Annex IV. Background information to study on dangerous substances and emissions

Annex IV contains background information to the study carried out by the Topic Centre on emission of dangerous substances and materials from treatment of WEEE. This background information consists of a description of the substance Flow Methods, data required and availability as well as a detailed description of the five appliances and the state-of-the-art treatment operation used in methods to calculate the results.

IV.1. Description of the substance flow method

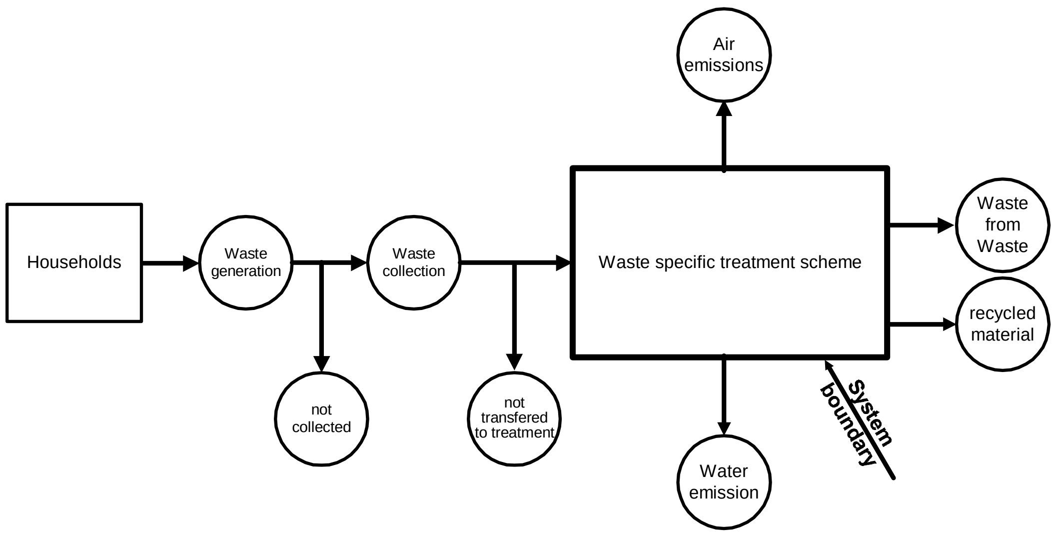
Substance flow analysis

Substance flow analysis tracks the flow of a substance through a technical system. At its simplest, it is an input-output balance, where the distribution of a specific input stream on several output streams is determined. For inorganic substances the input mass is equal to the output (mass conservation), in the case of organic substances material can be destroyed or new material generated.

The first step in conducting a substance flow analysis is to define the system boundaries. The system boundaries for this study are illustrated in Figure IV.1. The system starts with the treatment of WEEE and ends when treatment has concluded.

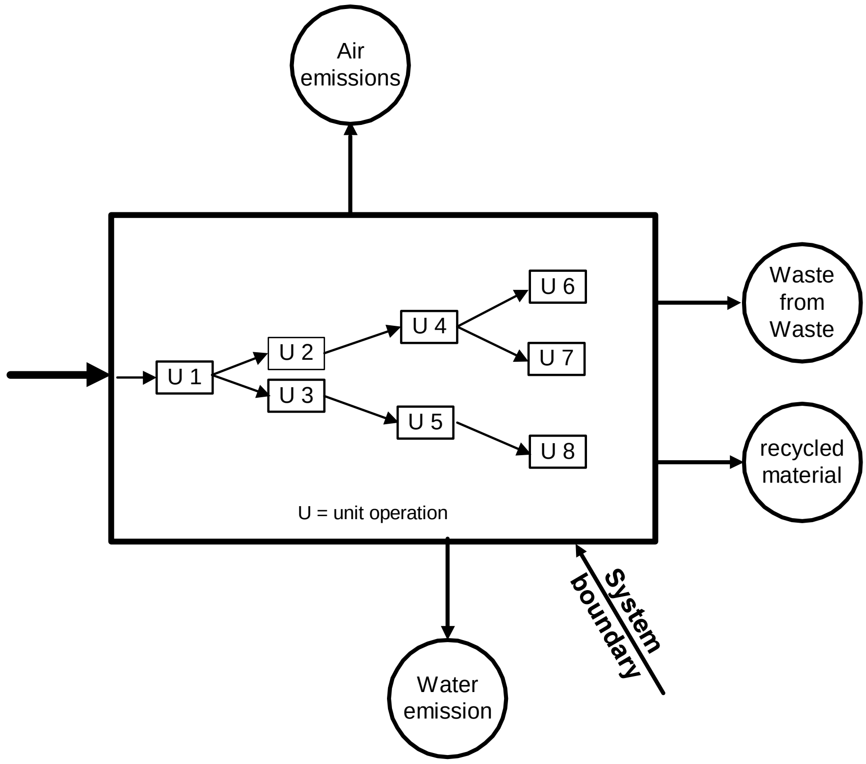
In this system all emissions to air, water and waste, that are related to the treatment of specific WEEE appliances are considered. Emissions from "unauthorised" treatment of waste are not considered.

