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TNO report

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LCA of thermal treatment of waste streams in cement clinker kilns in Belgium

Comparison to alternative treatment options

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Summary and conclusions

On request of Febelcem, TNO performed a Life Cycle Assessment (LCA) on the environmental impact of the thermal processing of waste streams in the Belgian cement industry, compared with the thermal treatment in alternative treatment options (waste incinerators). Five waste streams were defined: solvents/waste oil, filter cake, sawdust impregnated paint/ink sludge, fluff and waste water treatment sludge. Based on differences in physical properties between the waste streams, it was decided to compare to specific treatment options for each specific waste stream: rotary kiln incineration (for the three first mentioned wastes) and fluidised bed combustion (for the latter two).

The functional unit was defined as the thermal treatment of one ton of specific waste in Belgium in 2006 (and ***not*** the production of one ton of cement clinker). In this way the two intrinsically different systems (cement clinker production and waste incineration) can be compared without large difficulties.

From the Belgian cement industry, all required 2006-based data were gathered, from which the required input was defined for application of the LCA CML method. All six cement kilns (on four locations) that use wastes as a secondary fuel were taken into account. The calculations are based on the method of marginal changes, which defines impact results to a certain base case. The base case is the mix of primary and secondary fuels in the cement industry in Belgium in 2006, and the marginal change is defined as the treatment of one extra ton of one of the five waste streams. In this study, the combustion of petroleum cokes is used as basic substitution for the use of secondary fuel in the cement industry. To a certain extent, the substitution of raw materials by ashes from the defined waste streams is incorporated, as result of the substitution of petroleum cokes.

The models for the alternative treatment options (incinerators) were defined based on reference processes, gathered from an Eco-invent study performed on a Swiss incineration plant, and the TNO specific knowledge. For this industry, the replacement of fossil electricity and heat is defined as the outcome of the process. As well as for the cement industry, waste streams are substituted based on the calorific value of the respective fuels.

Based on the results of this study, TNO safely concludes[1] that, from an environmental point of view, the thermal treatment of the waste streams under regard in a cement kiln is in all cases favourable, compared to the most relevant alternative treatment options (incinerators). The minor negative impact in the pre-treatment of some of the waste streams is by far more than compensated for during the actual processing in the cement kilns. The largest positive effect of thermal treatment in cement kilns compared to the treatment in the incinerators is caused by the lower CO_2 emission at the stack, due to the different organic composition of the waste streams, compared to petroleum cokes. A second positive effect is the fact that cement kilns do not have emissions of toxic substances to water, whereas rotary kilns do have such emissions.

[1] Two out of eight members of the expert panel did not fully agree on all conclusions; see footnote under Goals and Scope.

Seven variables were subjected to a sensitivity analysis, to check the robustness of the conclusions:

- Variation in emissions of the different cement kilns, showing for instance the difference between dry and wet cement production processes.
- Plus or minus 50% of the heavy metal and S, Cl and F content in paint/ink residue.
- Minus 10% carbon content in fluff.
- Minus 10% of caloric value (or 10% higher moisture content) of the wastes.
- Plus 50% VOC emissions from the paint/ink-impregnated saw dust silo.
- Lower shadow prices for CO_2 and SO_x (€ 20 per ton and € 2,50 per kg, in stead of € 50 per ton and € 4,- per kg respectively).
- Other transfer coefficients for waste incineration (lower emissions to air and water)

In most cases the difference in shadow prices between cement kilns on the one hand and waste incineration on the other hand decreased, but in no single case the conclusions changed. So, the conclusions can be said to be robust. The difference between wet and dry cement production processes proved to be only marginal.

Samenvatting en conclusies

Op verzoek van Febelcem heeft TNO een Levens Cyclus Analyse (LCA) uitgevoerd naar de milieueffecten van de thermische verwerking van specifieke afvalstromen in de Belgische cementindustrie. Deze verwerking is vergeleken met alternatieve thermische verwerkingstechnieken (afvalverbranding). Vijf specifieke afvalstromen zijn gedefinieerd en onderzocht: oplosmiddelen / afvalolie, filter cake, met verf / inkt geïmpregneerd zaagsel, fluff (een mengsel van plastics, textiel, enz.), en slib afkomstig van (industriële) waterzuivering. Op basis van de (verschillen in) fysische eigenschappen is per afvalstroom de meest voor de hand liggende alternatieve verwerkingstechniek gekozen: een draaitrommeloven voor de drie eerstgenoemde afvalstromen en een wervelbedoven voor de twee laatstgenoemden.
Als functionele eenheid werd gedefinieerd de thermische verwerking van één ton van één van de specifieke afvalstromen in België, in 2006 (en dus ***niet*** de productie van één ton cementklinker). Op deze manier kunnen twee intrinsiek nogal verschillende processen (de productie van cementklinker en afvalverbranding) toch eenvoudig met elkaar worden vergeleken.

De benodigde gegevens over de cementproductieprocessen en de gebruikte secundaire brandstoffen werden aangeleverd door de Belgische cementindustrie zelf. Alle gegevens hadden betrekking op het referentiejaar 2006. Alle zes cementovens (draaiend op vier verschillende locaties) zijn in de LCA-studie betrokken. De uitgevoerde berekeningen zijn gebaseerd op de aanpak van ‘marginale verandering’. Deze aanpak houdt in dat de milieueffecten ten gevolge van een marginale verandering ten opzichte van een basissituatie in kaart worden gebracht. De situatie die als basissituatie is gehanteerd, is het gebruik van de bestaande mix van primaire en secundaire brandstoffen in de cementindustrie in België in 2006. Als marginale verandering is gedefinieerd de thermische verwerking van één (extra) ton van één van de genoemde specifieke afvalstromen. In deze studie is petroleum cokes gehanteerd als de standaard brandstof die wordt vervangen in het geval van de inzet van secundaire brandstoffen. In beperkte mate worden ook grondstoffen vervangen als gebruik wordt gemaakt van secundaire brandstoffen, vanwege de anorganische componenten die in de afvalstoffen opgesloten zitten en die na verbranding als as in het grondstoffenmengsel overblijven.

De modellen voor de alternatieve thermische verwerking (verbranding) zijn gedefinieerd op basis van gegevens van een referentie verbrandingsinstallatie en bij TNO aanwezige specifieke kennis op het gebied van afvalverbranding. De referentiegegevens waren afkomstig van een Eco-invent LCA-studie, uitgevoerd op een Zwitserse verbrandingsinstallatie. Voor deze alternatieve processen is als substitutie-scenario gekozen voor de productie van fossiele elektriciteit en warmte, omdat een afvalverbrandingsinstallatie niet draait (en dus ook geen elektriciteit en warmte produceert) als er geen afval wordt aangeleverd. In beide gevallen (cementovens en verbrandingsinstallaties) zijn de afvalstromen gesubstitueerd op basis van calorische waarde.

Gebaseerd op de resultaten van de uitgevoerde studie, concludeert TNO[2] dat, vanuit milieuoogpunt bezien, de thermische verwerking in een cementoven voor alle vijf

[2] Twee van de acht leden van het expert panel kunnen niet alle conclusies volledig onderschrijven; zie ook de voetnoot onder “Goals and Scope” en de opmerkingen, zoals opgenomen in Annex 6.

onderzochte afvalstromen de voorkeur heeft boven de verwerking ervan in het meest voor de hand liggende type afvalverbrandingsinstallatie. De beperkt negatieve milieugevolgen van de voorbehandeling die voor een aantal afvalstoffen noodzakelijk is in het geval van de verwerking in een cementoven worden in ruime mate gecompenseerd door de (positieve) milieugevolgen van de feitelijke verbranding in de cementoven. Het grootste positieve effect van de verwerking in een cementoven, ten opzichte van de verwerking in een verbrandingsinstallatie, wordt gevormd door de lagere CO_2-emissie via de schoorsteen. Dit wordt veroorzaakt door het verschil in organische samenstelling (CHO-verhouding) van de afvalstoffen ten opzichte van petroleum cokes. Een tweede positieve effect is dat cementovens geen emissies van toxische componenten naar water veroorzaken, terwijl een draaitrommeloven dat wel doet.

Na uitvoering van de feitelijke LCA zijn zeven variabelen onderworpen aan een gevoeligheidsanalyse, om de robuustheid van de getrokken conclusies te verifiëren:
- Onderlinge variatie in emissies van de verschillende cementovens, waaronder zowel zogenaamde natte als droge cementproductieprocessen.
- Plus of min 50% van de concentraties van zware metalen en S, Cl en F in verf/inkt residuen.
- Een vermindering van 10% in het koolstofgehalte in fluff.
- Een vermindering van 10% in de calorische waarde in de afvalstoffen (bijvoorbeeld ten gevolge van een 10% hoger vochtgehalte).
- Een verhoging met 50% van de emissie van vluchtige organische koolwaterstoffen (VOC) uit de opslag van zaagsel, geïmpregneerd met verf/inkt residuen.
- Een lagere “schaduwprijs” voor CO_2 en SO_x (nl. € 20 per ton en € 2,50 per kg, in plaats van respectievelijk € 50 per ton en € 4,- per kg).
- Andere verdelingscoëfficiënten voor de afvalverbrandingsinstallaties (lagere emissies naar lucht en naar water).

In vrijwel alle bovengenoemde gevallen worden de verschillen in schaduwprijzen tussen de cementovens en de afvalverbrandingsinstallaties wel kleiner, maar in geen enkel geval veranderen de conclusies. De conclusies zijn dus robuust. Het verschil in milieugevolgen tussen cementproductie in een nat en in een droog proces blijkt slechts marginaal te zijn.

Contents

1 Introduction

Febelcem is the association of Belgian cement producers. In the current practice of cement production, and more specifically the clinker[3] production, alternative fuels made from specific waste streams are of considerable importance. Febelcem has asked TNO to make an environmental comparison of waste treatment in clinker kilns with treatment in waste incinerators. The environmental assessment is a response on the proposed change in taxation on secondary fuels.

For the environmental assessment five waste streams have been selected (see Table 1). These five waste streams cover 91% of the mass input of energy carriers, excluding animal meal and fossil fuel as these last two fuels are no subject of the taxation on secondary fuels.

Table 1 Total dosage of energy carriers, excluding fossil fuels and animal meal.

	kT/y	% of total	GJ/y	% of total
1. Waste Oil/Solvents	54,1	9,8%	1.578.164	18,7%
2. Industrial Sludges	94,8	17,2%	781.366	9,3%
3. Filter cakes	85,0	15,4%	400.576	4,7%
4. Imp. Sawdust and Paintsludge	216,8	39,3%	3.152.302	37,4%
5. Plastics, Textiles, RBA, Fluff	50,8	9,2%	1.096.360	13,0%
Subtotal	**501,7**	**90,9%**	**7.008.769**	**83,1%**
Others	50,4	9,1%	1.423.483	16,9%
Total	**552,1**	**100,0%**	**8.432.252**	**100,0%**

The study started in February 2007 and was finalised in June 2007. It is conducted in cooperation with an expert panel, consisting of

- OVAM[4]
- Wallone representatives (chair)
- VITO[4]
- Neosys
- cement producers: Holcim, CCB and CBR
- Febelcem

[3] Clinker is the output product of the burning process. The main raw material is calcareous rock like limestone. It is the main constituent of cement.

[4] See footnote on next page, under Goal and Scope.

2 Study approach

2.1 Goal and scope

The **goal** of the study is:
The comparison of the environmental performance of the thermal treatment of a number of specific waste streams in the clinker production process with the thermal treatment of these waste streams in waste incinerators.

The target audience of the report is, besides Febelcem and its members, the Belgian authorities, the Belgian special waste processors and experts in the field of waste incineration. To follow the ISO guidelines for LCA and to improve the quality of the LCA study, an expert panel was consulted four times during the performance of the study. Jürg Liechti of Neosys acted as reviewer. The review statement and the reviewer's recommendations, as well as the comments made by the expert panel members (and the authors' reaction on that) are included as Annex 6 to this LCA report. The following parties were represented in the expert panel:

VITO[5]	Katleen Briffaerts
Ministère de la Région Wallonne	Philippe Decornet (chairman)
OVAM (representing the Flemish authority)[5]	Luk Umans and Dries Gommers
Febelcem	Benoit Lussis and Michel Calozet
CCB / Italcimenti	Eric Derycke (Chef de Département Développement Environnement)
CBR / Heidelberger Cement	Fabrice Foucart and Gaetan de Maere (Environmental Affairs Managers)
Geocycle/Holcim	Olivier Barbery (Director)
Neosys	Jürg Liechti (reviewer)

In the LCA study two systems are being compared with each other:
1. the use of specific waste streams as alternative fuels in the Belgian clinker production;
2. the incineration of these specific waste streams in dedicated waste incinerators in Belgium.

The time frame for comparison is the current situation with the focus on the year 2006.

The function that is provided by both product systems and that is the single base for comparison is the ***functional unit***. To this functional unit all input and output flows will be referred. For this comparison the functional unit is defined as follows:

The thermal treatment of 1 ton of a specific waste in Belgium in 2006.

The approach used to compare the two systems with each other is that of comparing the ***marginal changes***. This means that the changes and effects are studied that result from a minor change in a system. In this study the marginal change is the treatment of one

[5] The representatives of OVAM and VITO had (and still have) objections to some of the "starting points" of the study, and therefore cannot fully agree with the conclusions of the study. Their comments, and the reactions of the authors, are given in Annex 6.

(extra) ton of waste in either system. So, this LCA only includes effects that are changed by the additional input of 1 ton specified secondary fuel. For co-incineration in a clinker kiln, the changes included are:

– Transport and pre-treatment
– Emissions
– *Avoided utilization of primary fuels (pet coke or coal) and of raw material (minerals)*

For the alternative waste treatment systems, the changes included are:

– The use of auxiliaries
– Emissions
– Treatment of waste products
– Energy recovery *(avoided electricity and heat production)*
– Solvents: supportive fuel avoided

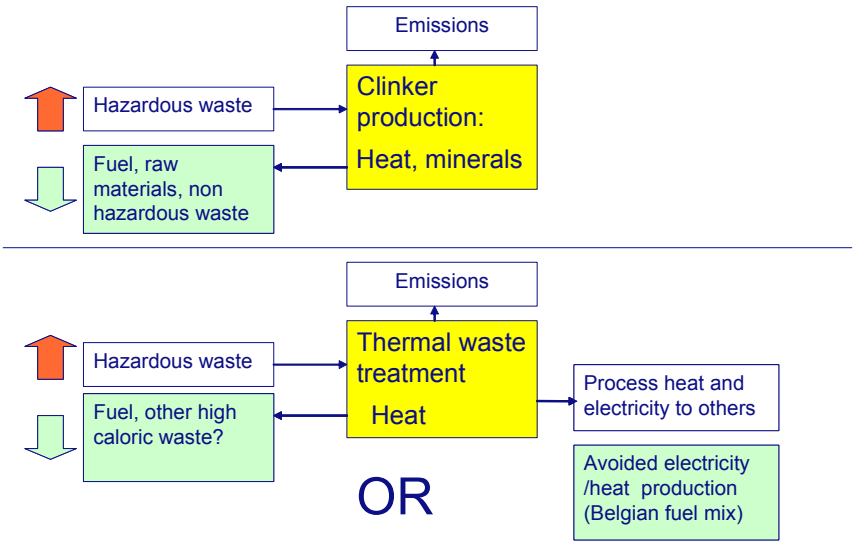

Figure 1 Marginal change and avoided environmental impact for equal comparisons of two thermal treatment systems.

Due to the approach of addressing only the marginal changes, the production of clinker in the clinker kiln as such is not relevant for the study, as the amount of clinker produced is not influenced by an increased input of one of the five waste streams. As a result of this approach, differences in energy efficiency between different clinker production processes are not within the scope of this study.

