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# Worldwide Impacts of Substance Restrictions of ICT Equipment

Perrine Chancerel, Karsten Schischke

Fraunhofer IZM

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Perrine Chancerel, Karsten Schischke

Fraunhofer IZM
Gustav-Meyer-Allee 25
13355 Berlin
Germany

perrine.chancerel@izm.fraunhofer.de
karsten.schischke@izm.fraunhofer.de

## Abstract

This paper was developed to depict the worldwide impacts of substance restrictions of ICT equipment. It comprises an overview on hazardous materials in electronics and on the worldwide substance restrictions, which were implemented in the European Union, China, California, Japan and other countries. The direct and secondary impacts of substance restrictions on materials in electronics are described, including the environmental impacts of the substance restrictions and of the substance substitutions, the effects on recycling, the economic impacts and other effects, for example on technological innovation. Present technology trends result in the restriction of further substances that are not part of the scope of the legislation through voluntary agreements and initiatives launched by the manufacturers.

# Table of Content

# Lists of Tables



# Lists of Figures

# Acronyms

| | |
|---|---|
| As | Arsenic |
| Be | Beryllium |
| Cd | Cadmium |
| Cr VI or $Cr^{6+}$ | Chromium VI |
| EEE | Electrical and electronic equipment |
| EU | European Union |
| FR | Flame retardant |
| Hg | Mercury |
| ICT | Information and Communication Technology |
| IT | Information Technology |
| JEITA | Japanese Electronics Information Technology Industries Association |
| OEM | Original Equipment Manufacturer |
| Pb | Lead |
| PBB | Polybrominated biphenyls (PBB) |
| PBDE | Poly-brominated diphenyl ether |
| PBDD/F | Polybrominated dioxins and furans |
| PC | Personal Computer |
| PCDD/F | Polychlorinated dioxins and furans |
| PVC | Polymer polyvinyl chloride |
| REACH | Registration, Evaluation and Authorization of Chemicals Directive |
| RoHS | Restriction of the use of certain Hazardous Substances in electrical and electronic equipment |
| Sb | Antimony |
| TBBPA | Tetrabromo bisphenol A |
| TV | Television |
| WEEE | Waste electrical and electronic equipment |

# 1. Introduction

This Desk Study describes the worldwide impacts of substance restrictions of ICT equipment and comprises the following:

- Overview on hazardous materials in electronics
- Overview on worldwide substance restrictions (such as EU RoHS, China RoHS)
- Impacts of substance restrictions on materials in electronics (direct replacement and secondary effects)
- Technology trends with an impact on content of hazardous substances, and "green" initiatives of OEMs

# 2. Overview on hazardous materials in electronics

According to the European Council Directive 92/32/EEC of 30 April 1992 amending the Dangerous Substances Directive 67/548/EEC, substances and preparations are "dangerous" if they are explosive, oxidizing, flammable, toxic, harmful, corrosive, irritant, sensitizing, carcinogenic, mutagenic, toxic for reproduction or dangerous for the environment.

Several studies investigated the composition of electrical and electronic equipment (EEE) and the environmental impacts related to EEE. They revealed for instance that the following materials are hazardous or closely linked to potential hazardous emissions (C4E Guidance 2002; DEFRA 2004; Dimitrakakis et al. 2009; Five Winds International 2001; Harant 2002; Öko-Institut 2008; Townsend et al. 2004):

- The heavy metals lead (Pb), cadmium (Cd), chromium VI (Cr VI), mercury (Hg), arsenic (As) and antimony (Sb)
- The light metal beryllium (Be) and its compounds
- Halogenated organic compounds like the flame retardants polybrominated biphenyls (PBB), polybrominated diphenyl ether (PBDE), tetrabromo bisphenol A (TBBP A) and the polymer polyvinyl chloride (PVC)

On 1 July 2006 the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC (RoHS directive) took effect in the European Union, restricting the use of six hazardous materials in electrical and electronics equipment. The six hazardous materials are lead, mercury, cadmium, hexavalent chromium ($Cr^{6+}$), polybrominated biphenyls and polybrominated diphenyl ether. A study of Öko-Institut (2007) listed around 18 other substances used in EEE that can be classified as dangerous and that are not regulated by the RoHS directive (table 1).

The potential environmental impacts of the hazardous substances are:

- Contamination of freshwater sources and sediments
- Contamination of soils
- Contamination of air
- Human health impacts

These impacts are especially caused by inappropriate methods to treat waste electrical and electronic equipment (WEEE), such as open burning, dumping and the uncontrolled use of chemicals (Widmer et al. 2005).

The review of Sepúlveda et al. (2009) presented data found in the scientific and grey literature about concentrations of lead (Pb), polybrominated diphenylethers (PBDEs), polychlorinated dioxins and furans as well as polybrominated dioxins and furans (PCDD/Fs and PBDD/Fs) monitored in various environmental compartments in China and India, where crude recycling methods are applied by the informal sector, like open burning, toner sweeping, plastic chipping and melting, heating and acid leaching, cyanide salt leaching, nitric acid and mercury amalgamation. The review highlights very high levels of Pb, PBDEs, PCDD/Fs and PBDD/Fs in air, bottom ash, dust, soil, water and sediments in waste electrical and electronic equipment (WEEE) recycling areas of the two countries. The concentration levels found sometimes exceed the reference values for the sites under investigation and pollution observed in other industrial or urban areas by several orders of magnitude. These observations suggest a serious environmental and human health threat, which is backed up by other studies that have examined the impact of concentrations of these compounds in humans and other organisms.

# 3. Overview on worldwide substance restrictions

Several regions in the world, including the European Union, China and California, adopted legislation restricting substances for EEE manufacturing. Table 2 compares the main characteristics of the legislations in these three regions, regarding the restricted substances, the scope, the exemptions and the certifications. Also Switzerland and Norway implemented legislations similar to the RoHS directive of the European Union.

The California RoHS Law is modeled after the European RoHS Directive, nonetheless with a reduced scope and regulating the four heavy metals but not the PBB and PBDE. However, pentabromodiphenyl ether (pentaBDE) and/or octabromodiphenyl ether (octaBDE) are addressed by legislations in several US and Canadian states, including California, Hawaii, Maine, Michigan, New York and Washington. Other legislations restricting the use of mercury were implemented in the USA and in Canada (Newark 2007). Moreover more general regulations are expected to go into effect in the very next years, like the California Green Chemistry Law that will encompass the restricted substances.