Figure IV.1: System boundary



The second step is to define the unit operations within the system boundaries. This means that a specific treatment scheme is designed for each of the selected appliances. The unit operations are technical processes such as dismantling, shredding or metallurgical treatment. A system can be very simple e.g. in the case of disposal technologies it is limited to a single process. In the case of recycling the system can be complex and may comprise several unit processes.

Figure IV.2: Definition of technical system



The third step is to describe the transfer of the substances in the various unit operations. This is done by assigning transfer factors for each substance and each unit operation. They are defined as follows:

$$t_i = \frac{m_{out,i}}{m_{,in}}$$

i = index for output paths (e.g. air); out = output; in = input
m = mass

The input vector for a particular substance also includes input of the substance from sources other than the appliance, such as process materials that are required to run the process.

The fourth step is to carry out the calculations. This was done using a commercial computer software package UMBERTO.

IV.2. Definition of factors

Various factors are defined that allow emissions from the different treatment schemes to be compared.

The **recycling factors** (f_r) are calculated as the ratio of kg recovered material (e.g. metals and plastic) per 1000 t input of appliance (e.g. fridge, pc etc).

$$f_r = \frac{kg_{recycl.}}{1000 t_{input}}$$

In addition, for the state-of-the-art treatment schemes the **recycling quota** is calculated using the EU definition[28] as the ratio of kg of recycled material per

[28] Proposal for a Directive on Waste Electrical and Electronic Equipment, 13.06.2000

average weight of appliance. For each appliance this quota is compared with the targets set by the EU in the WEEE directive.

The **waste for disposal factors** (f_{wfd}) are calculated as the ratio of kg of secondary waste per 1000 t input of appliance.

$$f_{wfd} = \frac{kg_{\sec.waste}}{1000 t_{input}}$$

The **waste for recycling factors** (f_{wfr}) are calculated as the ratio of kg of recycled waste per 1000 t input of appliance. This 'waste for recycling' results mainly from the additional process materials and is a couple product of the recycling process such as metal containing flue dusts or slags.

$$f_{wfr} = \frac{kg_{recycl.waste}}{1000 t_{input}}$$

Air emission factors (f_e) are calculated as the ratio of kg of emitted dangerous substance per 1000 t input of appliance.

$$f_e = \frac{kg_{ds}}{1000 t_{input}}$$

To assess and compare the emissions generated by the state-of-the-art treatment, various scenarios were set up. The emissions from state-of-the-art treatment are compared with emissions from the incineration of 1000 t of the appliance and the incineration of 1000 t municipal waste.

IV.3. Required data and availability

To calculate the emissions, several data sources are necessary:

1. The amount of WEEE as input to treatment
2. The composition of the input stream and location of dangerous substances
3. National treatment schemes
4. Emission and transfer factors for waste treatment facilities.

Amounts of WEEE
In the countries investigated statistical data on WEEE amounts is not available. Figures for collected WEEE are scarce and only available for some regions in Germany and Austria. To calculate the emissions from WEEE treatment at national level, estimated WEEE arisings data is used. This data is calculated from production, sales, lifetime and market saturation statistics and provide an upper limit for the WEEE amount entering the specific treatment scheme. This is because a certain percentage of the calculated end-of-life appliances are either stored in households, officially or unofficially exported or removed from the bulky waste stream.

Composition of WEEE and location of dangerous substances
The composition of WEEE is, generally, the same as that of the original appliance. Producers provide very limited information on product composition, especially on the content and location of dangerous substances. In the last year, however, several studies on product composition were published. Therefore data from literature and direct information from recyclers was used for this report. This information is quite reliable for appliances that currently enter the waste stream. For further investigations, especially projections of future emissions, changes in composition would have to be considered.

National treatment schemes

All of the five countries considered have regulations or rules for the treatment of WEEE, either as part of the general waste management system or specifically relating to the waste stream. Recycling facilities for the waste stream also exist, to differing extents, in the countries considered. None of the countries, however, have established monitoring systems that provide sufficient information to describe a representative 'treatment scheme' for the country or region. Therefore the same treatment scheme was used for each appliance for all countries. This treatment scheme is regarded as the state-of-the-art at present.

Emission and transfer factors for waste treatment facilities
For most of the processes used in the treatment scheme, data is available or could be obtained by direct contact to companies or from literature sources.

However, problems arose in relation to the link between input concentration and the emission of dangerous substances from metallurgical works. The Sevilla papers [29]and other scientific literature provide emission data in relation to the product output (emissions per t steel, copper produced etc).

