Environmental impact analysis PVC

For priority streams in Dutch lifecycle-based waste policy

Final report

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Amsterdam, 21 April 2010

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ISO Doc. nr.	1012o (English version, October 2010)
Title	Environmental impact analysis PVC For priority streams in Dutch lifecycle-based waste policy
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This study was commissioned by the Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM).

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Summary

‘Lifecycle-based waste policy’ is the new approach in the Netherlands’ Second National Waste Management Programme (LAP2). During the second planning period (2009-2015) this approach is to be further elaborated for seven priority streams (material flows). The aim is a reduction of 20% of the lifecycle environmental burden, to be achieved in 2015.

One of these material flows is polyvinyl chloride (PVC). In this document the analysis is described for the environmental burden of PVC window frames, PVC pipes and PVC cables. Starting point is a LCA approach, with the use of the recent impact method ReCiPe. For the mentioned PVC applications two aspects are studied in detail. On the one hand the environmental burden of the total lifecycle is analysed for the PVC in the applications – the PVC production, the use and the waste treatment – as well as the effect of different modes of waste treatment. On the other hand the PVC applications are compared with the use of alternative materials. For the comparison of alternative materials the LCA norms ISO 14040/44 are not completely met, meaning that not all the stakeholders are questioned (for other materials than PVC standard data from international sources are used) and no external reviews are held.

The most important conclusions are:

- A lot of practical information is at hands about the production of the PVC polymer. For the additives (in particular stabilisers and plasticisers) that give PVC its qualities, this is not the case. This despite the fact that for example soft PVC, applied in cable sheaths, exists for 30% of plasticisers.
- Both for window frames and for pipes recycling is rewarding (a positive environmental effect compared to incinerating and landfilling). This profit is gained because a lot of primary PVC is avoided. Increasing the recycling of PVC offers a reduction potential. For soft PVC this is less certain, because not enough data is found to be able to calculate this with a LCA. The results for hard PVC show however, even taking into account that recycling of soft PVC is less profitable than of hard PVC because it saves less primary PVC, that it can be assumed that recycling of soft PVC is profitable for the environment compared to incinerating and landfilling.
  Some comments are:
    - For precise conclusions it is necessary to verify the inventory of recycle systems (with regard to the use of energy, emissions for separating, cleaning and grinding of PVC). The results in this report for recycling originate from only one source (VKG MRPI dossier).
    - For separating after collection – lacking better data – the same amount of fall out is assumed as for the system of separated collection of window frames. On the one hand this might mean that separating after collection is pictured too positive, because the level of fall-out can be bigger for pipes compared to window frames. On the other hand, separating after collection focuses primarily on the reuse of PVC in pipes. This process requires a little less strict demands than the reuse of PVC in window frames (which probably leads to fewer fall out).
    - Because the reuse of PVC in both pipes and window frames has the advantage of diminishing the production of primary PVC, for this study it is not relevant whether the original application is reused in the same product (frames as frames and pipes as pipes) or in another product.
    - Filling in and leaving used pipes in the ground – until recently a common practice – is not a good option from a sustainable perspective. The materials that are left behind do not cause problems on a local scale, but because the materials are not reused, the production of primary PVC is also not avoided and therefore this practice is a relevant ‘missed chance’.
- For window frames recycling is the best alternative. Of the investigated alternative materials for window frames aluminium has nearly the same environmental burden compared with PVC. For wood the scores are not as good when the effects of land use are included and more or less equal when land

use is not taken into account. However, the recycling of PVC window frames is crucial. When the window frames are incinerated, aluminium (of which certainly a high percentage is recycled) scores better than PVC.

- Also for pipes is up scaling of recycling important to achieve reduction. PVC scores the best, in comparison with other materials, when recycling takes place. When PVC pipes are not recycled, than concrete scores better (assuming that recycling for this material is certain).
- Changing from PVC to rubber increases the environmental burden of electricity cables. From a LCA perspective and because of the results for window frames, it seems a good idea to further investigate the possibilities for further recycling of PVC in cables. Specific data about recycling of PVC cables which is usable for a quantitative environmental analysis is still lacking.

1. Introduction

1.1 Background

In the Dutch Second National Waste Management Programme (LAP2) a lifecycle-based approach has been adopted as a new policy framework. During the second planning period (2009-2015) this approach is to be further elaborated for seven material flows, in order to achieve 20% reduction of lifecycle environmental burden by 2015. One of these seven priority streams is polyvinyl chloride (PVC)[1].

In support of these policy intentions an environmental lifecycle assessment is needed for the current situation, the 'status quo', as a reference, and to show the available scope for improvement.

1.2 Goal

The goal of this project is to investigate the present (the reference situation) environmental impact of the PVC streams. This reference analysis covers the entire product chain from raw materials all the way through final waste disposal, in order to establish the magnitude of the aggregate lifecycle impact, and also the precise activities contributing most to that impact. Based on the reference analysis, a number of options for improvement are identified and an assessment is made of the potential environmental gains that can be achieved.

1.3 Reading guide

This report describes the reference analysis for the PVC stream and alternatives to reduce the environmental burden. Because of the lack of accurate data about the amount of PVC per application[2] the results are shown per weight unit (applied) PVC and for each characteristic unit (square meter, running meter depending on the product category) which can be compared. This implies that when the results for example for recycling are presented, this is 100% for recycling[3]. The reader can therefore build scenarios with a mix for disposal, incinerating and recycling. In chapter 2 the method is explained. Described is which restrictions are chosen, which references are used and which environmental themes are taken into account and which method for weighting is used. Chapter 3 describes the inventory. Chapter 4 describes the result: the impact per unit PVC for extraction of raw materials, production, use and waste treatment. In chapter 5 the environmental impact results of the alternatives are presented. Chapter 6 describes the conclusions and suggestions for further research. Appendix 3 holds the tables with the numbers that are shown in the bar charts throughout the report.

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[1] The other priority streams are textile, construction and demolition waste, bulky domestic residual waste, paper and cardboard, aluminum and food waste. For these streams a separate reference analysis is done. This report covers PVC.

[2] A separate analysis about the magnitude of the streams started in April 2010.

[3] Besides fall out which is inherent to recycling and which follows another route for treatment.

2. Method

2.1 Procedure

In this report the environmental burden of the PVC sub streams for window frames, pipes, cables (used for white and brown goods and wires) is presented, including options for improvement.

2.1.1 PVC reference and alternatives

The PVC reference and alternatives are:

1. Window frames
    - Alternatives are recycling, incinerating and disposal in landfill sites.
    - Besides PVC is compared to aluminium and wood.
2. Pipes (hard PVC)
    - Alternatives are recycling, incinerating and disposal in landfill sites.
    - The alternative to 'fill in and leave in the ground', thus no treatment, is analysed as well.
    - Finally a comparison is made between pipes of PVC and pipes of stoneware, concrete and polyethylene.
3. Cables (used for white and brown goods and in wires = soft PVC) and wire
    - Alternatives are to separate the PVC from the copper and then landfill, incinerate or recycle the PVC.
    - Also is analysed what happens when the PVC is exported to for example China: cable burning, with dioxins emissions to air.
    - Finally a comparison is made between PVC and rubber in this application.

For the comparison of alternative materials the LCA standards ISO 14040/44 are not completely met, as not all the stakeholders were involved (for other materials than PVC standard data from international sources were used) and no external review was held.

2.2 Scope and definition

PVC chain

The reference analysis is needed to further develop the lifecycle-based approach of the waste management policy. The starting point for this is the amount of PVC waste in the Netherlands per year.

Early 2010 a separate study started about the quantity of PVC waste from several sub chains. Therefore the LCA results in this report are given in weight units (or per product unit in which PVC is applied), when possible separately for 'extraction', 'production', 'use' and 'waste'. When the volume results are published than the related environmental burden for the reference situation and the alternatives can easily be calculated.

System outline

The entire product chain is taken into account, from raw materials to the disposal phase:

- Extraction of raw materials
- Production of (bulk) materials
- Shaping (such as extrusion and injection moulding)
- Use and maintenance
- Alternatives for disposal

- Transport and energy requirement in the above mentioned phases, including the production of energy carriers.

In chapter 3 more details are provided which aspects for each PVC sub chain are taken into account.

Allocation

Allocation plays a role in LCA in three types of processes:
- multi-input processes, such as waste treatment;
- multi-output processes, such as chlorine production (including emissions of hydrogen, NaOH and NaOCL);
- allocation of the avoided production or avoided emissions, in case of recycling.

In this reference analysis for the multi-input and multi-output processes economic allocation is used. In economic allocation is assumed that the 'co product' that is financially the most profitable, is also responsible for the largest share in the environmental impact of the preceding chain. Some variety through time is possible, but the long standing averages generally show limited variation.

The allocation of avoided emissions from production plays a role when materials are recycled in an open loop. When materials from chain A are used in chain B than normally this means avoided production (including emissions) but it is not unequivocally which chain is responsible for this. In theory for these situations the system could be elaborated, but in the project appendix is described why this is undesirable. In the waste treatment of PVC this takes place: the use of recyclate (see paragraph 3.5.1) and recovery of energy in a municipal waste incineration plant (MWIP). We have allocated the profit from this avoided production for 100% to the PVC.

Short cyclic CO_2

In LCA analyses it is important to decide how short cyclic CO_2 is taken into account. Biotic raw materials such as wood absorb CO_2 in the production phase. In the disposal phase this CO_2 is released again. There are two options:
1. Take the CO_2 into account when it is absorbed at the beginning of the chain, and when it is released at the end of the chain.
2. Leave out the short cyclic CO_2, because the net impact is zero.

For a Cradle-to-Grave LCA, in which the entire chain is taken into account, there is no difference which option is chosen. The results will be different for each phase, but the overall result will be the same. For a Cradle-to-Gate LCA in which only the emissions up to production are taken into account, the different methods have a different result. When short cyclic CO_2 is included, in the Cradle-to-Gate LCA the short-cyclic CO_2 is taken into account in the product, but because the disposal phase is not included, the emissions of short cyclic are also left out. In case of leaving out the short cyclic CO_2, the absorption of CO_2 in the product phase is not included, causing a difference at the 'Gate' in the two approaches, equal to the amount of CO_2 absorbed[4]. This does not play a role in this study because we apply the Cradle-to-Grave approach.

Only when the short-cycle CO_2 is conversed to methane, for example in the digestion system of ruminants (production of meat, milk), the global warming potential of methane should be corrected[5]. In this study about PVC this is not relevant.

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[4] In practice this is difficult in the Cradle-to-Gate LCA's in which fossil and bio-materials are compared.

[5] This is prescribed among others, in the PAS2050 guideline, but outside this context it is (still) not often applied.

Within the impact method ReCiPe which is used in this study (see paragraph 2.3) short cycle CO_2 is left entirely out and this is followed in this study. This implies that data for the production of bio-materials (wood, food) do not hold CO_2 absorption and data for waste treatment no emissions of CO_2. For the complete chain the net effect is zero, but it is relevant for the question which life-cycle phase has the largest environmental impact. For this study the choice has little effect because CO_2 does not play a role but for other priority streams (see paragraph 1.1) this could be relevant.

Land use and LULUCF[6]

Land use is an important theme, but has a somewhat anomalous status compared with other themes under study. In itself, land use is not really an environmental impact but rather an intervention leading to impacts, including biodiversity losses, changes to water tables and so on. All these impacts depend very much on the precise location where the land use is taken place and in a lifecycle inventory this is not generally known in any great detail. Because these impacts are potentially very important, in this study land use is used as an indicator. Whether or not land use is included is crucial in the assessment of the recycling of renewable materials such as wood.

The greenhouse gas emissions and loss of biodiversity associated with land use and, particularly, land use change (LUC), such as deforestation to create new cropland, may be very substantial. The precise allocation of concrete LUC to a particular product is tricky, however because it is scarcely ever feasible to trace a product back to a particular plot of land. Because of these uncertainties LUC and LUC impacts have not been included in our reference analysis. Neither have the sinks[7] or emissions associated with land use been included.

For certain flows, such as food – one of the six other priority streams – this probably means an underestimation of the aggregated impact, because in several flows deforestation and intensive agricultural practices take place. Both practices have a significant impact on biodiversity and the carbon balance. Owing to the major uncertainties in both the measurement and allocation of these impacts, as stated, this has been left out of consideration. This obviously means that it must likewise be ignored when calculating options for improvement. This means both the reference analysis and the reduction potential are lower in absolute terms. When considering any specific measures to improve performance, though, due care should be taken that these do not lead to any increase in Land Use Change, as this has not been factored into the analysis. For the PVC flow land use, short cycle CO_2 and emissions from LULUCF play a relatively small role compared with for example food chains. In this study this only plays a role for window frames when PVC and wood are compared (paragraph 5.1).

2.3 Data

Public process databases are used as much as possible, such as for example de Ecoinvent LCI[8] database and IVAM LCA Data, and other published LCA studies. These often focus on the average European or even worldwide production. For sub flows that are related to consumption in the Netherlands these data sources are generally representative. When there is a choice of several processes and there are no or just small arguments for one of the processes, than the use of Ecoinvent has an advantage because of the systematic approach and thus because mistakes are avoided when the processes are compared (because different background data might be used). Data is also gathered in the specific economic branches, for example via the 'Vereniging Kunststof Gevelelementenindustrie' (the association for plastic façade elements industry and the 'Buizen Inzamel Systeem' (BIS, the pipe collection system) and from literature sources.

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[6] Land Use, Land Use Change and Forestry.

[7] The sequestration of carbon in soils as a result of natural processes.

[8] LCI = Life Cylce Inventory, from which the environmental impact can be calculated.

The use phase is taken into account but in this report is shown that the impact is nearly zero and therefore it is not included in the analysis. For PVC window frames it concerns mainly transfer of heat and the maintenance with cleaning and – only for aesthetic reasons – to apply lacquer. For cables in the use phase probably emissions of plasticisers take place. For pipes nearly no maintenance takes place. The waste treatment takes place in the Netherlands, with the exception of the share of PVC waste that is exported for re-use.

For the inventory capital goods are left out as much as possible. However, in databases such as Ecoinvent it is not possible to exclude capital goods entirely. For some impact categories such as eco-toxicity, capital goods can contribute significantly, for example through the metal infrastructure in fossil production chains. This will in some cases come forward in the analyses and then can be adjusted.

2.4 Impact assessment, environmental impact categories & weighting method

Once the aim and scope of the LCA have been established and the required data collected, an aggregated inventory result is calculated. This inventory result is a very long list of emissions, raw materials consumed and sometimes other quantities, too. Interpretation of this list is not easy. To aid interpretation, a life cycle impact assessment (LCIA) method can be used. The LCIA results in this report have been calculated using the ReCiPe method, which in turn builds on Eco-indicator 99 and CML 2 methods, both in common use.

2.4.1 ReCiPe

The main aim of the ReCiPe method is to convert the long list of inventory results into a limited number of indicator scores. These scores indicate the relative seriousness of each environmental impact category. In ReCiPe, indicators are distinguished at three levels:

1. Eighteen midpoint indicators
2. Three endpoint indicators
3. A single score indicator

The model used in ReCiPe is based on the concept of environmental mechanisms, to be regarded as a series of impacts that together cause a certain level of harm to, say, human health or ecosystems. In the case of climate change, for example, we know that a number of pollutants lead to increased radiative forcing, which means a reduction in the amount of heat radiated from earth back into space. The upshot is that more energy remains on the planet and that global temperatures rise. As a result we can expect changes in the natural environment that is home to biological species, with as a potential consequence a certain fraction of these species becoming extinct. This example is shown in Figure 1.

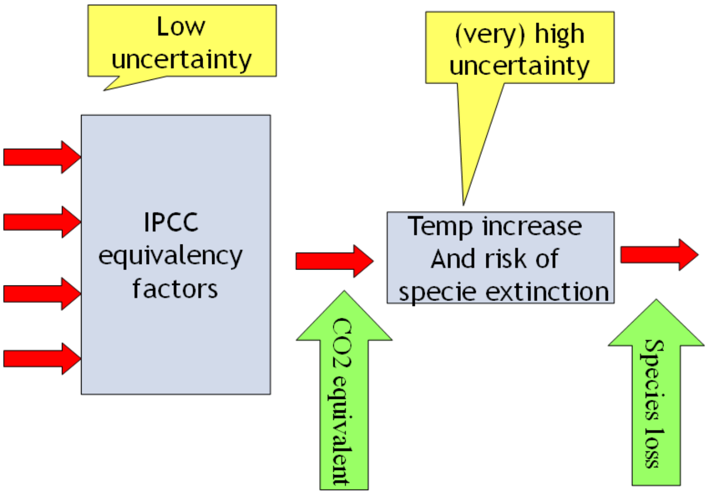

Figure 1 Example of a harmonised midpoint-endpoint model of climate change, coupled to human health and damage to ecosystems [source: www.lcia-recipe.net]

As this example makes clear, the longer the environmental mechanism that is adopted, the greater will be the uncertainties. While radiative forcing (in Figure 1 the 'IPCC equivalency factors') is a physical parameter that is fairly simple to measure in the laboratory, the resultant temperature rise is less straightforward to determine, as there are numerous positive and negative impacts acting in parallel, our understanding of likely changes in the natural environment is incomplete, and so on.

The clear advantage of only including the first step is thus the relatively low degree of uncertainty but the disadvantage is that radiative forcing does not show directly its consequences. Therefore it is less easy to interpret and to compare with other impacts on the environment.

2.4.2 ReCiPe combines mid- and endpoints

In ReCiPe, factors have been calculated for eighteen of these midpoint indicators, as well as for three far more uncertain endpoint indicators. The reason for also calculating endpoint indicators is that the large number of midpoint indicators is very hard to interpret, partly because of the sheer number and partly because their meaning is highly abstract. How is one to compare 'radiative forcing' with 'base saturation', the measure of acidification, for example? The indicators at the endpoint level are intended to facilitate the interpretation process, because there are only three in number and because they are more readily comprehensible.

The idea is that each user can choose the level at which they wish to have their results:

- Eighteen relatively robust midpoints that are hard to interpret, though,
- Three easy to understand but more uncertain endpoints:
  - Damage to human health ('years/quality of life lost').
  - Damage to ecosystem ('lost species times years').
  - Damage to resource availability ('surplus cost of extraction').

The user can thus choose between uncertainty in the indicators themselves and uncertainty in correct interpretation thereof. This study focuses on the assessment of a relative reduction; therefore a correct interpretation of the indicators (the relation of the different impact categories) is important. This is way 'endpoint' is chosen.

Figure 2 provides a synopsis of the overall method structure.

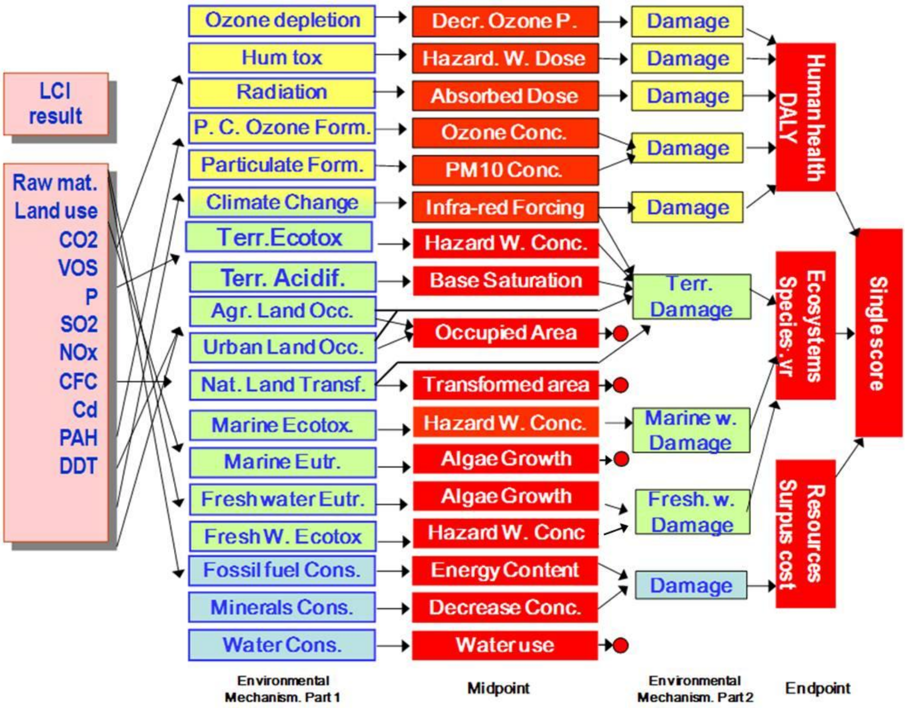

Figure 2 *Outline structure of the ReCiPe method [source: www.lcia-recipe.net]*

Note that water consumption and marine eutrophication are not included at endpoint level. The theme of climate change (unit: CO_2 equivalents) breaks down into tow midpoint categories: one contributing to the endpoint category 'human health' (unit: 'years/quality of life lost'), the other to the endpoint category 'ecosystem damage' (unit: lost species times years'). The factors in between the midpoint and endpoint categories are given in Appendix 1.