Some of the elements in the waste will end up in the clinker product and finally in cement. Therefore the clinker product itself needs to be within the scope of the study. However a previous study [6] states that the environmental impact is the same for cement produced with or without the input of (hazardous) waste. Additional leaching of elements out of clinker due to co-incineration of waste could not be quantitatively measured. That means that the impact thereof in the framework of this study is negligible.

There are 6 cement kilns in Belgium, located at four locations that use at least one of the five specified waste streams. For each of the five waste types, the average environmental impact will be calculated, according to the treatment in 2006; the average is based on the actual amount of the specified waste treated in the kilns (see Annex 1).

2.2 Substitution scenario's

The substitution scenario is based on the caloric value of the specific waste stream. The input of a certain amount of energy in the form of waste in a clinker kiln avoids the same amount of energy in the form of petcokes or coal. The substitution by coal is relatively low, compared to that of petcokes. In practice approximately 20% of the total fuel requirement is fulfilled by means of coal.
As most wastes contain more minerals compared to petcokes or coal, the difference is compensated by a decrease in raw meal. Solvents and waste oils are an exception: they contain less minerals compared to petcokes and coal, and therefore a little more raw meal is needed.

Table 2 Substitution scenario's for each of the five wastes in clinker kilns.

	Petcokes		Coal	
	Fuel	Rawmeal	Fuel	Rawmeal
	(T/T)	(T/T)	(T/T)	(T/T)
1. Imp. Sawdust	0,44	0,18	0,43	0,16
2. Sludge	0,25	0,27	0,26	0,27
3. Solvents	0,88	-0,01	0,86	0,00
4. Fluff	0,65	0,12	0,64	0,13
5. Filtercake	0,14	0,24	0,14	0,24

Table 3 shows the substitution scenario's for waste incinerators. They are as far as possible based on the Belgian situation, with the perspective of marginal change. The selected waste streams are regarded as if they were treated by Indaver. At the Antwerp site (rotary kiln) energy is recovered from the incineration of (hazardous) waste. Part of this energy is used within the process as steam and electricity; the remaining is delivered, as steam and electricity, to other processes at the Antwerp site. The same holds for the Fluidised Bed Combustor of Indaver. The system is in both cases balanced by subtracting the avoided energy production from the impact of incineration – to keep the functionality the same between the two systems (cement kiln and incinerators). The substitution for waste incineration is based on the caloric value of the waste, similar to clinker kilns (see Table 2).

Table 3 Recovered energy delivered to external users in MJ per MJ caloric content of waste.

Recovered energy	Rotary kiln	Fluidised Bed	Grate incinerator
Steam	0.209	0.254	0.254
Electricity	0.022	0.102	0.102

For the externally delivered energy the avoided production of steam and electricity is subtracted from the system. To reflect the actual situation the Belgian electricity mix is used as the avoided product. For steam it will be the conventional generation of industrial process steam.

For Solvents/waste oils, an additional substitution scenario is calculated, as in the review panel it was argued that increased input of solvents/waste oils decreases the need for supportive fuel (light oil) for start up of the waste incineration plant. For the other waste streams this is not a realistic scenario, as that (solid) wastes cannot directly replace diesel oil. Even for solvents/waste oils this is only a marginal, and not representative scenario, because in practice only 2% (based on caloric value) of fuel oil is being used per ton of waste. Besides, Indaver uses waste oil as a supportive fuel. This could be replaced by the specific waste stream 'solvents / waste oils', but in LCA terms this is the same material, not leading to a real substitution.

2.3 Impact assessment

The baseline categories of the CML impact assessment method is used to calculate environmental impact results. A sensitivity analysis will be made using the Eco-indicator 99 method. Table 4 gives an overview of the impact assessment categories in these two methods, and the units of the results. CML is a midpoint method: the results within a category are integrated using equivalency factors. Eco-indicator 99 is a damage-oriented method: the results are expressed in damage units for:

- Human Health (Disability Adjusted Life Years – DALYs),
- Ecosystem quality (Potentially Disappeared of Affected Fraction – PDF of PAF, on a certain area during a certain time period)
- Depletion of resources (surplus energy for future extraction)

Table 4 Overview of Impact categories in CML and Eco-indicator 99 impact assessment methods.

CML		**Eco-indicator 99 (*sensitivity analysis)***	
Impact category	**Midpoint unit**	**Impact category**	**Damage unit**
Abiotic Depletion	kg Sb eq.	Depletion of Fossils	MJ surplus energy
		Depletion of Minerals	MJ surplus energy
Global Warming	kg CO_2 eq.	Global Warming	DALY
Ozone Depletion	kg CFC-11 eq.	Ozone Depletion	DALY
Human Toxicity	kg $C_6H_4Cl_2$ eq.	Carcinogenics	DALY
Photochemical Oxidant Creation	kg C_2H_4 eq.	Respiratory organics	DALY
		Respiratory inorganics	DALY
Freshwater Aquatic Ecosystem Toxicity	kg $C_6H_4Cl_2$ eq.	Eco-toxicity	PAF.m2.year
Terrestrial Ecosystem Toxicity	kg $C_6H_4Cl_2$ eq.		
Marine Aquatic Ecosystem Toxicity	kg $C_6H_4Cl_2$ eq.		
		Land use	PDF.m2.year
Acidification	kg SO_2 eq.	Acidification and	PDF.m2.year
Eutrophication	kg PO_4^{3-} eq.	Eutrophication	

For further interpretation, the results are integrated to one indicator using standardized weighting methods to keep the integration step transparent:

- The results of CML are integrated with shadow prices – more explanation on this method can be found in Annex 4.
- The Eco-indicator 99 results are integrated using the default weighting set of 40% for damage to Human Health, 40% for damage to Ecosystems and 20% for depletion of resources.

To follow the ISO guidelines for interpretation, the calculation of the results needs to be transparent. Therefore the unweighed characterized results are presented in Annex 5. The Annex also reports the weighing factors per impact category and the methods used to derive these weighing factors. In addition to the results reported in graphs in this report, the weighed results are also presented in tables in Annex 5.

3 Model description

3.1 Waste characteristics

As stated in the project description and changed during the discussions with the expert panel, the study focuses on five waste streams. The main characteristics of these streams are listed in Table 5. The data for the waste streams are received from the Belgian cement industry and represent the average 2006 values. If possible, minimum and maximum values are given. For the substitution scenarios, Petcokes and Coal are defined. In Annex 1 additional properties of the different waste streams and fuels are given, including the amount of CO_2 produced per ton of waste or fuel.
Filter cakes are big lumps of fine solids, that are filtered under pressure, to remove the moisture. Filter cakes still contain about 50% of moisture, but are solid-like materials. Sludges differ from filter cakes. They mostly are less de-watered, and still contain around 70% of water. It are pasty materials, that most often can still flow. The 31,9% that is mentioned in Table 5, is the average moisture content in the sludges after pre-treatment (drying).

Table 5 Summary of main characteristics of waste streams and fuels.

		Imp. Saw dust			Sludges			Solvents		
		MEAN	min	max	MEAN	min	max	MEAN	min	max
Dosage	T/y	216.817	-	-	94826	-	-	54145		
LHV	MJ/ton	14.539	12.113	17655	8240	4460	13090	29147	29078	36002
moisture	% a.r.	30,4	26,7	33,2	31,9	9,0	50,6	14,6	0,0	15,0
ashes	% a.r.	18,2	17,3	18,9	27,0	25,6	48,9	0,0	0,0	0,5

		Filtercake			Petcokes			Coal		
		MEAN	min	max	MEAN	min	max	MEAN	min	max
Dosage	T/y	85.048	-	-	330631	-	-	148508	-	-
LHV	MJ/ton	4710	-	-	33130	31100	34534	33840	-	-
moisture	% a.r.	50,6	-	-	10,4	8,4	14,4	14,4	-	-
ashes	% a.r.	23,8	-	-	1,2	0,4	2,0	2,0	-	-

		Fluff		
		MEAN	min	max
Dosage	T/y	50828	-	-
LHV	MJ/ton	21570	-	-
moisture	% a.r.	5,5	-	-
ashes	% a.r.	12,7	-	-

The definition of Coal is based on the average composition of coal used in Belgium over the year 2006. The composition of Petcokes is based on actual numbers, as provided by the Belgian cement industry.

3.2 Pretreatment and transport

The pre-treatment of waste and transport to clinker kilns and waste incinerators is included in this study. Table 6 gives an overview of the pre-treatment scenarios as used in this study.

Table 6 Summary of pre-treatment of waste when used in clinker kilns or in waste incinerators.

Waste type	Clinker kiln	Waste incinerator
1. Solvents/ waste oils	VOC emissions during storage, handling at pre-treatment site	No pre-treatment
2.Sludge	Drying with natural gas, including use of electricity	No pre-treatment
3. Paint/ink	Absorption in wood residue (saw dust) at pre-treatment site; VOC emissions during storage	No pre-treatment
4. Fluff	Electricity for grinding/milling	Same as for clinker kilns
5. Filtercake	No pre treatment	No pre-treatment
Petcoke/ Coal	Milling, grinding: energy use and emissions to air	Not relevant
Raw meal	Mining, transport and emission of particulates, energy for crushing, milling and other handling	Not relevant
Supportive fuel	Not relevant	No pre-treatment

Both Solvents / waste oils and paint / ink residue are pre-treated at a dedicated facility. In this study we have collected data for the transport of waste to the pre-treatment location, input of energy, auxiliary materials and wood residue and emissions of VOC at the Geocycle facility.

Figure 2 shows an overview of the Geocycle activities. In fact the impregnated saw dust silo is not completely closed. VOC-emissions from this silo are taken into account based on the following assumptions:

– The VOC content on the paint/ink is 10% (mixture of liquid and solid residues and mixture of water based and solvent based paint/inks).
– 10% of the VOC in paint/ink residues is emitted to air, after impregnation when stored in the open silo. This assumption is based on the expertise of Jurg Liechti of Neosys.

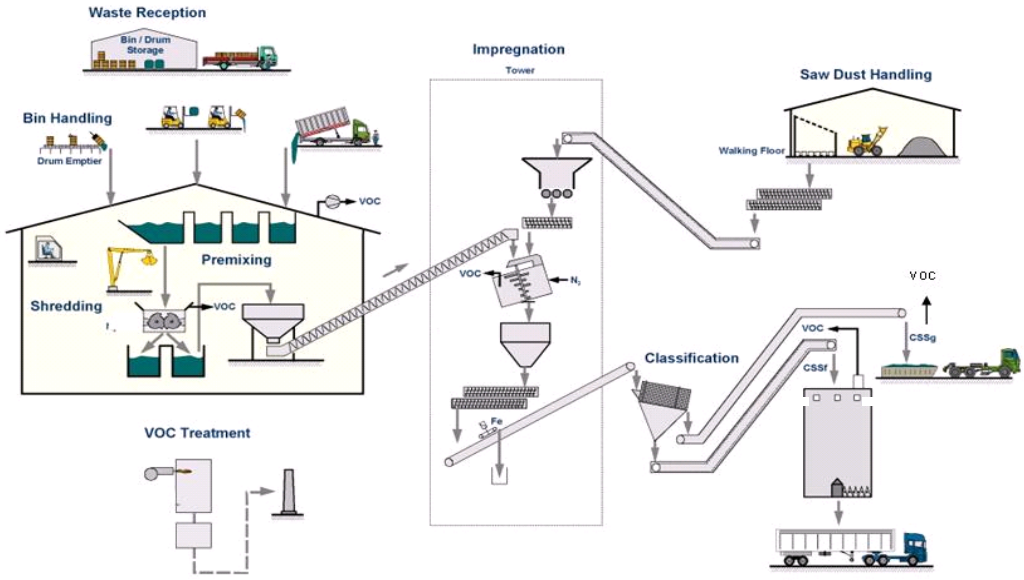

Figure 2 Pre-treatment of hazardous waste at the Geocycle site in Seneffe.

The input of wood residue is entirely allocated to the treatment of paint/ink residues. This also holds for the VOC emission from the impregnated saw dust silo. The other inputs and emissions are allocated based on the mass of treated solvents/waste oils and of paint/ink, and the total amount of waste handled at Geocycle in 2006.
Not all wastes that are used in the Belgian cement industry are pre-treated at the Geocycle plant. However, the majority is. Furthermore the different pre-treatment processes are to a large extent alike. Therefore the pre-treatment process at the Geocycle plant is taken as representative.

Sludge is dried before it is used in clinker kilns. The moisture content of the sludge, as it arrives at the pre-treatment site, is around 70%. After drying the sludge contains still around 30% moisture. For the production of 1 ton dry sludge out of wet sludge, 50 Nm^3 natural gas is used and 45 kWh electricity. In the case of incineration the sludge is not dried beforehand, but directly fed into the FBC.

The pre-treatment of petcoke, coal and raw meal is included when the input is avoided. Electricity is used for the handling and milling of petcoke and coal. As a result of the milling carbon components are emitted to the air. For these emissions we have used data from a Belgian clinker producer involved in this study.

The pre-treatment of raw meal (in the substitution scenario) consists of mining, transport, crushing and milling. Because limestone is the main ingredient of the raw meal, for the calculation of the impact of pre-treatment and transport, the data of this material are taken as representative for all ingredients. These data are taken from the Eco-invent database, including particulate emissions to air as a result of crushing and milling. The electricity consumption data for milling, crushing and other raw meal handling comes from one of the Belgian clinker producers.

Travelling distances for the thermal treatment of the wastes in cement kilns were determined, based on the real sources, specified by the cement producers. The used wastes mainly come from Belgium (all directions) and the North of France, the west of

Germany (close to Belgium) and the South of the Netherlands. The transport distance from France to Indaver is slightly longer, from the Netherlands slightly shorter compared to the distance to the cement kilns. The difference for transports from Germany depends on the location of the cement kiln. The average net result is more or less the same for waste treatment at Indaver and for waste treatment in the cement kilns. For transparency reasons we have taken the same distance and transport means. Travel distances cannot be left out, however, because of the fact that the transport distances for the substituted fuels are not the same.
For paint/ink and solvents/waste oils, the transport from the pre-treatment site to the clinker kilns is not accounted for in the transport scenario to waste incinerators, as this waste is not pre-treated before waste incineration. The transport models used are directly derived from Ecoinvent. For transport by road we have used a 32t lorry.

3.3 Thermal treatment in cement kilns

Cement manufacturing consists of raw meal grinding, blending, pre-calcining, clinker burning and cement grinding. This is visualised in figure 3. In short, limestone and other primary and secondary materials, containing calcium, silicon, aluminium and iron oxides are crushed and milled into a raw meal. This raw meal is heated in the pre-heating system, to initiate the dissociation of calcium carbonate to calcium oxide and carbon dioxide. The preheating system consists of one or more cyclones (mostly 3 or 4), and a pre-calciner. Part of the fuel is fed into the pre-calciner to keep the temperature sufficiently high. The temperature at this place is at least 600 °C (up to 1000 °C). After pre-heating and pre-calcining the meal is fed into the kiln, for further heating and reaction between calcium oxide and other elements to form calcium silicates and aluminates, at a temperature up to 1450 °C. Most of the fuel is used to keep the temperature high enough in the burning zone for the chemical reactions to take place. The reaction products leave the kiln as a nodular material, called clinker. The clinker is than inter-ground with gypsum, limestone and/or ashes to the final cement product. A more extended description of the cement production process is given in Annex 2.

