.eisenschrott.ch/pdf/Nomenklatu_Stahlwerksschrott.pdf; accessed April 21, 2005.

Tickner JA, Geiser K. The precautionary principle stimulus for solutions – and alternatives – based environmental policy. EIAR 2004;24:801–24.

WBGU. Welt im Wandel - Strategien zur Bewältigung globaler Umweltrisiken Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen. Berlin, Germany: Springer-Verlag; 1998.

Wiedemann PM, Brüggemann A. Vorsorge aus der Perspektive der Sozialwissenschaft: Probleme, Sachstand und Lösungsansätze, Arbeit zur Risiko-Kommunikation. Forschungszentrum Jülich GmbH, Programmgruppe Menschvol. 82. Jülich, Germany: Umwelt Technik; 2001.

Willbold J. Alumiumschmelzwerk Oetinger GmbH. Private communication; September 2004.

Williamson GH, Hulpke H. Das Vorsorgeprinzip, Internationaler Vergleich, Möglichkeiten und Grenzen, Lösungsvorschläge. Z Umweltchem Ökotox 2000;12(1):27–39.

Wingspread Statement. Common sense way to protect Wingspread Conference Center Racine, Wisconsin, January 23–25, 1998; 1998. [available at: www.gdrc.org/u-gov/precaution-3.html; accessed April 21, 2005].

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