Input related emission factors (emissions per t WEEE input) were obtained by recalculating the literature values. The emission data given in literature differs in a wide range.

For heavy metals this problem was addressed by making the assumption that dangerous substances are removed, to a large extent, by state-of-the-art treatment. Therefore minimum emission factors were used. Emission factors also account for emissions caused by process materials (e.g. limestone).

For POPs especially Dioxins this problem is more severe. POPs and Dioxins are generated during thermal processes. At present, there is insufficient scientific knowledge about mechanisms that lead to the generation of POPs from incineration and metallurgical works The average values for the emissions as stated in the Sevilla papers were therefore used.

Emission data available for metallurgical processes is listed in Table IV.1

Table IV.1: Data availability for metallurgical processes

Metallurgical process	Cd	Hg	Pb	PCDD/F	PCB
Aluminium Recycling				X	
Steel recycling	X	X	X	X	X
Copper recycling	X		X	X	
Copper recycling / printed circuit boards	X		X	X	
Copper recycling / printed circuit boards	X		X	X	
Lead recycling	X		X		
Incineration	X	X	X	X	X

X = data available

Detailed description of the five appliances and the state-of-the-art treatment for the appliances used to calculate the results.

Refrigerators
Refrigerators are of environmental significance because they contain chlorofluorohydrocarbons (CFCs). Refrigerators that were produced between 1990 and 1995 contain over 90 % R12 in the circulating coolant. By optimising the circulating coolant, it was possible to reduce the quantity of R12 that needed to be added. The change to isobutane as coolant followed in the mid-1990s. As well as R12 filled

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[29] The European IPPC Bureau (Sevilla) exists to catalyse an exchange of technical information on best available techniques under the IPPC Directive 96/61/EC and to create reference documents (BREFs) which must be taken into account when the competent authorities of Member States determine conditions for IPPC permits (http://eippcb.jrc.es/).

appliances, there are still smaller numbers of very large coolers which are normally used for commercial purposes and which are filled with R22 (CFC). About 2 to 5 percent of all refrigerators are adsorption appliances that are filled with an ammonia - water mixture to which chromium has been added for corrosion protection purposes. In insulation foam - polyurethane - R11 is to be found. This was replaced in the mid-1990s with n-pentane or c-pentane. Refrigerators being disposed of today are between fifteen and twenty years old and therefore contain both R12 and R11. The collection and treatment of appliances containing CFCs - even if in decreasing quantities - has therefore to be planned for at least up to the year 2010.

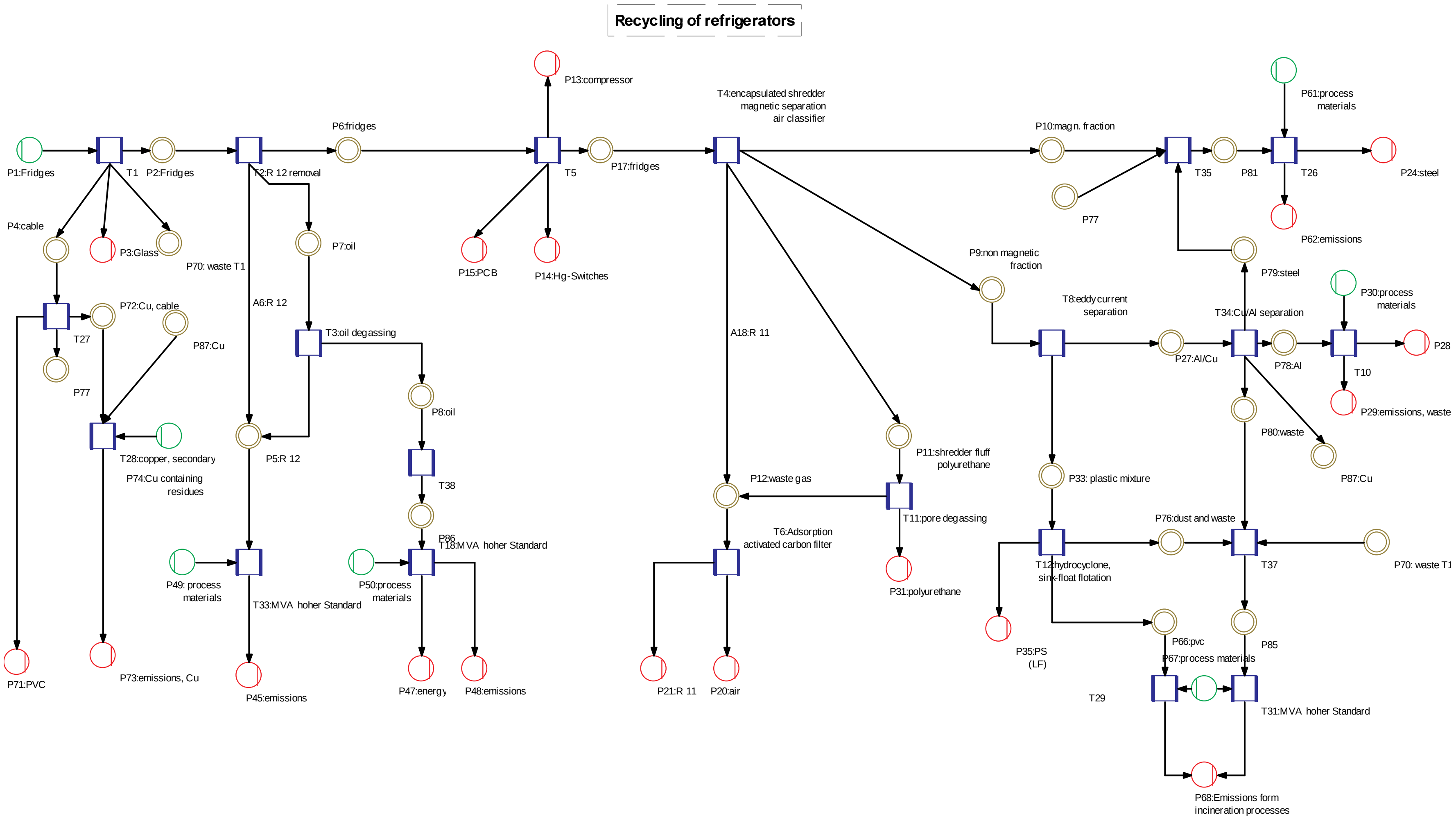
Information that refrigerators are collected separately and brought to special plants is available for the partner countries Austria, Spain (Catalonia) and Germany. However, details regarding the collection quota and method of disposal are missing. It is still the practice that refrigerators, for example, are shredded in unsealed plants and that insulation polyurethane foam from which gas has not been completely removed, is dumped or incinerated in household waste incineration plants. A leakage of R11 during transportation as well as from the dump has to be reckoned with. There is no data available regarding the practice for disposal in Ireland and Denmark