In Table 1 provides a summary of the environmental themes that have been included in the present reference analysis with their respective units. In the reference analysis the category land use change has been left out (see paragraph 2.2). To determine the aggregate impact, the scores on the various different impact categories need to be weighted. To this end the ReCiPe H/A weighting set has been used, with European normalization. This weighting set is available as a standard in ReCiPe and assigns a weight of 40% to both human health and ecosystems and a weight of 20% to resource depletion. In this report, when the term 'environmental burden' is employed without any further explanation, this is to be taken to refer to the 'single-score' result, calculated according to this weighting set[9]. This is the basis for the reference analyses, which are used to assess the environmental burden reduction targets.

All the results in this report are expressed in Pt, that is, they have been normalized and weighted.

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[9] ReCiPe 2008 method, version 1.02, October 19th 2009 [www.lcia-recipe.net]. Adapted to this analysis by explicitly excluding land use change and the associated CO_2 emissions, normalisation without the contribution of land use change and a PM formation characterisaton factor for PM2.5 that is 1.577 times higher than for PM10.

Table 1 Impact categories (Midpoint indicators)

Impact category	Unit	Name - short
Climate change Human Health	DALY[(a)]	Climate, health
Climate change Ecosystems	Species.yr	Climate, eco
Ozone depletion	DALY	Ozone depl.
Terrestrial acidification	Species.yr	Acidification
Freshwater eutrophication	Species.yr	Eutrophication
Marine eutrophication[(b)]		
Human toxicity	DALY	Human tox
Photochemical oxidant formation	DALY	Summer smog
Particulate matter formation	DALY	Particulate m.
Terrestrial ecotoxicity	Species.yr	Ecotox, terr
Freshwater ecotoxicity	Species.yr	Ecotox, freshw
Marine ecotoxicity	Species.yr	Ecotox, marine
Ionising radiation	DALY	Ion. radiation
Agricultural land occupation	Species.yr	Land, agr
Urban land occupation	Species.yr	Land, urb
Water depletion[(b)]		
Minerals depletion	$	Minerals depl.
Fossil depletion	$	Fossil depl.

2.4.3 Brief explanation of ReCiPe midpoints

Climate change, Human health & Climate change, Ecosystems

Climate change, the reinforced greenhouse effect, triggers a number of environmental mechanisms of influence on the endpoints ‘human health’ and ‘ecosystems’. Because these endpoints are expressed in different units (DALY and species.yr) they are already split at the midpoint level. Carbon dioxide (CO_2) is the best known greenhouse gas.

Ozone layer depletion

Most atmospheric ozone is found at an altitude of around 15-30 kilometres and this part of the atmosphere is therefore known as the ozone layer. This layer absorbs much of the damaging ultraviolet radiation emitted by the sun and since the 1980s there has been a general decline in its thickness. Each year in spring, over half the ozone over the South Pole still disappears for a while. Above our part of the world, the ozone layer has also grown thinner. Here too this reduction is greatest in spring; although by autumn levels are almost back to normal. The ozone layer is depleted by a variety of gases, including chlorofluorocarbons (CFCs). These end up in the ozone layer, where they break down, releasing the chlorine atoms, which in turn destroy the ozone molecules to yield chlorine monoxide and oxygen (Cl + O3 -> ClO + O2). The UV radiation then breaks down the chlorine monoxide molecule into two free atoms, after which the chlorine atom goes on to break down another ozone molecule.

Acidification, terrestrial

Acidification of soils (and water) is a consequence of air pollutant emissions by factories, agricultural activities, power stations and vehicles. These acidifying emissions include sulphur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3) and volatile organic compounds (VOC), which are transported via the atmosphere or the water cycle and end up in soils. This is referred to as acid deposition. By way of foliage and root systems these substances penetrate trees and other plants, making them more susceptible to disease. Acid deposition also causes damage to lakes and rivers, ultimately harming the wildlife that lives or drinks there, because of elevated acid and aluminium concentrations.

Eutrophication, freshwater
Eutrophication is the term used for elevated nutrient concentrations in water in particular. In biology it is used to refer to the phenomenon of certain species exhibiting strong growth and/or reproduction following addition of a nutrient surplus, generally leading to a sharp decline in species richness, i.e. loss of biodiversity. Eutrophication may occur, for example, in freshwater bodies subject to fertiliser run-off, particularly nitrogen and phosphate deriving from manure, slurry and artificial fertilisers from farming activities. The result is pronounced 'algal bloom', recognisable as dark-coloured water masses with an unpleasant smell. Eutrophication can lead to hypoxia, a deficiency of oxygen in the water.

Human toxicity
The impact category 'human toxicity' covers emissions to air, water and soils that result (ultimately) in damage to human health.

Photochemical oxidant formation
Photochemical oxidant formation, or smog (a combination of the words 'smoke' and 'fog'), is a form of air pollution involving mist polluted by smoke and exhaust fumes, which may in certain periods suddenly increase in severity, with potential consequences for human health. The substances of greatest influence on smog formation are ozone and airborne particulates and, to a lesser extent, nitrogen dioxide and sulphur dioxide.

Particulate matter formation
Particulate matter (PM) refers to airborne particulates with a diameter of less than 10 micrometres. It consists of particles of varying size, origin and chemical composition. When inhaled, PM causes health damage. In people with respiratory disorders and cardiac problems, chronic exposure to airborne particulates aggravates the symptoms, while in children it hampers development of the lung function. The standards for particulate levels are currently exceeded at numerous locations in Europe, particularly along busy roads.

Ecotoxicity, terrestrial, freshwater and marine
The impact category 'ecotoxicity' covers emissions to air, water and soils that result (ultimately) in damage to the ecosystems in soils, freshwater and marine waters.

Ionising radiation
Ionising radiation results from the decay of radioactive atoms like those of uranium-235, krypton-85 and iodine-129. There are two types of ionizing radiation: particle-type radiation (alpha radiation, beta radiation, neutrons, protons) and high-energy electromagnetic radiation (X-rays, gamma radiation). Ionising radiation can damage DNA and cause a variety of cancers.

Land use, agricultural and urban
The impact category 'land use' refers to the damage to ecosystems associated with the effects of human land occupation over a certain period of time. Because of insufficient inventory data and uncertainties in these data, in the results presented in this report the ReCiPe category 'land transformation' has been left out of consideration (see paragraph 2.2)

Depletion, minerals and fossil
Consumption of mineral resources and fossil fuels has been weighted using a factor that increases in magnitude as the resource in question becomes scarcer and their concentration declines. The measure used is the marginal increase in extraction costs (expressed in Dollars per kg).

3. Inventory

This chapter gives an overview of which data is used to calculate the results.

3.1 PVC production

The production of vinyl chloride exists of two steps. From ethene and chlorine gas dichloroethane is produced, with iron(III) chloride as a catalyst. Then this dichloroethane is broken down into vinyl chloride (chloroethene) and hydrochloric acid. Approximately 30% of the world production of chlorine is used for vinyl chloride production. From the vinyl chloride monomer (VCM) the thermoplast polyvinyl chloride (PVC, a white powder) is formed, after polymerization.

Ecoinvent relies for PVC on the most recent 'ecoprofile' information of Plastics Europe[10]. This data, and the way they are composed, is seen as the best available in the LCA world. This data is used as basis to calculate the results, which are presented in this report.

The data in the Ecoinvent process inventory data sheets for PVC production are aggregated, as are the data from Plastic Europe. This implies that although more chain steps exists (chlorine production, production of the monomer) the contribution of the underlying processes is not visible in the total environmental burden of PVC.

For this report however, this insight is needed, and for the calculation of sub processes other sources are used, whether or not available in the Ecoinvent database. To avoid misunderstandings we specifically note that for the production and the avoided production of PVC the most recent data is used from the Ecoinvent database. Where other sources are mentioned these are used to gain an impression of the contribution of the several chain steps to the total environmental burden.

3.1.1 Chlorine production

Chlorine is produced when a sodium chloride solution is electrolysed. This can be done with three processes:

- Mercury cell electrolysis (56%), out of date and forbidden after 2010 (still used on a large scale in 2005).
- Diaphragm cell electrolysis (11%).
- Membrane cell electrolysis (33%), at present the most used method.

The above mentioned percentages originate from the Eco-profiles report about chlorine [Ostermayer, 2006a]. In this report the aggregated data about chlorine production is presented, based on the above mentioned production percentages and allocation on mass basis for multi-output (with the production of chlorine also hydrogen and sodium hypochlorite are produced). This process is not available in the Ecoinvent database, and therefore it is not possible to analyse in more detail. The above mentioned mix of chlorine processes is used in this report to calculate the results for PVC production (and also to assign to the avoided PVC production when PVC is recycled).

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[10] Reports 2005; last calculations 2005-2007.

We had a look at other processes in the Ecoinvent database to gain more insight in the chlorine production. The Ecoinvent process 'Chlorine, liquid, production mix, at plant/RER U'[11] is based on data of the Association of European Chlorine Producers (EuroChlor). Also here allocation of the Multi-output is based on mass. The data of the individual processes are based on averaged values of the bandwidths from EC IPPC-BAT documents. The shares of production methods (the production mix) based on the official statistics from EuroChlor, differ a little from those of Plastics Europe:

- Mercury cell electrolysis (55.1%);
- Diaphragm cell electrolysis (23.5%);
- Membrane cell electrolysis (21.4%)

The process uses also energy for liquefying the gas. A separate analysis shows that the membrane cell and diaphragm cell electrolysis have approximately the same environmental burden, and the mercury cell electrolysis scores 25% worse. Because the differences in the several production mixes relate mainly to membrane- and diaphragm electrolysis, the difference in environmental burden is rather small.

These processes are used for a sensitivity analysis, whereby the 56% of the mercury cell electrolysis is replaced by diaphragm cell- and membrane cell electrolysis (in a ratio of 1:3, see the last column in the figure below).

A fourth production route for chlorine offered by Ecoinvent ('Chlorine, gaseous, lithium chloride electrolysis, at plant/GLO U'), whereby is allocated on the basis of stoichiometry, has a much higher environmental impact. Because none of the references mention this production route in relation to PVC production, this process is not taken into consideration.

Figure 3 presents the results, for 1 ton chlorine production, expressed in normalised and weighted ReCiPe points according to:

1. Diaphragm cell electrolysis
2. Membrane cell electrolysis
3. Mercury cell electrolysis
4. Production mix (liquid): 11% diaphragm, 33% membrane and 56% mercury cell electrolysis; this is used as a standard in the calculations for this report.
5. 75% membrane and 25% diaphragm electrolysis; this is used for a sensitivity analysis to show the effect of this near future scenario.

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[11] 'RER' is the Ecoinvent code for Europe; 'U' stands for 'unit process' which means that is build up from single processes (thus non-aggregated); in contrast to 'S' which describes the underlying system in one data sheet. When the reference uses aggregated data, then this is used as well because there is no distinction between the 'U' and 'S' process.

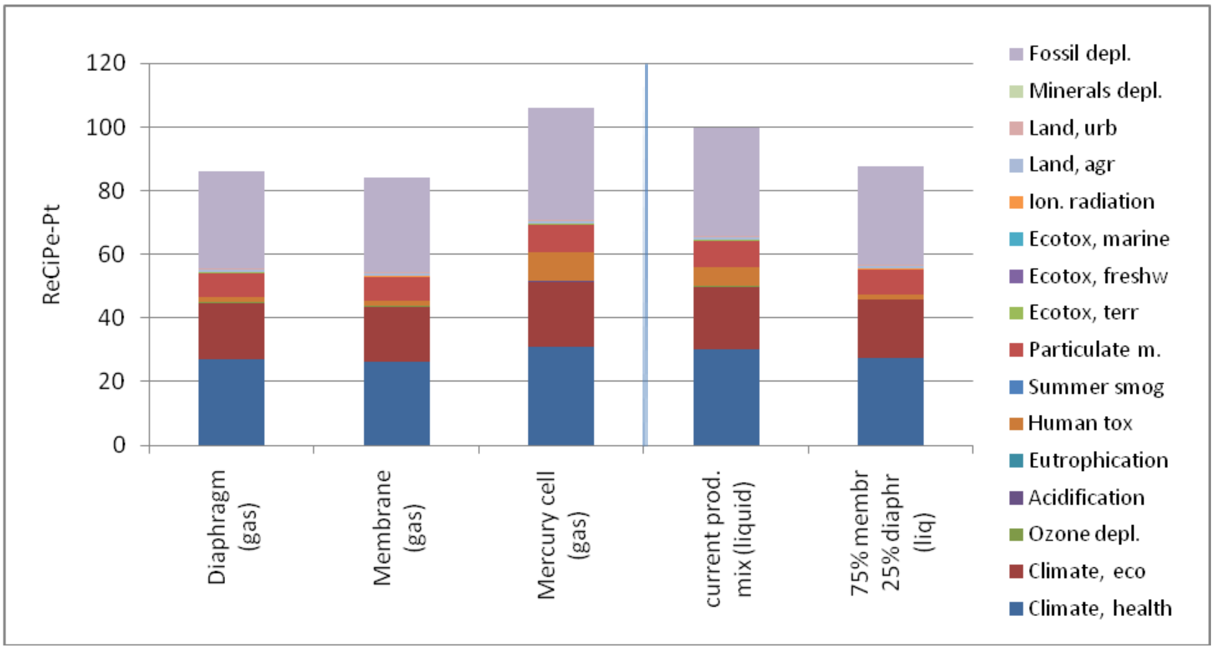

Figure 3 Chlorine gas production made by three production routes, the present production mix for liquid chlorine and the adapted production mix for liquid chlorine (without mercury cell); each per ton

In all the routes of chlorine production approximately 85% of the score is determined by the use of fossil fuels and climate change, with effects on human health and ecosystems as a result of the energy requirement. The future production mix based on 25% diaphragm- and 75% membrane electrolysis, means that 12% reduction compared to the present chlorine production mix, which still uses the mercury cell electrolysis.

Based on this is decided that it is not necessary to add calculations for a sensitivity analysis to the calculations based on the recent ecoprofile of Plastics Europe (see paragraph 3.1) in order to visualise the effect of the several routes of chlorine production.

3.1.2 Vinyl chloride production

The process 'Vinyl chloride, at plant/RER U' describes cradle-to-gate production of the monomer. The data are aggregated. In this study this process is not used because the more recent ecoprofile of Plastics Europe is used, but it is used to visualize to which extent the sub process 'Production vinyl chloride monomer' determines the environmental burden (see paragraph 3.1).

The production of VCM and dichloride ethane is also source of dioxin emissions. Dioxin is a POP[12]. These dioxin emissions are often not taken into account in LCA because the concentration in the air on the work floor is lower than the allowed maximum concentration. This, however, does not inform us about the total amount of dioxins which are emitted during the production. It is possible that with this assumption dioxins will be wrongly excluded and not contribute to the total environmental burden of the PVC product. Dioxins are in 'Vinyl chloride, at plant/RER U' and also in the recent ecoprofile of Plastics Europe part of the inventory and consequently are taken into account in this study.

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[12] Persistent Organic Pollutant

3.1.3 Polyvinyl chloride production

"Polyvinyl chloride, at regional storage/RER U" uses the European average of the three production routes, for which the polymerisation process differs:

- 85% suspension PVC ("Polyvinyl chloride, suspension polymerised, at plant/RER U[13]");
- 10% emulsion PVC ("Polyvinyl chloride, emulsion polymerised, at plant/RER U[13]"); en
- 5% bulk PVC ("Polyvinyl chloride, bulk polymerised, at plant/RER U[13]").

This process, 'Polyvinyl chloride, at regional storage/RER U' consists also of road and rail transport of the bulk production to the regional storage centres. It is the best available process, based on the latest known inventory of Plastics Europe. This has the disadvantage that the processes of the three production routes consist of the underlying data, thus it offers little possibility to analyse which sub processes contribute the most to the environmental burden and where the potential environmental gains are.

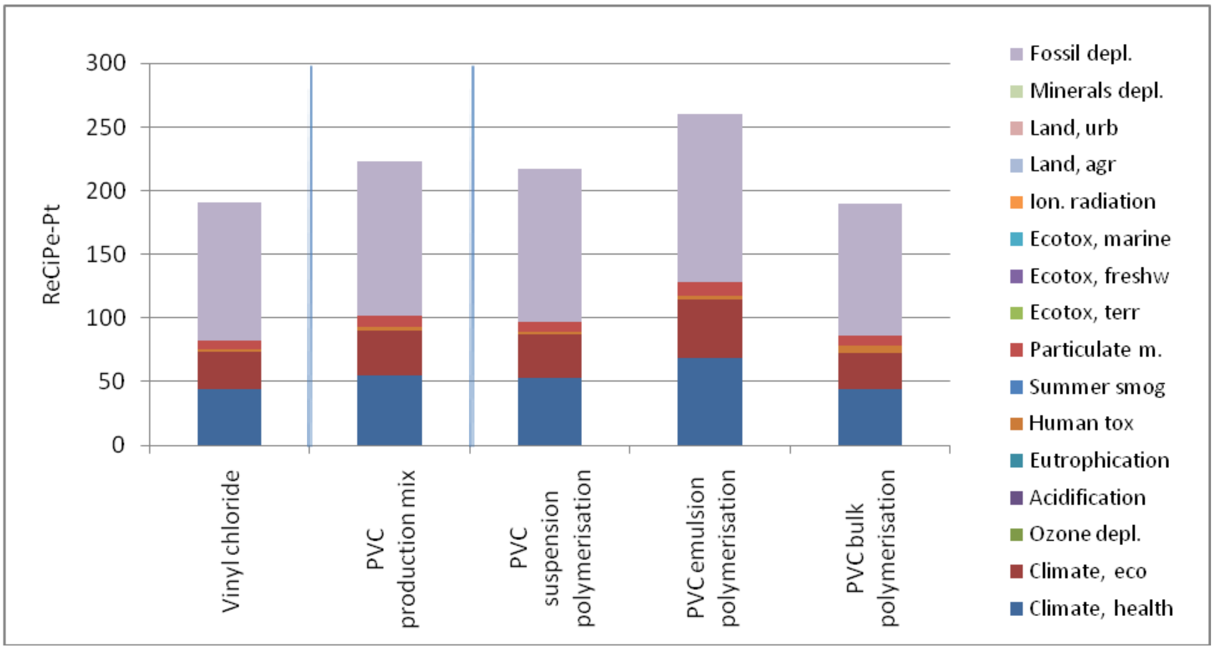

Figure 4 Vinyl chloride production, the PVC production mix and the three different production routes (polymerisation process), each per ton

In all the above mentioned bar charts approximately 95% of the score is determined by the use of fossil fuels with effects for climate change, human health and ecosystems. The chloride production requires a lot of electricity, and the crude oil use in the process to produce PVC contributes to the depletion of fossil fuels.

The bulk polymerisation of PVC scores 15% better in comparison with the PVC production mix and PVC emulsion polymerisation scores 17% worse than the PVC production mix.

The bars in Figure 4 show that the step 'production of the PVC-monomer' and the step 'polymerisation of the PVC-polymer' contribute in the same magnitude to the environmental burden. The differences between the several ways of polymerization are little and there is no large difference in the nature of the environmental burden that they cause (the same impact categories play a role in all the processes). Based on this is decided that it is not necessary to calculate a sensitivity analysis to visualize the effects of different polymerization processes on top of the calculations which are based on the recent ecoprofile of Plastics Europe (see paragraph 3.1).

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[13] This unit-proces of Ecoinvent contains only aggregated interventions and is therefore similar to the System proces.

3.2 Additives and shaping techniques

3.2.1 Additives

Additives give PVC its final qualities and vary strongly per application. Additives are for example heat stabilisers, lubricants, plasticisers, filling agents and colouring agents.

Because PVC is thermally unstable, stabilisers need (0.02 up to 1.8 weight-%) such as lead and calcium zinc mixtures for nearly every application. These mixtures protect against degradation caused by heat and/or UV radiation.

Other additives are:

- Plasticisers, up to 50 weight percentage: phtalates, chlorified paraffins, polyesters.
- Lubricants: stearates, paraffin oils, paraffin wax.
- Filling agents, up to 50 weight percentage, zinc oxide, kaoline.
- Flame retardant, up to 10 weight percentage: chlorifide substances, boron substances, zinc oxide.
- Colour agents, 0.5-1 weight percentage: Zn, Cu, Ni, Cr [Asif, 2005]

In many LCA studies, additives are not or scarcely taken into account although their environmental burden can be large. Also in Ecoinvent additives are limited. See also paragraph 3.2.2 and 3.3.1. Qualitative information for additives can be found, but usable quantitative information for LCA such as recipes and inventory data are is scarce.

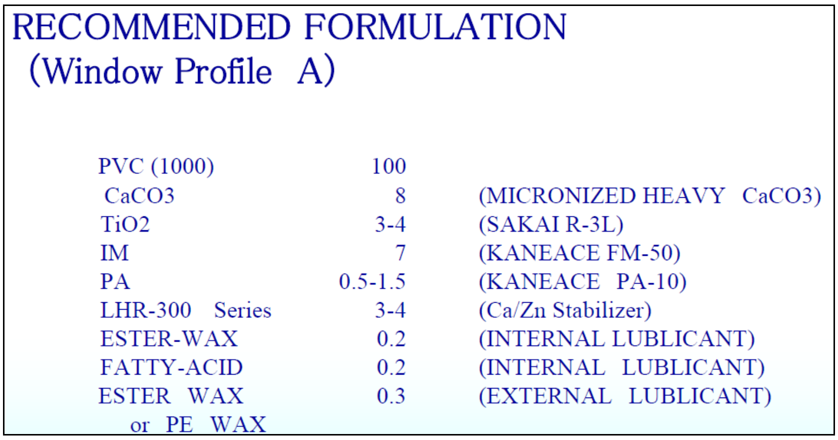
Stabilisers and plasticisers have been given special attention in this study because of their importance.