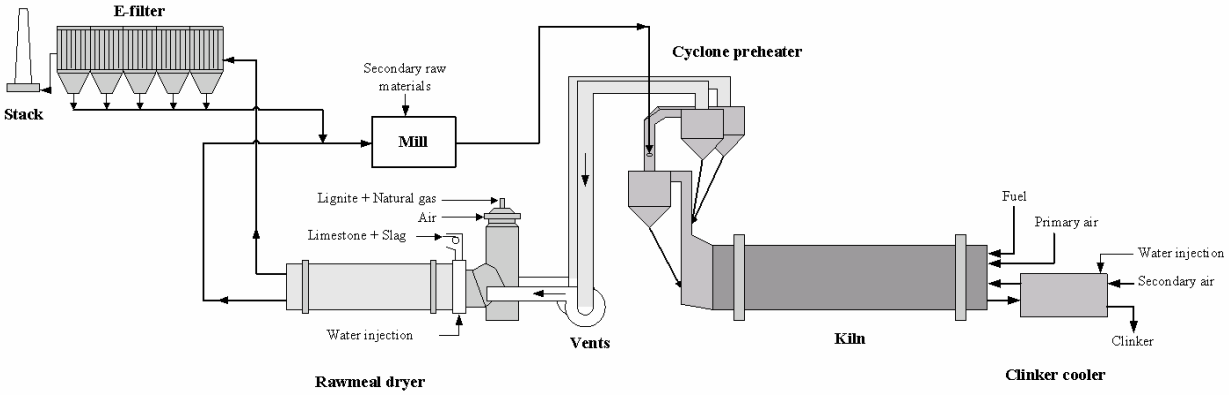

Figure 3 Process scheme of a cement production process.

The production of cement clinker is energy intensive. The energy requirement for the production of clinker is approximately 3.5 GJ/tonne clinker produced in the dry process (and approximately 5 GJ/tonne in the wet process). Regular fuels are fuel oil, petcokes

and coal. In order to meet financial and environmental standards, conventional raw materials and fuels are substituted by secondary streams. This study focuses on that waste streams or secondary streams that are used for energy supply as such. All these secondary fuels are fed into the cement kiln on the hot side of the kiln.

For the study, a linear plant model is used, which means that linear transfer functions between inputs and outputs of predefined species are defined. Knowing these functions enable us to relate changing inputs to resulting outputs. For example, if we know the transfer function of sulphur, we can calculate the change of sulphur emission at the stack as a result of the change of sulphur input, caused by a change in the fuel package. Although the process of clinker production is by far linear, in contrast to for instance incineration of waste in grate incinerators, the use of a linear model can be justified by the following reasons:

- The used approach is the method of marginal changes (see 3.5). By application of this method, based on the extra input of 1 ton of specified waste, defined changes to the system are small and can thus be regarded linear.
- The study focuses on species that, to some extent, have linear behaviour in the system. Exceptions are for instance sulphur and NO_x.

For each kiln in the Belgian cement industry, inputs of chemical species are defined from raw materials and fuels. In addition, data of emissions to water, air, soil and product were retrieved. For each kiln, a set of transfer coefficients is determined based on these data. The transfer functions are not published in this report, as agreed with the expert panel, because of confidentiality reasons[6].

In the study, the main assumptions with regard to the treatment in cement kilns are:

- As a result of the application of waste streams as energy supply, no additional changes to maintenance of the cement kilns are required. This means that from the base-case no change to the usage of materials is applied, for instance insulation and lubrification.
- For NO_x, no transfer model can be obtained due to the nature of the formation of this component. In fact 90% or more of the NO_x that is formed in a cement kiln is not caused by the nitrogen of the raw materials and fuels, but by the high temperature conversion of nitrogen from the air. This 90% of the NO_x emission is therefore process intrinsic, and does not depend on the usage of more or less waste as a fuel. This part is out of the scope of the study because of the approach of marginal change. As far as the 10% originating from the fuel is concerned, from measurements in practical situations, it is known that the use of waste streams leads to a decrease in the formation of NO_x. These measurements were done, for example, at the ENCI plant in Maastricht. The actual data however are confidential. This means that in this study the assumption that the NO_x emission will not increase, as a result of the use of more waste as a fuel, in fact is the worst case. So, in this study 90% of the NO_x from the clinker kilns is assumed to be process intrinsic, and in not due to marginal changes. With regard to the remaining 10% it is assumed that the NO_x emission caused by one ton of waste is the same as that caused by the same equivalence, in terms of caloric value, of petcoke or coal.
- Streams that are not leaving the plant, but are rather recycled or mixed with the final product, are not regarded as ‘waste streams’ or emissions. This concerns

[6] Not all expert panel members were happy with this (see also Annex 6). However, from confidentiality viewpoint this was the only solution. The confidential data and calculations were reviewed by Jürg Liechti of Neosys.

especially the fines from the E-filter. These fines are recycled into the product. Due to the choice of the system boundaries, only emissions outside the plant are taken into account.
– All transfer functions are linear. For species streams, driven by temperature, this assumption holds. However, for species that are formed from chemical transitions, this approach fails. Due to the small changes to the base-case, linearity around the base-case situation is justified, and linear models for the transfer coefficients can be applied.

3.4 Alternative thermal treatment scenarios

For the LCA study to Febelcem the environmental impact of waste, when treated in the cement industry is compared with the environmental impact when incinerated in a suitable incineration system. The following starting points are used:
– The five specific waste streams are:
  1. Solvents and waste oils
  2. Filter cake
  3. Industrial sludges
  4. Paint, ink residues
  5. Fluff
– Based on the Belgian situation, using the processes of Indaver

The most suitable incineration system for the indicated five waste streams is not in all cases the same type of incinerator. In principal, three incinerator types have been taken into account, namely a rotary kiln, a FBC (Fluidised Bed Combustor), and a grate incinerator. Based on specific information of Indaver (Mr. Wauters) it is assumed that the Rotary Kiln is most suitable for the incineration of solvents / waste oils, paint/ink residues and filter cakes, and that the FBC would be used for the incineration of industrial sludges and fluff. The grate incinerator would not be used for the treatment of one of the five waste streams. The selection of the alternative thermal treatment options is made on the basis of the physical properties of the waste streams, such as moisture content, viscosity, ash content, particle size, etc.

The rotary kiln incinerator plant at Indaver (in Antwerp) consists of a rotary kiln with afterburner, a steam boiler and a flue gas cleaning system. The flue gas treatment is based on a wet system with wet scrubbers, resulting in a waste water stream, causing emissions to surface water. After passing the dustfilters (ESP = Electro Static Precipitator) and wet scrubbers a pilot filter using (activated) coal is operational to clean the flue gasses to such a degree, that they can easily strike all threshold limits for emissions to the air. Residues like slag (after treatment for removal of metals), boiler ash, ESP-ash and filter cake are solid residues that are landfilled. This incineration process is shown in figure 4.

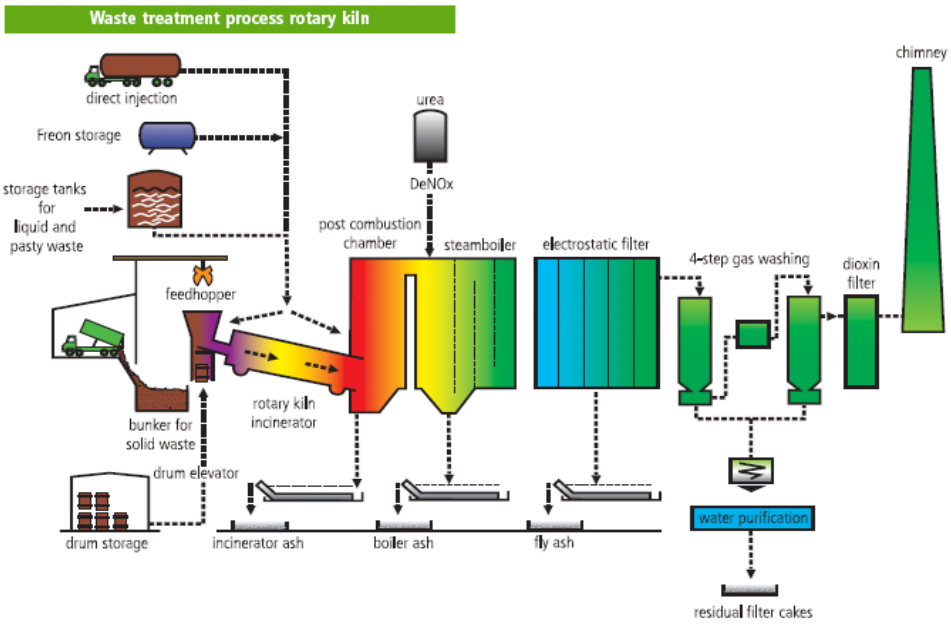

Figure 4 Process scheme of the rotary kiln incinerator at Indaver.

A fluidised bed combustor (FBC) is a quite different incinerator (see figure 5). In the case of Indaver, also the flue gas cleaning system differs from the system of the rotary kiln. The most relevant difference is the fact that the FBC is provided with a semi-dry flue gas cleaning system, resulting in a larger amount of solid residues, but without a remaining waste water stream.

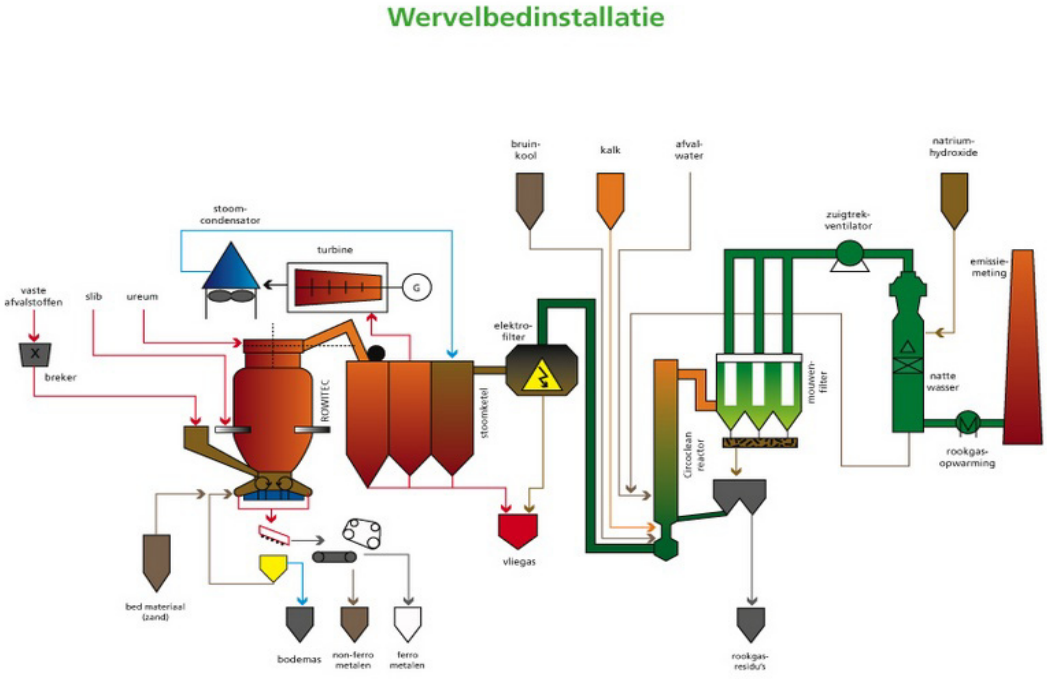

Figure 5 Overview of Fluidise Bed Combustor at Indaver.

Transfer coefficients for waste incineration
During the study it was not possible for TNO to retrieve all required data regarding the waste incinerators from Indaver. Indaver was not involved in the project as member of the expert panel. Indaver therefore was not prepared to provide company-specific data, but provided public data only (Annual report 2005). For this reason, with regard to the transfer coefficients for waste incineration, it was required to find other sources of data.

An important source of data proved to be an Eco-invent study performed on a Swiss incineration plant. This hazardous waste incinerator plant is very similar to the rotary kiln of Indaver. Based on this analogy, TNO retrieved transfer coefficients, required for calculation of the environmental impact. The transfer coefficients themselves are presented in Annex 3, together with a more extensive description of the incineration process. Because some of the used Eco-invent data were outdated, a sensitivity analysis is made on this subject in paragraph 4.3.7.

The data of Eco-invent and the data of Indaver were checked against data of a third rotary kiln incinerator, that was described as the best available technique for waste incineration in the 2006 document of IPPC. The plant involved is the hazardous waste incinerator in Vienna: Simmeringer Haide. The most important differences in conversion factors between the plants of Simmering Haide and Indaver are caused by the use of brown coal (for the filter) and the use of fuel oil. This gives rise to slight differences in transfer coefficients, related to the emissions.

For the FBC transfer coefficients were deduces from the Eco-invent values, taking into account the differences between a rotary kiln and a FBC. These main differences concern differences in solid waste streams and in the fact that a FBC does not have any waste water stream. Also these differences are presented in Annex 3.

3.5 The method of marginal changes

In order to compare the different systems for thermal treatment of waste streams, the decision on the mathematical method is trivial. In regular cases, absolute values of the outcomes of the LCA are simply compared. In this study, however, the systems to be compared are intrinsically different in behaviour and output. Cement kilns produce clinker, alternative treatment processes treat waste and produce heat and electricity. The best method to compare the environmental impact of the thermal treatment of waste streams in those two different processes is the method of marginal changes.

The mathematical method of marginal changes defines changes of a system to a predefined baseline, in this case the 2006 situation. Based on this baseline, small changes to desired and predefined inputs are applied, and the effect on the system is determined. In this study the marginal changes were defined as the extra input of one ton of one of the five predefined waste streams. The applied changes are relatively small compared to the absolute response of the system. Due to this, the linearity requirement is fulfilled. Furthermore, by defining changes to a baseline, the intrinsic function of a system is filtered. In this study, the application of this method is therefore justified. This is also the reason that the energy efficiency of the different cement kilns is out of the scope of this study; not the production of one ton of clinker is the functional unit, but the treatment of one ton of waste (or secondary fuel).

4 Results

4.1 Overall results

This report starts with the main conclusions on the question which thermal treatment (clinker kiln or waste incinerator) causes overall the lowest environmental impact, given the assumptions and limitations of this study.

Figure 6 and **Fout! Verwijzingsbron niet gevonden.**7 show the environmental comparison of the thermal treatment of 5 waste streams in a clinker kiln with that in a waste incinerator, calculated with two different impact assessment methods - CML with shadow prices and Eco-indicator 99.

For both methods a higher score represents more environmental impact. A negative score (below zero) represents an environmental bonus. More negative points reflect a better result from an environmental point of view.
Figure 6 and Figure 7 show results for cement kilns when the input of waste substitutes petcoke and raw meal as all clinker producers have indicated that this change is the most realistic change in a marginal change calculation. In the following paragraph the results are also shown for the theoretical substitution of coal; those results point in the same direction as the results for the petcokes scenario.
With regard to the alternative treatment options (waste incineration) the Figures 6 and 7 show the results for electricity and heat substitution only, because the substitution of supportive fuel cannot be a substantial one in practice. For the waste stream solvents and waste oil in the following paragraph the results are shown also for the marginal substitution of fossil fuel.

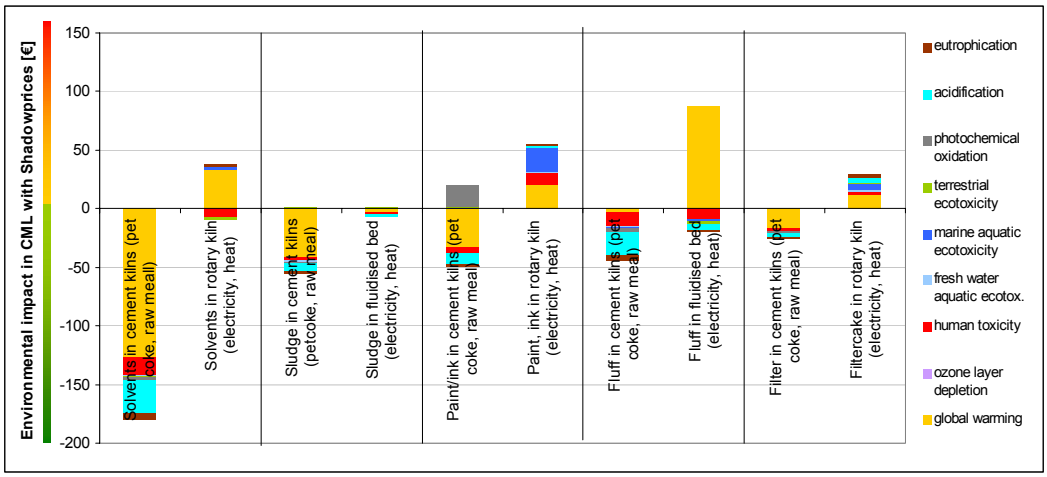

Figure 6 Environmental comparison of the thermal treatment of 5 waste streams in a clinker kiln or a waste incinerator, calculated with the CML method and integrated with shadow prices.