State-of-the-art treatment
The state-of-the-art treatment for refrigerators is illustrated in Figure IV.3: State-of-the-art treatment scheme for refrigerators. The calculations are based on an input of 1000t undamaged refrigerators, where the coolant circulation and insulation CFCs (R12, R11) are still intact[30]. Initially, all the loose interior parts such as glass shelves, racks and plastic parts are removed from the coolers and the electric cable is cut off. Following that, the cooling system is pierced and the coolant and compressor oil sucked out. Coolant and compressor oil yield depend on the size of the appliance and the duration of the suction. The best current achievable values were used. Having removed the compressors and dismantled further components containing dangerous substances (such as capacitors containing PCB, mercury switches), the appliance is shredded in a sealed shredder.

The magnetic fraction is sent directly to an electro-steel works. In other plants, the shredder heavy fraction is separated into aluminium, copper and polystyrene, which can be reused. The shredder light fraction, which consists mainly of polyurethane, is repeatedly ground to press out bound R11. Residual CFC in the polyurethane powder is approximately 1 %. Recovered polyurethane can be used as an oil binder. R11 is removed from the process air by passing it through an activated carbon filter. R11 is cracked in a high temperature plant to form hydrochloric acid and hydrofluoric acid.

[30] Between 20 and 30 % of refrigerators arriving at recycling plants are defective. As a rule, this means that the coolant circulation system has been damaged. We are assuming no damage prior to treatment for the state-of-the-art treatment. It should also be noted that precise data on the quantities of CFCs used in appliances was not readily available from cooler manufacturers, so the theoretical input values are based on average values.

Figure IV.3: State-of-the-art treatment scheme for refrigerators



TV
Televisions (TVs) contain a number of dangerous substances and traditional disposal at either landfill or incineration can lead to environmental problems. Disposal to landfill can result in increased concentrations of heavy metals in landfill leachate. Disposal at waste-to-energy facilities can result in the concentration of heavy metals in the ash, limiting disposal or reuse options.

For some time there has been a trend towards dismantling used TVs into several fractions, which can then be directed to either material recycling or energy recovery. This will be described below under state-of-the-art treatment.

State-of-the-art treatment
The state-of-the-art treatment for televisions is illustrated in Figure IV.4. The collected TV-sets are sent to a 'rough dismantling' process where they are manually dismantled. The components that are separated out are restricted to picture tubes, housing, cables and circuit boards.