In Japan the ministerial ordinance Japanese industrial standard for Marking of Specific Chemical Substances (J-MOSS), effective from 1 July 2006, directs that some electronic products (personal computers, unit-type air conditioners, TVs, fridges, washing machines, clothes dryers and microwaves) exceeding a specified amount of the six toxic substances restricted by the RoHS Directive must carry a warning label. South Korea and Turkey also promulgated regulations that have aspects of RoHS contained in their scopes. In India, the draft notification of E-waste (Management and Handling) Rules 2010 was published in May 2010, including a rule on the reduction in the use of hazardous materials in the manufacture of electrical and electronic equipment (Chapter V). Schedule-III of the rules lists 20 substances that are intended to be restricted in electrical and electronic equipment and the threshold limits. The reduction in use of hazardous substances shall be achieved within a period of three years from the date of commencement of these rules.

**Table 1: High priority hazardous substances in EEE (source: Öko-Institut 2008)**

| Substance name | Further potential hazard | Main use in EEE | [t/y in EU] Quantity used in EEE |
|---|---|---|---|
| Tetrabromo bisphenol A (TBBP-A) | Dangerous degradation products, Detections in biota | Reactive FR in epoxy and polycarbonate resin, Additive FR in ABS | 40 000 |
| Hexabromocyclododecane (HBCDD) | Dangerous degradation products, Detections in biota | Flame retardant in HIPS, e.g. in audio-visual equipment, wire, cables | 210 |
| Medium-chained chlorinated paraffins (MCCP) (Alkanes, C14-17, chloro) | Dangerous degradation products, Detections in biota | Secondary plasticizers in PVC; flame retardants | Total use: up to 160 000 however no data available on share of EEE applications |
| Short-chained chlorinated paraffins (SCCP) (Alkanes, C10-13, chloro) | Dangerous degradation products, Detections in biota | Flame retardant | No reliable data available |
| Bis (2-ethylhexyl) phthalate (DEHP) | Detections in biota | Plasticizer in PVC cables; Encapsulation/potting of electronic components | 29 000 |
| Butylbenzylphthalate (BBP) | Detections in biota | Plasticizer in PVC cables Encapsulation/potting of electronic components | Total use: 19 500 however no data available on share of EEE applications |
| Dibutylphthalate (DBP) | Detections in biota | Plasticizer in PVC cables; Encapsulation/potting of electronics components<br>Silver conductive paint for variable resistors | Total use: 14 800 however no data available on share of EEE applications |
| Nonylphenol [1] /<br>4-nonylphenol, branched [2]<br>Nonylphenol ethoxylates | - | Surfactants used in coatings for films in EEE and in formulations to clean printed circuit boards; adhesives | No reliable data available |

| Substance name | Further potential hazard | Main use in EEE | [t/y in EU] Quantity used in EEE |
|---|---|---|---|
| Beryllium metal | - | Beryllium metal and composites: - Optical instruments, - X-ray windows;<br>Beryllium-containing alloys: - Current carrying springs, - Integrated circuitry sockets | Be metal and composites: 2;<br>Be-containing alloys: 11,5 |
| Beryllium oxide (BeO) | - | BeO ceramic applications: Laser bores and tubes | 1.5 |
| Antimony trioxide | Detections in biota | Synergist brominated flame retardant<br>Melting and fining agent in special glass, enamel and ceramic manufacture | Total use: 24 250 however no data available on share of EEE applications |
| Bisphenol A (4,4'-Isopropylidendiphenol) | - | Intermediate in polycarbonate and epoxy resin production | Total use: 1 149 870 however no data available on share of EEE applications |
| Diarsenic trioxide; arsenic trioxide | - | Fining agent in certain special glasses and glass ceramics | No data available |
| Dinickel trioxide | - | Used as colouring agent in certain special glasses.<br>In certain optical / filter glasses + in radiation shielding applications (e.g. welding);<br>Part of ceramics (varistors, NTC) | No data available |
| Organochlorine and organobromine compounds | Dangerous degradation products | Flame retardants | No data available |
| PVC | Dangerous degradation products | Cables & wires | ca. 385 000 |

**Table 2: Main facts relating to legislations restricting hazardous substances (source: RoHS directive, Farnell 2009)**

| | EU | CHINA | CALIFORNIA |
|---|---|---|---|
| Name of the legislation | Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC (RoHS Directive) and Directive 2011/65/EU (RoHS Recast) | China Order No. 39: Administrative Measures on the Control of Pollution caused by Electronic Information Products[1] | Electronic Waste Recycling Act, published in Health and Safety Code Section 25214.9-25214.10.2 |
| Data Law Passed | 23 February 2003 (RoHS Recast: 8 June 2011) | 28 February 2006 | 25 September 2003 |
| Effective Date | 1 July 2006 (RoHS Recast: 1 July 2011) | 1 March 2007 | 1 January 2007 |
| Restricted Substances | Lead (Pb)<br>Cadmium (Cd)<br>Mercury (Hg)<br>Hexavalent chromium ($Cr^{6+}$)<br>Polybrominated biphenyls (PBB)<br>Polybrominated diphenyl ether (PBDE) | | Lead (Pb)<br>Cadmium (Cd)<br>Mercury (Hg)<br>Hexavalent chromium ($Cr^{6+}$) |
| Maximum Concentration Values | Cd: 0.01% per "homogeneous material"[2], all others 0.1% per "homogeneous material" | Cd: 0.01%, others: 0.1%. These limits are also applicable to coatings (including multiple layers as one material) and for very small components (<4mm$^3$ being regarded as a homogeneous material) | Cd: 0.01%, others: 0.1% per "homogeneous material"[2] |
| Marking | None<br>RoHS recast: Compliance is demonstrated by the CE mark | Three Marking Requirements: Restricted Materials, Environment-Friendly Use Period, Packaging Materials | None |

[1] An update called "Draft Administrative Measures on the Control of Pollution caused by Electrical and Electronic Products" was issued for public consultation until 19 August 2010