Stabilisers

The European branch organisation for lead stabiliser producers [ESPA (2009)] gives the characteristic lead content[14] in the most important applications. These content figures will be used for the reference situation:

- Tubes 0.75%
- Window frames 2.7%
- Wires and cables 2.0%

The use of lead in stabilisers decreases quickly. According to (Vinyl, 2009, 2010) 50% less lead stabiliser was used in the EU-15 in 2008 than in 2002 (2 years for the interim goal of 2010); the goal is to stop using lead stabilisers in the EU-27 in 2015. Stabilisers based on calcium (in particular calcium zinc) will be used instead.



RECOMMENDED FORMULATION
(Window Profile A)

PVC (1000)	100	
CaCO3	8	(MICRONIZED HEAVY CaCO3)
TiO2	3-4	(SAKAI R-3L)
IM	7	(KANEACE FM-50)
PA	0.5-1.5	(KANEACE PA-10)
LHR-300 Series	3-4	(Ca/Zn Stabilizer)
ESTER-WAX	0.2	(INTERNAL LUBLICANT)
FATTY-ACID	0.2	(INTERNAL LUBLICANT)
ESTER WAX or PE WAX	0.3	(EXTERNAL LUBLICANT)

Figure 5 Example composition of PVC window profile with stabilisers (source: www.sakai-chem.co.jp / LHR-300 series)

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[14] "lead metal content" (assumption: of PVC); lead content in lead sulfate is 68% ➔ 2.7% lead in window frames means 4% stabiliser.

Figure 5 shows the assumption that 100% PVC contains 3 – 4% calcium zinc stabiliser. For tubes the same reference (LHR-200 series) also uses the same content: 2.5-3% calcium zinc stabiliser. Data about the exact composition of calcium zinc stabiliser is not available, as is LCI data. Pure CaZn of 1 kg exists of 0.62 kg zinc and 0.38 kg calcium. Often the calcium is isolated with the use of electrolysis from calcium chloride and calcium fluoride. A calcium component was generated[15], because of the lack data. A comparison of this roughly constructed calcium zinc stabilisers with lead ('lead stabiliser' from the IVAM LCA Data) shows a reduction in environmental burden of approximately 75%, in particular caused by the decrease of toxic effects. The scores are respectively 256 Pt/ton and 984 Pt/ton stabiliser (see Figure 6). The assumption that the functionality per weight unit is comparable is based on the comment: 'this reduction was achieved by a transmission to stabilisers on the basis of calcium, which show a comparable increase in the same period (+50.879 ton)' [Vinyl 2009, 2010].

Plasticisers

Plasticisers make the normally hard PVC flexible. Soft PVC can contain up to 60% stabiliser [EC, 2004], on average it is 30%. Of the three main applications in this report, plasticisers are only applied in cables/installation wire. Plasticisers are mainly (95%, EC, 2004) phthalates. Ecoinvent does not have information about plasticisers. The data in [Ecobilan, 2001] is average for high volume commodity phthalates (DEHP/DINP/DIDP) and is aggregated, a reason why they are not so suitable for use in combination with the other data. Bis (2-ethylhexyl) phthalate (DEHP) is the most important plasticizer. For cables with PVC is assumed that 30% DEHP is used. This soft PVC thus exists of 70% PVC and 30% DEHP[16].

DEHP is produced by a reaction of phthalic anhydride (PAN) with 2-ethylhexanol:

$$C_6H_4(CO)_2O + 2\ C_8H_{17}OH \rightarrow C_6H_4(CO_2C_8H_{17})_2 + H_2O$$

$$148\ g + 2 * 130\ g \rightarrow 391\ g + 18\ g$$

Data is available in Ecoinvent about the production of PAN. No data is available about the production of 2-ethylhexanol, although there is data for the group to which it belongs: Fatty Alcohol. Due to the lack of data for this reaction the required energy is left out, as are possible emissions. The effect of this is probably small, estimated to be less than 5% for the production of DEHP.

The phthalate DEHP is suspected to have a hormonal influence that damages fertility and the unborn child [RIVM, 2009]. This possible effect is not taken into account in LCA (ecotoxicity and humane toxicity) and therefore the environmental burden is possibly higher than presented in this report.

The environmental burden of the production of plasticiser is with 359 Pt per ton (see Figure 6) 60% higher than that of PVC (see Figure 4).

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[15] According to [http://www.pvc.org/What-is-PVC/How-is-PVC-made/PVC-Additives/Calcium-Zinc-stabilisers] calcium-zinc stabilisers are generally based on metal carboxylates, espacially by neutralisation of acids of these with metaloxides or -hydroxides. Given that electrolysis is not included the effect of this is expected to be low, also because PVC only consists of few procents of these stabilisers.

[16] The Steering Committee PVC and Chain Management brought up that DEHP in 2008 represented only 17,5% of the European plasticeres and DINP + DIDP together 67%, of which DINP (in cables too) is used most. No detailled LCI data are available, but we expect the environmental impact of DINP to be in the same order of magnitude as of DEHP because there are often presented as obne group.

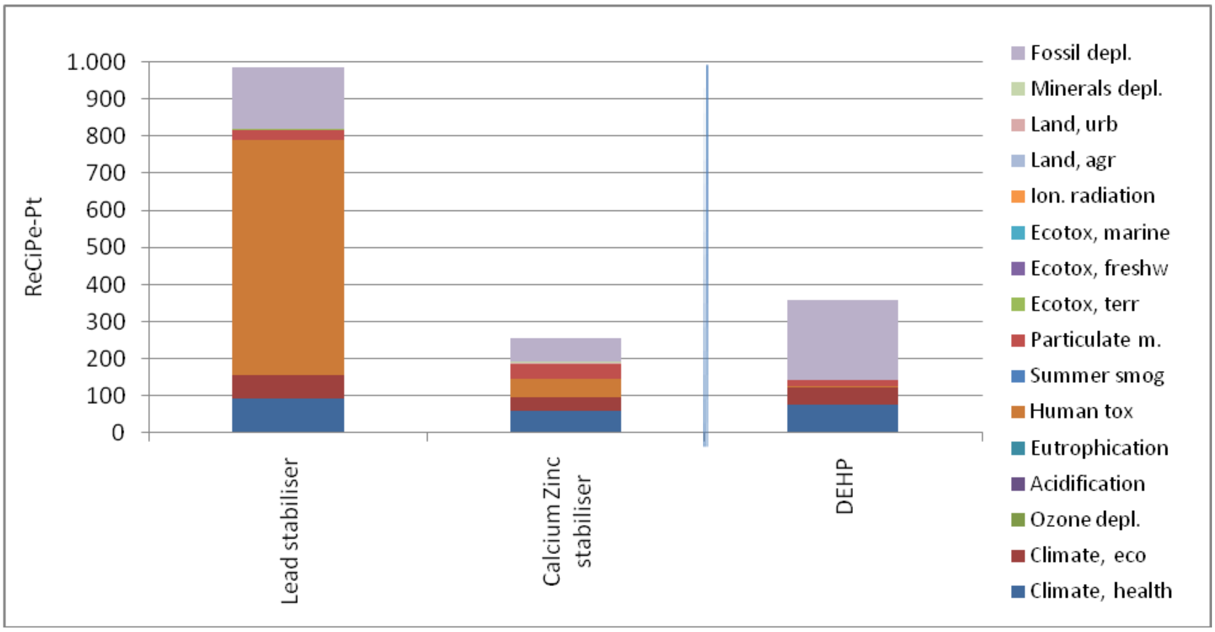

Figure 6 Production of lead stabiliser, calcium zinc stabiliser and DEHP plasticiser (per ton)

The lead stabiliser and the related lead emissions to air explain 65% of total score for human toxicity; the other part of the score is mainly energy related. For the calcium zinc stabiliser many air emitted metals (lead, zinc, arsenic) contribute to the much lower score of the humane toxicity. The other part is mainly energy related. For DEHP 95% of the score is determined by the xylene-, ethylene- and paraffin production and energy requirement.

3.2.2 Shaping techniques

In Ecoinvent several shaping techniques ('conversion of plastics') are included. For flexibility reasons - techniques can be used for several plastics – the process data excluding the plastics, based on the amount of used product (thus not the shaped product). The user of the data needs to take this into account when modelling. The losses caused by the extrusion process are small: for 1 kg product 1.0037 kg plastic is used ('PVC pipe extrusion') and 0.0037 kg waste is generated.

- For extrusion the Ecoinvent process 'Extrusion, plastic pipes/RER U' is used, which is based on a PlasticsEurope report dating from 1997 and a BUWAL report (precursor of Ecoinvent) from 1998. '1 kg of this process equals 0.996 kg of extruded plastic pipes', which means 0.4% loss. For this process no additives are included, other than needed for the extruding itself.
- For injection moulding the Ecoinvent process 'Injection moulding/RER U' is used, based on a PlasticsEurope report from 1997 and a BUWAL report (precursor Ecoinvent) from 1998. In contrast with the extrusion process for this process stabiliser, pigment and filler are included, although not very precise (page 175 EI report 11 – part II): stabiliser as unspecified organic chemicals, pigment as titanium oxide, and fillers (not specified).

For the three selected PVC sub chains (window frames, pipes and cables) extrusion is the most important shaping technique. Injection moulding is hardly used for window frame production (for the non-frame parts) and is not included in the calculations.

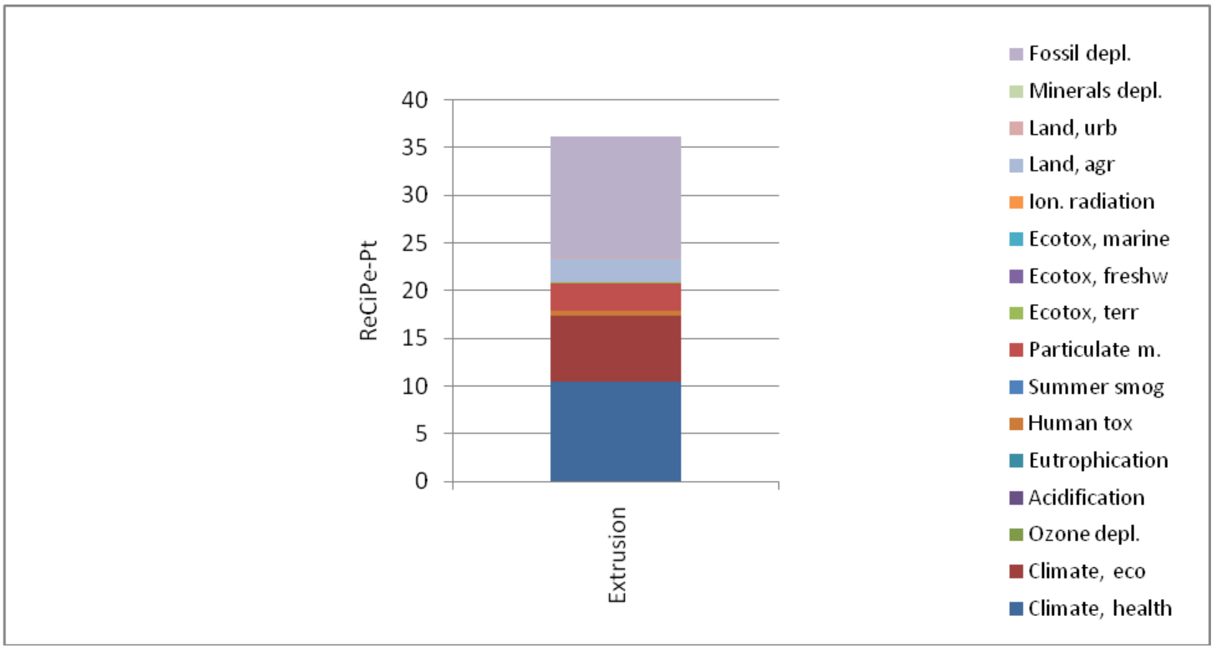

Figure 7 Extrusion per ton processed material

The score is mainly determined by electricity use (66%) and other electricity use.

3.3 Production of window frames, pipes and cables

3.3.1 Production of a PVC window frame

For production of a PVC window frame Ecoinvent has 'Window frame, plastic (PVC, U=1.6W/m^{2}K, at plant/RER U'. This process, per 1 m^2 transparent surface, pretends to be complete. This would imply that the amount of additives is very small, with only those that are included with the process of injection moulding, whereas most of the window frames exist of extrusion profiles. See appendix 2 for the composition of the plastic window frame, which consists of much more than PVC only (without the glazing). Because stabilisers in PVC are missing, these were added to the original process. Of the 2.34 kg lead sulphate, based on 4% lead stabilisers[14] and the gross input of 58.4 kg PVC for 1 m^2 window frame, 50%[17] has been replaced by calcium zinc stabiliser because of the decreasing use of lead in stabilisers. Thus, per m^2 window frame has been calculated with 1.17 kg lead stabiliser and 1.17 kg calcium zinc stabiliser.

3.3.2 Production of a PVC pipe

At the start of the project was proposed to focus on PVC drainage pipes (outdoor sewage pipes) so that material alternatives such as stoneware and concrete could be included. The unit for comparison for pipes is 5 running meters with an internal diameter of 200 mm. A PVC pipe weighs 21.9 kg per 5 meter. [18]. Assumed is that the pipes are formed with extrusion and 1.1% lead stabiliser is added with 0.75% lead content (see stabilisers, paragraph 3.2.1). This is replaced for 50% by calcium zinc stabiliser because the decreasing use of lead as stabiliser. Per 5 meter pipe is calculated with 0.12 kg lead stabiliser and 0.12 kg calcium zinc stabiliser. This is assumed to be representative for the use of stabilisers in PVC in 2009.

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[17] In the VKG MRPI (Rouwette, 2006) lead as stabiliser is calculated with. The Ecoinvent data are seen as more representative.

[18] Based on Wavin PVC U3 pipe with 4.9 mm wall thickness and a density of 1390 kg/m^3.
Another 200 mm PVC pipe (www.walraven.com) with 5.9 mm wall thickness weighs 26.85 kg per 5 m.

3.3.3 Production of cables

Based on 'Cable, printer cable, without plugs, at plant/GLO U' cables are modelled. Installation wires (in buildings) are not analysed separately. The results for PVC in the chosen cables are expected to be similar for installation wires. According to Ecoinvent the process description of the selected dataset can be used to describe the production of commonly used wires for computers in 2006. The total weight of 1 meter cable is 0.065 kg (without the plugs). The information for this dataset is based on weighing and analyses in the EMPA laboratories. The type of cable is produced all over the world and is available all over the world. This cable mainly consist of 0.0195 kg drawn copper wire, 0.0325 kg 'Polyvinyl chloride, at regional storage/RER U' (without additives) and 0.0129 kg 'Tube insulation, elastomere, at plant DE U' (which exists for 93% of rubber and some PVC); both plastics are extruded (0.0454 kg extrusion, plastic pipes/RER U). Also here no additives in the PVC are used, and thus no plasticiser. In this study this is corrected by calculating with 70% PVC and 30% DEHP, see paragraph 3.2.1.

The website www.drakaservice.nl shows that 230 volt cables can be produced with PVC insulation and PVC sheaths, but also with rubber insulation and rubber sheaths. In the last case little or no PVC is used. The type of rubber is EPR, Ethene Propene Rubber.

Above mentioned Ecoinvent printer cable is used as the starting point for the cable calculations. Per running meter this cable consists of 0.0454 kg insulation and cable sheath, which could exist entirely of PVC (with plasticiser). For the reference cable in this study the insulation and sheath of the Ecoinvent printer cable are replaced by 0.0454 kg soft PVC, existing of 70% PVC and 30% DEHP plasticizer (see 3.2.1). To gain insight in the range of on the market available alternatives, a cable with 0.0454 kg rubber has been analysed. See paragraph 5.3.

3.4 Use of window frames, pipes and cables

[ESPA, 2009] mentions that lead-stabilised PVC is inert. This is taken into account in this study, for the use phase and in case the material is landfilled. [ESPA, 2009] also mentions that when lead is locked in the plastic matrix, it cannot be removed.

3.4.1 Use of window frames

In general the following aspects in the use phase of window frames are relevant from environmental perspective:

- Heat transfer through the window frames
- Maintenance (in particular lacquering)
- Replacement

Heat transfer through the window frames

The environmental burden of heat transfer through window frames depends on many aspects, such as the type of dwelling, the related surface and the type of heat generation (gas, electricity, efficiency, etc.). The description below is indicative.

In [Vollebregt, 2006] the difference between the U-value 2.4 W/m²K (standard glazing) and 1.4 W/m²K for window frames with HR++ glass in several newly built reference houses result in a difference of 0.03 on the EPC value. With EPvar is calculated that the use of HR++ glass in a 'Novem dwelling'[19] results in a difference of 1800 MJ of primary energy (gas). With a model for the generation of energy with a natural

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[19] This dwelling has 4.9 m2 window at the front side and 9.4 m2 at the back side.

gas fired boiler is calculated that this is comparable with an environmental burden of 13 Pt per year. This is an indication of the environmental burden of the mentioned difference in U-value. This environmental burden returns yearly and has the same magnitude as the window frame life cycle per m^2 (see Figure 12). The relation is not linear, in other words: when the difference in U-value is halved this will not lead to 6.5 Pt. For example: the window frames that are compared in this report (see paragraph 5.1) have a U-value that does not differ much in Ecoinvent: aluminium and PVC both 1.6 W/m^{2}K and wood 1.5 W/m^{2}K. According to [Vollebregt, 2006] the heat transfer (U-value) for regular window frame is 1.4-1.8 W/m^{2}K.

Energy losses through the window frame are relevant in absolute terms. The differences in heat resistance of the window frames which are compared in this report (1.5-1.6 W/m^{2}K) are rather small compared to the differences described in the text frame above. Therefore the differences in energy losses are small as well. The absolute energy loss through window frames depends on many other factors and is therefore difficult to determine. Therefore the heat loss through window frames is not included in the following analyses in this report.

Maintenance

The advantage of PVC window frames is that these are (almost) maintenance free. For aluminium this is more or less the same. If any, cleaning takes place 'with some regularity', but it can be questioned whether it actually takes place and whether the cleaning is different for wooden window frames. For wooden window frames the lacquering has to be taken into account.

Replacement

Replacement is of importance when the life spans of the alternatives differ. According to the most recent reference with a comparison of window frame life spans [SBR, 1998] the life span can vary considerably:

- Not preserved spruce or pine: 25 years (provided that it is maintained with lacquer)
- Meranti: 50 years (provided that it is maintained with lacquer)
- Merbau/Iroko: 75 years (provided that it is maintained with lacquer)
- Anodised aluminium: 25-50 years
- PVC: 40 years.

The technical developments are such that these life spans of PVC and aluminium will have changed over time. [Rouwette, 2006] assumes a life span of 75 years for a PVC window frame, with replacement of hinges and closure, and sealing rubbers every 25 years. Also VMRG gives (1999, 2009) a life span of 75 years for aluminium frames with only the replacement of some parts. The replacement of parts is expected not to be different for the several window frames material alternatives.

Because of the uncertainty about the life spans we chose one life cycle for the comparison of aluminium and PVC window frames, and for the soft wood window frame (see paragraph 5.1) 2 life cycles – with 1 lifecycle for a sensitivity analysis. See Figure 19.

Summarised

Based on the previous, the environmental burden for the use phase for PVC window frames can be assumed to be '0'. This is the same for aluminium window frames. For wooden frames the lacquering should be taken into account. Furthermore, for wooden frames a shorter life span should be taken into account.

3.4.2 Use of pipes

All warm tap water pipes cause heat losses which are not taken into account. For sewage pipes in the ground heat loss is no issue.

There is no maintenance in the use phase.

Replacement is particularly important when the lifespan of several alternatives differs. In [SBR, 1998] the following lifespan, depending on vibrations and the stability of the ground) in the category 'outdoor sewage' is mentioned:
- PVC: 40 years (high pressure cleaning);
- Stoneware: 40 years (high pressure cleaning);
- (Concrete is not mentioned in this category).

According to [Breen, 2007] the life span of PVC pipes is at least 100 years. The life span of PVC drainage pipes and alternatives in this study are assumed to be equal. No environmental burden has been accounted to the use phase of the pipes.

3.4.3 Use of cables

The electricity through the cables is not different for different alternatives, as is the energy loss caused by resistance. Both are not included in the study. Plasticisers have the ability to 'leave' the PVC.

As mentioned in paragraph 3.2.1, with plasticisers, the possible hormonal effects of DEHP are not taken into account in the LCA. For emission to the air no factor is available within ReCiPe; for emission to water there is one available. Probably the largest share of DEHP emission to water takes place at a sewage treatment plant. For a sensitivity analysis it is assumed that in the extreme, half of the 30% DEHP which is used in soft PVC leaches to water. For a ton soft PVC (150 kg DEHP emission) this results in a score of 13.8 Pt. This is 5% of the score for the production of soft PVC (264 Pt). This result, in combination with the framework of this study and developments such as REACH, make that the environmental burden caused by the use of cables can safely be taken as '0'.