The picture tubes are recycled in the 'picture tube recycling process'. Using a separating oven, cone glass and screen glass are separated from each other. Steel components from inside the picture tube are recycled in electro-steel works. Cone glass is reprocessed into working lead in lead works. Lead is used in solders (40 g/TV) and as oxide in the picture tubes. Colour picture tubes utilise leaded frit seals between the funnel and the face[31]. It was found that most of the investigated colour picture tubes exceeded the mandatory limit for leachable lead to be characterised as a hazardous waste, but none of the monochrome picture tubes did. The major contributor to leachable lead in monochrome picture tubes is the neck glass between the electron gun and funnel glass. Because cone glass contains silicon-oxide which is a slag-binding material (replacement for sand), it can be utilised in lead smelters. The coating on the screen glass is washed off in the 'light material removal' process. The coatings are disposed of in special waste depots while the screen glass is dumped.

Plastic housing and backs containing flame retardants are used for energy production after being broken up. Occasionally, pure sorted plastics, the quantities of which are not known, are recycled in special industries.

Dangerous substances are removed from the circuit boards. In this process, round cell batteries, and capacitors that are large or contain PCB are removed from the circuit boards and disposed of appropriately. The circuit boards are then sent to a copper works.

The cables are separated into different fractions. Fractions of iron, copper and plastic are formed and each sent for further processing. The magnetic fraction goes into the production of electro-steel in electro-steel works. The copper fraction is used to produce cathode copper in copper works. The PVC fraction is passed on to the plastic processing industry.

The remaining fractions from 'rough dismantling' are passed to the shredder in order to separate out the iron, copper, aluminium and plastic fractions. The iron fraction goes to electro-steel works, the copper fraction is passed to the copper works while the aluminium fraction is processed to form metallic aluminium in secondary aluminium works. The plastic fraction is converted into energy in a household waste incinerator.

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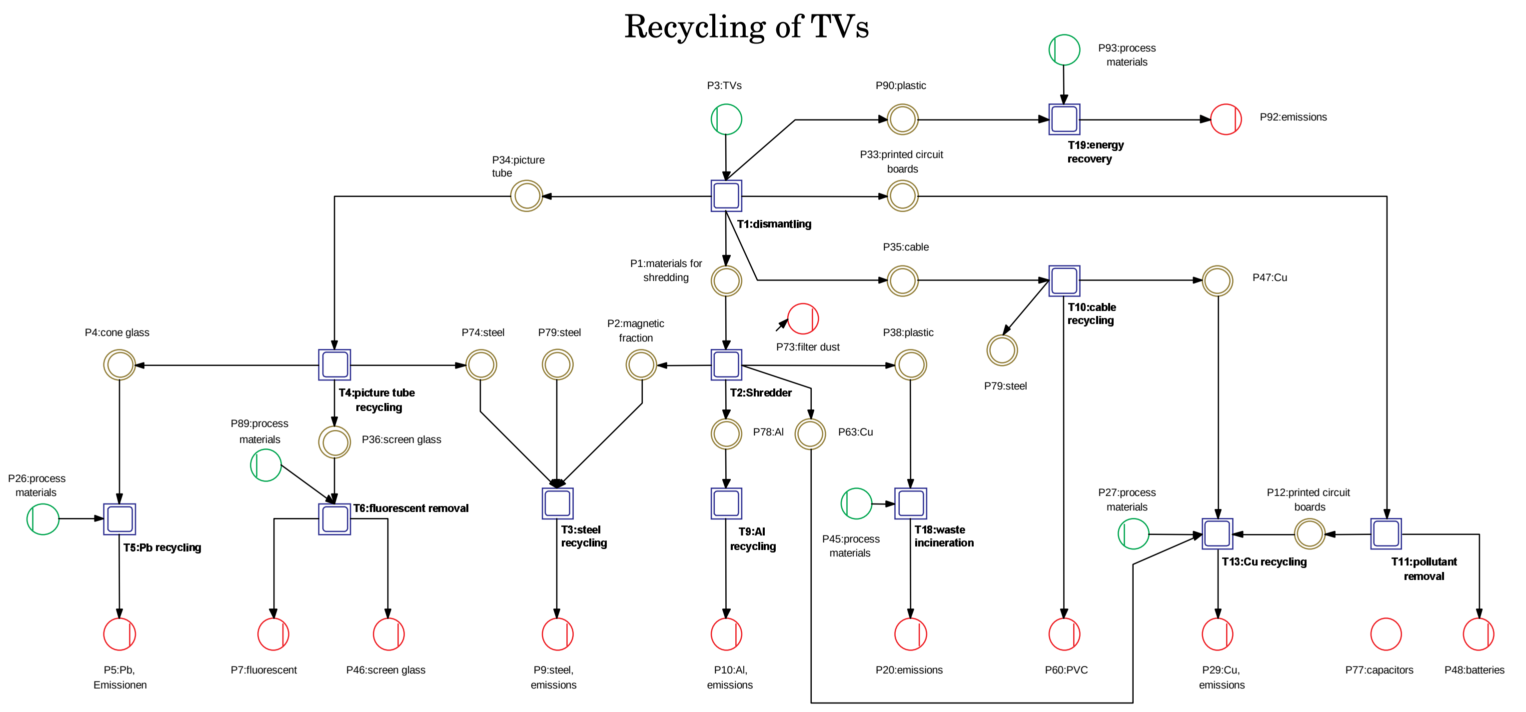
[31] Townsend, T. G. *et al.*, Characterisation of lead leachability from cathode ray tubes using the toxicity characteristic leaching procedure, Florida center for solid and hazardous waste management, Gainesville/Florida, Report 99-5.