[2] Defined as material that cannot be mechanically disjointed into different materials, i.e. that cannot be separated by mechanical actions such as unscrewing, cutting, crushing, grinding and abrasive processes

| | EU | CHINA | CALIFORNIA |
|---|---|---|---|
| Scope | 10 categories defined in Annex IA to Directive 2002/96/EC (WEEE Directive):<br>1. Large household appliances<br>2. Small household appliances<br>3. IT and telecommunications equipment<br>4. Consumer equipment<br>5. Lighting equipment<br>6. Electrical and electronic tools<br>7. Toys, leisure and sports equipment<br>8. Medical devices<br>9. Monitoring and control instruments<br>10. Automatic dispensers<br>RoHS Recast: Category 11 for "other electrical and electronic equipment" was added (effective on 22 July 2019) | 'Electronic Information Products', as defined in the 'Annotation of the Category of Electronic Information Products'. The products listed in the 'Key products Catalogue' need a CCC (China Compulsory Certification) approval. The first draft catalogue, limited to telephones (including mobiles, landline telephones and networked handsets) and printers that attach to a computer, was published for consultation on 9 October 2009.[3] | Covered electronic device: video display device with a screen greater than four inches, listed in nine categories:<br>1. Cathode ray tube containing devices<br>2. Cathode ray tubes (CRTs)<br>3. Computer monitors containing CRTs<br>4. Laptop computers with liquid crystal display (LCD)<br>5. LCD containing desktop monitors<br>6. Televisions containing CRTs<br>7. Televisions containing LCD screens<br>8. Plasma televisions<br>9. Portable DVD players with LCD screens<br>The scope was extended on 1 January 2010 by the California Lighting Efficiency and Toxics Reduction Act to general purpose lights |
| Exemptions | Material application exemptions defined; can be petitioned | Not defined yet. The 'Key products Catalogue' may also define material application "exemptions" | Exemptions defined by the European RoHS Directive 2002/95/EC, or by an amendment to this Directive |
| Packaging Materials | Out of scope | Non-toxic/Recycleable, Disclosed in mark | Out of scope |
| Production Materials | Out of scope | Restricted per materials restrictions | Out of scope |
| Testing/Certification | Not a prerequisite | Is a prerequisite (Chinese Lab test results only) for Catalogue items | The Lighting Efficiency and Toxics Reduction Act requires manufacturers of general purpose lights to provide sellers with certification that the lighting complies with the RoHS Directive of the European Union, upon request. |

[3] The scope of the updated Administrative Measures expands from 'Electronic Information Products' to 'Electrical and Electronic Products'. The 'Key products Catalogue' will be updated too

# 4. Impacts of substance restrictions on materials in electronics

## 4.1. Direct environmental impacts of the substance restrictions

Four environmental and human health effects due to the implementation of the RoHS Directive were identified by Arcadis (2008):

1. **Restricted substances avoided in the production of EEE**. According to Arcadis, the use of large amounts of lead, cadmium and hexavalent chromium for manufacturing was avoided, for instance due to modifications of the composition of TVs, PCs and fridges. This implies a decrease in the demand for restricted substances and of emissions in the supply chain, and therefore of the impacts of manufacturing on environment and health.

2. **Decrease in human toxicity potential and eco-toxicity potential** of EEE through the different environmental compartments (air, fresh water, terrestrial). For cadmium and hexavalent chromium, it seems that the RoHS Directive impact has been the largest on the human toxicity potential via the air compartment. For lead and mercury, the impacts on the human toxicity potential via the soil and fresh water compartment are also relevant.

3. **Decrease of the waste emissions being disposed** to the environment. It is estimated that the yearly amount of waste avoided being disposed to the environment will be 89,800 tonnes of lead, 4,300 tonnes of cadmium, 537 tonnes of hexavalent chromium, 22 tonnes of mercury and 12,600 tonnes of Octa-BDE (Arcadis 2008), as a consequence of the substance restrictions in the new products. However, these numbers have to be considered with caution for the following reasons:

   a. They are time-dependant (there is a time delay between bringing on the market of RoHS-compliant products and waste generation),

   b. They depend on the recycling processes applied to treat the waste material and

   c. They also do not take into account the substitution materials, which, like the restricted materials, require adequate recycling to limit the negative direct and indirect environmental impacts.

4. **Reduction of the Octa-BDE volatilization losses**. Brominated flame retardants (BFR) such as Deca-BDE and Octa-BDE tend to volatilize from products during service life [JRC 2002, 2003], which may impact the environment and human health. The RoHS Directive has a positive effect on the Octa-BDE volatilization losses.

The elimination of lead through the introduction of the lead-free solders has a small effect on the environmental impact of the metal production system as a whole (Reuter & Verhoef 2004). The reason is that solder for electronics before the implementation of the RoHS Directive accounted for only 1.5% of the lead production.

The collection of data on the impacts of the RoHS Directive is challenging, due to the following reasons (COM 2008):

- There is little information about the quantities of hazardous substances used in EEE before RoHS and it is not possible to elaborate a realistic scenario on what the current situation would have been if RoHS had never existed.

- There are uncertainties about the quantities of restricted substances contained in EEE currently placed on the market: manufacturers point out that it is very difficult to know exactly the product composition in particular when it incorporates thousands of components from a long supply chain stretching around the world.
- There are uncertainties about the quantities of EEE placed on the EU market.
- It is not always easy to determine to which extent the reduction of the hazardous substances in EEE can be attributed to RoHS or is due to other factors as well, such as technology changes (e.g. shift from cathode ray tube TVs to flatscreen TVs), consumer preferences or other EU legal acts.

The environmental impacts of the RoHS Directive do not only affect the European Union primarily because a large proportion of the EEE sold in the European Union is produced outside Europe and the non-European manufacturers had to adapt their manufacturing. This possibly reduced the amounts of restricted substances emitted locally during manufacturing to the environment, for instance the composition of production waste. Moreover, some manufacturers modified the product design and the production systems not only for the products intended to be sold in the European Union, but for their whole production, so that RoHS-compliant components or products are placed on markets outside the European Union as well (Inform 2003). This is also confirmed by the claims made by several brand name consumer electronics and IT manufacturers, as compiled by Greenpeace for their "Greener Electronics" ranking of companies. Finally, the treatment of WEEE by EU Member States partly takes place outside Europe. The implementation of the RoHS Directive may reduce the hazardousness of WEEE and, therefore, the hazardousness of the emissions related to recycling and disposal of WEEE (Arcadis 2008). Unfortunately, no data are available on the international impacts of the implementation of the RoHS Directive.

## 4.2. Impacts of the substance substitutions

The implementation of the RoHS Directive resulted in the substitution of the restricted substances by non-restricted substances. Table 3 presents the main substitutions. The examples of lead-free solders and flame retardants are described in more detail in Table 3.

### 4.2.1. Lead-free solders

To meet the requirements of RoHS, the printed circuit board industry had to move away from lead containing solders and surface finishes (on printed circuit boards and components' contacts) to alternative materials; however, the electronics industry did not adopt a universal alternative. The alternatives for surface finishes include organic solderability preservatives, electroless nickel/immersion gold, immersion silver and immersion tin (Van der Pas 2007). In 2004 lead-containing soldering retained 55% market share of the final finishes used in manufacturing of printed circuit boards and this worldwide market share was estimated to have decreased to 37% in 2008 (Van der Pas 2007). According to a recycler of production waste of the electronics industry in Malaysia, the use of substitution materials during production is continuously evolving: the recycler first observed a decrease of the lead content in the production waste associated with an increase of the content of precious metals, especially palladium, and after some months a decrease of the precious metals content due to the use of more resource-efficient manufacturing processes.