3.5 Disposal of window frames, pipes and cable sheaths

After disposal, PVC window frames, pipes and cables can be incinerated in a municipal waste incineration plant (MWIP), dumped in a landfill site or recycled. For the cables it is suspected that only the copper is recycled.

3.5.1 AVI

PVC contributes largely to the chlorine in MWIPs. The presence of chlorine in MWIPs can lead to the production of dioxin – one of the most toxic synthetic chemicals. [Asif, 2005][20] In the modern MWIPs the main problem of chlorine is not so much the emission of dioxins, but chlorine corrosion [HVC, 2009]. Based on the Ecoinvent data sheet 'Disposal, polyvinyl chloride, 0.2% water, to municipal incineration / CH U' the incineration of PVC in a MWIP is taken into account in the analyses.[21]. Ecoinvent MWIP processes mention combustion values (for PVC the lowest combustion value is 21.51 MJ/kg) but do not assign avoided production. IVAM takes electricity and heat production into account, based on the averaged net efficiency of the Dutch municipal waste incineration plants: 22% electricity and 7% thermal.
- For the avoided electricity the Ecoinvent process 'Electricity mix/NL U' (>20 kV; production and import, no transformation- and transport/distribution losses) is used, and

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[20] Other sources, Dyka, 2009; including CML and TNO) assume that the PVC in MWIP does not influence the dioxin-emissions.

[21] In this process the composition of PVC is assumed 'Pb 16.002 ppm'. This is so low, that it is safe to say that stabilisers were not accounted for. Dioxin emissions to air are not part of the (extended) inventory (or are '0').

- For the avoided heat ‘Heat, natural gas, at industrial furnace low-NOx >100 kW/RER U’.

The technology as described in the Ecoinvent process, is the average for the Swiss municipal waste incineration plants in 2000 with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% Selective Non-Catalytic Reduction (SNCR), Selective Catalytic Reduction installation (SCR), 32.2% SCR ‘high dust’ (before dust filter), 24.6% SCR ‘low dust (after the dust filter) – DeNOx installation and 13.8% without DeNOx. One ton PVC waste produces according to the Ecoinvent MWIP process 48.4 kg slack and 13.8 kg residues, which is landfilled. For further capturing 5.5 kg cement per ton is used. In the Netherlands the process of dry flue gas scrubbing is used often, which means that the chlorine from the PVC (57% of the pure polymer) is captured, often as calcium chloride and sometimes as sodium chloride. With this process much more flue gas scrubbing residue is produced than in the Swiss Ecoinvent process: approximately 900 kg per ton PVC incinerated in a MWIP (assuming 100% efficiency). This flue gas scrubbing residue contains many heavy metals. Because these originate from other incinerated fractions, they cannot be assigned to the PVC. Landfilling scores relatively low in LCA (see Figure 9 for landfilling of PVC: 7.53 Pt/ton). When the production of PVC (274 Pt) and the mentioned MWIP incineration (49.9 Pt, including avoided energy production) are taken as a basis, this means that this score for incineration is 2% too positive (at the most) because these Swiss data about flue gas scrubbing residues are used in the calculations. It was decided not to correct for this and to apply the Swiss process sheet unadapted.

For PVC cables the idea was to include the impact of cable incinerations in open air. This does not take place in the Netherlands anymore but many plastics, including PVC, are exported to countries where this takes place. Because these practices do not take place in the Netherlands since a long time, no reliable and recent data, suitable to be compared to other alternatives, was found. Based on a RIVM report [Bremmer, 1993] measurements of dioxins in cable incineration plants in the Netherlands are expressed in a score (ReCiPe-Pt). It is not certain whether that Dutch practice is representative for the way cable incinerations are executed in other parts of the world. The material that was investigated at the time is probably very different compared to the material of the cable that was investigated for this study. Apart from these two uncertainties related to the representativeness, even within the measurements that were held at the time, the range in the dioxin emissions is large: 3.3 – 2280 μg I-TEQ/ton input cable incinerations. In ReCiPe-points 1 μg I-TEQ/ton input cable incineration results in 1.40E-06 ReCiPe-Pt. The scope of 3.3 to 2280 μg I-TEQ/ton input incineration results in 4.62E-06 to 3.19E-03 ReCiPe-Pt. This can be ignored compared to the other contributions in the chain. The result does not contribute significantly. When this alternative ‘burning in the open air’ is further taken into account, this needs further investigation.

3.5.2 Landfilling

Landfilling of PVC can happen when small PVC parts, for example broken profiles, are part of landfilled residual waste. The Ecoinvent database for landfilling PVC is ‘Disposal, polyvinyl chloride, 0.2% water, to sanitary landfill/CH U’. Based on the composition of PVC and a model, the small effects of water treatment and leaching (short term: within 100 years) to the sewage treatment and long term emissions from landfill to ground water (emitted through the ‘impermeable’ base) are included. Emissions related to energy requirement and of metals to water, due to the use of capital goods, determine the score. The mentioned process is used for hard PVC but because the lack of specific data also for soft PVC (with 30% DEHP). For soft PVC this is probably underestimated, although the results for landfilling (with relatively low environmental burden) will not become much worse. See paragraph 3.4.3.

3.5.3 Recycling in general

Some general considerations

Recycling of PVC-polymer products demands that waste is sorted in material categories. The quality and usability of the recyclate strongly depend on:

1. The presence of other materials (such as other polymers or reinforcement material) from several sources with a large variety of additives), but also on
2. The homogeneous of PVC types (PVC waste streams are a complex mix of materials from a large range of sources and with a variety of additives) and not in the least on
3. The extent to which the first two variables can be limited to a certain fixed bandwidth (better a higher and constant … with other materials than sometimes a low and sometimes a higher level of 'contamination').

This causes that recycling is technically and economically difficult because for several applications the right mixture of additives in the recycled PVC cannot be achieved with recyclate made of several formulas. This can lead to PVC recyclate that cannot be used for the original applications ('downcycling').

Separated collection versus post-separation

VKG and BIS have selective collection systems for window frames and pipes that overcome the mentioned difficulties. This is described in the paragraphs 3.5.4 and 3.5.5. Because the collection is selective, the material can be applied with high quality. When the contamination increases the quality of the recyclate decreases or more waste cannot be used. Separating PVC from integrally gathered waste, probably leads to a somewhat higher environmental burden because extra sorting is needed and probably more rejects.

Secondly, PVC from separating after collection is not suitable for all the applications. Tubes and pipes can be produced of PVC from separating after collection and there is no problem when the recyclate contains PVC from window frames. Window frames though, only can be produced from PVC from window frames. When the recyclate contains other PVC this can easily be a problem. Experience learns that recycled PVC from post-separating (for tubes and pipes) can have a comparable quality as the recycled PVC from the BIS system [BRBS Recycling, 2010].

Thirdly, apart from the question for which application the collected PVC is the most suitable and whether the environmental gains are lower or not for separated collection, it is relevant that post-separating systems can possibly have a larger turnover then several systems that collect PVC selectively.

Separated waste collection versus separating after collection – in this study

For this study not enough data were found about the waste level in the 'post-separation' system. For the analysis of the recycling route, data is used that is known for the VKG system. This comes down to replacing 900 kg primary PVC per ton collected PVC waste (paragraph 3.5.4). On the one hand this can mean that the amount of waste for 'post-separation' is underestimated because in general this material is more contaminated than the separated collected material. On the other hand, using the VKG system implies a choice for the system with the highest standards for quality and homogeneity of the recyclate, which can lead to more rejects than a system that focuses on reuse in pipes.

No distinction is made in this study between the application of secondary PVC in window frames or in tubes and pipes. For both applications the same amount of primary PVC is avoided and thus the use of window frame-PVC in window frames will have the same environmental gain as the use of window frame PVC in tubes and pipes.

Other systems of recycling, not included in this study

'Vinyloop' is a mechanical recycling technology of Solvay, based on solvents which are nowadays probably applied on a large scale. From 1425 kg PVC waste, 1 ton R-PVC (recycled PVC) is gained and 285 kg filter residues and 140 decanted residues are formed [Vinyl 2010, 2009]. No LCI or LCA data were found. This alternative is not included in this study. Also chemical recycling exists which reduces PVC to the elements of what it is made of [EC, 2004]. No LCI or LCA data were found. Chemical recycling is not included in this study.

3.5.4 Window frame recycling

Data about the recycling of window frames was found in a LCA for a MRPI-sheet[22], provided on request of commissioner VKG [Rouwette, 2006]. The following description of the treatment at the end of the lifecycle is partly based on this. Within the framework of the PVC study the focus is on PVC but most of the other materials in a window frame have higher recycling percentages than usual. This side effect of PVC recycling on other material chains is not taken into consideration in this study.

Plastic window elements exist of materials that can be reused and recycled. Nearly all the window elements taken back in the recycling system are shreddered and the different materials are separated. The recycling system guaranties that all materials from the used window elements are reused in the production of new window elements; 10% of the plastic material however is rejected and ends in a MWIP.

For the production of new plastic profiles up to 70% secondary material is used. Technically it is possible to use 100% secondary material in the production of new window frames, unless they need to be pure white. In practice this does not happen, and up to 70% secondary material is used. The profile producers make a co-extrusion, for the aesthetic quality of the upper layer a white virgin layer of primary PVC is used. In this way the material can be used in ten cycles. Because the window frames are removed in one piece and because the materials are separated after shreddering, no material is lost.

The waste scenario for plastic window elements in the MRPI-study [Rouwette, 2006] is as follows:

- PVC parts: 100% recycling within the return system at the end of the third cycle incineration in a MWIP.
- PVC frames for connection to the surrounding construction: 100% recycling within the return system at the end of the third cycle incineration in MWIP.
- Other parts/materials, that often have a higher recycling percentage than usual, are not included in this PVC study.

In theory PVC can be recycled 10 times. The hardship clause (in MRPI) states that the number of cycles needs to be clear. Therefore the VKG LCA assumes three cycles (recycling two times and then incineration). Assumed are, for the PVC that is treated via the VKG system and based on extra information about the process, transport to the processor, electricity use for shreddering and granulating and some emissions. The sources mention that 10% rejects is not fed into the closed loop. For this share incineration is assumed. The avoided use of primary PVC is assigned to the recycling. Different than in the VKG MRPI for the goal of this study is assumed that every ton PVC recyclate avoids a ton primary PVC. With every ton PVC window frame waste 900 kg primary PVC (as used in window frame production, see paragraph 3.3.1) avoided and 100 kg incinerated in a MWIP. This reflects the best what probably will happen in reality in the next decades: secondary PVC from window frames avoids the use of primary PVC. To get an idea of the consequences of this assumption, the assumptions of the VKG LCA are used in a sensitivity analysis. See paragraph 4.1, Figure 10.

3.5.5 Pipe recycling

The BIS system is open for several plastics, among which PVC. We asked BIS and its members for LCI information. This did not lead to for LCA usable data about the BIS recycle system. It is expected that the

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[22] MRPI = Environmentally Relevant Product Information, an ecolabel type III (LCA) of the Dutch provisioning building industry (NVTB).

BIS PVC recycling is comparable to the PVC recycling with the VKG system; the process data for energy requirement and transport of the latter system are used. The difference is that 'PVC for tubes' (with fewer stabilisers, see 3.3.2) is avoided. As with VKG 10% reject is assumed that is treated in a MWIP. With every ton PVC BIS scrap 900 kg primary PVC for pipe production is avoided. The other 100 kg is incinerated.

3.5.6 Cables recycling

Cable waste can be treated by means of cryogenic grinding (freezing then grinding) or via the earlier mentioned Vinyloop-process, depending on the purity of the waste. It takes place, but what exactly is avoided by the use of this recyclate is not clear. No LCI or LCA data were found[23], therefore the environmental effects of the recycling of PVC cable could not be quantified as was done for the recycling of window frames. It is, taken the description of the soft PVC recycling processes and the large amount of plasticiser into consideration, likely that the recycling of soft PVC results in more environmental burden and less granulate that can replace primary PVC than the recycling of hard PVC. Looking at the good results for window frame recycling, recycling of soft PVC is also interesting when it for example gives half as much environmental profit.

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[23] The Steering Committee PVC mentioned the study 'PVC Recovery Options Environmental and Economic System Analysis' of PE Europe, commissioned by Vinyl 2010. This study can have data that will lead to differentation in a later phase.

4. Results PVC

In this chapter for three sub chains (window frames, pipes and cables) the environmental burden is described for winning, production, use and waste per unit applied PVC, based on the assumptions as described in Chapter 3. As far as the data allow, the sub chains that contribute the most are further analysed.

4.1 PVC Window frames

A plastic window frame consists of more materials than only PVC (see for the composition Appendix 2). A plastic window frame with 1m² 'visible surface' weighs 94.5 kg, of which 55.5 kg PVC. To follow the PVC stream, the life cycles (production, waste treatment with incineration, landfilling and VKG recycling) per ton applied PVC in window frames are shown in Figure 8.

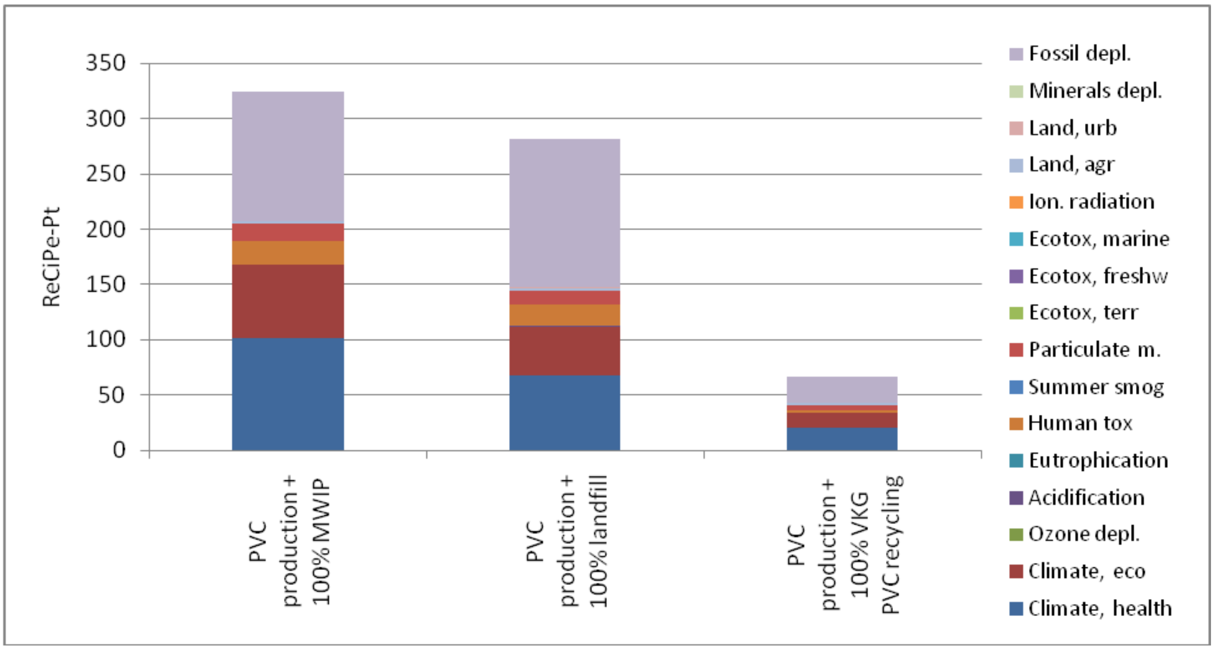

Figure 8 PVC in window frames, lifecycle (per ton): production + disposal via incineration/landfilling/VKG recycling [24]

The lifecycle with recycling scores much better than the lifecycles with incineration (-79%) and landfill (-76%).

Figure 9 shows per ton applied PVC in window frames, the material production and options for disposal treatment separately. Figure 8 and Figure 9 show the extremes because the options for waste treatment are used for 100% in the calculation of each option.

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[24] VKG disposal of a ton PVC waste implies the replacement of 900 kg primary PVC and the incineration of 100 kg PVC in an incineration plant; see paragraph 3.5.4.

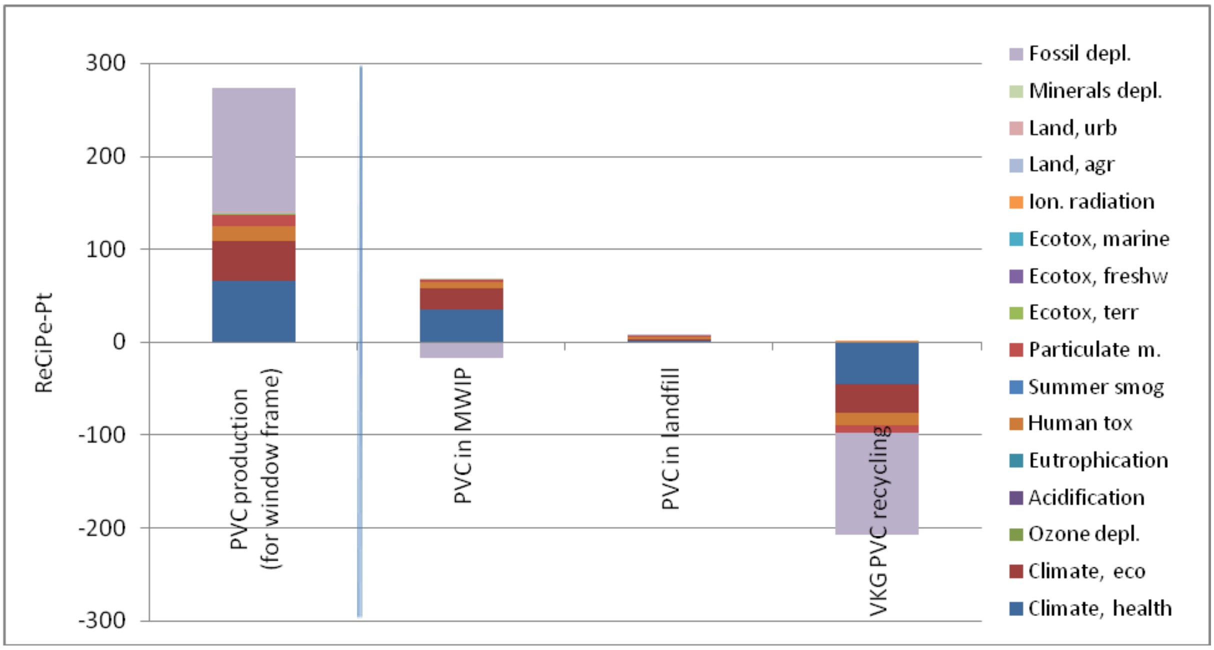

Figure 9 PVC in window frames: production and waste treatment options separately (per ton)

The explanation of the PVC production score is given in the paragraphs 3.1.3 (polyvinyl chloride), 3.2.1 (additives), 3.2.2 (extrusion) and 3.3.1 (window frame production).
With incineration of PVC the electricity use for sodium hydroxide production contributes for more than a third to the gross score above the X-axe (135 Pt). The other part of the score is mainly caused by emissions from PVC incineration. The avoided electricity production (gross – 76 Pt) and avoided heat production (gross – 11 Pt) result in the net score of incineration of PVC: 50 Pt per ton incinerated PVC. See paragraph 3.5.1. For additional explanation on PVC in landfill see paragraph 3.5.2. VKG PVC recycling is described hereafter.

Extrusion (Figure 7), the production of a window frame (paragraph 3.3.1) and taking into account the stabiliser (Figure 6) explain the differences between production of PVC in this figure and the PVC production mix in Figure 4. That dumping in landfill sites scores better than incineration, by the relatively low combustion value of PVC and the small impact of dumping in landfill sites – is not surprising. Recycling of PVC scores much better than landfill (or incineration in an installation). Figure 10 shows that the little use of electricity for recycling and transport is such, that it is compensated by the avoided primary PVC.

A further distinction in the extraction of raw materials and production is, based on the aggregated data, not possible. See Chapter 3 for further explanation and more insight in the environmental burden of the underlying processes.

Figure 10 presents how the VKG PVC recycling is build up. As described in paragraph 3.5.4, for all the recycled PVC is assumed that it replaces 90% primary PVC and that 10% will be incinerated.