Figure IV.4: State-of-the-art treatment scheme for television sets



Fluorescent tubes
Light sources are divided into two classes: incandescent lamps, where the light is generated by electrically heating a filament (not part of this report) and gas discharge lamps, where the light is generated from an electrical discharge of a gas or gas mixture which contains a small amount of mercury. About 25 % of the light sources installed in Europe are gas discharge lamps. They provide 70 % of all artificial light generated in Europe. The remaining 30 % is mainly produced by incandescent lamps which are predominantly installed in private homes. Approximately 350 million gas discharge lamps are sold each year in Europe. More than 90 % of these are fluorescent lamps of which less than 10 % are being used in domestic applications [32]. In private households it is expected that in the future incandescent lamps will be replaced by compact (single ended) fluorescent lamps. Single-ended fluorescent lamps currently represent about 3 % of lamps sold in Europe.

At present there is no substitute for the mercury contained in the lamps. Mercury is consumed in various mechanisms taking place in the lamp between the phosphorus and the inner glass bulb. The consumption rate depends on the type of phosphorus which is used to convert UV into visible light. The mercury consumption can be reduced by applying a barrier coating between the phosphorus layer and the inner glass bulb.

State-of-the-art treatment
The state-of-the-art treatment for fluorescent lamps is illustrated in Figure IV.5. Different recycling processes have been developed and are at present in commercial use. Most of them involve dismantling or shredding (wet or dry) at a mobile or stationary plant. In the following, the dry process is described. Equipment containing PCB was not taken into consideration.

In the cap separating machine the lamps are aerated with a spot burner. The end caps are broken off by heating and cooling. The fluorescent powder and the mercury are blown out of the glass tube. The process air is cleaned using cyclone and fine dust filters. Mercury is absorbed by an activated carbon filter, which is subsequently sent for mercury recovery. The glass tube is crushed and treated in a vibrating fluid bed. The remaining mercury and fluorescents are carried away by hot air, which flows through the bed. The end caps are crushed and passed through a vibrating fluid bed, which removes mercury, fluorescents and other fine grained particles (base cement, glass). In a separator the magnetic fraction is removed. The aluminium/brass fraction is removed via eddy current separation.

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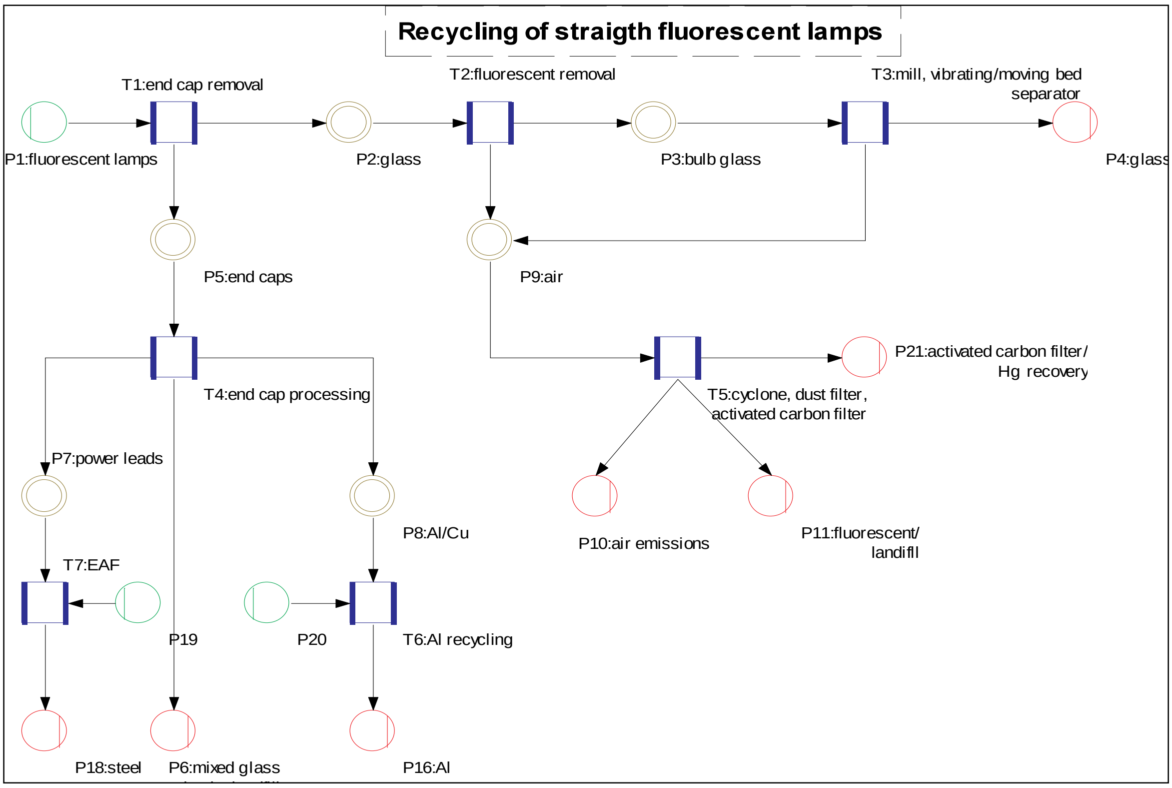
32 European Lighting Companies Federation ELC, Collection and Recycling of End-of-life Light Sources, Brussels, June 1998.