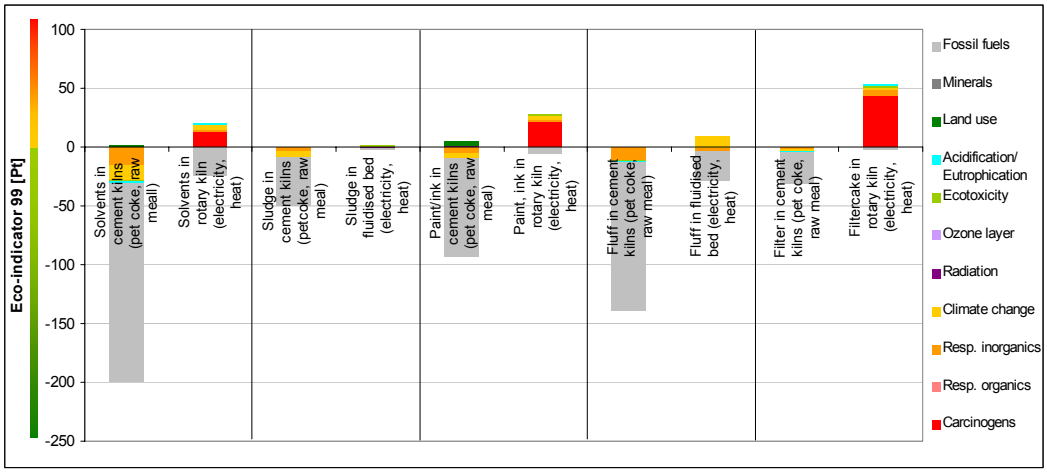

Figure 7 Environmental comparison of the thermal treatment of 5 waste streams in a clinker kiln or a waste incinerator, calculated with Eco-indicator 99 (H/A).

From Figure 6 and figure 7 we can conclude that the environmental performance of thermal treatment of all 5 selected waste streams in cement kilns is better compared to treatment in waste incinerators. The main difference between clinker kilns and waste incineration is the avoided product – as will also become more obvious when we take a closer look at the origin of the results in the next paragraph. The bonus is larger for avoiding petcoke or coal compared to the bonus for avoided electricity and heat production.

This conclusion does not depend on the choice of impact assessment method; as two different methods point in the same direction for all waste streams.

The results calculated with CML and shadowprices are dominated by the impact of CO_2, whereas the Eco-indicator results are dominated by depletion of fossil resources. In both methods emissions of heavy metals from waste and petcoke, coal or raw meal, contribute little to the overall weighted results.

4.2 Origin of results

In annex 5 tables with characterised and weighed results can be found for
- Pre-treatment and transport, and emissions per ton waste, petcokes, coal and raw meal
- The same for 1 ton of waste in waste incinerators, and for the avoided energy (per MJ caloric value in waste).

These tables and the substitution scenarios per ton waste can be used to recalculate the environmental impact scores on every level. The net results (after subtraction of the substitution bonus) are also presented in tables in Annex 5; both the characterised and weighed results per ton waste.

4.2.1 Solvents and waste oils

In Figure 8 you will find the characterised results for the comparison of thermal treatment of 1 ton solvents/waste oils, analysed with the CML method. Because the calculated results of the different environmental impact categories are expressed in

different units, they cannot be visualised in one figure, in absolute numbers. Therefore these results have been normalised. Per impact category the highest score in the comparison of 4 scenario's (two for the cement kiln and two for the waste incinerator) has been put on 100% and the results of the other scenarios have been scaled relative to this maximum score. However, this does not mean that all impact categories have the same environmental significance. In Annex 5 you can find the absolute results expressed in equivalency factors per impact category.

The environmental bonus for decreased input or avoided energy generation results in lower impacts than caused by the incineration of the solvents/waste oils itself for some environmental impact categories. This lower impact results in net negative (below zero) impact results:

– When petcokes are avoided, this has a positive effect (= negative scores) on 8 out of 10 environmental categories
– When coal is avoided, this has a positive effect on 5 out of 10 categories.

For incineration of solvents in a rotary kiln, the bonus results in:

– a positive effect on 6 out of 10 categories when electricity and heat is avoided
– a positive effect on 9 out of 10 categories for the small amount of fossil fuel that might be substituted.

As the avoided petcoke scenario for thermal treatment in a cement kiln has a lower impact in 6 out of 10 categories, and the waste incinerator has the lowest impact in 1 category for each bonus scenario, no conclusion can be drawn on which one is the best without weighing of the categories.

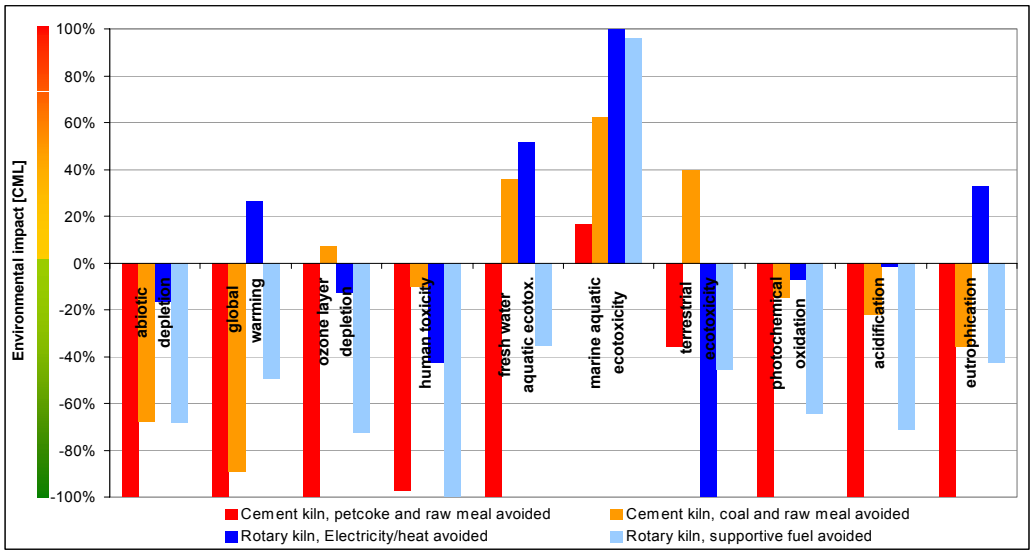

Figure 8 Characterised CML results comparing thermal treatment of solvents/waste oils in a clinker kiln or in a waste incinerator. For both installations two substitution scenarios have been calculated.

Figure 9 shows the weighed results for the thermal treatment of solvents/waste oils, with a split up in the contribution of transport/pre-treatment and the emissions resulting from incineration. Left from the black line you can find the scenarios for the cement kiln, right for incineration in a rotary kiln. The net impact results form subtracting the

impact of input or energy to be avoided. The dotted lines split the incineration of 1 ton solvents/waste oils and the substitution scenarios.

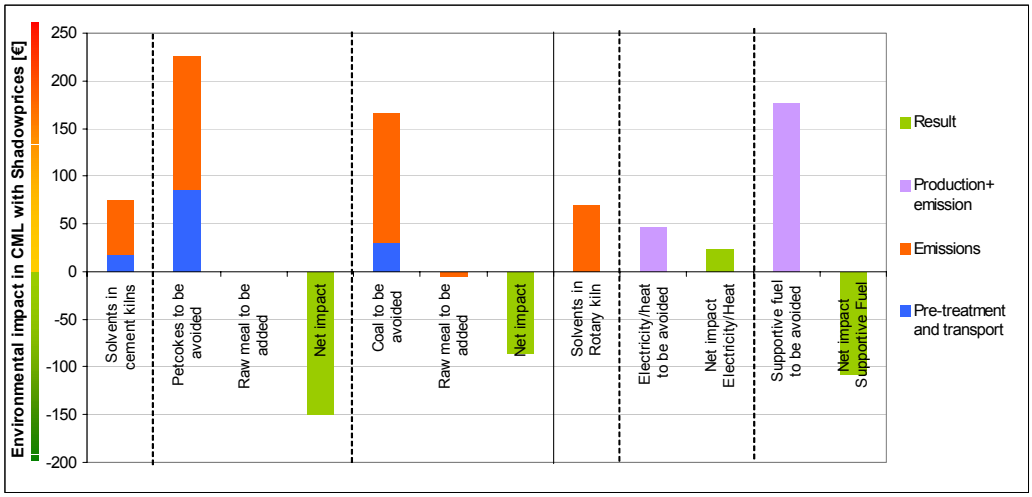

Figure 9 Shadow price weighed CML results comparing thermal treatment of solvents/waste oils in a clinker kiln or in a waste incinerator, with a split up in the contribution of the transport/pre-treatment and the emissions due to incineration.

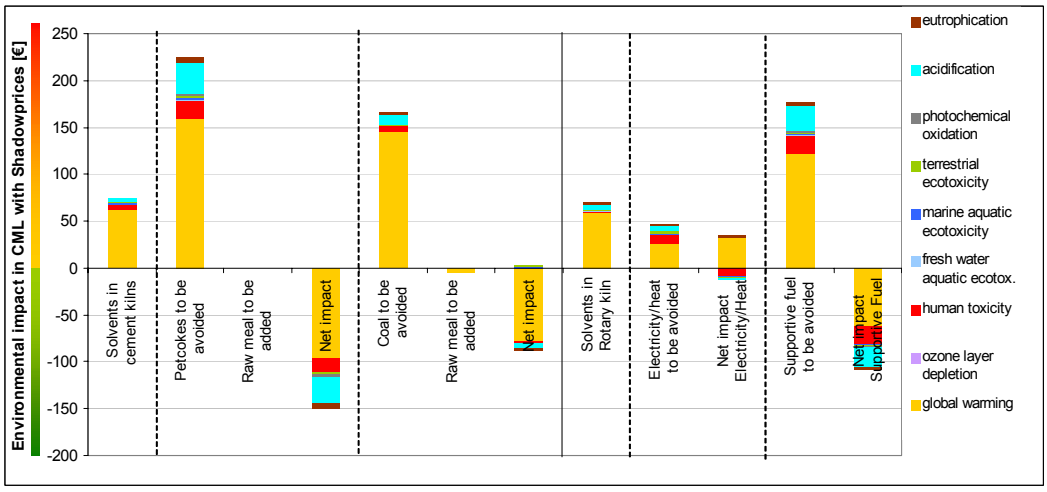

Figure 10 Shadow price weighed CML results comparing thermal treatment of solvents/waste oils in a clinker kiln or in a waste incinerator, with a split up in the contribution environmental categories to the shadow costs.

The impact from incineration of solvents/waste oils is comparable between the clinker kiln and the rotary kiln (see Figure 9). Therefore the net avoided impact is determined by the impact of the avoided processes. It appears that for the clinker kiln the avoided impact by petcoke or by coal exceeds the avoided impact of energy generation for the rotary kiln. In case the use of fossil fuel oil is substituted by the incineration of solvents/waste oils in the rotary kiln, more impact is avoided than in the case of energy generation. But even in this not representative case it is still less than is the case of the clinker kiln.

The net avoided burden of the thermal treatment of solvents and waste oils in cement kilns is due to the avoidance of incineration emissions of petcoke/coal and by the avoidance of the impact of the pre-treatment stage (see Figure 9). The impact of the use of additional raw meal is insignificant. In the case of petcoke this latter is beneficial as it avoids the emission of SO_2 from the flare of crude oil production, which is the source of petcoke. In case of the avoided use of coal the avoided SO_2 of the transoceanic transport of coal is important.

For the incineration of solvents and waste oils in a rotary kiln the main burden is the emission of CO_2, which makes up 90% of the shadow cost. The emissions of the avoided energy production cannot counteract the impact of the solvents/waste oils incineration fully and a net burden remains. In case the solvents/waste oils are seen as to avoid the use of supportive light fuel oil in the waste incinerator a net avoided burden remains. This is the result of (heat from) light fuel oil having an almost 3 times higher CO_2 emission per MJ. Other avoided emissions like that of SO_2 play a minor role.

When applying the alternative impact assessment (EI99) the avoidance of fossil fuels dominates the results. Results can be found in the Annex 5.

4.2.2 *Sludge*

Figure 11 shows the characterised results for the comparison of thermal treatment of 1 ton sludge, analysed with the CML method. Incineration in fluidized bed has the lowest impact in 1 out of 10 categories. Incineration in a clinker kiln avoiding petcoke has the lowest impact in 8 out of 10 categories. Again weighing is needed to draw conclusions on which scenario has the lowest environmental impact.

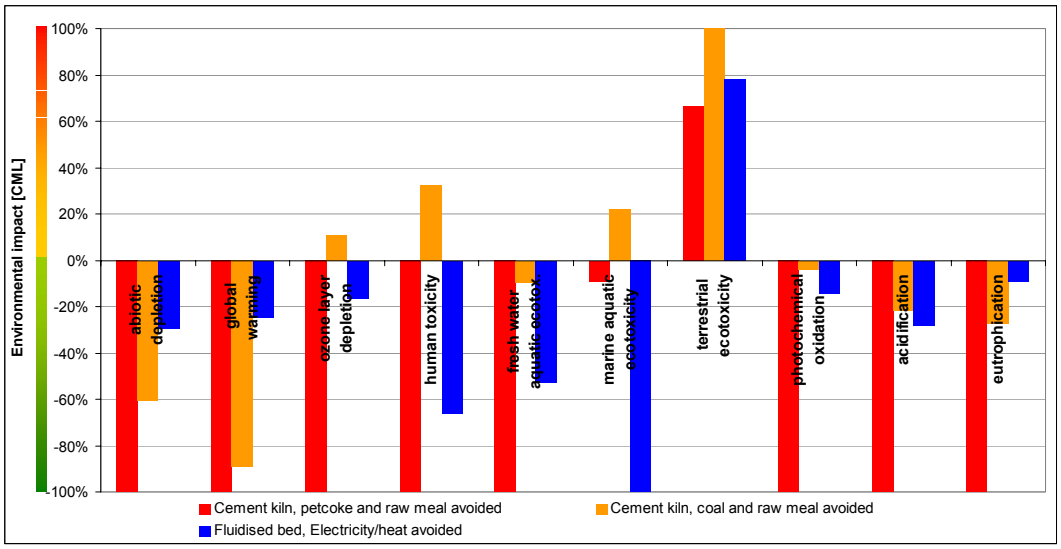

Figure 11 Characterised CML results comparing thermal treatment of sludge in a clinker kiln or in a waste incinerator.

The weighed results for sludge are shown in Figure 12 and Figure 13.

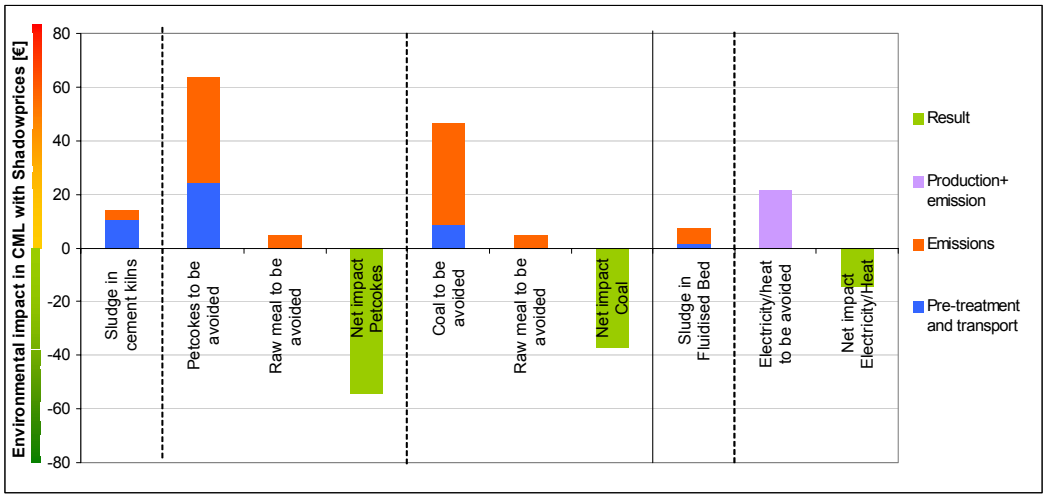

Figure 12 Shadow price weighed CML results comparing thermal treatment of sludge in a clinker kiln or in a waste incinerator, with a split up in the contribution of the transport/pre-treatment and the emissions due to incineration.