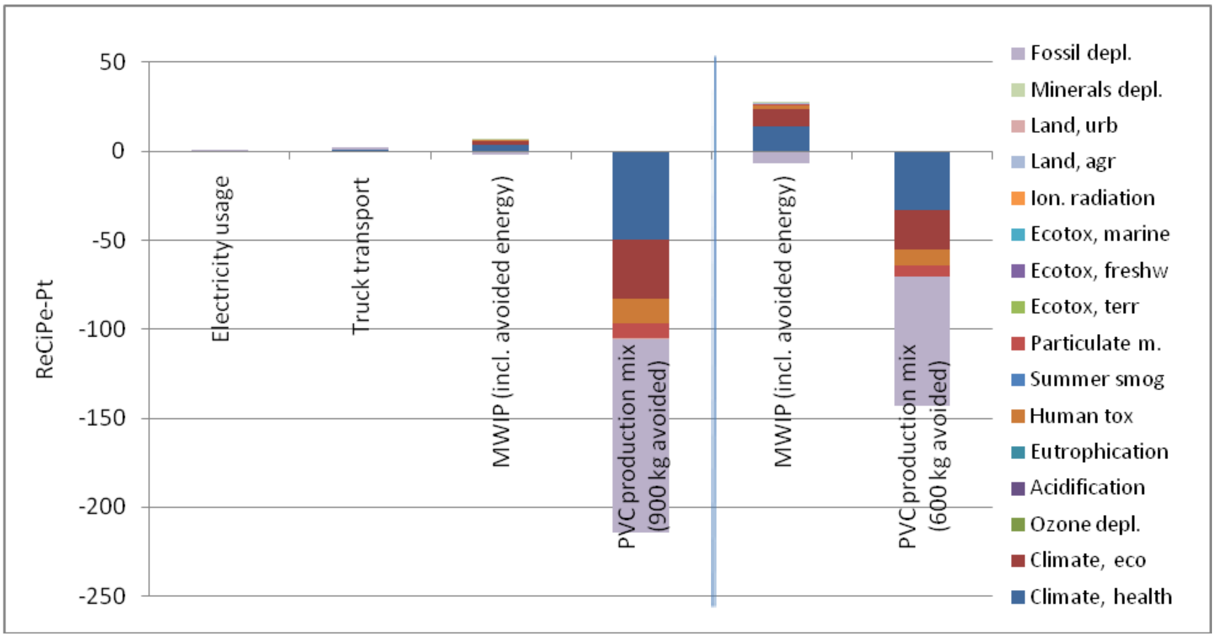

Figure 10 VKG recycling per ton processed PVC; contribution of the processes (in total: -207 Pt) and sensitivity analysis with two times recycling (on the right side of the vertical line; in total: -121 Pt)

The starting points of the VKG MRPI LCA, which include two times recycling and then incineration, are used in a sensitivity analysis. This results in a score of -121 Pt/ton, instead of -207 Pt/ton. See Figure 10: the last bar shows 60% avoided PVC production and the bar before the last bar now shows 40% incineration (instead of respectively 90% and 10%, shown in the fourth and third bar).

This sensitivity analysis shows that the result changes considerably when the VKG starting points are used. It would not lead to another final conclusion: recycling of PVC window frames is by far the best waste treatment option.

As described in 3.3.1 a PVC window frame is not only made of PVC. Figure 11 shows the contribution of the several materials to the total environmental impact of which the window frame is made (heat transfer coefficient U=1.6 W/m^{2}K).

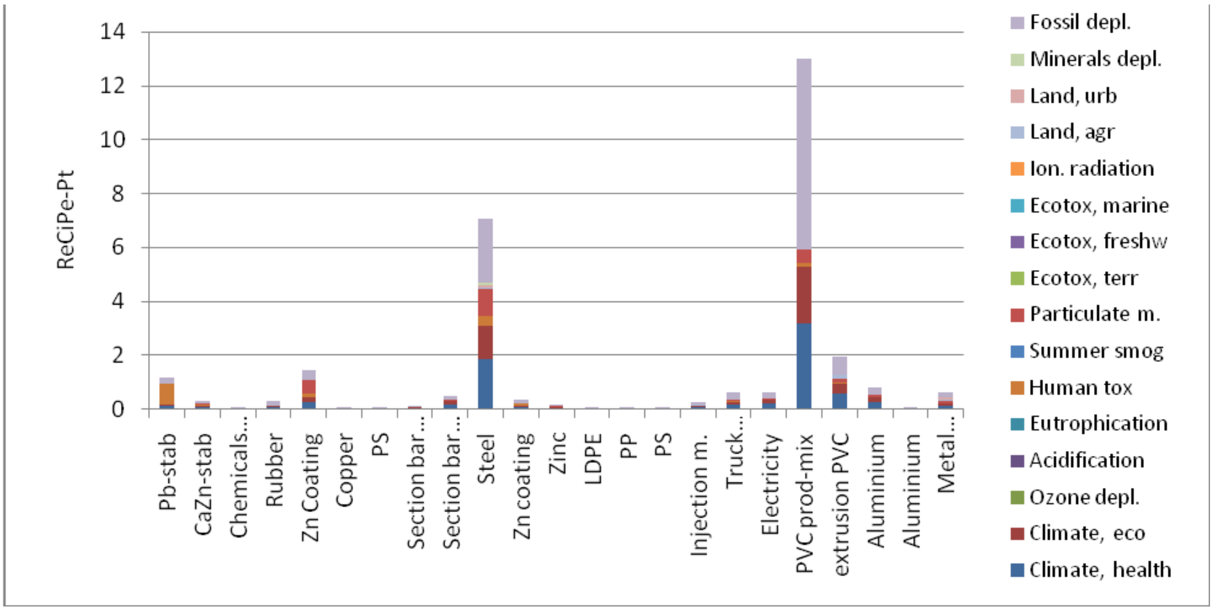

Figure 11 *PVC window frame production, contribution of several processes (total = 29.4 Pt/m²)*

The share of PVC (including stabiliser and extrusion) in the production of a window frame is with 16.4 Pt/m² approximately 56%. For the comparison with aluminium and wooden window frames the plastic frame is considered in total (including suspended structure and closure), because not only the main material is different but with it also the design of the window frame.

A more detailed analysis of the life cycles (production and waste treatment with respectively incineration, landfilling and VKG recycling) of 1m² window frame (PVC and other materials; see Appendix 2) is shown in Figure 12. The proportions of the bars in Figure 12 differ from those of Figure 8 because the differences in the results are suppressed by the production and waste treatment of the other materials in the window frame. For example, the metals are largely recycled, despite the treatment route of the window frame itself. To see the results for PVC part per m² figure 8 can serve as a basis combined with the fact that a plastic window with 1m² visible surface consists for 55.5 kg of PVC.

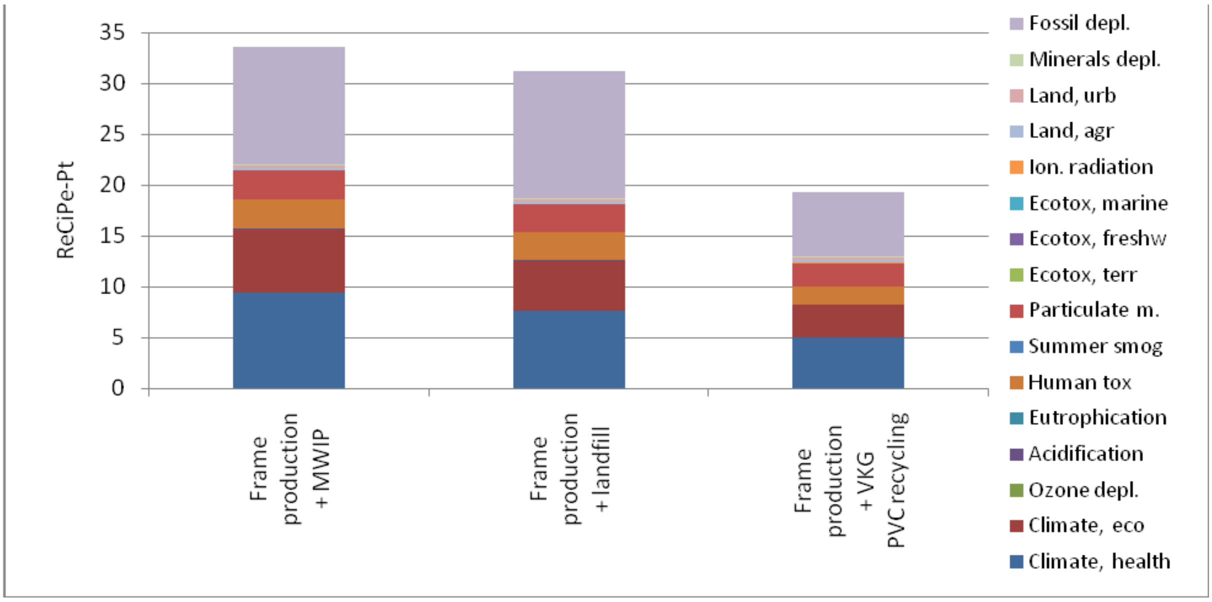

Figure 12 *Plastic window frame life cycle (per m²): production and incineration via incineration / dumping in landfill sites / VKG recycling*

Figure 13 shows the analysis for material production and several waste treatment options separately. The production is build up of parts that are shown in Figure 11. The non-PVC-parts determine 44% of the score.

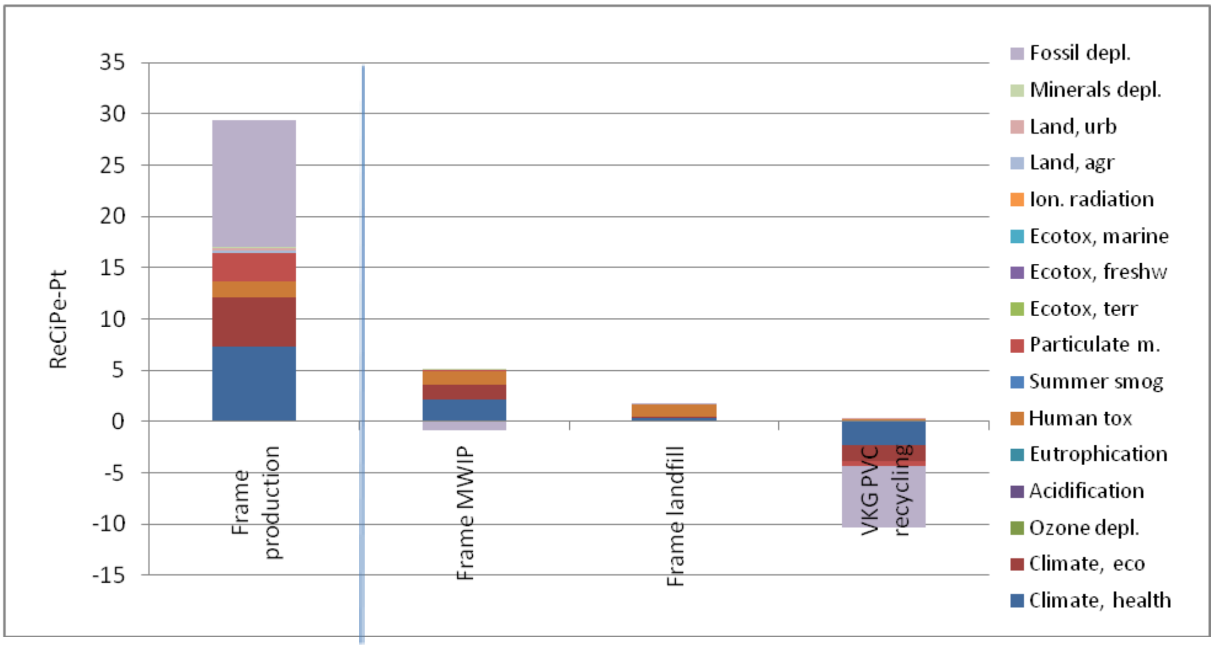

Figure 13 Plastic window frame: production and waste treatment options separated (all per m^2)

As mentioned before, for production it is not possible to further differentiate for the extraction of raw materials and the use phase is set to '0'. See paragraph 3.4.1.

4.2 PVC pipes

In this paragraph the environmental burden per ton PVC is analysed: the material production and waste treatment options: dumping in landfill sites, incineration and recycling. The environmental impact of the use phase is set to '0' (see paragraph 3.4.2). Because of lack of data it is assumed that the recycle system for window frames is also representative for pipes, which seems justified because both systems treat hard PVC that is gathered with relatively little impurities. Here again the extraction of raw materials cannot be distinguished from production. Figure 14 and 15 show the extremes because the analyses were done with 100% of each waste treatment option.

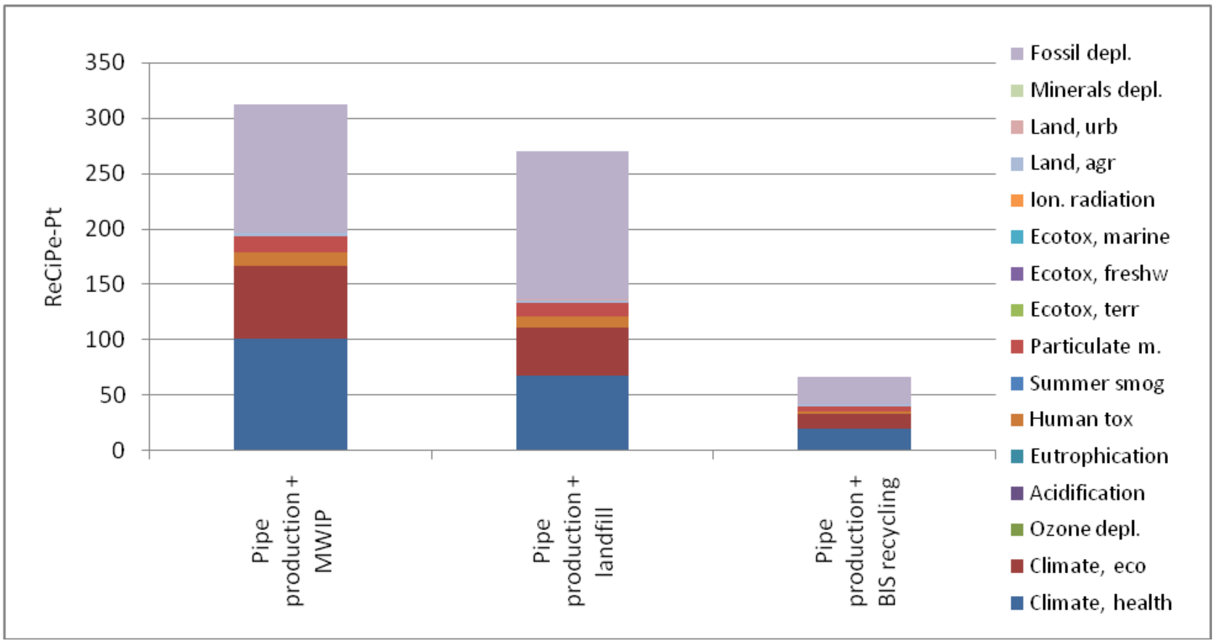

Figure 14 PVC pipe, life cycle (per ton): production + disposal: incineration, landfilling and BIS recycling[25]

The life cycle with recycling obviously score much better than the life cycles with incineration (-79%) and dumping in landfill sites (-76%).

Figure 15 shows the material production and waste treatment options separately, per ton applied PVC in pipes.

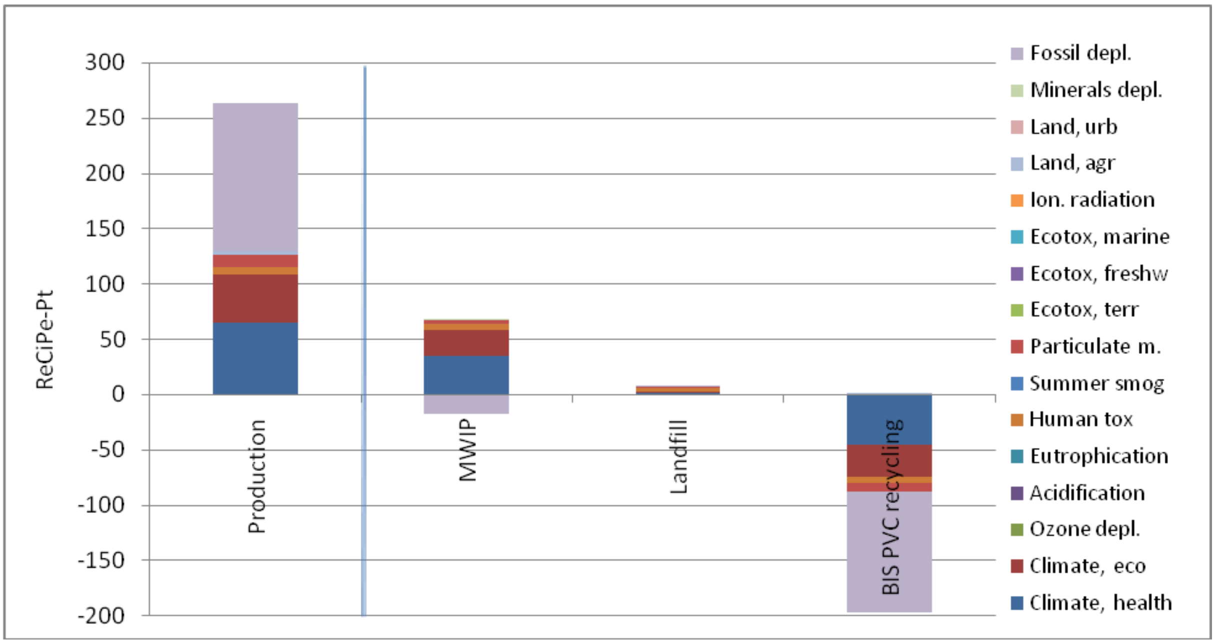

Figure 15 PVC pipe production and disposal: incineration, landfilling and BIS recycling (all per ton)

Figure 15 shows resemblance with Figure 9. The difference in production between PVC for window frames and PVC for pipes is explained by the smaller amount of stabiliser (50% lead / 50% calcium-zinc stabiliser) in pipes. Because for the pipe production no further treatments are known after extrusion, the

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[25] BIS recycling means that per ton PVC waste 900 kg primary PVC is replaced and 100 kg PVC is incinerated; see paragraph 3.5.5.

environmental profile is calculated from these data per ton pipe, recalculated to running meters. This is, with its alternatives, presented in the next chapter.

4.3 PVC cables

Figure 16 shows the environmental burden of PVC for cables, with 30% plasticiser. The results are expressed per ton soft PVC.

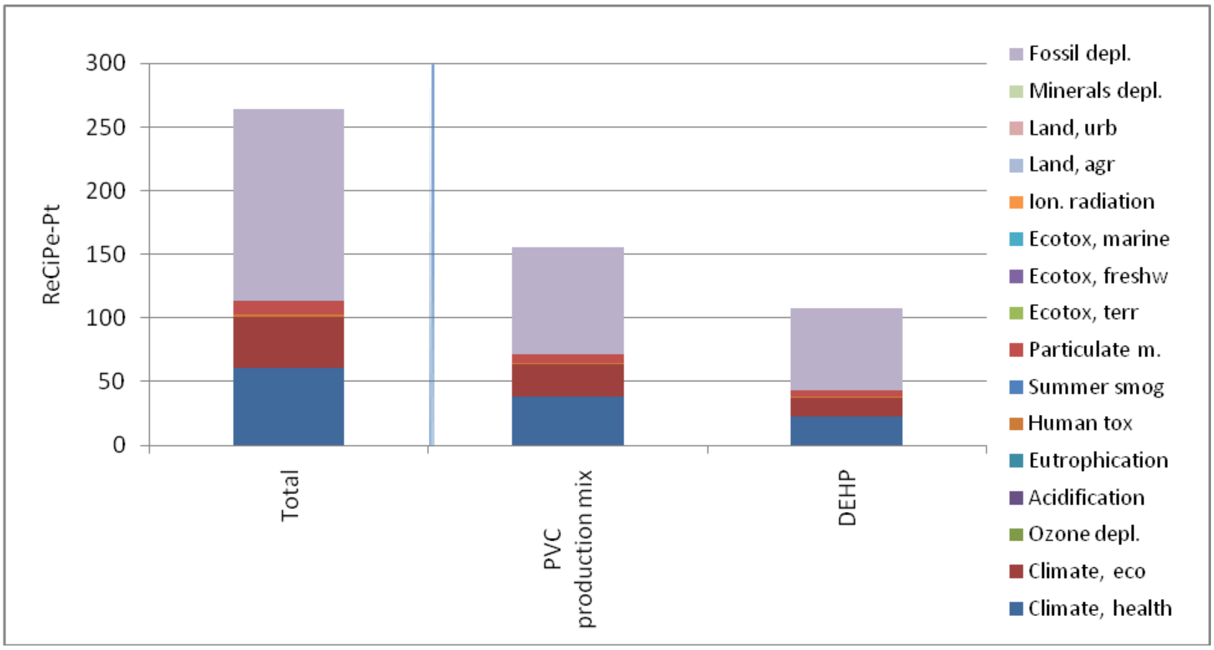

Figure 16 Production of soft PVC for cables (per ton soft PVC)

As described in paragraph 3.2.1 the environmental burden of plasticisers is 60% higher than PVC. Therefore the plasticiser in soft PVC contributes considerably to the environmental burden of soft PVC production. For DEHP it is the xylene-, ethylene- and paraffin production and energy requirement that determine 95% of the environmental impact.