Figure IV.5: State-of-the-art treatment scheme for fluorescent lamps



PCs
Personal computers are of environmental significance because they contain both heavy metals and halogen-containing flame retardant.

Most of the heavy metals in PCs are to be found in the cone and screen glass in the picture tube, and in fully-furnished circuit boards. In cone glass, approximately 16 % PbO is added on average and in screen glass about 7 % BaO.

So-called flame retardants made from halogenated compounds are predominantly found in PC plastic parts. They account for about 15 % of the weight of plastic. According to one computer manufacturer, PBDE (poly-bromide-diphenyl-ether) was used until 1985 with TBB-A (tetra-bromide-biphenal A) or phosphoric-acid-ester together with antimony-oxide mainly used since then.

Up to forty different plastics are used in PCs, making recycling often impossible and leaving only energy utilisation as a realistic option. Since the 1990s steel parts have been increasingly substituted by plastic parts. As a result, there has automatically been an increase in the amount of flame retardants used in each PC. This trend is predicted to continue into the future and so the plastic parts used in PCs will play an ever greater role in PC recycling.

State-of-the-art treatment
The state-of-the-art treatment for PCs is illustrated in Figure IV.6. The collected PCs are sent to a 'rough dismantling' process where they are manually dismantled. The components which are separated out are restricted to picture tubes, cables and circuit boards.

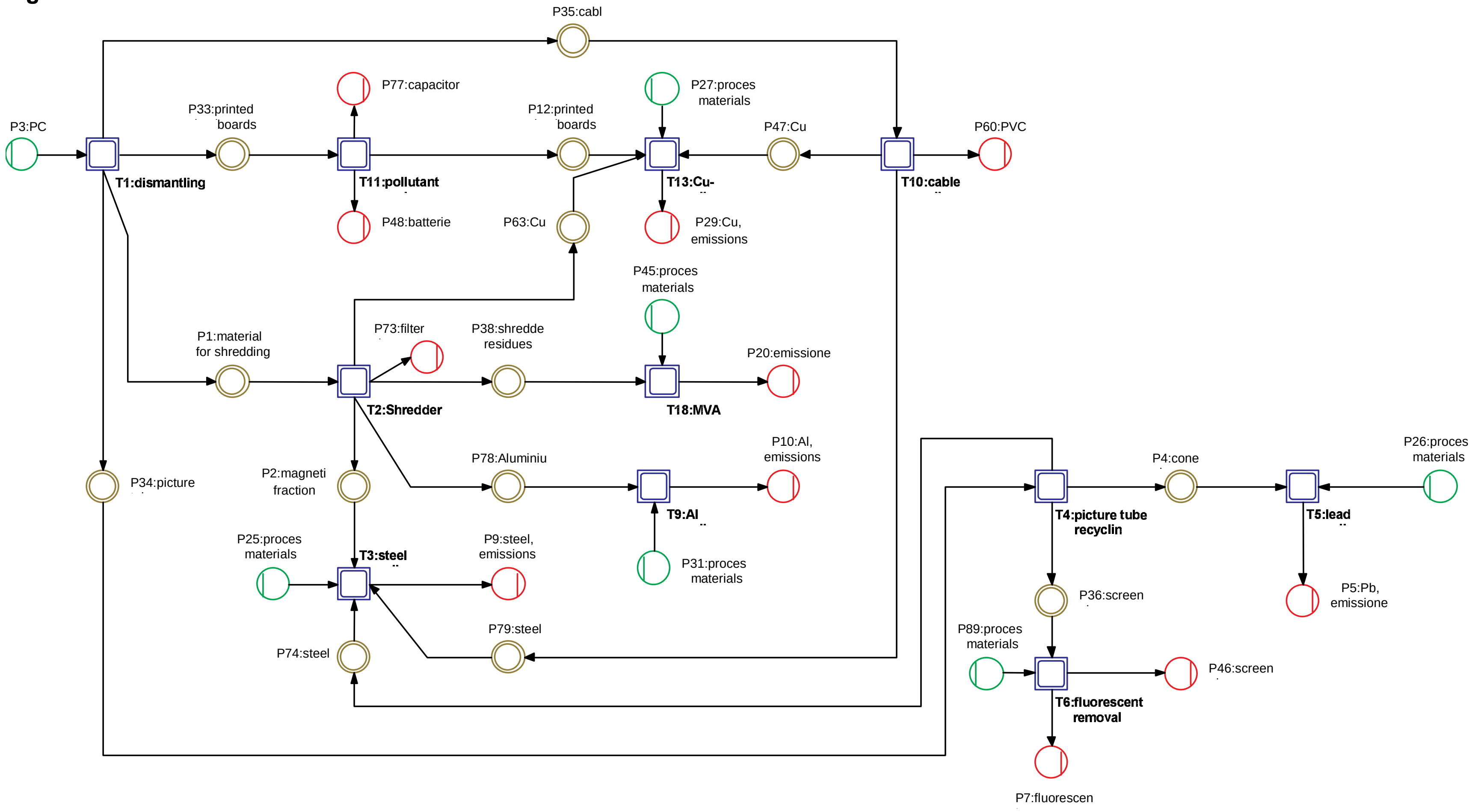
The picture tubes are recycled in the 'picture tube recycling process'. Using a separating oven, cone glass and screen glass are separated from each other. Steel components from inside the picture tube are recycled in electro-steel works. Cone glass is reprocessed into factory lead in lead works. The coating on the screen glass is washed off in the 'light material removal' process. The coatings are disposed of in special waste depots while the screen glass is stored in old mines.