The environmental impacts related to the use of substitutions to replace the restricted substances have not been extensively investigated. Some studies looked into the effects of lead substitution (Arcadis 2008, Deubzer 2007, Reuter&Verhoef 2004, US EPA 2005). Besides the positive environmental effects of lead substitution in solders, especially on its toxicity, the use of alternative materials like tin, copper and silver to substitute lead in solders also has negative environmental effects over the product life cycle, e.g. on energy consumption, resource depletion, photochemical smog and air particulates. As the discussion on the environmental impact of lead-free soldering is very complex, ambiguous and still ongoing, no definitive conclusion can be drawn on this topic (Arcadis 2008).

The implementation of the lead restriction hardly changed, or did not change at all, the production volumes of the bulk metals like lead, zinc or copper. In contrast the lead substitution drastically increased the demand for and production of metals like bismuth and tin, which production volumes are much smaller (Reuter & Verhoef 2004). The variations of the use of metals replacing lead-containing solders can be investigated based on the example of silver (figure 1). The worldwide use of silver for fabrication of EEE has strongly increased in the years 2001 to 2007 (figure 1).

A comparison to the worldwide trade statistics, for example the semiconductor market (figure 2), shows parallel trends: increase in the years 2001 to 2007, and decrease in 2008 and 2009.

The variation of the use of silver to manufacture electrical and electronic equipment is therefore mainly explained by economic fluctuations. However, the replacement of the lead-free solders possibly played a role, since a strong increase of the silver use took place in the years around the adoption of the RoHS Directive (2004 to 2007). The increase of the silver use was especially strong in Japan in 2004 (+26% compared to 2003) and 2005, which is probably partly a consequence of the voluntary agreement of manufacturers called 'Japanese Electronics Information Technology Industries Association's (JEITA) lead-free roadmap'. The JEITA lead-free roadmap required the complete supplying of lead-free components by 1 January 2005 and the complete lead elimination in IT equipment by 1 January 2006.

### 4.2.2. Flame retardants

The environmental impacts of substitution options for brominated flame retardants are currently being investigated in the frame of the ENFIRO project (ENFIRO 2010). A practical approach is followed in which the alternative flame retardants are evaluated regarding their flame retardant properties, their influence on the function of products once incorporated, and their environmental and toxicological properties. The outcomes of the project will be a comprehensive dataset on viability of production and application, environmental and human safety and a complete life cycle assessment.

Three flame retardant (FR) product combinations were selected for case studies (e.g. metal-based FRs, phosphorous- based and nanoclay-based FRs in printed circuit boards, paints and foam). The case studies will provide recommendations for industrial and governmental stakeholders and will be useful for similar substitution studies, e.g. under the REACH Directive (Registration, Evaluation and Authorization of Chemicals, EC 1907/2006). The results of the project will be available in 2012.

**Table 3: Main substitutions of the substances restricted by the RoHS Directive**

| Restricted substances | Application | Substituting materials |
|---|---|---|
| Lead | Solders | Mixtures containing tin, silver, copper, bismuth, zinc, organic solderability preservatives, nickel, antimony, gold and/or palladium (Van der Pas 2007, Deubzer 2007, Nihon 2010) |
| Cadmium | Plastic colouring | Other colouring materials |
| | Contacts | Silver-Nickel (AgNi), Silver-Tin-Oxide ($AgSnO_2$) |
| Mercury | Switch | Other metals or metal alloys (e.g. gallium alloy) |
| | Sensor | |
| | Contacts | |
| Hexavalent chromium | Pigment | Trivalent chromium, tungsten carbide |
| | Anticorrosion agent | |
| | Plating | |
| Flame retardants Polybrominated biphenyls and Polybrominated diphenyl ether | Flame retardants (FR) in general | Changes of the combination of polymers to reduce the inflammability. Bis(pentabromophenyl) ethane, ethylene bis(tetrabromophthalimide), other halogenated and halogen-free flame retardants like the phosphorous-based FR resorcinol bis(diphenylphosphate) and bisphenol A diphosphate (Danish EPA 2006, Rossi&Heine 2007) |
| | Wire and cables | Aluminium-tri-hydroxide, magnesium-dihydroxide, boehmite, phosphorus flame retardants, zinc borate, phosphate esters, melamine cyanurate, melamine phosphate, red phosphorus, intumescent products based on ammonium polyphosphate, aluminium phosphinates, aryl phosphates (pinfa 2010) |
| | Electronic enclosures | Triphenyl phosphate, resorcinol bis- (diphenyl phosphate), bisphenol A bis- (diphenyl phosphate), resorcinol bis(2,6-dixylenyl phosphate) (pinfa 2010) |
| | Electrical installations | Metal phosphinates (often combined with N-synergists), Inorganic Metal phosphinates, Melamine Polyphosphate, Melamine cyanurate, Red phosphorus, Aryl phosphates and phosphonates, Magnesium hydroxide, Ammonium polyphosphate in combination with nitrogen synergists (pinfa 2010) |
| | Printed wiring boards | Aluminium Trihydroxide, Aluminium monohydrate, metal phosphinates and polyphosphates, DOPO (Dihydrooxaphosphaphenantrene), Poly(1,3-phenylene methylphosphonate) (pinfa 2010) |