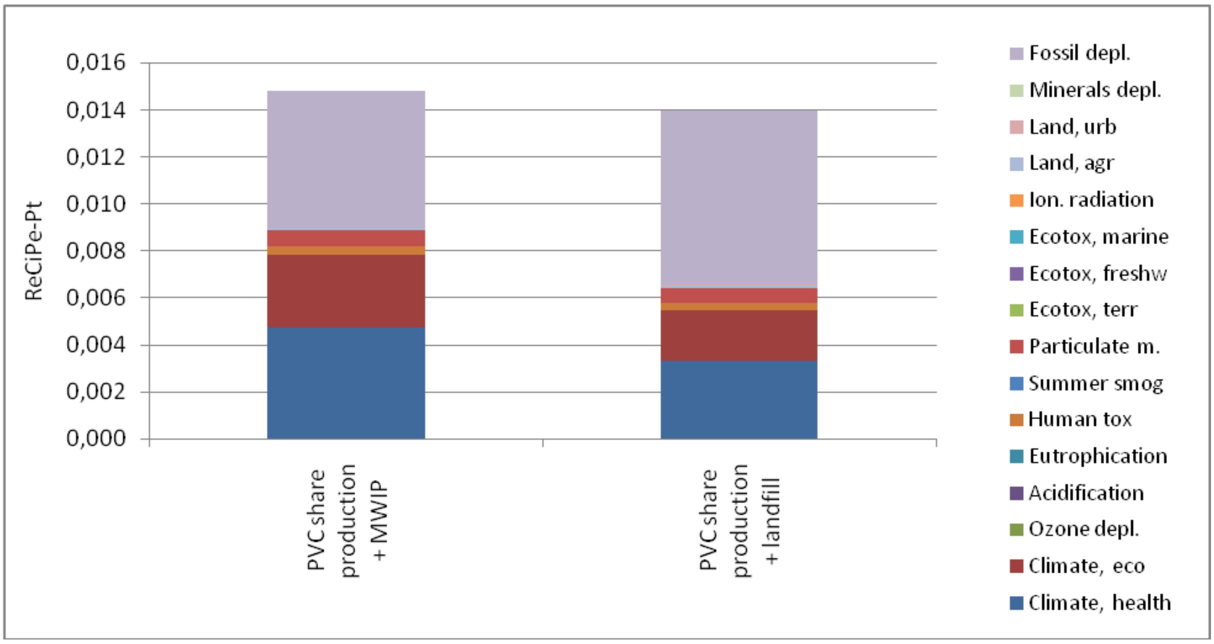

Figure 17 PVC cable (PVC share only): production + disposal through incineration / landfilling (per m)

Figure 17 shows that the differnce between PVC production and disposal through incineration and PVC production and disposal via landfilling is small (5%). For recycling of the cable not enough quantitative information could be found and therefore this could not be included in the LCA.

Figure 18 shows the environmental burden per meter cable; first for the entire cable (without plug) and secondly only for the PVC part, and for the PVC part the waste treatment options incineration and dumping in landfill sites. Per running meter the cable consists of 0.0454 kg insulation and cable sheath, which consist of PVC (with plasticiser).

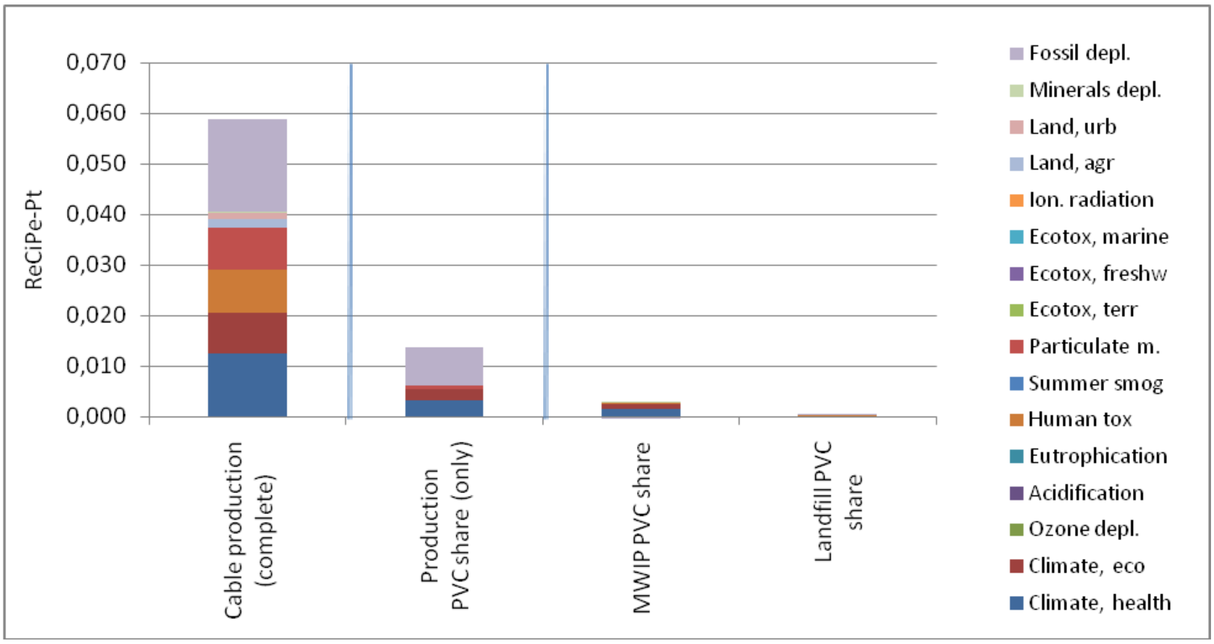

Figure 18 PVC cable production (total and PVC only) and PVC share with incineration and landfilling (per m)

Because the plasticiser has a higher combustion value than PVC, the incineration plant has a lower environmental impact (nett) because more electricity generation is avoided compared to PVC without additives.

As described in paragraph 3.5.3 it was not possible to quantify the recycling of PVC cables, due to the lack of data. This treatment practice, however, is used. It is not exactly clear what is avoided by using this recyclate. Considered the good results of the recycling of hard PVC, the recycling of soft PVC is probably interesting as well, even when it for example gives half as much environmental profits.

5. Alternatives for PVC

The alternatives for the PVC sub chains window frames, pipes and cables are described in this chapter. Partly this is the up scaling of existing practices (and thus part of the reference situation), partly these are new initiatives or ideas. The alternatives are:

1. Window frames
    - Alternatives are recycling, incinerating and disposal in landfill sites.
    - PVC is compared to aluminium and wood.
2. Pipes (hard PVC)
    - Alternatives are recycling, incinerating and disposal in landfill sites.
    - The alternative to 'fill in and leave in the ground', thus no treatment, is analysed as well.
    - Finally a comparison is made between pipes of PVC and stoneware, concrete and poly ethene.
3. Cables (used for white and brown goods and in wires = soft PVC) and wire.
    - Alternatives are to separate the PVC from the copper and then landfill, incinerate or recycle PVC.
    - Also is analysed what happens when the PVC is exported to for example China: cable burning, with dioxins emissions to air.
    - Finally a comparison is made between PVC and rubber in this application.

5.1 Window frames

Besides the described variations in production and disposal routes, the PVC window frame can be compared with alternatives aluminium and wood with comparable thermal resistance (see paragraph 3.4.1). To make the comparison as good as possible the lifecycle as available in the Ecoinvent database for these materials (PVC, aluminium, wood) is taken as the starting point. Thus, production and disposal of the three types of window frames (complete, including the other used materials, except glass). For PVC the lifecycle data are adapted, as described earlier, in particular stabiliser is added to PVC and it is included in the VKG recycle system, as well as avoided energy generation from incineration in a incineration plant.

For the recycling of aluminium window frames is calculated with the percentage of recycling that is given by the Association of Metal windows and façades (VMRG): 94%. The other 6% goes to the incineration plant, after which 47% is separated with eddy current from the bottom ashes. In the recycling process there is loss of 10.8% [EAA, 2008]. Regarded the economic value of aluminium the percentage of recycling (94%) is probably not much lower. This is the reason why in the comparison below no alternatives are included. All the adjustments to the aluminium window frame, as included in Ecoinvent, are described in the report about aluminium.

For the wooden window frames the only wooden window frame in Ecoinvent 'Window frame, wood, U= 1.5 W/m2K, at plant/RER U' is used. This is a soft wooden window frame because the wood in the process that is described is 0.211 m^3 soft wood and 0.00171 m^3 hard wood. For the maintenance during the lifecycle extra paint is included. For this is assumed that the total amount of paint that is initially needed in the window frame production phase is needed again in the use phase: 5.49 kg. The influence of this assumption is visible in the end result, the contribution of 5.49 kg paint is 1.68 Pt (6.2%) – the total is 26.9 Pt for a wooden window frame lifecycle. See the last bar in Figure 19. At the end of the lifecycle the wood is incinerated in an incineration plant, whereby the avoided energy generation is taken into account (see paragraph 3.5.1).

Considered the uncertainty about the life expectancy (see paragraph 3.4.1) it is chosen to use one lifecycle in the comparison of aluminium and PVC window frames, and for the soft wooden window frame two lifecycles and one lifecycle as a sensitivity analysis.

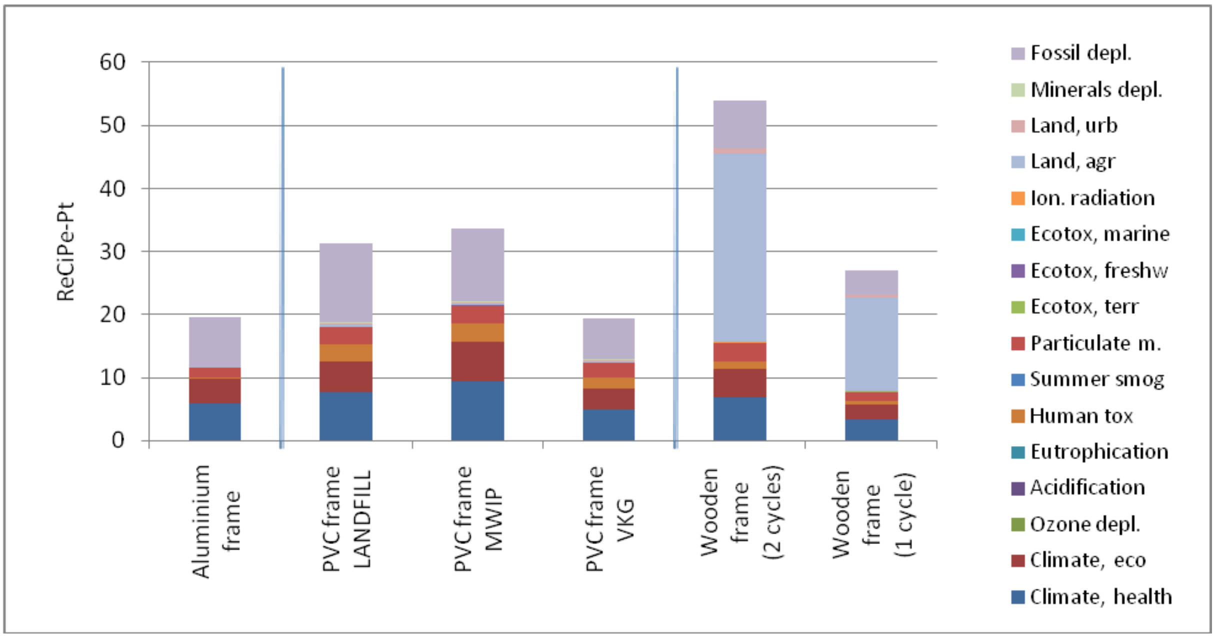

Figure 19 Comparison of the lifecycle of three types of complete window frames per m^2: aluminium, PVC (disposal via landfilling, incineration and VKG) and wood (2 and 1 lifecycles).

The most remarkable findings are:

- The PVC window frame with disposal via VKG and aluminium score (nearly as) good. As for PVC, for aluminium this is caused by the high percentage of recycling (94%).
- Wood scores high on land use. This impact category has relatively large uncertainties. When land use is not included, wood scores in the same range as aluminium and PVC.
- The scores for wood are the worst compared to the other alternatives, when is assumed that it lasts not as long as aluminium and PVC and, provided that both PVC and aluminium are recycled at the end of the life of the window frame.
- For PVC the waste treatment options landfilling, incineration and recycling are analysed to gain more insight in the spread of the results. For all the other (non-PVC) materials the standard Ecoinvent treatment route is used (in which is no variation).

5.2 Pipes

The unit for the comparison of pipes (gravity sewer) is 5 running meters with an internal diameter of 200 mm. The life expectancy for all the alternatives is assumed to be the same (50 years) [26]. Apart from PVC, which weighs 21.9 kg per 5 meter, the material alternatives are:

1. PVC weighs 21.9 kg per 5 meter (wall thickness 4.9 mm; see 3.3.2);
2. Stoneware (clay) weighs on average 200 kg per 5 meter[27];
3. Concrete weighs 260 kg per 5 meter[28];
4. Poly ethene (PE) [29] weighs 24.1 kg per 5 meter [30].

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[26] Announcement J. Driessen Grontmij, per e-mail december 2009.

[27] 100 kg per 2,5 meter (depening on the type of connection, source www.steinzeug.com Leveringsprogramma_dec09_5590.pdf).

[28] 52 kg per meter (http://www.verhulstbeton.be/producten/betonbuizen)

The characteristics of clay stoneware are comparable to both stoneware and porcelain. The lack of data about clay stoneware is the reason to use the average of two processes from Ecoinvent: "Sanitary ceramics, at regional storage/CH U" (289 Pt / ton) and "Ceramic tiles, at regional storage/CH U" (149 Pt / ton)" for the clay stoneware production. For both concrete 'Concrete, normal, at plant/CH U' and stoneware a debris crusher is accounted for 50% at the end of the life cycle.

For both clay stoneware and concrete for the disposal scenario is assumed that 100% is treated in debris crusher (for application as filling material or replacement of gravel). For PVC see paragraph 4.2.

For PE production data the "Polyethylene, HDPE, granulate, at plant/RER U" is taken as the lead process, whereby extrusion and stabilisers are included (as for PVC was done, see paragraph 3.3.2). For PE disposal, landfilling, incineration and VKG recycling are shown separately. Landfilling and incineration, including the avoided energy generation, based on the standard PE processes in Ecoinvent. The VKG process consists of similar interventions but results per ton PE waste in 900 kg PE recyclate that replaces primary PE with stabilisers.

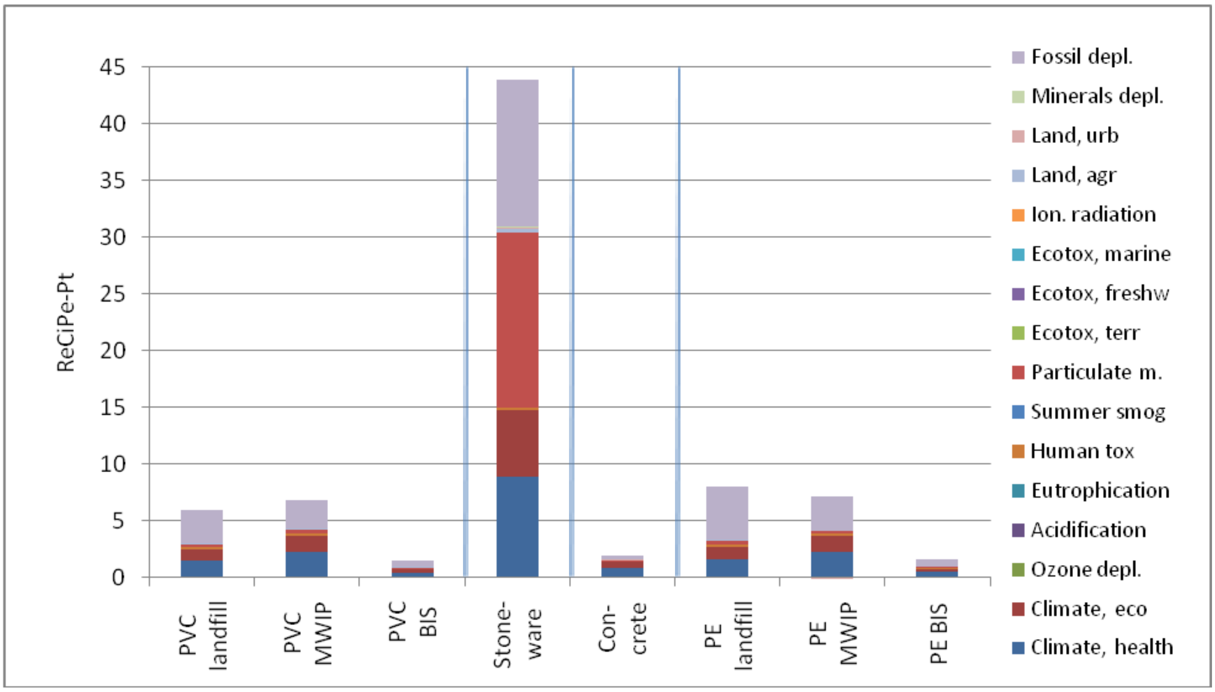

Figure 20 Life cycle pipe: PVC, stoneware, concrete and PE: production and several disposal methods (per 5 meters)

Stoneware obviously scores the worst (see Table 20). The assumptions for clay stoneware are relatively rough, but it is not likely that the environmental impact is estimated 100% too high, for example. The high score is energy related and is caused by the oven.

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[29] Only PE alternatives are found for indoor plumbing sewage pipes.

[30] Based on Wavin PE 80 pipe with a wall thickness of 7.7 mm; and a density of 960 kg/m3. Another WAVIN pipe 200 mm PE 80 has a wall thickness of 6.2 mm. This weighs 19.3 kg per 5 meter.

The question is whether all the pipes can fullfill the same function. Their diameter is equal but (1) clay stoneware might be more resistant for roots or acids. It is also argued that (2) the difference in smoothness on the inside of pipes with an equal diameter but of different materials leads to a different capacity. It cannot be excluded (3) that because of the different weight other processes for installation or lifting are required which can result in different environmental burdens. Another point is (4) that pipes of different materials are not always free from leaking. And sometimes even a certain level of permeability is designed in the pipe. In this study these specific differences – when they really exist and can be quantified – are not included in the analyses and it is assumed that all the pipes with the same diameter have the same function and life expectancy. Following this assumption, PVC with recycling scores the best, closely followed by PE with recycling and then concrete.

A sensitivity analysis was done for 100 mm and 300 mm. Concrete and PE were not found in 100 mm (PP was found but was not considered); stoneware weighs 70 kg per 5 meter and PVC 4 kg per 5 meter. This proportion for 100 mm (70 kg / 4 kg = 17.5) deviates considerably compared to the 200 mm (200 kg / 21.9 = 9.1). The conclusions for PVC and stoneware however do not change because of this. PVC and PE were not found in 300 mm; stoneware weighs 430 kg per 5 meter and concrete 650 kg per 5 meter. This proportion for 300 mm (650 kg / 430 kg = 1.5) deviates much less then for 200 mm (260 kg / 200 kg = 1.3).

The alternative 'filling in and leaving without digging up' (thus no treatment) of sewage pipes is not included in Figure 20. The environmental burden is close to the landfilling of PVC (first bar: 5.93 Pt per 5 meter, or 21.kg PVC pipe). A decent excavator that operates an hour corresponds with 2 Pt (or 0.15 Pt per ton excavated ground)[31]. The corresponding amount of digged pipe is unknown. Expected is that so many meters pipe are involved, that the contribution to the total environmental burden for digging and recycling can be ignored. Due to the uncertainty in the data (type of machine, depth in the ground, how much time it costs per meter pipe – and how this all relates to the diameter) and the low share in environmental burden it was decided not to include the excavator. The avoided transport to the landfill site (1 ton transport over 50 km, coincides with 0.64 Pt) is low as well.

5.3 Cables

As described in paragraph 3.3.3 besides the PVC alternative also the alternative with rubber is analysed. The total weight of 1 meter cable is 0.065 kg (without the plugs). Per running meter this cable consists of 0.0454 kg insulation and cable sheath, which entirely consists of PVC (with softener) or rubber (equal shares in weight of PVC or rubber). For both PVC and rubber the production and the lifecycle (production and disposal via incineration or landfill) are shown in Figure 21.

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[31] Average of techniques and machines: bulldozer komatsu D 58P-1, dig/load combi 580 superK, hydr. exacavator on tires caterpillar 206BFT, m315, hitachi 60WD, 100wd, liebherr A900c, A902lit.; mini hydr.machine track kubota KH36, adn61; hydr. machine tracked caterpillar 215DLC, 330L, hitachi609, 300LC

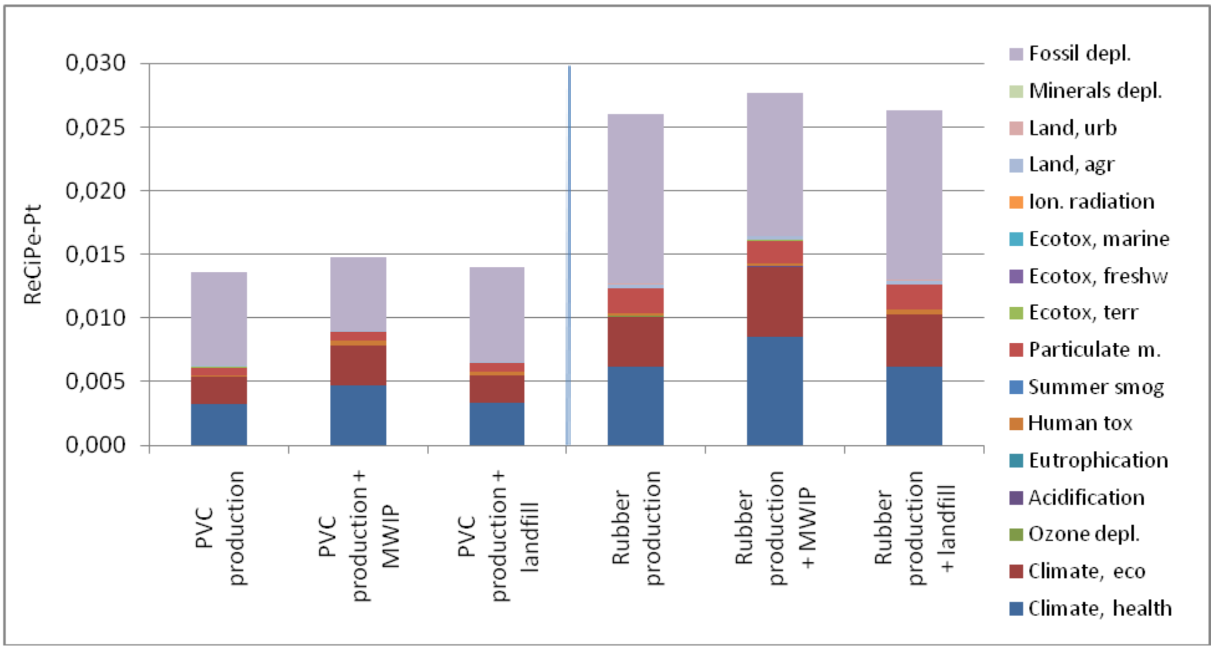

Figure 21 Cable production and disposal (incineration and landfilling): PVC share and rubber share (per m)

Rubber (EPR) has clearly a higher environmental burden in the production phase, with a dominant contribution because of the use of fuels (ample 50%). With incineration in an incineration plant more energy production is avoided based on the higher combustion value of 27.2 MJ/kg rubber (PVC 21.5 MJ/kg).
A closer look on rubber production ('tube insulation elstomere') shows that 60% of the environmental burden is determined by the synthetic rubber production; the other 40% is determined by tube insulation (elstomere) production and electricity use. Oil, carbon black, plastic production and the different energy requirements are responsible for the environmental impact of synthetic rubber production.