Dangerous substances are removed from the circuit boards. In this process, round cell batteries, and capacitors that are large or contain PCB are removed from the circuit boards and disposed of appropriately. The circuit boards are then sent to a copper works.

The cables are separated into different fractions. Fractions of iron, copper and plastic are formed and each sent for further processing. The magnetic fraction goes into the production in electro-steel works. The copper fraction is used to produce cathode copper in copper works. The PVC fraction is passed on to the plastic processing industry.

The remaining fractions from 'rough dismantling' are passed to the shredder in order to separate out the iron, copper, aluminium and plastic fractions. The iron fraction goes to electro-steel works, the copper fraction is passed to the copper works while the aluminium fraction is processed to form metallic aluminium in secondary aluminium works. The plastic fraction is converted into energy in a household waste incinerator.

Figure IV.6: State-of-the-art treatment scheme for PCs



Small appliances
The term small appliances includes appliances that are normally disposed of with household waste and subsequently landfilled or incinerated depending on regional practices. Included in these appliances are small kitchen and household appliances, health and beauty appliances, clocks, power tools, toys, IT and telecommunications equipment, entertainment equipment and lighting. In accordance with the EU directive, they belong to categories 2-4,6 and 7. Household waste analysis provides the following weights:

Table IV.2: Quantities of small appliances in household waste

Category	% per weight
small household appliances	40
IT and telecommunication equipment	8
toys, clocks	1
consumer equipment	25
lighting equipment	4
electrical and electronic tools	2
other electrical and electronic scrap	20

The different appliances have different dangerous substance potential in terms of both type and quantity of dangerous substances. Dangerous substance components include:

- Mercury containing components: tube lights, batteries, round cell batteries, printed circuit boards, mercury temperature regulators (e.g. in heating and hot water appliances), irons;
- Ni-Cd-rechargeable batteries;
- Capacitors (PCB) e.g. in salon hairdryers, tube lights, parts containing asbestos (e.g. in toasters, irons, hair dryers);
- Printed circuit boards;
- Plastics with polybrominated diphenylethers (up to 15 % by weight).

State-of-the-art treatment
The state-of-the-art treatment for small appliances is illustrated in Figure IV.7. Once the appliances have been removed from the general waste stream, batteries, rechargeable batteries, cables and large steel parts are manually separated out. Capacitors which are clearly labelled as containing PCB and capacitors above a certain volume are separated out. After the manual dismantling, the remaining plastic, elastomer, glass, wood mix is incinerated. The other appliances, those not initially dismantled and those considered not to contain dangerous substances, are shredded in order to reclaim iron, copper and aluminium. The shredder residue, a mixture of light shredder fraction and filter dust is landfilled or incinerated. This fraction consists mainly of different plastics (with and without flame retardants) elastomers, textiles, wood and glass[33].

[33] Kommission der Niedersächischen Landesregierung zur Verwertung und Vermeidung von Abfällen, Abschlußbericht des Arbeitskreises 13 „Elektronikschrott“, Umweltministerium Hannover, 1997.

Figure IV.7: State-of-the-art treatment scheme for small appliances