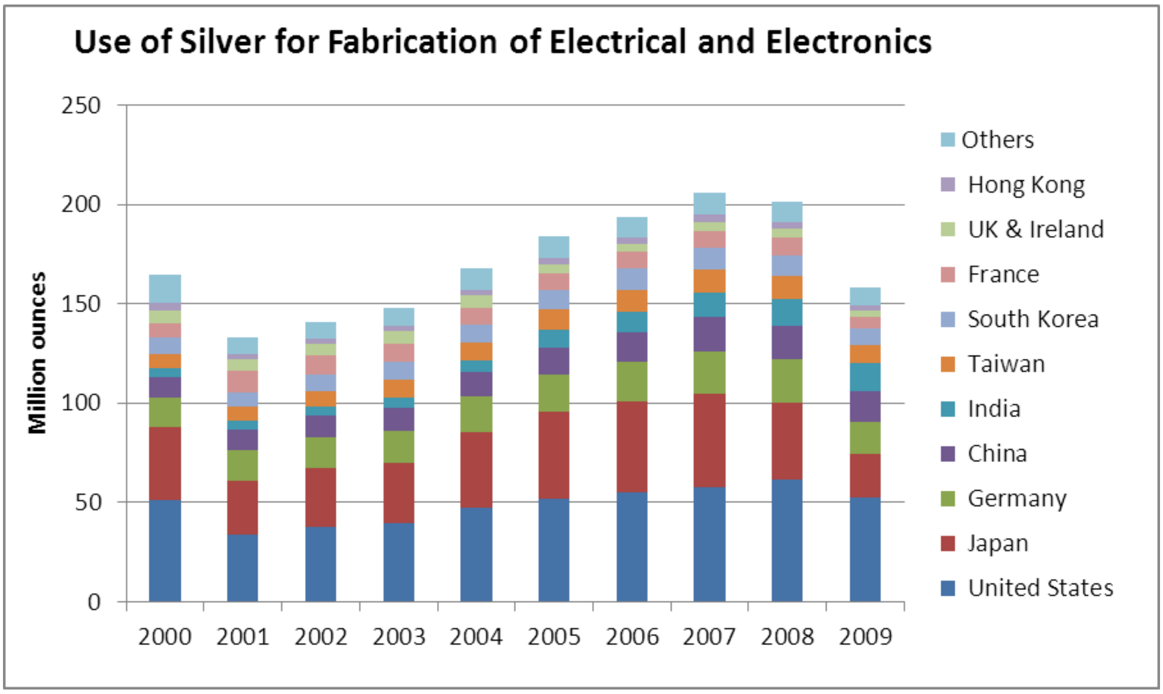


**Figure 1: Use of silver for manufacturing of electrical and electronic equipment**

**(source: Silver Survey 2010)**

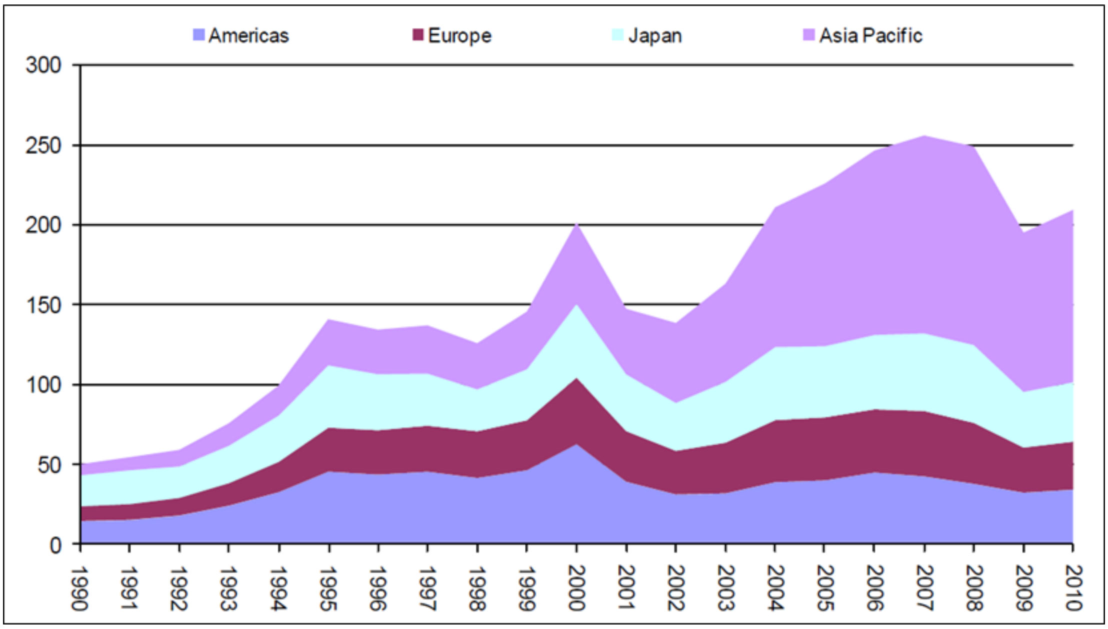


**Figure 2: Worldwide semiconductor market by region, 1990–2010, in USD billions**

**Note: 2009 and 2010 are forecast**
**(source: OECD 2009, based on World Semiconductor Trade Statistics, July 2009)**

## 4.3. Effects on recycling

Two main changes in product compositions caused by the implementation of the RoHS Directive are reported:

1. Modification of the material composition of electronic as a consequence of the replacement of lead-containing solders by lead-free solders containing for instance tin and silver
2. Use of other flame retardants to replace polybrominated biphenyls and polybrominated diphenyl ether

The elimination of lead from electronics products may have increased their recycling value, because lead substitutes such as silver have considerable value (Turbini et al. 2000). The higher economic value of the lead-free solders can provide an incentive for increased recycling of the electric and electronic scrap and a reduction in recycling costs (Reuter & Verhoef 2004).

European recyclers reported changes of the lead/tin ratio in end-of-life electronic materials over the past years, i.e. an increase in the tin content in the end-of-life printed circuit boards. Tin does not pose a problem in copper smelters where printed circuit boards are primarily recycled.. However, an increased content of bismuth in lead-free solders may lead to challenges for the recycling of electronic scrap in copper processing. Some of the bismuth in the feed of copper smelters may follow the copper smelt and contaminate the cathodes. Some smelters currently are not able to separate this bismuth from the cathodes; other processes can separate the bismuth after the copper furnace (Reuter & Verhoef 2004). For example, Umicore, a smeltering facility in Belgium, can recover copper, tin, antimony, bismuth and other lead-free solder elements (Hagelüken 2008).

The temperature needed for desoldering lead-free solders is higher compared to the temperature required to smelt lead-containing solders (table 4). Therefore, a possible negative effect of the use of lead-free solders is that desoldering requires higher temperature which can result in the release of more hazardous emissions. This depends on the vapor pressure of the material mixes.

**Table 4: Melting temperature of selected solder alloys required for (de)soldering**

| Solder | Melting temperature °C |
|---|---|
| $SnPb_{37}$ | 183 |
| $SnZn_{9}$ | 199 |
| $SnAg_{3,8}Cu_{0,7}$ | 217 |
| $SnAg_{3,5}$ | 221 |
| $SbCu_{1}$ | 227 |

Desoldering processes are mainly used in countries where electronic components are separated through manual processes, e.g. in developing countries. According to Indian recyclers, the elevated temperatures required for desoldering do not pose a problem for recovery of components nor are more critical emissions observed, rather less than with conventional SnPb soldered boards (ZeroWIN 2010). However, the lack of reliable knowledge regarding the destination of the elements contained in lead-free solders (for example tin), which might end up in residues in larger quantities, needs to be addressed.