Sludge for cement kilns is dried, whereas for waste incineration it is not. This difference results in a different result for pre-treatment and transport. The emissions from sludge co-incineration differ between the cement kiln and the waste incinerator. This is due to differences in the set of transfer coefficients of the two processes. Where for the fluidised bed cadmium and nickel are main contributors it is mercury for the clinker kiln.

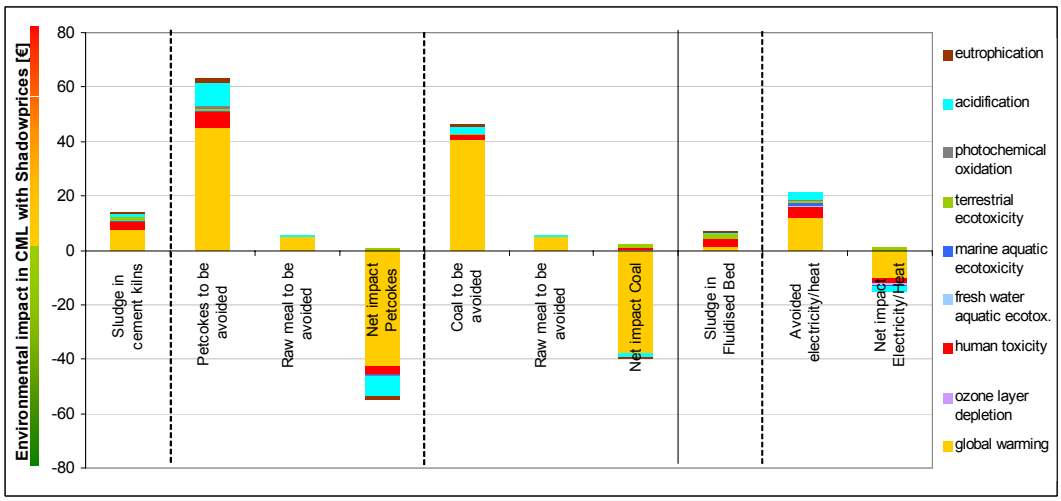

Figure 13 Shadow price weighed CML results comparing thermal treatment of sludge in a clinker kiln or in a waste incinerator, with a split up in the contribution environmental categories.

The drying of sludge with heat from natural gas incineration leads to emissions of CO_2 and this is the main cause of the burden of sludge pre-treatment for cement kilns.

Sludge is not dried before it is incinerated in a fluidised bed resulting in a smaller impact of pre-treatment and transport compared to pre-treatment for cement kilns.

As the carbon in sludge is non-fossil it does not contribute to global warming. Therefore the emissions from co-incineration of sludge contribute little to the environmental profile of both the cement kilns and the fluidised bed.

The incineration of petcoke does lead to fossil CO_2 emissions and these emissions are avoided by the incineration of sludge. Furthermore the avoided production of petcoke avoids the emission of SO_2 (flare). This eventually results in a net avoided environmental impact of the thermal treatment of sludge in a cement kiln.

The emissions of mercury, cadmium and nickel through the fluidised bed flue gasses determine the impact of the 'Emissions' in Figure 12. The benefit of the avoided energy is largely due to the avoided emission of CO_2; avoided emissions of SO_2 and vanadium are of lesser importance.

4.2.3 *Paint and ink*

Figure 14 shows the characterised results for the comparison of thermal treatment of 1 ton paint/ink residue. In most toxicity categories the substitution bonus cannot compensate the impact caused by the thermal treatment of 1 ton paint/ink residue. The avoided petcoke scenario for cement kilns results in the lowest environmental impact in 9 out of 10 categories. In all environmental categories, the incineration in a rotary kiln causes more environmental impact compared to cement kilns for at least one of the two cement substitution scenarios. In the contribution analysis (Figure 15 and Figure 16) we will see that cement kilns have a lower impact in most categories as a result from a larger substitution bonus, compared to the substitution bonus for avoided electricity/ heat.

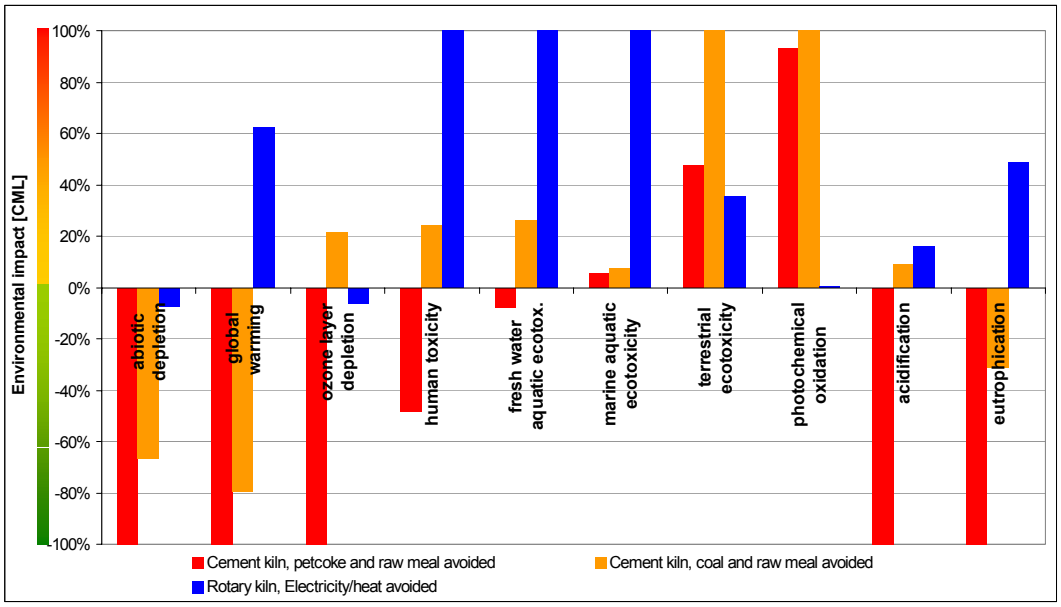

Figure 14 Characterised CML results comparing thermal treatment of paint/ink residue in a clinker kiln or in a waste incinerator.

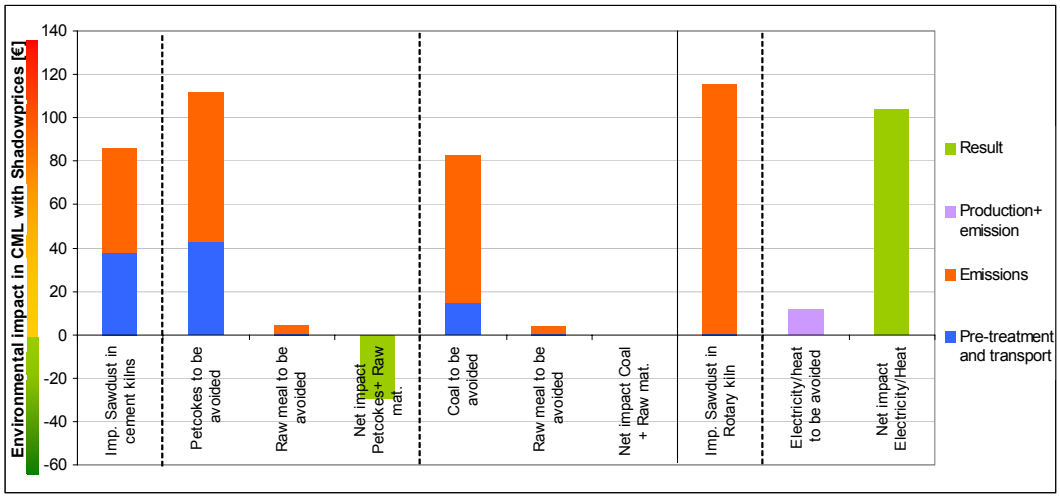

Figure 15 Shadow price weighed CML results comparing thermal treatment of paint/ink residue in a clinker kiln or in a waste incinerator, with a split up in the contribution of the transport/pre-treatment and the emissions due to incineration.

Due to the difference in pre-treatment the impact of the thermal treatment of paint and ink in the clinker kiln has a higher impact compared to the incineration of paint/ink residue in the rotary kiln (see Figure 15). For thermal treatment in cement kilns, paint and ink residues are absorbed using wood. The electricity used at the pre-treatment site is contributing most to the impact of pre-treatment of paint and ink residues.

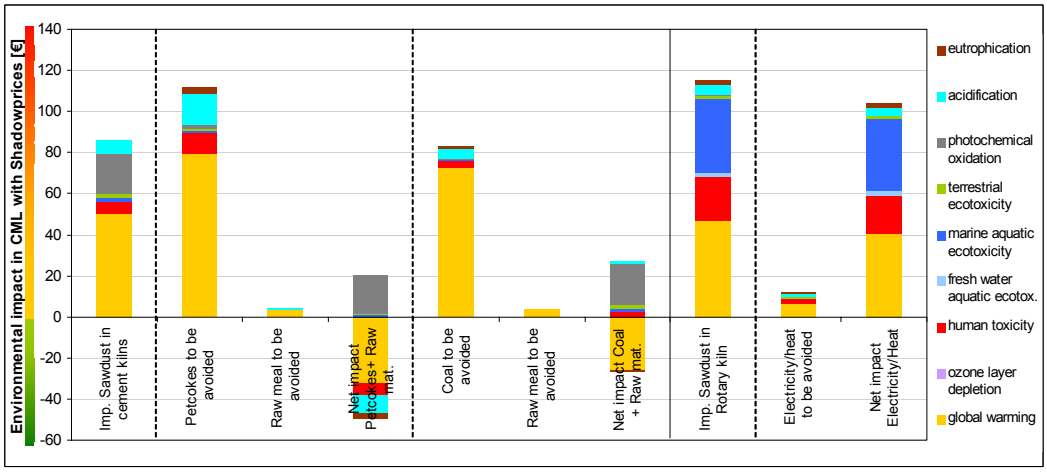

Figure 16 Shadow price weighed CML results comparing thermal treatment of paint/ink residue in a clinker kiln or in a waste incinerator, with a split up in the contribution environmental categories.

The environmental burden of the thermal treatment of paint/ink impregnated sawdust in cement kilns is due to the emission of CO_2 and SO_2. It must be noted that only the fossil carbon accounts for the CO_2 emissions, and not the non-fossil CO_2 from the sawdust that is used for impregnation. In the pre-treatment it is mainly the CO_2 related to the use of electricity and the emissions of VOCs at the pre-treatment sites that contribute to the impact.

The emissions of CO_2 and hydrogen fluoride from the rotary kiln determine the impact of the incineration of paint and ink residues. Due to the relatively lower heating value of the paint/ink residues (7.3 MJ/kg) the amount of avoided energy is limited. The avoided energy emissions can therefore not fully compensate the incineration emissions and a net burden remains.

4.2.4 *Fluff*

The characterised results for the comparison of thermal treatment of 1 ton fluff are shown in Figure 17. The avoided petcokes scenario of cement kilns results in the lowest environmental impact in 7out of 10 categories. Treatment of fluff in a fluidised bed results in the lowest impact in 2 out of 10 categories.

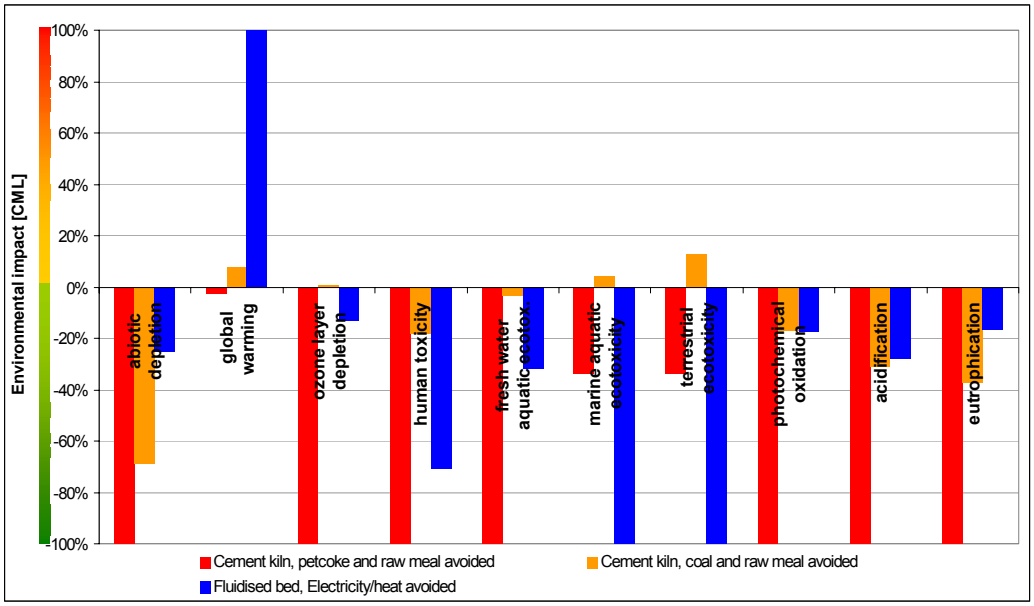

Figure 17 Characterised CML results comparing thermal treatment of fluff in a clinker kiln or in a waste incinerator.

The contribution to the results is shown in Figure 18 and Figure 19.

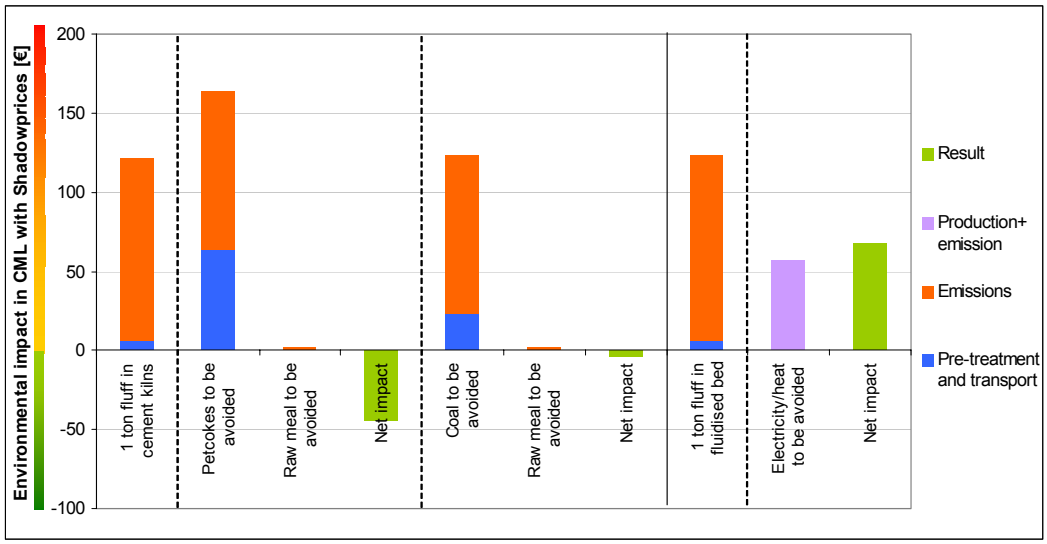

Figure 18 Shadow price weighed CML results comparing thermal treatment of fluff in a clinker kiln or in a waste incinerator, with a split up in the contribution of the transport/pre-treatment and the emissions due to incineration.