Recycling of PVC of cables is not included because of the lack of suitable data for the LCA. From LCA perspective it seems, regarding the results elsewhere in this report, a good option. See paragraph 3.5.3.

6. Conclusions and suggestions for further research

- About PVC polymer production a lot of practical LCI information is available.
- For the additives (in particular stabilisers and plasticisers) that give PVC its qualities, this is not the case. This despite the fact that for example soft PVC, applied in cable sheaths, exists of 30% plasticisers.
- Recycling initiatives such as the Dutch VKG and BIS are very profitable because a lot of primary PVC is avoided.
  - Up scaling of these recycle systems offers reduction potential.
  - It is important to verify the inventory of recycle systems (input of energy and emissions for separating, cleaning and grinding of PVC). The data on which all the recycle results in this report are based, originate from one reference (VKG MRPI dossier).
  - Even recycle systems with more pollution and thus fall out are interesting. When for example the avoided PVC production is about the half compared to VKG/BIS, the system is still interesting, provided that not unequivocally more energy is needed. Separating after collection which separates PVC from unsorted waste, will probably have less positive environmental effects per weight unit but can probably be applied on a larger scale. This requires further investigation.
- For window frames recycling is the best alternative. Of the investigated alternative materials, aluminum has a comparable environmental burden. For wood the scores are not as good when the effects for land use are included and more or less equal when land use is not taken into account. This conclusion is only valid when both PVC and aluminum are recycled at the end of the window frame life.
- Also for pipes up scaling of recycle initiatives such as BIS seems a good way to achieve reduction. PVC scores the best in this application, provided that it is recycled.

- Changing from PVC to rubber increases the environmental burden of electricity cables. From a LCA perspective and because of the results for window frames, it seems a good idea to further investigate the possibilities for further recycling of PVC in cables. Specific data about recycling of PVC cables which is usable for a quantitative environmental analysis is still lacking.
- The dioxin emissions from burning of cables in the open air, a practice outside the Netherlands, are low and do not contribute significantly. When this practice is further taken into account this certainly needs further investigation.

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Appendix 1: ReCiPe factors

Within ReCiPe midpoint as well as endpoint characterisation factors exists. Whithin this study endpoint characterisation is used, to come to an unambiguous final score. The 'translation' from midpoint to endpoint-indicators is given in Table 2. The complete list with characterisation factors of ReCiPe 1.02 (nearly 6000 lines) is separately available.

Table 2 Factors midpoint – endpoint

Human Health (Endpoint-unit: DALY)	**Midpoint-unit**	**Factor**	**Unit**
Climate change Human Health	kg CO_2-eq.	1,40E-06	DALY / kg CO_2-eq.
Ozone depletion	kg CFC-11-eq.	2,61E-03	DALY / kg CFC-11-eq.
human toxicity	kg 1,4-DB-eq.	6,99E-07	DALY / kg 1,4-DB-eq.
photochemical oxidant formation	kg NMVOC	3,90E-08	DALY / kg NMVOC
particulate matter formation	kg PM_{10}-eq.	2,60E-04	DALY / kg PM_{10}-eq.
ionising radiation	kg U235-eq.	divers	DALY / kg U235-eq.
Ecosystems (Endpoint-unit: species.yr)			
Climate change Ecosystems	kg CO_2-eq.	7,93E-09	species.yr / kg CO_2-eq.
terrestrial acidification	kg SO_2-eq.	5,80E-09	species.yr / kg SO_2-eq.
freshwater eutrophication	kg P-eq.	4,45E-08	species.yr / kg P-eq.
terrestrial ecotoxicity	kg 1,4-DB-eq.	1,27E-07	species.yr / kg 1,4-DB-eq.
freshwater ecotoxicity	kg 1,4-DB-eq.	2,60E-10	species.yr / kg 1,4-DB-eq.
marine ecotoxicity	kg 1,4-DB-eq.	8,00E-13	species.yr / kg 1,4-DB-eq.
agricultural land occupation	m2a	divers	species.yr / m2a
urban land occupation	m2a	1,93E-08	species.yr / m2a
Resources (Endpoint-unit: $)			
metal depletion	kg Fe-eq.	7,14E-02	$ / kg Fe-eq.
fossil depletion	kg oil-eq.	16,1E 00	$ / kg oil-eq.

The final addition sum until ReCiPe-'points' takes place by normalisation of the endpoint-scores and-weigting (see explanationin 2.4).

Table 3 Normalisation- and weigting factors: Europe - Recipe H/A, without land transformation

	Normalisation	**Weighting**
Human Health	49,5/DALY	400
Ecosystems	5726/species.yr	400
Resources	3,37E-05/$	200

All results in this report are expressed in Pt, thus normalised and weighted.

Appendix 2: Window frame, plastic (PVC) in Ecoinvent

For production of a PVC window frame Ecoinvent includes:
"**Window frame, plastic (PVC), U=1.6 W/m2K, at plant/RER U**". This process pretends to be complete ("includes all important and necessary information to use the data correctly"[32]).

Input in the window frame proces, per "m^2 visible area":

Chemicals organic, at plant/GLO U	0,0287	kg
Synthetic rubber, at plant/RER U	0,798	kg
Zinc coating, coils/RER U	2,11	m
Copper, at regional storage/RER U	0,00698	kg
Polystyrene foam slab, at plant/RER U	0,184	kg
Section bar extrusion, aluminium/RER U	1,1	kg
Section bar rolling, steel/RER U	37,9	kg
Steel, low-alloyed, at plant/RER U	38	kg
Zinc coating, pieces/RER U	0,463	m
Zinc, primary, at regional storage/RER U	0,325	kg
Polyethylene, LDPE, granulate, at plant/RER U	0,00578	kg
Polypropylene, granulate, at plant/RER U	0,219	kg
Polystyrene, high impact, HIPS, at plant/RER U	0,208	kg
Injection moulding/RER U[33]	1,9	kg
Transport, lorry 20-28t, fleet average/CH U	30,5	tk
Electricity, medium voltage, production UCTE, at grid/UCTE U	13,8	kW
Polyvinyl chloride, at regional storage/RER U	58,4	kg
Extrusion, plastic pipes/RER U[34]	54,3	kg
Aluminium, production mix, at plant/RER U	1,1	kg
Aluminium, production mix, cast alloy, at plant/RER U	0,0174	kg
Metal working factory/RER/I U	4,32E-8	p

Translated name: Fensterrahmen, Kunststoff (PVC), U=1.6 W/m2K, ab Werk
Included processes: Included processes are injection moulding and extrusion of PVC, section bar rolling for steel fittings, section bar extrusion for aluminium parts, all the road transport at different production phases and the process heat waste.
Remark: This dataset describes all the processes and material inputs needed to produce a plastic window frame with 1 m2 visible area. 1 m2 of visible plastic window frame weighs 94.5 kg.; Geography: Window frames produced and sold in Switzerland and Germany.
Technology: The dataset describes highly automated technology processes in window frame manufacturing.

A plastic window frame with 1 m^2 'transparent surface' weighs 94. 5 kg, of which 55.5 kg exists of PVC. The difference with the PVC input (58,4 kg) has to be production waste, but processing is not included in the same process sheet. This is not taken into account.

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[32] About data quality of all three window frames in Ecoinvent background report 7 is stated: "The window frame datasets are of good quality. The list of input materials (metals/plastics/chemicals) is very detailed and accurate. The electricity consumption is derived from confidential data by private companies. The disposal data for the window frames are as accurate as possible, taking into account that the standard disposal scenario is a disposal via MSWI *(= AVI)*. Only big metal pieces and parts (aluminium or steel) are assumed to be recycled at 100%. Smaller metal pieces are assumed to be incinerated, as they are often glued to other materials or too small to be (cost-) efficiently recycled. This might not represent the real situation."

[33] Additives are included in this process (stabiliser, pigment and filler), but quite roughly (page 175 EI report 11 – part II)). Only a minor part of the total PVC quantity in the window frame is produced through injection moulding.

[34] No additives included, besides for the extruding itself.

Appendix 3: List of Tables

Table 4 Chlorine production per ton (all scores in Pt); corresponds with Figure 3

Impact category	Diaphragm (gas)	Membrane (gas)	Mercury cell (gas)	Current prod. mix (liquid)	75% membr. + 25% diaphragm (liquid)
Climate, health	2,70E+01	2,63E+01	3,10E+01	3,01E+01	2,75E+01
Climate, eco	1,77E+01	1,73E+01	2,03E+01	1,97E+01	1,81E+01
Ozone depl.	1,11E-01	1,11E-01	1,11E-01	1,11E-01	1,11E-01
Acidification	5,70E-02	5,58E-02	6,49E-02	6,32E-02	5,82E-02
Eutrophication	5,92E-03	5,96E-03	6,16E-03	6,12E-03	6,01E-03
Human tox	1,68E+00	1,75E+00	9,33E+00	5,94E+00	1,77E+00
Summer smog	1,75E-03	1,74E-03	1,99E-03	1,94E-03	1,80E-03
Particulate m.	7,58E+00	7,43E+00	8,60E+00	8,38E+00	7,73E+00
Ecotox, terr	2,84E-02	2,84E-02	6,26E-02	4,81E-02	2,92E-02
Ecotox, freshw	1,24E-03	1,24E-03	1,34E-03	1,32E-03	1,26E-03
Ecotox, marine	4,92E-06	4,93E-06	6,41E-06	5,83E-06	5,01E-06
Ion. radiation	2,22E-01	2,14E-01	2,58E-01	2,50E-01	2,25E-01
Land, agr	7,11E-01	7,09E-01	7,59E-01	7,49E-01	7,22E-01
Land, urb	3,01E-01	3,02E-01	3,23E-01	3,19E-01	3,07E-01
Minerals depl.	5,30E-02	5,38E-02	5,40E-02	5,39E-02	5,38E-02
Fossil depl.	3,05E+01	2,98E+01	3,51E+01	3,40E+01	3,11E+01
TOTAL (Pt)	**8,60E+01**	**8,41E+01**	**1,06E+02**	**9,98E+01**	**8,78E+01**

Table 5 Production vinyl chloride, PVC prod.mix and 3 prod.routes per ton (in Pt); see Figure 4

Impact category	Vinyl chloride	PVC production mix	PVC suspension polymerisation	PVC emulsion polymerisation	PVC bulk polymerisation
Climate, health	4,42E+01	5,45E+01	5,25E+01	6,89E+01	4,40E+01
Climate, eco	2,89E+01	3,57E+01	3,44E+01	4,51E+01	2,88E+01
Ozone depl.	1,37E-05	1,49E-04	1,37E-05	1,37E-05	1,37E-05
Acidification	5,25E-02	6,74E-02	6,32E-02	8,50E-02	6,54E-02
Eutrophication	8,37E-03	8,74E-03	8,67E-03	8,72E-03	8,63E-03
Human tox	2,25E+00	2,47E+00	2,08E+00	3,48E+00	5,33E+00
Summer smog	5,54E-03	6,46E-03	6,27E-03	6,88E-03	6,06E-03
Particulate m.	6,48E+00	8,63E+00	8,04E+00	1,08E+01	8,19E+00
Ecotox, terr	1,50E-02	1,82E-02	1,71E-02	2,34E-02	1,20E-02
Ecotox, freshw	9,43E-04	1,17E-03	1,15E-03	1,19E-03	1,05E-03
Ecotox, marine	2,23E-06	2,43E-06	2,35E-06	2,61E-06	1,86E-06
Ion. radiation	1,67E-04	1,89E-03	1,67E-04	1,67E-04	1,67E-04
Land, agr	8,23E-03	1,33E-02	8,23E-03	8,23E-03	8,23E-03
Land, urb	8,01E-03	2,55E-02	8,01E-03	8,00E-03	8,00E-03
Minerals depl.	1,37E-03	2,87E-03	1,51E-03	1,55E-03	5,66E-03
Fossil depl.	1,09E+02	1,21E+02	1,20E+02	1,32E+02	1,03E+02
TOTAL (Pt)	**1,91E+02**	**2,23E+02**	**2,17E+02**	**2,60E+02**	**1,90E+02**

Table 6 Production lead-, calcium zinc stabiliser, DEHP per ton (all in Pt); see Figure 6

Impact category	**Lead stabiliser**	**Calcium zinc stabiliser**	**DEHP**
Climate, health	9,39E+01	5,87E+01	7,47E+01
Climate, eco	6,15E+01	3,84E+01	4,90E+01
Ozone depl.	1,88E-02	5,17E-03	7,14E-03
Acidification	3,04E-01	3,50E-01	1,32E-01
Eutrophication	2,82E-04	4,42E-03	5,71E-03
Human tox	6,33E+02	4,76E+01	1,96E+00
Summer smog	1,13E-02	1,03E-02	1,04E-02
Particulate m.	2,86E+01	4,00E+01	1,69E+01
Ecotox, terr	9,62E-01	6,11E-01	4,52E-02
Ecotox, freshw	6,13E-04	2,35E-03	1,45E-03
Ecotox, marine	4,54E-05	8,95E-05	7,32E-06
Ion. radiation	5,85E-03	1,67E-01	7,84E-02
Land, agr	0,00E+00	1,12E+00	7,52E-01
Land, urb	0,00E+00	2,72E+00	3,47E-01
Minerals depl.	1,07E-02	8,57E-01	6,72E-02
Fossil depl.	1,65E+02	6,50E+01	2,15E+02
TOTAL (Pt)	**9,84E+02**	**2,56E+02**	**3,59E+02**

Table 7 Extrusion per ton processed material (all scores in Pt); see Figure 7

Impact category	**Extrusion**
Climate, health	1,05E+01
Climate, eco	6,88E+00
Ozone depl.	1,25E-03
Acidification	2,24E-02
Eutrophication	6,99E-04
Human tox	4,38E-01
Summer smog	6,90E-04
Particulate m.	2,98E+00
Ecotox, terr	1,38E-02
Ecotox, freshw	3,92E-04
Ecotox, marine	1,69E-06
Ion. radiation	7,13E-02
Land, agr	2,47E+00
Land, urb	1,48E-01
Minerals depl.	1,11E-02
Fossil depl.	1,26E+01
TOTAL (Pt)	**3,62E+01**

Table 8 PVC life cycle: production + disposal through MWIP / landfill / VKG (per ton; scores in Pt); see Figure 8

Impact category	**PVC production (for frame) + MWIP**	**PVC production (for frame) + landfill**	**PVC production (for frame) + VKG PVC recycling**
Climate, health	1,01E+02	6,77E+01	2,02E+01
Climate, eco	6,64E+01	4,44E+01	1,32E+01
Ozone depl.	1,59E-03	2,01E-03	1,45E-03
Acidification	1,21E-01	1,01E-01	3,37E-02
Eutrophication	1,23E-02	9,22E-03	1,90E-03
Human tox	2,15E+01	1,92E+01	2,56E+00
Summer smog	7,90E-03	7,43E-03	1,56E-03
Particulate m.	1,53E+01	1,28E+01	4,47E+00
Ecotox, terr	7,57E-02	7,48E-02	2,08E-02
Ecotox, freshw	9,69E-03	1,13E-02	1,34E-03
Ecotox, marine	2,77E-05	3,21E-05	4,35E-06
Ion. radiation	1,60E-01	7,72E-02	8,09E-02
Land, agr	2,67E+00	2,51E+00	2,49E+00
Land, urb	3,32E-01	4,09E-01	1,77E-01
Minerals depl.	5,82E-02	3,10E-02	1,64E-02
Fossil depl.	1,16E+02	1,34E+02	2,39E+01
TOTAL (Pt)	**3,24E+02**	**2,82E+02**	**6,71E+01**

Table 9 PVC production and MWIP, landfill and VKG/PVC recycling (per ton; scores in Pt); see Figure 9

Impact category	**PVC production (for frame)**	**PVC in MWIP**	**PVC in landfill**	**VKG PVC recycling**
Climate, health	6,59E+01	3,54E+01	1,83E+00	-4,57E+01
Climate, eco	4,32E+01	2,32E+01	1,20E+00	-3,00E+01
Ozone depl.	1,85E-03	-2,60E-04	1,61E-04	-4,06E-04
Acidification	9,98E-02	2,07E-02	9,94E-04	-6,61E-02
Eutrophication	9,20E-03	3,10E-03	2,68E-05	-7,30E-03
Human tox	1,59E+01	5,63E+00	3,33E+00	-1,33E+01
Summer smog	7,32E-03	5,77E-04	1,12E-04	-5,76E-03
Particulate m.	1,26E+01	2,64E+00	1,98E-01	-8,14E+00
Ecotox, terr	6,16E-02	1,40E-02	1,32E-02	-4,08E-02
Ecotox, freshw	1,58E-03	8,11E-03	9,77E-03	-2,38E-04
Ecotox, marine	6,62E-06	2,11E-05	2,55E-05	-2,27E-06
Ion. radiation	7,64E-02	8,33E-02	7,17E-04	4,42E-03
Land, agr	2,50E+00	1,67E-01	9,87E-03	-1,09E-02
Land, urb	2,25E-01	1,07E-01	1,85E-01	-4,81E-02
Minerals depl.	3,06E-02	2,76E-02	4,20E-04	-1,42E-02
Fossil depl.	1,34E+02	-1,74E+01	7,64E-01	-1,10E+02
TOTAL (Pt)	**2,74E+02**	**4,99E+01**	**7,53E+00**	**-2,07E+02**

Table 10 VKG recycling of 1 ton PVC; contribution several processes (in Pt) ; see Figure 10

Impact category	Electricity usage	Truck transport	MWIP 100 kg (incl. avoided energy)	PVC production mix (900 kg avoided)	MWIP 400 kg (incl. avoided energy)	PVC-production mix (600 kg avoided)
Climate, health	7,60E-02	5,21E-01	3,54E+00	-4,99E+01	1,42E+01	-3,32E+01
Climate, eco	4,98E-02	3,41E-01	2,32E+00	-3,27E+01	9,27E+00	-2,18E+01
Ozone depl.	5,40E-06	1,59E-04	-2,60E-05	-5,45E-04	-1,04E-04	-3,63E-04
Acidification	5,39E-05	1,44E-03	2,07E-03	-6,97E-02	8,26E-03	-4,65E-02
Eutrophication	1,64E-06	4,28E-05	3,10E-04	-7,65E-03	1,24E-03	-5,10E-03
Human tox	1,64E-03	1,38E-02	5,63E-01	-1,39E+01	2,25E+00	-9,28E+00
Summer smog	3,13E-06	1,43E-04	5,77E-05	-5,97E-03	2,31E-04	-3,98E-03
Particulate m.	8,32E-03	2,51E-01	2,64E-01	-8,66E+00	1,06E+00	-5,78E+00
Ecotox, terr	9,16E-05	6,74E-04	1,40E-03	-4,30E-02	5,62E-03	-2,87E-02
Ecotox, freshw	4,48E-07	1,62E-05	8,11E-04	-1,07E-03	3,25E-03	-7,10E-04
Ecotox, marine	4,24E-09	5,77E-08	2,11E-06	-4,44E-06	8,43E-06	-2,96E-06
Ion. radiation	1,40E-04	5,76E-04	8,33E-03	-4,63E-03	3,33E-02	-3,09E-03
Land, agr	1,06E-03	2,17E-03	1,67E-02	-3,09E-02	6,68E-02	-2,06E-02
Land, urb	4,70E-04	9,85E-03	1,07E-02	-6,91E-02	4,28E-02	-4,61E-02
Minerals depl.	4,61E-05	5,48E-04	2,76E-03	-1,75E-02	1,10E-02	-1,17E-02
Fossil depl.	9,91E-02	7,75E-01	-1,74E+00	-1,09E+02	-6,94E+00	-7,26E+01
TOTAL (Pt)	**2,37E-01**	**1,92E+00**	**4,99E+00**	**-2,14E+02**	2,00E+01	-1,43E+02