In general the impacts of lead-free solder on the metal recovery processes depends on the technology used (e.g. pyrometallurgical or hydrometallurgical treatment). A key issue is the monitoring of the substance flows in order to know where the elements end up after the process (e.g. to product or waste, effluent, residue) and what happens with the residues. Even though the toxic element lead is removed from the solder, the replacement elements can contribute to the hazardousness of the residues.

The consequences of the use of non-restricted flame retardants for the printed circuit boards and the other plastic parts of the products on the recycling processes were not investigated until now. An adaptation of the recycling processes may be necessary to consider the changes in the material composition.

To conclude, research gaps remain to better and more comprehensively understand the consequences of the material substitutions on e-waste recycling. Because the lifetime of electronic products often exceeds five years, e-waste recyclers are currently mainly treating end-of-life products that were manufactured before the implementation of the RoHS Directive, and therefore that are not RoHS compliant. The massive arrival of "RoHS-compliant e-waste" to the recycling facilities is expected for the next years.

## 4.4. Economic impacts

According to a stakeholder consultation conducted by Arcadis (2008), the total costs incurred by the companies to comply with the RoHS Directive amount to a maximum of € 59.6 million, with an average of € 10 million and a weighted average of € 21 million. These figures include following costs:

- Administrative costs (training and information measures; collection, organization and review of information (e.g. material declarations); exemption procedures; organizational implications causing monetary losses)
- Technical costs related to RoHS compliance (capital expenditure; operating expenditure; research and development) for all restricted substances

Yearly costs companies are expecting in the future amount to a maximum of € 4.7 million.

However, the RoHS legislation has also a number of positive economic impacts. For example, the communication across the supply chain was massively increased, which is also necessary to comply with other requirements like REACH. The equipment development and process control required for RoHS led to an increasing knowledge of solders, interfaces, processing and reliability, which resulted in an overall reduced number of defects, an increased production efficiency and functionality to consumers (Arcadis 2008).

The restriction of metals stipulated by RoHS affects the configuration of the metal production system (Reuter & Verhoef 2004). For example, Reuter & Verhoef (2004) estimated that switching from lead solders to silver solders may consume 6–9% of the world's total output of silver, putting pressure on silver supplies and affecting the metal prices. Despite the higher costs of the lead-free alternatives, an increase in the cost of printed wiring boards was not expected, because solder accounts for such a marginal percentage of total costs (Reuter & Verhoef 2004).

## 4.5. Other secondary effects

The question whether or not the RoHS Directive has inspired or hindered innovation is strongly contested (Arcadis 2008). The main arguments of the stakeholders that think that RoHS enabled innovation are (Arcadis 2008):

- Manufacturers of EEE and component suppliers have been forced to develop and implement a range of innovations and technologies in order to ensure that products are in compliance with the substance restrictions. Trankell & Sandahl (2010) report that the yields in printed circuit board production were improved during the introduction process of low halogen printed board materials. Another positive effect was a more uniform specification of low halogen materials, which resulted in more robust design. Also a better understanding of solder behaviour and properties has been gained.

- In the years around the entry into force of the Directive, significant increases in applications for patents in RoHS compliance related areas in the US, Japan and Europe were observed.

However, the antagonists argue that:

- The innovation efforts undertaken to comply with the RoHS may have been at the expense of other broader R&D activities for product development.
- The avoidance of the restricted substances may hinder the development of new technology, as fewer materials are considered.

RoHS also supported the development of monitoring and knowledge tools to support RoHS and the longing for electronics with more benign substances. For example, the Clean Production Action delivers solutions to enterprises for green chemicals, sustainable materials and environmentally preferable products. Among others, the Clean Production Action made the free screening tool "Green Screen for safer Chemicals" publicly accessible. The companies (e.g. Hewlett Packard) use such tools not only directly for a safer management of substances, but also to design more innovative products, to improve the competitiveness, and to implement marketing strategies.

According to Arcadis (2008), the RoHS Directive was certainly a driver for innovation with respect to the restricted materials.

# 5. Technology Trends

The restrictions of the RoHS Directive were extended to other substances through voluntary actions of manufacturers like the 'Halogen-free policy' of the 'High Density Packaging User Group (HDPUG)', an association of OEMs and components manufacturers from telecommunications and the computer industry. Table 5 presents the bans or restrictions of hazardous substances adopted by the manufacturers. A substance is banned when it is totally prohibited (concentration of zero), whereas substance restrictions imply the definition of a concentration limit under which the substance is allowed and/or of applications that are exempted to fulfill the substance restrictions.

Besides the substance restrictions required by the legislation, producers of the electronics industry have agreed on further restrictions through voluntary actions. The practical implementation of the restrictions requires defining the concentration limit under which the substances are considered as restricted. For the example of halogenated flame retardants (the chemical definition of a halogenated compound is a compound containing chlorine, bromine, fluorine or iodine), the concentration limits adopted by some companies like Ericsson refer to the definitions in the following standards and draft guidelines (Trankell & Sandahl 2010):

- According to the IPC-4101 [4], printed circuit boards are classified as low halogen if they contain up to

[4] Specification for Base Materials for Rigid and Multilayer Printed Boards, IPC-4101

0.09% of chlorine or bromine and up to 0.15% of bromine and chlorine together.

- For components other than printed circuit boards the draft guideline IPC-4903[5] applies. Class A in this draft defines low halogen such that each plastic part in the component shall contain <1000ppm (0.1%) of bromine and <1000ppm (0.1%) of chlorine if the source is from flame retardants or PVC.
- For cables the IEC 60754-2[6] standard contains requirements for testing corrosive gases evolved during combustion. This indirectly defines low halogen, including fluorine content.

The producers report that for technical reasons, it is currently not possible to migrate to the restriction of all hazardous substances in all areas of the electronics industry. For example, low halogen alternatives for applications with low electrical signal loss requirements, e.g. power amplifiers in radio units, will probably not be commercially available until 2012-2015 (Trankell & Sandahl 2010).

A trend towards the restriction of an extended number of hazardous substances is easily recognizable in large companies producing electronic products for consumers. This trend was not only an effect of the implementation of the RoHS Directive, but also by voluntary actions that are a part of the marketing strategy aiming at “greening” the products. However, it is questionable whether this trend can be observed for products placed on business-to-business markets and for products manufactured by small and medium enterprises. Almost 30% of the Spanish and German SMEs contacted in the frame of a survey conducted in 2009/2010 do not know about the RoHS Directive, meaning that in the case they were affected they are not aware of it (Chancerel et al. 2010).