Similar to analysis of wastes in this study, the impact of the emissions of the clinker kiln and the fluidised bed incinerator do not differ significantly (see Figure 18). It is the substitution that determines the balance between the clinker kiln and the fluidised bed incinerator. The clinker kiln is therefore in advantage.

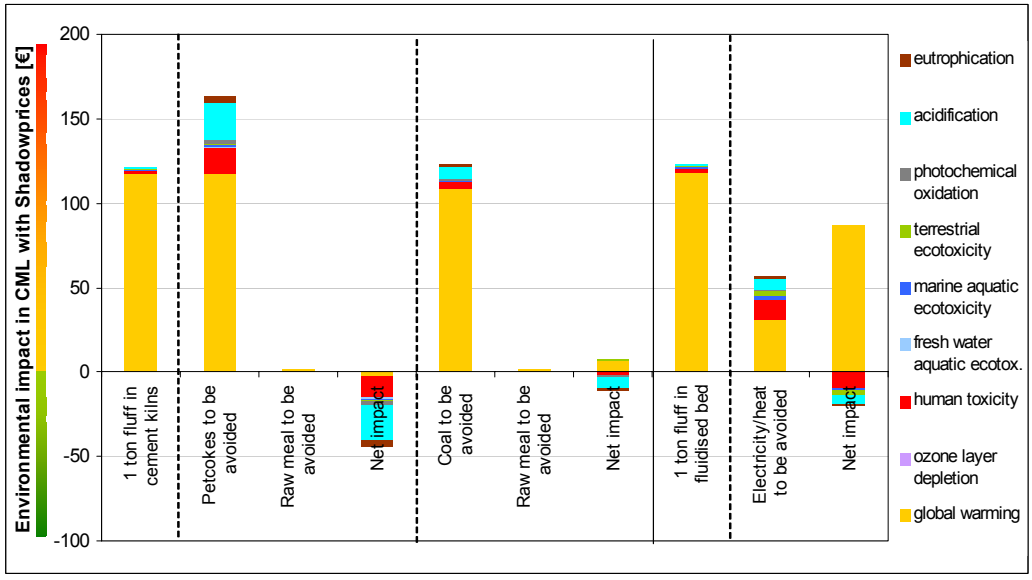

Figure 19 Shadow price weighed CML results comparing thermal treatment of fluff in a clinker kiln or in a waste incinerator, with a split up in the contribution environmental categories.

The thermal treatment of the fluff in a cement kiln and in a fluidised bed incinerator is dominated by the emission of CO2. For both processes the impact of the pre-treatment is limited and almost related to the use of electricity for fluff handling.

The avoided use of either petcoke or coal at the cement kiln results in a net avoided environmental impact of the thermal treatment of fluff in cement kilns. The CO_2-emission is more or less the same for fluff and for either petcoke or coal, but the other emissions (especially of SO_2) are less in the case of fluff.

Due to the limited energy efficiency of the rotary kiln the avoided energy does not results in a net avoided environmental impact.

4.2.5 *Filter cake*

Figure 20 shows the characterised results for the thermal treatment of filter cake. The avoided petcoke scenario of cement kilns results in the lowest environmental impact in all categories. Even without weighing it can be concluded that treatment of filter cake in cement kilns results in a lower environmental impact compared to treatment in a waste incinerator. In the contribution analysis we will see that this is mainly due to more impact of emissions from the rotary kiln and a larger substitution bonus in cement kilns.

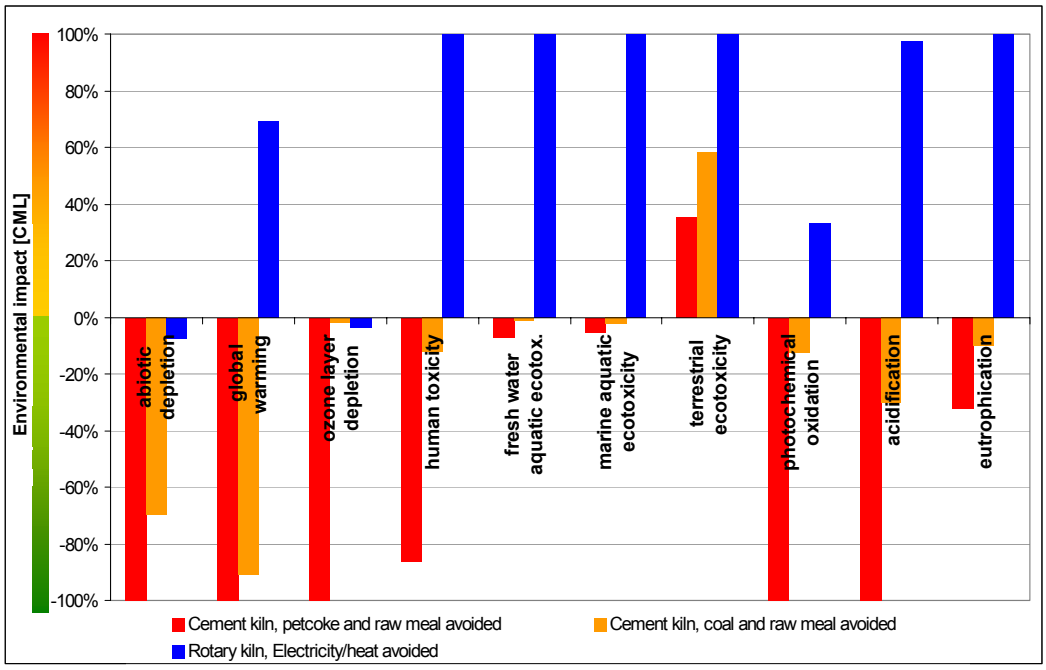

Figure 20 Characterised CML results comparing thermal treatment of filter cake in a clinker kiln or in a waste incinerator.

Filter cake treated in a rotary kiln causes emissions to water and NO_x emissions and this results in the impact result for toxicity, acidification and eutrophication. Cement kilns have no emission to water and the NO_x emissions are substituted by the avoided fuel, and supposed to be equally high in both cases (as is explained in chapter 3.3). In addition there is a large difference in the substitution bonus.

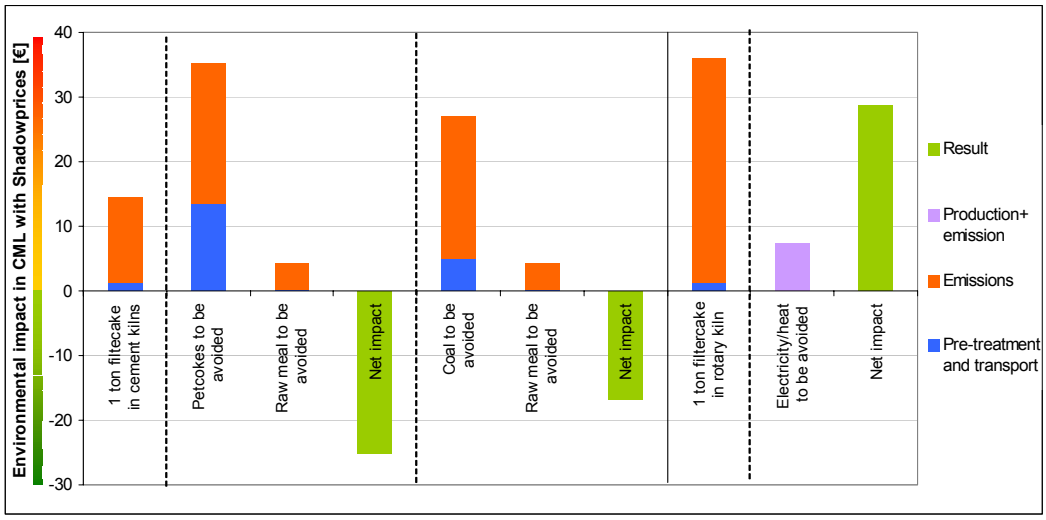

Figure 21 Shadow price weighed CML results comparing thermal treatment of filter cake in a clinker kiln or in a waste incinerator, with a split up in the contribution of the transport/pre-treatment and the emissions due to incineration.

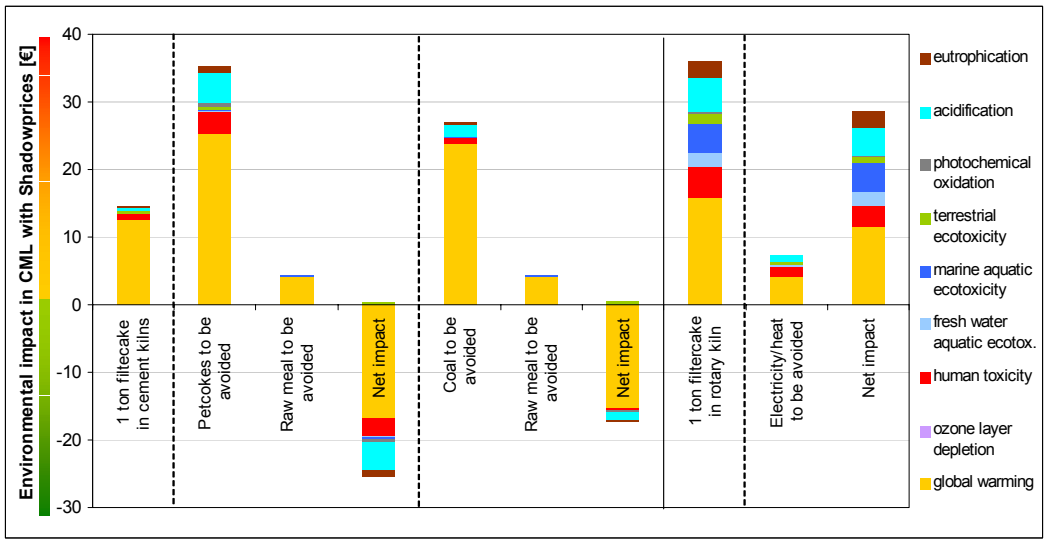

Figure 22 Shadow price weighed CML results comparing thermal treatment of filter cake in a clinker kiln or in a waste incinerator, with a split up in the contribution environmental categories.

The environmental impact of this type of waste in a cement kiln is dominated by the release of CO_2. The use pre-treatment and transport gives small contribution only.

The thermal treatment emissions of filter cake clearly differ in the rotary kiln from those of the cement kilns. The amount of CO_2 produced is the same. However, the rotary kiln shows larger emissions of process related nitrous oxides and substance related hydrogen fluoride. Incineration of filter cake in a rotary kiln thus shows a net impact and the bonus for avoided energy is limited.

4.3 Sensitivity analysis

4.3.1 Variation in emissions of cement kilns

The emissions at cement kilns differ due to differences in the cement kiln process characteristics, like wet and dry process, etc. The annex reports for all results the minimum and maximum environmental impacts caused by the cement kiln emissions.

Figure 23 shows the minimum and maximum of environmental impact of emissions at cement kilns related to one ton input for the five waste streams, petcokes and coal and for raw meal, and the minimum and maximum environmental impact.

The small variation is caused by variation in emission of toxic elements (like metals, HF and SO_x). However the emission of toxic elements contributes little to the environmental impact expressed in shadow prices, as most impact comes from the CO_2 emission. The CO_2 emission for 1 ton input does not vary between the cement kilns as CO_2 emission is directly related to the carbon content of the waste which was the same in the calculation for all kilns. So, from an LCA point of view, the different cement production processes, including wet and dry processes, only differ marginally. Because of the 'marginal change' approach, in which the thermal treatment of one ton of waste is the functional unit, any mutual differences in energy efficiency between the cement kilns in Belgium cannot be made visible in this study. In the framework of this study, and also in the framework of the taxation of high caloric waste streams the question of energy-efficiency is not relevant either, because the energy-efficiency does not depend on the kind of fuel (primary or secondary), but on the cement clinker production process.

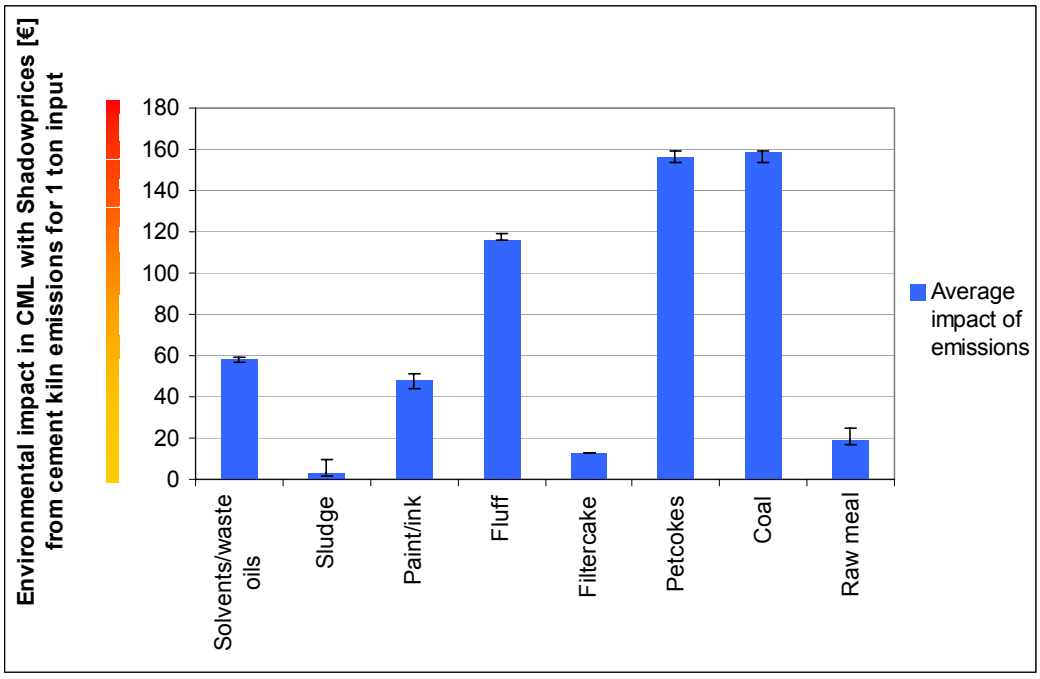

Figure 23 Sensitivity analyses on the variation of environmental impact due to variation in emissions between cement kilns.

4.3.2 *+/- 50% heavy metal content, S, CL and F in paint/ink*

A theoretical calculation is made to find out if conclusions can change when metal, Sulfur, Chloride and Fluor content is different. As these elements contribute most in the results for paint/ink mixture, this waste stream is selected for sensitivity analysis. The sensitivity analysis is based on a theoretical variation of 50% higher and lower content of metals, sulfur, chloride and fluoride. This is a theoretical calculation as real variation in not known by TNO. However, 50% higher content of these elements would not occur in practice as emissions limits would be exceeded.

Figure 24 shows the results on the environmental impact for 50% higher and lower content of toxic components in paint/ink. This variation has a small influence on the environmental impact of cement kilns, as these elements have a minor contribution to the result (see also paragraph 4.2.3). However the water emissions in the rotary kiln have a relative large contribution to the environmental impact, and there a variation on toxic components has a large influence on the results. A decrease of 50% in toxic components in paint/ink would result in a similar environmental impact between cement kilns and rotary kiln for the pretreatment, transport and incineration of 1 ton paint/ink. However the environmental bonus for energy substitution is has not changed and is larger for cement kilns. Therefore, the conclusion that cement kilns are preferred from an environmental point of view does not change, even not with a 50% lower toxic component content.