Table 11 PVC window frame production, 8 highest contributions (total = 29,4 Pt/m^2; all scores in Pt); see Figure 11

Impact category	PVC prod. mix	Steell	Extrusion PVC	Zn Coating	Pb-stab	Electricity	Truck transport	Section bar rolling, steel
Climate, health	3,19E+00	1,86E+00	5,70E-01	2,62E-01	1,10E-01	2,03E-01	1,63E-01	1,76E-01
Climate, eco	2,09E+00	1,22E+00	3,74E-01	1,72E-01	7,18E-02	1,33E-01	1,07E-01	1,15E-01
Ozone depl.	8,70E-06	1,52E-04	6,76E-05	7,91E-05	2,20E-05	1,77E-05	5,00E-05	3,42E-05
Acidification	3,94E-03	3,54E-03	1,22E-03	8,43E-03	3,55E-04	4,06E-04	4,55E-04	2,30E-04
Eutrophication	5,10E-04	2,27E-03	3,79E-05	1,86E-05	3,30E-07	1,22E-05	1,10E-05	2,92E-04
Human tox	1,44E-01	3,80E-01	2,38E-02	1,16E-01	7,39E-01	6,13E-03	3,91E-03	1,28E-02
Summer smog	3,77E-04	1,99E-04	3,75E-05	3,04E-05	1,32E-05	1,18E-05	4,62E-05	9,88E-06
Particulate m.	5,04E-01	9,91E-01	1,62E-01	5,06E-01	3,34E-02	5,22E-02	8,01E-02	3,64E-02
Ecotox, terr	1,06E-03	2,54E-03	7,50E-04	1,61E-03	1,12E-03	1,62E-04	2,12E-04	1,27E-03
Ecotox, freshw	6,84E-05	7,70E-04	2,13E-05	9,67E-06	7,16E-07	4,25E-06	4,33E-06	7,95E-05
Ecotox, marine	1,42E-07	2,50E-06	9,17E-08	2,29E-07	5,30E-08	1,70E-08	1,58E-08	2,42E-07
Ion. radiation	1,10E-04	4,13E-03	3,87E-03	7,81E-04	6,83E-06	1,88E-03	1,65E-04	4,93E-04
Land, agr	7,75E-04	4,43E-02	1,34E-01	3,60E-03	0,00E+00	2,43E-03	5,59E-04	6,39E-03
Land, urb	1,49E-03	9,72E-02	8,05E-03	6,84E-03	0,00E+00	1,07E-03	2,86E-03	1,48E-03
Minerals depl.	1,67E-04	9,78E-02	6,04E-04	2,05E-03	1,25E-05	4,46E-05	1,40E-04	5,80E-04
Fossil depl.	7,07E+00	2,36E+00	6,85E-01	3,51E-01	1,93E-01	2,30E-01	2,40E-01	1,50E-01
TOTAL (Pt)	**1,30E+01**	**7,06E+00**	**1,96E+00**	**1,43E+00**	**1,15E+00**	**6,31E-01**	**5,99E-01**	**5,01E-01**

Table 12 *Plastic window frame life cycle: production + disposal through MWIP / landfill / VKG (per m^2; scores in Pt) ; see Figure 12*

Impact category	Frame production + MWIP	Frame production + landfill	Fame production + VKG PVC recycling
Climate, health	9,46E+00	7,59E+00	4,95E+00
Climate, eco	6,20E+00	4,98E+00	3,25E+00
Ozone depl.	6,10E-04	6,34E-04	6,02E-04
Acidification	2,22E-02	2,11E-02	1,74E-02
Eutrophication	3,65E-03	3,48E-03	3,08E-03
Human tox	2,90E+00	2,77E+00	1,85E+00
Summer smog	8,68E-04	8,42E-04	5,16E-04
Particulate m.	2,85E+00	2,71E+00	2,25E+00
Ecotox, terr	1,25E-02	1,25E-02	9,48E-03
Ecotox, freshw	4,84E-03	4,93E-03	4,38E-03
Ecotox, marine	1,44E-05	1,46E-05	1,31E-05
Ion. radiation	1,84E-02	1,39E-02	1,41E-02
Land, agr	2,64E-01	2,55E-01	2,54E-01
Land, urb	2,40E-01	2,44E-01	2,31E-01
Minerals depl.	1,06E-01	1,04E-01	1,04E-01
Fossil depl.	1,15E+01	1,25E+01	6,37E+00
TOTAL (Pt)	**3,36E+01**	**3,12E+01**	**1,93E+01**

Table 13 *Plastic window frame: production and disposal (all per m^2; scores in Pt) ; see Figure 13*

Impact category	Frame production	Frame MWIP	Frame landfill	VKG PVC recycling
Climate, health	7,31E+00	2,15E+00	2,85E-01	-2,36E+00
Climate, eco	4,79E+00	1,41E+00	1,86E-01	-1,54E+00
Ozone depl.	6,09E-04	1,75E-06	2,51E-05	-6,35E-06
Acidification	2,09E-02	1,37E-03	2,77E-04	-3,45E-03
Eutrophication	3,35E-03	3,02E-04	1,31E-04	-2,75E-04
Human tox	1,59E+00	1,30E+00	1,18E+00	2,51E-01
Summer smog	8,12E-04	5,54E-05	2,96E-05	-2,96E-04
Particulate m.	2,66E+00	1,84E-01	4,86E-02	-4,14E-01
Ecotox, terr	1,12E-02	1,29E-03	1,24E-03	-1,76E-03
Ecotox, freshw	1,02E-03	3,82E-03	3,91E-03	3,35E-03
Ecotox, marine	3,70E-06	1,07E-05	1,09E-05	9,39E-06
Ion. radiation	1,38E-02	4,68E-03	9,80E-05	3,03E-04
Land, agr	2,54E-01	9,69E-03	9,68E-04	-1,86E-04
Land, urb	2,30E-01	9,36E-03	1,37E-02	7,48E-04
Minerals depl.	1,04E-01	1,59E-03	8,48E-05	-7,24E-04
Fossil depl.	1,24E+01	-8,87E-01	1,18E-01	-6,01E+00
TOTAL (Pt)	**2,94E+01**	**4,19E+00**	**1,83E+00**	**-1,01E+01**

Table 14 PVC pipe life cycle: pipe production + disposal through MWIP / landfill / BIS (per m^2; scores in Pt); see Figure 14

Impact category	Pipe production + MWIP	Pipe production + landfill	Pipe production + BIS PVC recycling
Climate, health	1,01E+02	6,71E+01	2,01E+01
Climate, eco	6,60E+01	4,40E+01	1,32E+01
Ozone depl.	1,27E-03	1,69E-03	1,41E-03
Acidification	1,13E-01	9,37E-02	3,30E-02
Eutrophication	1,25E-02	9,39E-03	1,92E-03
Human tox	1,22E+01	9,95E+00	1,63E+00
Summer smog	7,77E-03	7,31E-03	1,54E-03
Particulate m.	1,45E+01	1,21E+01	4,40E+00
Ecotox, terr	5,45E-02	5,37E-02	1,87E-02
Ecotox, freshw	9,68E-03	1,13E-02	1,34E-03
Ecotox, marine	2,59E-05	3,03E-05	4,17E-06
Ion. radiation	1,57E-01	7,48E-02	8,06E-02
Land, agr	2,65E+00	2,50E+00	2,49E+00
Land, urb	2,95E-01	3,73E-01	1,73E-01
Minerals depl.	4,63E-02	1,92E-02	1,52E-02
Fossil depl.	1,16E+02	1,34E+02	2,39E+01
TOTAL (Pt)	**3,13E+02**	**2,71E+02**	**6,60E+01**

Table 15 PVC pipe production and -disposal (all per ton; in Pt) ; see Figure 15

Impact category	Pipe production	MWIP	Landfill	BIS PVC recycling
Climate, health	6,53E+01	3,54E+01	1,83E+00	-4,52E+01
Climate, eco	4,28E+01	2,32E+01	1,20E+00	-2,96E+01
Ozone depl.	1,53E-03	-2,60E-04	1,61E-04	-1,13E-04
Acidification	9,27E-02	2,07E-02	9,94E-04	-5,97E-02
Eutrophication	9,37E-03	3,10E-03	2,68E-05	-7,45E-03
Human tox	6,62E+00	5,63E+00	3,33E+00	-4,98E+00
Summer smog	7,20E-03	5,77E-04	1,12E-04	-5,65E-03
Particulate m.	1,19E+01	2,64E+00	1,98E-01	-7,50E+00
Ecotox, terr	4,05E-02	1,40E-02	1,32E-02	-2,18E-02
Ecotox, freshw	1,57E-03	8,11E-03	9,77E-03	-2,30E-04
Ecotox, marine	4,84E-06	2,11E-05	2,55E-05	-6,63E-07
Ion. radiation	7,41E-02	8,33E-02	7,17E-04	6,51E-03
Land, agr	2,49E+00	1,67E-01	9,87E-03	2,59E-03
Land, urb	1,88E-01	1,07E-01	1,85E-01	-1,51E-02
Minerals depl.	1,87E-02	2,76E-02	4,20E-04	-3,49E-03
Fossil depl.	1,34E+02	-1,74E+01	7,64E-01	-1,10E+02
TOTAL (Pt)	**2,63E+02**	**4,99E+01**	**7,53E+00**	**-1,97E+02**

Table 16 Production of soft PVC for cables (per ton cable; scores in Pt) ; see Figure 16

Impact category	**Total**	**PVC production mix**	**DEHP**
Climate, health	6,06E+01	3,82E+01	2,24E+01
Climate, eco	3,97E+01	2,50E+01	1,47E+01
Ozone depl.	2,25E-03	1,04E-04	2,14E-03
Acidification	8,67E-02	4,72E-02	3,95E-02
Eutrophication	7,83E-03	6,12E-03	1,71E-03
Human tox	2,31E+00	1,73E+00	5,88E-01
Summer smog	7,63E-03	4,52E-03	3,11E-03
Particulate m.	1,11E+01	6,04E+00	5,07E+00
Ecotox, terr	2,63E-02	1,28E-02	1,36E-02
Ecotox, freshw	1,25E-03	8,20E-04	4,34E-04
Ecotox, marine	3,90E-06	1,70E-06	2,20E-06
Ion. radiation	2,48E-02	1,32E-03	2,35E-02
Land, agr	2,35E-01	9,29E-03	2,26E-01
Land, urb	1,22E-01	1,78E-02	1,04E-01
Minerals depl.	2,22E-02	2,01E-03	2,02E-02
Fossil depl.	1,49E+02	8,48E+01	6,46E+01
TOTAL (Pt)	**2,64E+02**	**1,56E+02**	**1,08E+02**

Table 17 PVC in cable life cycle:
production + disposal through MWIP / landfill (per m; scores in Pt); see Figure 17

Impact category	**PVC share production + MWIP**	**PVC share production + landfill**
Climate, health	4,74E-03	3,31E-03
Climate, eco	3,11E-03	2,17E-03
Ozone depl.	8,12E-08	1,66E-07
Acidification	5,19E-06	5,00E-06
Eutrophication	4,76E-07	3,89E-07
Human tox	3,54E-04	2,76E-04
Summer smog	3,72E-07	3,83E-07
Particulate m.	6,60E-04	6,49E-04
Ecotox, terr	1,66E-06	2,42E-06
Ecotox, freshw	6,39E-07	5,18E-07
Ecotox, marine	1,83E-09	1,41E-09
Ion. radiation	5,78E-06	4,40E-06
Land, agr	1,20E-04	1,23E-04
Land, urb	1,24E-05	2,06E-05
Minerals depl.	2,34E-06	1,53E-06
Fossil depl.	5,81E-03	7,39E-03
TOTAL (Pt)	**1,48E-02**	**1,40E-02**

Table 18 PVC cable production (complete and PVC share) and PVC share MWIP + landfill (per m; in Pt); see Figure 18

Impact category	**Cable production (complete)**	**Production PVC share (only)**	**MWIP PVC share**	**Landfill PVC share**
Climate, health	1,24E-02	3,23E-03	1,51E-03	8,29E-05
Climate, eco	8,12E-03	2,11E-03	9,90E-04	5,43E-05
Ozone depl.	1,16E-06	1,59E-07	-7,73E-08	7,32E-09
Acidification	5,76E-05	4,95E-06	2,37E-07	4,51E-08
Eutrophication	5,81E-06	3,87E-07	8,90E-08	1,22E-09
Human tox	8,48E-03	1,25E-04	2,29E-04	1,51E-04
Summer smog	1,68E-06	3,78E-07	-5,83E-09	5,09E-09
Particulate m.	8,38E-03	6,40E-04	2,00E-05	8,97E-06
Ecotox, terr	4,65E-05	1,82E-06	-1,62E-07	5,98E-07
Ecotox, freshw	1,90E-06	7,47E-08	5,64E-07	4,43E-07
Ecotox, marine	1,74E-08	2,54E-10	1,58E-09	1,16E-09
Ion. radiation	4,28E-05	4,36E-06	1,41E-06	3,25E-08
Land, agr	1,70E-03	1,23E-04	-3,05E-06	4,48E-07
Land, urb	1,05E-03	1,23E-05	1,61E-07	8,38E-06
Minerals depl.	4,06E-04	1,51E-06	8,29E-07	1,91E-08
Fossil depl.	1,81E-02	7,36E-03	-1,55E-03	3,47E-05
TOTAL (Pt)	**5,88E-02**	**1,36E-02**	**1,20E-03**	**3,42E-04**

Table 19 Comparison of 3 types complete frames per m^2: aluminium, PVC (disposal through landfill, MWIP and VKG) and wood (1 and 2 life cycles) (all scores in Pt) ; see Figure 19

Impact category	**Aluminium frame**	**PVC frame LANDFILL**	**PVC frame MWIP**	**PVC frame VKG**	**Wooden frame**	**Woodemn frame (2 life cycles)**
Climate, health	5,97E+00	7,59E+00	9,46E+00	4,95E+00	3,42E+00	6,84E+00
Climate, eco	3,91E+00	4,98E+00	6,20E+00	3,25E+00	2,24E+00	4,48E+00
Ozone depl.	9,28E-04	6,34E-04	6,10E-04	6,02E-04	5,60E-04	1,12E-03
Acidification	9,78E-03	2,11E-02	2,22E-02	1,74E-02	9,23E-03	1,85E-02
Eutrophication	1,49E-03	3,48E-03	3,65E-03	3,08E-03	1,29E-03	2,59E-03
Human tox	2,21E-01	2,77E+00	2,90E+00	1,85E+00	6,42E-01	1,28E+00
Summer smog	3,82E-04	8,42E-04	8,68E-04	5,16E-04	4,96E-04	9,92E-04
Particulate m.	1,37E+00	2,71E+00	2,85E+00	2,25E+00	1,44E+00	2,89E+00
Ecotox, terr	2,60E-03	1,25E-02	1,25E-02	9,48E-03	2,49E-02	4,97E-02
Ecotox, freshw	4,33E-04	4,93E-03	4,84E-03	4,38E-03	1,43E-03	2,85E-03
Ecotox, marine	1,34E-06	1,46E-05	1,44E-05	1,31E-05	4,11E-06	8,21E-06
Ion. radiation	1,21E-02	1,39E-02	1,84E-02	1,41E-02	1,64E-02	3,27E-02
Land, agr	2,07E-01	2,55E-01	2,64E-01	2,54E-01	1,50E+01	2,99E+01
Land, urb	7,71E-02	2,44E-01	2,40E-01	2,31E-01	4,04E-01	8,08E-01
Minerals depl.	6,06E-03	1,04E-01	1,06E-01	1,04E-01	1,85E-02	3,71E-02
Fossil depl.	7,76E+00	1,25E+01	1,15E+01	6,37E+00	3,76E+00	7,53E+00
TOTAL (Pt)	**1,95E+01**	**3,12E+01**	**3,36E+01**	**1,93E+01**	**2,69E+01**	**5,39E+01**

Table 20 Pipe per 5 m: PVC, stoneware, concrete and PE, production and disposal; (in Pt); see Figure 20

Impact category	PVC landfill	PVC MWIP	PVC BIS	Stoneware	Concrete	PE landfill	PE MWIP	PE BIS
Climate, health	1,47E+00	2,20E+00	4,41E-01	8,89E+00	8,44E-01	1,62E+00	2,23E+00	4,65E-01
Climate, eco	9,63E-01	1,44E+00	2,89E-01	5,82E+00	5,53E-01	1,06E+00	1,46E+00	3,05E-01
Ozone depl.	3,69E-05	2,77E-05	3,09E-05	1,96E-03	5,18E-05	3,73E-05	-8,87E-05	2,21E-05
Acidification	2,05E-03	2,48E-03	7,22E-04	9,36E-03	6,91E-04	2,52E-03	1,75E-03	6,97E-04
Eutrophication	2,06E-04	2,73E-04	4,20E-05	7,69E-04	1,89E-05	1,56E-04	1,39E-04	3,01E-05
Human tox	2,18E-01	2,68E-01	3,58E-02	2,88E-01	1,54E-02	2,44E-01	1,96E-01	2,94E-02
Summer smog	1,60E-04	1,70E-04	3,38E-05	4,09E-04	4,93E-05	1,81E-04	1,35E-04	3,20E-05
Particulate m.	2,65E-01	3,18E-01	9,63E-02	1,54E+01	1,05E-01	3,08E-01	1,90E-01	8,99E-02
Ecotox, terr	1,18E-03	1,19E-03	4,08E-04	4,79E-03	2,09E-04	6,32E-04	-4,93E-04	2,69E-04
Ecotox, freshw	2,48E-04	2,12E-04	2,93E-05	2,02E-04	6,09E-06	9,64E-04	5,64E-04	6,53E-05
Ecotox, marine	6,65E-07	5,67E-07	9,14E-08	8,77E-07	2,52E-08	2,92E-06	1,69E-06	2,08E-07
Ion. radiation	1,64E-03	3,45E-03	1,77E-03	2,10E-02	1,02E-03	1,76E-03	-4,36E-04	1,52E-03
Land, agr	5,47E-02	5,81E-02	5,45E-02	2,28E-01	5,57E-03	6,02E-02	4,52E-02	5,81E-02
Land, urb	8,17E-03	6,47E-03	3,79E-03	2,03E-01	3,19E-02	8,52E-03	-1,66E-03	3,30E-03
Minerals depl.	4,19E-04	1,01E-03	3,34E-04	1,21E-02	3,98E-04	4,16E-04	3,21E-04	2,88E-04
Fossil depl.	2,94E+00	2,55E+00	5,23E-01	1,30E+01	3,65E-01	4,75E+00	2,97E+00	5,92E-01
TOTAL (Pt)	**5,93E+00**	**6,86E+00**	**1,45E+00**	**4,39E+01**	**1,92E+00**	**8,05E+00**	**7,09E+00**	**1,55E+00**

Table 21 Cable production and disposal (MWIP and landfill): PVC share and rubber share (per m) (all scores in Pt) ; see Figure 21

Impact category	PVC production	PVC production + MWIP	PVC production + landfill	Rubber production	Rubber production + MWIP	Rubber production + landfill
Climate, health	3,23E-03	4,74E-03	3,31E-03	6,12E-03	8,48E-03	6,20E-03
Climate, eco	2,11E-03	3,11E-03	2,17E-03	4,01E-03	5,56E-03	4,06E-03
Ozone depl.	1,59E-07	8,12E-08	1,66E-07	1,80E-06	1,66E-06	1,81E-06
Acidification	4,95E-06	5,19E-06	5,00E-06	1,67E-05	1,60E-05	1,68E-05
Eutrophication	3,87E-07	4,76E-07	3,89E-07	5,87E-07	5,92E-07	5,88E-07
Human tox	1,25E-04	3,54E-04	2,76E-04	1,92E-04	1,92E-04	3,43E-04
Summer smog	3,78E-07	3,72E-07	3,83E-07	5,86E-07	5,42E-07	5,91E-07
Particulate m.	6,40E-04	6,60E-04	6,49E-04	1,96E-03	1,84E-03	1,97E-03
Ecotox, terr	1,82E-06	1,66E-06	2,42E-06	5,10E-06	3,81E-06	5,70E-06
Ecotox, freshw	7,47E-08	6,39E-07	5,18E-07	2,42E-07	2,91E-07	6,86E-07
Ecotox, marine	2,54E-10	1,83E-09	1,41E-09	6,68E-10	7,57E-10	1,83E-09
Ion. radiation	4,36E-06	5,78E-06	4,40E-06	1,89E-05	1,66E-05	1,89E-05
Land, agr	1,23E-04	1,20E-04	1,23E-04	3,01E-04	2,84E-04	3,01E-04
Land, urb	1,23E-05	1,24E-05	2,06E-05	4,77E-05	4,19E-05	5,61E-05
Minerals depl.	1,51E-06	2,34E-06	1,53E-06	5,22E-06	5,20E-06	5,24E-06
Fossil depl.	7,36E-03	5,81E-03	7,39E-03	1,33E-02	1,12E-02	1,33E-02
TOTAL (Pt)	**1,36E-02**	**1,48E-02**	**1,40E-02**	**2,60E-02**	**2,77E-02**	**2,63E-02**