Material restrictions are by far not the only driver for changed material composition of electrical and electronic equipment. Numerous technology trends, shifts from certain product types to others and disruptive technology developments lead to shifts in the overall material composition of electronics. Table 6 provides a summary of the material content of particularly relevant materials for electronics (data based on Hagelüken 2008) complemented by technology trend estimates by Fraunhofer IZM. For precious metals content in particular there are trends going in opposite directions, whereas content of tin and indium is expected to rise.

[5] A guideline for Defining “Low Halogen” Electronic Products, IPC-4903, Working Draft, August 2010

[6] Test on gases evolved during combustion of electric cables, IEC 60754-2

**Table 5: Restrictions or bans of hazardous substances carried out by the manufacturers (source: Greenpeace 2010, company reports)**

| | Substances restricted by RoHS | | | | | Substances that are not restricted by RoHS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Restricted substances** | **PBB PBDE** | **Lead** | **Mercury** | **Cad-mium** | **Chromium VI** | **Other BFR** | **Beryllium / BeO** | **Arsenic** | **PVC** | **Antimony trioxid** | **Phtha-lates** | **Nickel**[7] |
| Acer | n/a | Banned | Banned | Restricted | Restricted | 2011[8] | 2012 | | 2011 | 2012 | 2012[9] | Re-stricted |
| Apple | n/a | n/a[10] | By moving to LEDs[11] | n/a | n/a | 2008 | | in LCDs | 2008 | | | |
| DELL | n/a | n/a | n/a | n/a | n/a | 2011 | | planned | 2011[12] | | 2014 | |
| Fujitsu | n/a | n/a | n/a | n/a | n/a | 2013 | 2012 | | 2013 | | 2013 | |
| HP | n/a | Banned | Banned | n/a | n/a | 2011 | Banned | | 2011 | Banned | Banned | |
| Lenovo | n/a | n/a | n/a | n/a | n/a | 2011 | Banned | | 2011 | Banned | | |
| LGE | n/a | n/a | n/a | Restricted | n/a | 2010[13] | BeO[14] | | 2010[13] | 2012[15] | 2012[15] | |
| Microsoft | n/a | Re-stricted | Restricted | n/a | Restricted | 2010 | | | | | 2010 | |

[7] On product surfaces intended to come into contact with the skin

[8] Dates indicate the year of implementation of the substance ban

[9] Certain phthalates are to be phased out by 2009

[10] "n/a" means that the information was not provided

[11] June 2007: first mercury free LED display

[12] Ban by 2011, PVC has been restricted since 2002

[13] Only mobile phones; banned from TV, monitors & PC by 2012; for all products by 2014

[14] BeO banned in mobile phones; other kinds of beryllium compounds will be banned in new products by 2012

[15] Banned in new mobile phones, TVs, monitors, PCs; 2014 all household applications

| | Substances restricted by RoHS | | | | | Substances that are not restricted by RoHS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Restricted substances** | **PBB PBDE** | **Lead** | **Mercury** | **Cad-mium** | **Chromium VI** | **Other BFR** | **Beryllium / BeO** | **Arsenic** | **PVC** | **Antimony trioxid** | **Phtha-lates** | **Nickel[7]** |
| Motorola | n/a | Re-stricted | Restricted | Banned | Restricted | 2010 | Banned | Banned | 2010 | Banned | Banned | Re-stricted |
| Nintendo | n/a | Re-stricted | Restricted | Restricted | Restricted | | Banned | | Banned | Banned | Banned | |
| Nokia | Banned | Banned | Banned | Banned | n/a | Banned | 2010 BeO 2004 | Banned | Banned | 2010 | Banned | Banned |
| Philips | n/a | Re-stricted | Restricted | Restricted | Restricted | 2010 | 2008 | 2008 | 2010 | 2010 | 2010 | Re-stricted |
| Panasonic | n/a | Banned | Banned | Banned | Banned | 2011 | Banned | | 2011 | Banned | Banned | |
| Samsung | n/a | Banned | Banned | Restricted | Banned | 2010 | 2013 | Re-stricted | 2010 | 2013 | 2012 | Re-stricted |
| Sharp | n/a | Banned | Banned | Banned | Banned | 2011 | Banned | | | 2010 | 2010 | |
| Sony | Banned | n/a | n/a | n/a | n/a | Banned | BeO 2008, BeCu | | 20 11 | | Planned | |
| Sony Ericsson | Banned | Banned | Banned | Banned | Banned | Banned in newer mod-els | 2010 | | 2007 | Banned[16] | 2010 | Re-stricted |
| Toshiba | Banned | n/a | n/a | n/a | n/a | Banned[17] | 2012 | free LCD | Banned[18] | 2012 | 2012 | |

[16] Apart from some minor applications

[17] For casing and all plastic parts weighing 10g or more

[18] Excluding external cables

**Table 6: Metal demand for electronic equipment and technology trends (source: Hagelüken 2008, Fraunhofer IZM)**

| Metal | Primary production in 2006 *t/y* | Demand for EEE in 2006 *t/y* | Demand/ production *%* | Price (2007 average) *USD/kg* | Value in EEE *USD millions* | Main applications | Trend (Fraunhofer IZM estimate) | |
|---|---|---|---|---|---|---|---|---|
| **Silver (Ag)** | 20 000 | 6 000 | 30 | 430 | 2.6 | Contacts, switches, solders… | ↑ | Pb ban: Ag containing solders; Ag antennas in transponders |
| **Gold (Au)** | 2 500 | 300 | 12 | 22 280 | 6.7 | Bonding wire, contacts, IC, … | ↑<br>↓ | Mobile products in general with higher precious metal content<br>Desktop products |
| **Palladium (Pd)** | 230 | 33 | 14 | 11 413 | 0.4 | Multilayer capacitors, connectors | ↑<br>↓ | Mobile products in general with higher precious metal content<br>Desktop products |
| **Platinum (Pt)** | 210 | 13 | 6 | 41 957 | 0.5 | Hard disk, thermocouple, fuel cell | ↓ | Miniaturization of HDD, less Pt per drive |
| **Ruthenium (Ru)** | 32 | 27 | 84 | 18 647 | 0.5 | Hard disk, plasma displays | → | Miniaturization of HDD, less PGM per drive, but shift from Pt to Ru |
| **Copper (Cu)** | 15 000 000 | 4 500 000 | 30 | 7 | 32.1 | Cable, wire, connector, … | → | Cu will remain dominating constituent of electronics for the foreseeable future |
| **Tin (Sn)** | 275 000 | 90 000 | 33 | 15 | 1.3 | Solders | ↑↑ | Pb ban: increased Sn content (+50%) |
| **Antimony (Sb)** | 130 000 | 65 000 | 50 | 6 | 0.4 | Flame retardant, CRT glass | ↓ | Shift from CRT to LCD displays |
| **Cobalt (Co)** | 58 000 | 11 000 | 19 | 62 | 0.7 | Rechargeable batteries | ↑ | Trend towards mobile products leads to growing market for rechargeable batteries |
| **Indium (In)** | 480 | 380 | 79 | 682 | 0.3 | LCD glass, solder, semiconductor | ↑↑ | Massive growth of LCD products |
| **Magnesium (Mg)** | 690 000 | n/a | n/a | 2.10 | n/a | Housing metal parts | ↑ | Light weight material for mobile products |