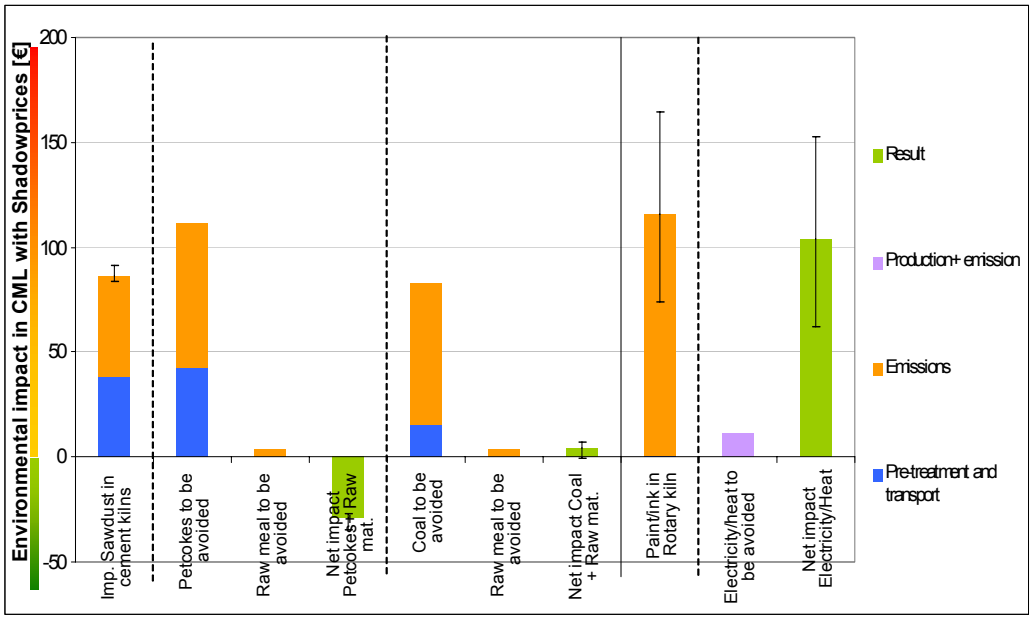

Figure 24 Sensitivity analysis on 50% higher and lower content of toxic components (metals, Fluor, Chloride and Sulfur) in paint/ink.

4.3.3 *-10% Carbon content in Fluff*

Fluff is a mixture of plastics, textiles etc. Differences in composition may lead to differences in carbon content, resulting in a different environmental profile for fluff. In the sensitivity analysis, a theoretical calculation is made: what is the carbon content decreases 10% due to an increased paper fraction. That would result in:

– A decrease in CO_2 emission from 2300 ton CO_2 per ton fluff to 2070 ton CO_2

– A decrease in caloric value from 21,6 to 19,1 GJ/ton, resulting in a decreased substitution:
  - For Petcokes from 0,65 T/T[7] to 0,58 T/T
  - For Coal from 0,64 T/T to 0,56 T/T
  - For Waste incineration from 21,6 GJ/ton to 19,1

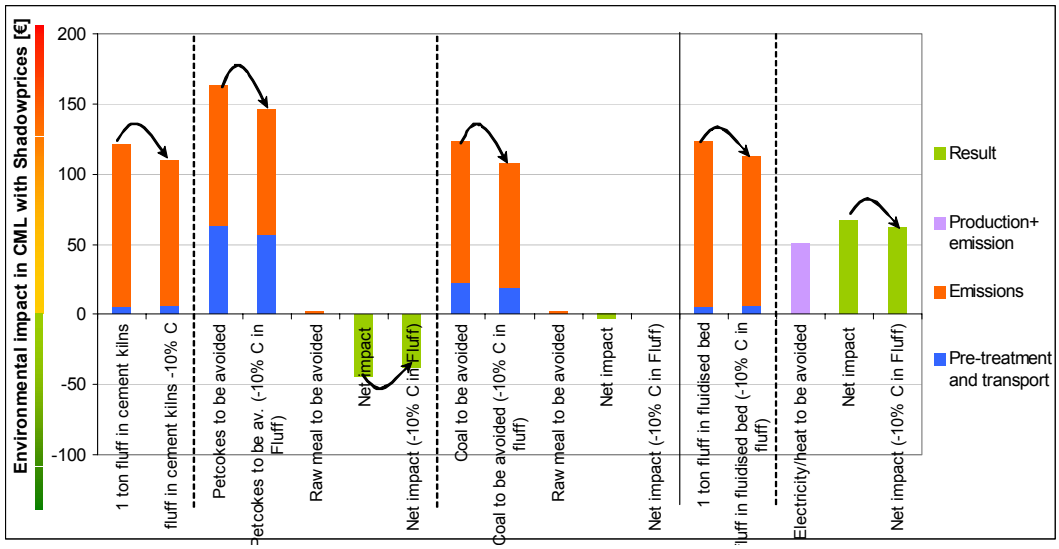

Figure 25 Sensitivity analysis for 10% decreased of carbon content in fluff due to increased paper content.

Figure 25 shows the results of the sensitivity analysis on carbon content of fluff. A decrease in carbon content would lead to a decrease of environmental benefit of treatment in cement kilns and a decrease in environmental damage for treatment in waste incinerators. Although the differences between cement kilns and waste incineration become smaller, the conclusion does not change; even with a lower caloric content, the cement kilns have a better environmental performance compared to waste incineration.

4.3.4 *-10% caloric value*

Another topic of sensitivity analysis is the caloric value of waste: it may decrease as a result of increased moisture content. If 1 ton of waste contains 10% more water, this would result in:

– 10% lower emissions (as the emissions are related to the waste and not to water)
– 10% less energy substitution as a result of 10% less waste in a ton ‘wet waste’
– Less energy substitution as a result of energy loss for water heating and evaporation

The results are shown in Figure 26. Comparing these outcomes to the summary results in Figure 6, it can be seem that the conclusions are still the same. This is of no surprise as the contribution of the energy loss of water evaporation is limited compared to the caloric content of the waste. 10% less waste per ton results in 10% lower emissions and a little more than 10% less energy substitution.

[7] T/T = ton fuel per ton fluff

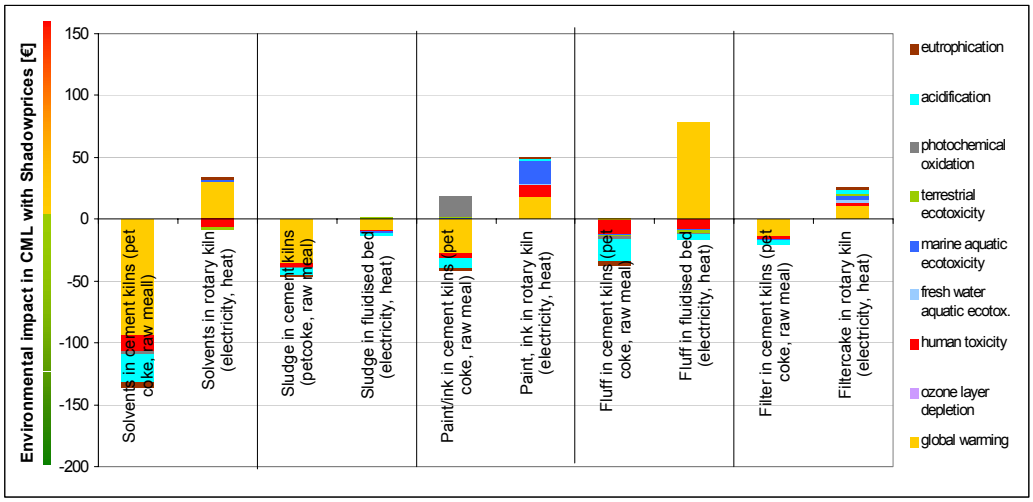

Figure 26 Sensitivity analysis for 10% increase of water content in waste.

4.3.5 *VOC content in paint/ink*

The VOC emissions related to storage of impregnated sawdust are estimated based on the assumptions:

– 10% average VOC content of paint ink mixtures as processed in the pre-treatment facility
– 10% of these VOCs are emitted to air when stored in open silo's or during transport.

A sensitivity analysis is made: do the conclusions change if VOC emissions as a result of open storage are doubled or 50% lower. The results are presented in Figure 27. When the VOC emissions related to storage of impregnated sawdust double, the environmental impact of pre-treatment and transport expressed in shadow prices increases from € 38 to € 58. When the VOC emissions are only 50% of the assumed emissions, the environmental impact of pre-treatment and transport decreases to € 28. As a result the net environmental result (after fuel substitution) varies. However the conclusions regarding the comparison with waste incineration do not change.

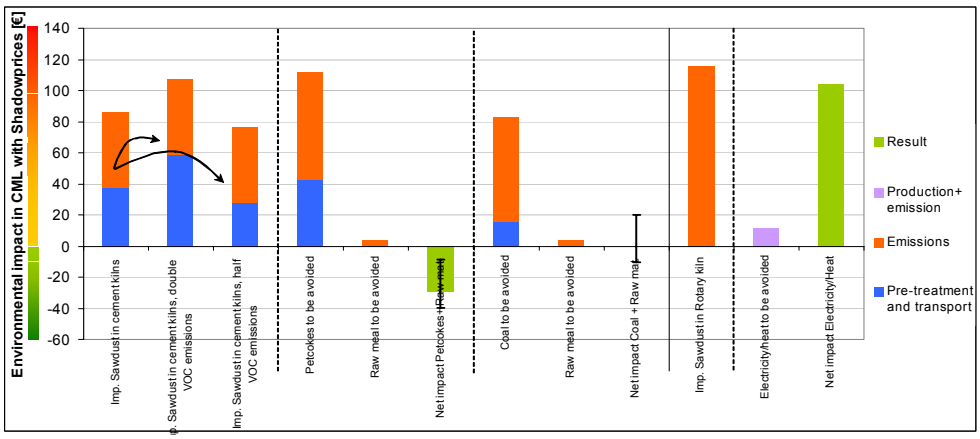

Figure 27 Sensitivity analysis on VOC emissions related to storage of impregnated saw dust.

4.3.6 *Shadow prices for CO_2 and SO_x*

The shadow prices are based on Dutch policy. For SO_x and CO_2 Flanders has set shadow prices in previous studies, and these are used in a sensitivity analysis.

TNO uses a shadow price of 50 € /ton CO_2 (based on Dutch policy). For CO_2 several shadow prices (or marginal costs) can be used, depending on the policy, on future scenarios for economic development and the time frame. For CO_2 the shadow prices range from 15 to 18 €/ton for low economic development and from 40 to 48 €/ton for high economic development in the BAU+ study from VITO [10]. In the EU trade market for CO_2, the current price for CO_2 is around 20 € per ton [11] . This value is used in the sensitivity analysis, as it is the lowest value that is used in Europe in long-term assessments, and it is close to the low range of CO_2 shadow prices used in Flanders in other studies. If an even lower value would be taken, also the other shadow prices would have to be changed, because these values, as used now, assume long-term perspectives.

For SO_x, TNO has used a shadow price of 4 €/kg SO_x equivalent. A Flemish study on environmental costs in Flanders shows that the Flemish goal on acidification can be met with a marginal cost level of 2,5 €/kg SO_x eq [12]. This value is used in the sensitivity analysis.

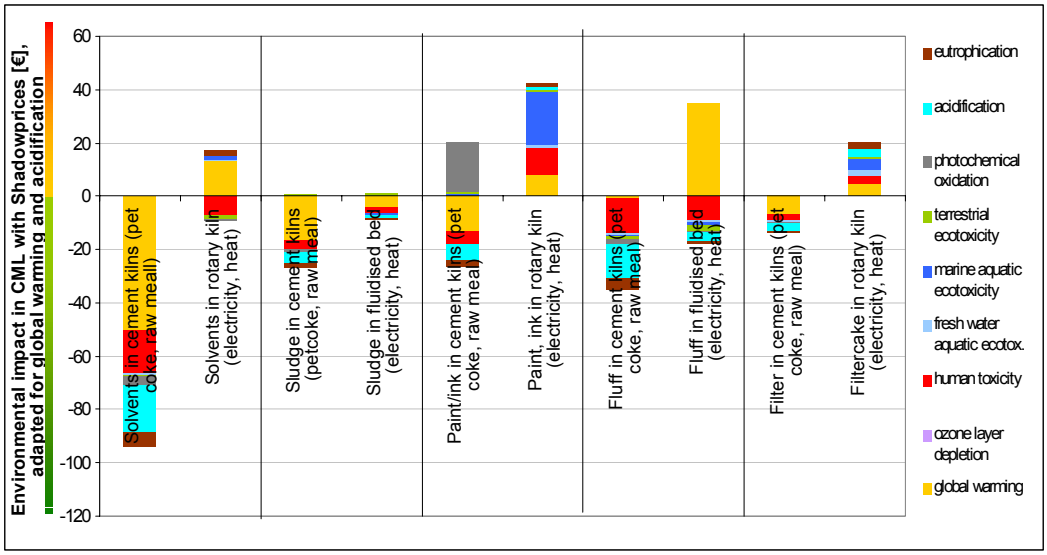

Figure 28 Sensitivity analysis on shadow prices: 20 €/ton instead of 50€/ton for global warming and 2,5€/kg instead of 4 €/kg for acidification.

Figure 28 shows the results when the shadow prices for global warming (CO_2) and acidification (SO_x) are adapted. When we compare these results to the results calculated with the original unadapted method in Figure 6, we see a smaller contribution of global warming and acidification to the overall result. However the conclusions on the comparison do not change. It can be deduced from figure 25 that, even if a value of € 15,- per ton CO_2 would have been used in the calculation, and the contribution of global warming would decrease with 25%, the conclusion would not change.

4.3.7 *Transfer coefficients for waste incineration*

As some of the transfer coefficients available from the used ecoinvent data [9] on waste incineration are rather old - see Annex 3 – a sensitivity analysis is made using lower transfer coefficients for emissions to air and water[8]. Table 5 shows that factors that are varied in this sensitivity analysis: the factor left of the slash (/) are the factors as reported in Annex 3. The factors right from the slash are applied in this sensitivity analysis for both the rotary kiln (air and water emissions) and fluidized bed (air emissions only). As the contribution of solid residues to the environmental impact of waste incineration is very small (maximum 0.5%), the increased concentration in solid residues is not taken into account in the calculation as this would hardly change the result.

Table 5 Transfer coefficients of typical hazardous waste incineration: ecoinvent factors (base case) / factors applied in sensitivity analysis.

Element	Air_emissions	Water_emissions	Solid residues
S	0,06%/0.66%	95,7%/17.9%	4,28%/81.44%
Cl	0,03%/0.03%	99,8%/96.7%	0,17%/3.27%
Cd	0,899%/0%	10,2%/0%	88,9%/100%
Co	0,07%/0%	99,9%/0%	0%/100%
Cr	7,39E-06%/0%	0,32%/0%	99,7%/100%
Cu	0,07%/0.03%	4,29%/0%	95,6%/99.9%
Hg	4,02%/0.05%	10,6%/0.07%	85,3%/99.88%
Ni	0,07%/0.08%	20,5%/0.00%	79,5%/99.92%
Pb	0,331%/0.09%	11,5%/0.03%	88,1%/99.88%
Se	5,03E-07%/0%	0,0118%/0%	100%/100%
Zn	0,07%/0.02%	1,34%/0.01%	98,6%/99.97%

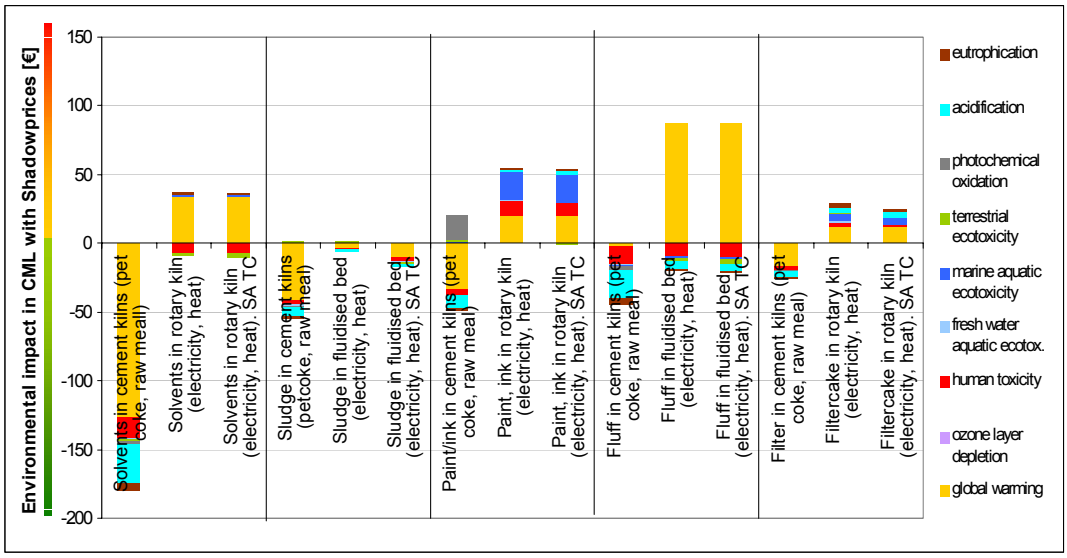

Figure 29 Sensitivity analysis on TC coefficients for waste incineration: lower emissions to air and water.