# 6. Conclusion

The implementation of substance restrictions in general, and of the RoHS Directive in particular, had manifold impacts, especially on the environment and on the activities of the electronics industry and of the recycling industry.

Figure 3 graphically depicts that further steps and research are still needed over the life cycle. These needs concern the identification of further substances to be restricted, the development of alternative materials, the characterization and quantification of the environmental, economic and social impacts of the restrictions and of the use of alternative materials, the testing of the products, and the development or adaptation of recycling processes to the changes due to the use of alternative materials.

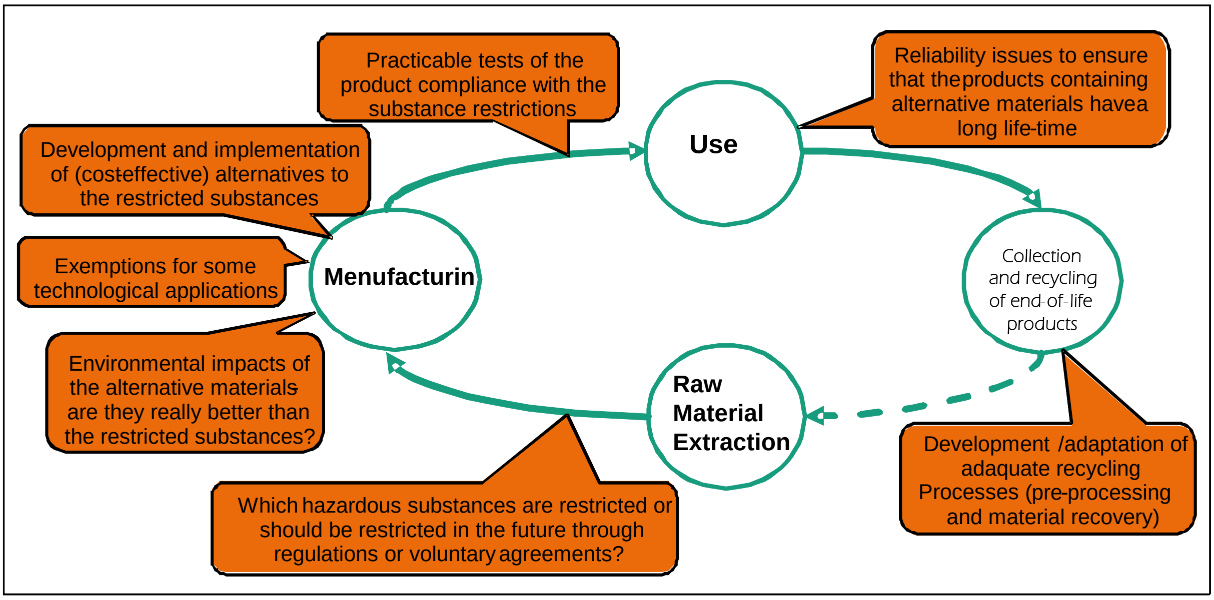


**Figure 3: Research needs related to substance restrictions over the life cycle**

The specific characteristics and needs of the stakeholders, for example small and medium enterprises, need to be better considered for a more efficient implementation of the restrictions, and above all to achieve the final goal of substance restrictions in an effective manner, which is the reduction of the environmental impacts of the products and processes. A holistic approach is necessary to ensure that the overall impacts of a substance restriction, and therefore of the substitution of the restricted substance, are favourable on the whole product life cycle, including raw materials extraction, manufacturing, use and end-of-life management.

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"StEP envisions a future in which societies have reduced to a sustainable level the e-waste-related burden on the ecosystem that results from the design, production, use and disposal of electrical and electronic equipment. These societies make prudent use of lifetime extension strategies in which products and components – and the resources contained in them – become raw materials for new products."

Our name is our programme: solving the e-waste problem is the focus of our attention. Our declared aim is to plan, initiate and facilitate the sustainable reduction and handling of e-waste at political, social, economic and ecological levels.

**Our prime objectives are:**

- Optimizing the life cycle of electric and electronic equipment by
  - improving supply chains
  - closing material loops
  - reducing contamination
- Increasing utilization of resources and re-use of equipment
- Exercising concern about disparities such as the digital divide between industrializing and industrialized countries
- Increasing public, scientific and business knowledge
- Developing clear policy recommendations

As a science-based initiative founded by various UN organizations we create and foster partnerships between companies, governmental and non-governmental organizations and academic institutions.

**StEP is open to companies, governmental organizations, academic institutions, NGOs and NPOs and international organizations which commit to proactive and constructive participation in the work of StEP by signing StEP's Memorandum of Understanding (MoU). StEP members are expected to contribute monetarily and in kind to the existence and development of the Initiative.**

### StEP's core principles:

1. StEP's work is founded on scientific assessments and incorporates a comprehensive view of the social, environmental and economic aspects of e-waste.
2. StEP conducts research on the entire life cycle of electronic and electrical equipment and their corresponding global supply, process and material flows.
3. StEP's research and pilot projects are meant to contribute to the solution of e-waste problems.
4. StEP condemns all illegal activities related to e-waste including illegal shipments and re-use/ recycling practices that are harmful to the environment and human health.
5. StEP seeks to foster safe and eco/energy-efficient re-use and recycling practices around the globe in a socially responsible manner.

## Contact:

StEP Initiative
c/o United Nations University
Institute for Sustainability and Peace (UNU-ISP)
Operating Unit SCYCLE
Hermann-Ehlers-Str. 10
53113 Bonn, Germany
Phone: +49-228-815-0271
Fax: +49-228-815-0299
info@step-initiative.org
www.step-initiative.org
www.isp.unu.edu

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