[8] These transfer coefficient data are not directly gathered from literature, but are brought in by one of the expert panel members (see also Annex 6).

Figure 29 shows the results for calculations with the Eco-invent transfer coefficients for waste incineration and for lower transfer coefficients for emissions to air and water as given in Table 5 (SA TC). Applying lower transfer coefficients for emissions to air and water results in a smaller environmental impact results in 2%, 3% and 5% reduced environmental impact for waste incineration for fluff, paint-ink and solvents respectively. The environmental impact of filter cake in a waste incineration decreases 12%, and the environmental benefit of sludge in a fluidized bed doubles as a result of lower emissions to air.
However when waste incineration of these five waste streams is compared to the environmental impact of waste in cement kilns, the conclusions do not change: even with lower emissions for waste incineration, the co-combustion in cement kilns has a preference from an environmental point of view.

5 References

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[11] http://www.co2prices.eu/. European CO_2 trade market.

[12] Milieukostenmodel Vlaanderen - MIRA 2006 Achtergronddocument

6 Signature

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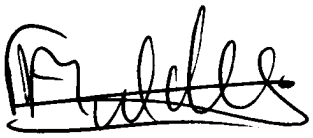
Date upon which, or period in which the research took place:

February - June 2007

Signature:



Ir. E. Mulder
Project manager

Approved by:

Dr L.B.M. van Kessel
Team manager Thermal Processes

1 Waste streams and representativeness

1.1 Properties of selected waste streams and fuels

Table 1 Average properties of selected waste streams and fuels.

		Imp. Saw dust	Sludges	Solvents	Fluff	Filtercake	Petcokes	Coal
Dosage	T/y	216817	94826	54145	50828	85048	330631	148508
LHV	MJ/T a.r.	14539	8240	29147	21570	4710	33130	33840
moisture	% a.r.	30,4	31,9	14,6	5,5	50,6	10,4	14,4
ashes	% a.r.	18,2	27,0	0,0	12,7	23,8	1,2	2,0
S (as SO3)	% a.r.	4,9	1,5	1,0	0,5	1,0	3,4	0,7
Cl	% a.r.	0,2	0,5	0,0	0,7	2,0	0,2	0,0
Sb	ppm a.r.	41,1	40,1	3,0	223,9	22,7	1,3	0,6
As	ppm a.r.	3,2	10,0	2,9	69,6	4,5	0,9	2,7
Be	ppm a.r.	0,5	0,2	0,5	0,0	0,0	0,1	0,1
Cd	ppm a.r.	3,4	9,0	2,9	6,6	7,0	1,4	0,1
Cr	ppm a.r.	147,6	308,3	16,7	196,9	189,2	9,0	19,0
Co	ppm a.r.	19,7	30,9	6,6	22,6	22,8	5,2	5,6
Cu	ppm a.r.	326,0	416,3	54,8	185,5	218,5	3,1	12,0
Sn	ppm a.r.	59,3	220,0	3,3	91,5	0,0	0,7	2,3
Mn	ppm a.r.	262,7	533,7	11,8	153,3	0,0	5,6	50,0
Hg	ppm a.r.	1,0	1,3	0,5	0,4	0,6	0,2	0,1
Ni	ppm a.r.	82,7	334,5	6,3	54,1	179,2	334,3	16,0
Pb	ppm a.r.	447,9	208,8	65,2	361,1	112,6	2,4	8,8
Se	ppm a.r.	3,0	3,1	0,1	0,2	0,0	0,2	1,7
Tl	ppm a.r.	2,1	7,0	3,0	1,9	3,0	2,0	1,0
V	ppm a.r.	39,2	123,5	4,5	34,3	53,9	1094,7	29,0
Te	ppm a.r.	0,1	1,5	4,2	0,0	0,0	0,1	0,1
Zn	ppm a.r.	1625,7	2742,3	156,6	1432,6	1317,8	13,3	29,0
F	ppm a.r.	65,4	269,6	16,7	113,3	27,3	41,7	110,0
Br	ppm a.r.	3,7	57,9	45,4	68,3	25,0	52,0	48,0
I	ppm a.r.		3,80	6,7	45,9	0,5	0,3	11,0

Table 2 Minimum and maximum values of main characteristics.

		Imp. Saw dust			Sludges			Solvents		
		MEAN	min	max	MEAN	min	max	MEAN	min	max
Dosage	T/y	216.817	-	-	94826	-	-	54145		
LHV	MJ/ton	14.539	12.113	17655	8240	4460	13090	29147	29078	36002
moisture	% a.r.	30,4	26,7	33,2	31,9	9,0	50,6	14,6	0,0	15,0
ashes	% a.r.	18,2	17,3	18,9	27,0	25,6	48,9	0,0	0,0	0,5
CO2 prod	ton/ton	0,86	-	-	0,00	-	-	1,12	-	-

		Filtercake			Petcokes			Coal		
		MEAN	min	max	MEAN	min	max	MEAN	min	max
Dosage	T/y	85.048	-	-	330631	-	-	148508	-	-
LHV	MJ/ton	4710	-	-	33130	31100	34534	33840	-	-
moisture	% a.r.	50,6	-	-	10,4	8,4	14,4	14,4	-	-
ashes	% a.r.	23,8	-	-	1.2	0,4	2,0	2,0	-	-
CO2 prod	ton/ton	0,18	-	-	3,07	-	-	3,14	-	-

		Fluff		
		MEAN	min	max
Dosage	T/y	50828	-	-
LHV	MJ/ton	21570	-	-
moisture	% a.r.	5,5	-	-
ashes	% a.r.	12,7	-	-
CO2 prod	ton/ton	2,30	-	-

Comments:

- In case only one value was available, no min and max values are given
- A.r. means ‘as received’ (so, gross; not on dry matter)
- The moisture content of the sludge (31,9%) is after drying (= pre-treatment)
- Dosage is also ‘as received’
- Biogenic CO_2 (from saw dust and from sludge) is not counted

1.2 Representativeness of selected waste streams

Introduction

In the comparative LCA on the thermal treatment of waste streams in the cement industry five waste streams have been selected:

1. Waste oils & waste solvents;
2. Filter cakes;
3. Industrial sludge (wet & dry);
4. Impregnated saw dust (paint & ink);
5. Fluff (incl. automotive plastics and textiles).

The question was risen in as much these waste streams were representative for the thermal waste processing by the Belgian cement industry. To answer this question the contribution of these waste streams to the total of waste thermally treated by the Belgian cement industry in 2006 was ascertained.

Results

The total amount of thermally treated wastes is in terms of mass 659.000 tonnes per year (see Table 3). In terms of energy content (LHV) the amount was 10.300.000 GJ per year.

Table 3 Thermally treated waste streams in the Belgian cement industry in 2006.

	kT/y	% of total	GJ/y	% of total
1. Waste Oil/Solvents	54,1	8,2%	1.578.164	15,3%
2. Industrial Sludges	94,8	14,4%	781.366	7,6%
3. Filters	85,0	12,9%	400.576	3,9%
4. Imp. Sawdust and Paintsludge	216,8	32,9%	3.152.302	30,6%
5. Plastics, Textiles, RBA, Fluff	50,8	7,7%	1.096.360	10,6%
Subtotal	**501,6**	**76,1%**	**7.008.769**	**68,0%**
Animal meal	106,9	16,2%	1.867.718	18,1%
Others	50,4	7,6%	1.423.483	13,8%
Total	**659,0**	**100,0%**	**10.299.970**	**100,0%**

However, for several reasons the taxation on thermal treatment of waste is not charged for animal meal. For this reason in table 4 animal meal is left out, and the contributions of the 5 selected waste streams are calculated again.

Table 4 Thermally treated waste streams (without animal meal).

	kT/y	% of total	GJ/y	% of total
1. Waste Oil/Solvents	54,1	9,8%	1.578.164	18,7%
2. Industrial Sludges	94,8	17,2%	781.366	9,3%
3. Filters	85,0	15,4%	400.576	4,7%
4. Imp. Sawdust and Paintsludge	216,8	39,3%	3.152.302	37,4%
5. Plastics, Textiles, RBA, Fluff	50,8	9,2%	1.096.360	13,0%
Subtotal	**501,7**	**90,9%**	**7.008.769**	**83,1%**
Others	50,4	9,1%	1.423.483	16,9%
Total	**552,1**	**100,0%**	**8.432.252**	**100,0%**

Table 4 shows that the five selected waste streams have a contribution of around 90% to the total when excluding animal meal (90,9% based on mass, and 83,1% based on energy content). The remaining (not selected) waste streams comprise sewage & bio sludge, seeds, tyres and rubber. These streams do not highly deviate from the five selected waste streams, in terms of energy content or composition.

For completeness, in Table 5, the total amount of fuels in the Belgian cement industry is shown.

Table 5 Thermally treated waste streams and fossile fuels.

	kT/y	% of total	GJ/y	% of total
1. Waste Oil/Solvents	54,1	4,8%	1.578.164	6,7%
2. Industrial Sludges	94,8	8,3%	781.366	3,3%
3. Filters	85,0	7,5%	400.576	1,7%
4. Imp. Sawdust and Paintsludge	216,8	19,0%	3.152.302	13,3%
5. Plastics, Textiles, RBA, Fluff	50,8	4,5%	1.096.360	4,6%
Subtotal	**501,7**	**44,1%**	**7.008.769**	**29,6%**
Animal meal	106,9	9,4%	1.867.718	7,9%
Others	50,4	4,4%	1.423.483	6,0%
Fossile	479,1	42,1%	13.377.082	56,5%
Total	**1.138,1**	**100,0%**	**23.677.052**	**100,0%**

Conclusions

The contribution of the five waste streams of more than 90% on mass basis is seen as representative for the total package of waste streams especially when considering that the not selected waste streams like tires and others have a likeness with the already included waste streams with regard to content and caloric value.

2 Cement Clinker Production

2.1 Cement Clinker in General

Portland cement is a fine powder, gray or white in color, that consists of a mixture of hydraulic cement materials comprising primarily calcium silicates, aluminates and aluminoferrites. More than 30 raw materials are known to be used in the manufacture of portland cement, and these materials can be divided into four distinct categories: calcareous, siliceous, argillaceous, and ferrifrous. These materials are chemically combined through pyroprocessing and subjected to subsequent mechanical processing operations to form gray and white portland cement.

Gray portlandcement is used for structural applications and is the more common type of cement produced. White portland cement has lower iron and manganese contents than gray portland cement and is used primarily for decorative purposes. Portland cement manufacturing plants are part of hydraulic cement manufacturing, which also includes natural, masonry, and pozzolanic cement.

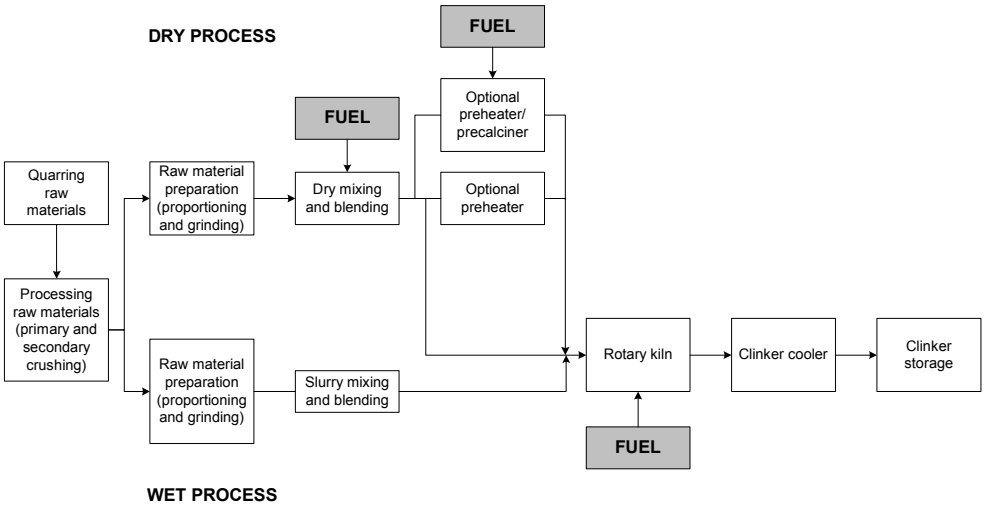


Figure 1 Schematic overview of the cement clinker production process, wet and dry and pre-heater / pre-calciner options. Indicated are fuel injection locations.

Portland cement accounts for more than 90% the hydraulic worldwide cement production. The balance of domestic cement production is primarily masonry cement. Both of these materials are produced in portland cement manufacturing plants. A diagram of the process is shown in Figure 1. As shown in the figure, the process can be divided into the following primary components: raw materials acquisition and handling, kiln feed preparation, pyroprocessing, and finished cement grinding (not shown). Each of these process components is described briefly below.

2.2 Cement Clinkering

The primary focus of this discussion is on pyroprocessing operations, which constitute the core of a portland cement plant. The initial production step in portland cement manufacturing is raw materials acquisition. Calcium, the element of highest concentration in portland cement, is obtained from a variety of calcareous raw materials, including limestone, chalk, marl, sea shells, aragonite, and an impure limestone known as “natural cement rock”. Typically, these raw materials are obtained from open-face quarries, but underground mines or dredging operations are also used. Raw materials vary from facility to facility. Some quarries produce relatively pure limestone that requires the use of additional raw materials to provide the correct chemical blend in the raw mix. In other quarries, all or part of the noncalcarious constituents are found naturally in the limestone. Occasionally, pockets of pyrite, which can significantly increase emissions of sulfur dioxide (SO_2), are found in deposits of limestone, clays, and shales used as raw materials for portland cement.

Because a large fraction (approximately one third) of the mass of this primary material is lost as carbon dioxide (CO_2) in the kiln, portland cement plants are located close to a calcareous raw material source whenever possible. Other elements included in the raw mix are silicon, aluminum, and iron. These materials are obtained from ores and minerals such as sand, shale, clay, and iron ore. Again, these materials are most commonly from open-pit quarries or mines, but they may be dredged or excavated from underwater deposits. Either gypsum or natural anhydrite, both of which are forms of calcium sulfate, is introduced to the process during the finish grinding operations described below. These materials, also excavated from quarries or mines, are generally purchased from an external source, rather than obtained directly from a captive operation by the cement plant. The portland cement manufacturing industry is relying increasingly on replacing virgin materials with waste materials or byproducts from other manufacturing operations, to the extent that such replacement can be implemented without adversely affecting plant operations, product quality or the environment. Materials that have been used include fly ash, mill scale, and metal smelting slags.

The second step in portland cement manufacture is preparing the raw mix, or kiln feed, for the pyroprocessing operation. Raw material preparation includes a variety of blending and sizing operations that are designed to provide a feed with appropriate chemical and physical properties. The raw material processing operations differ somewhat for wet and dry processes, as described below. Cement raw materials are received with an initial moisture content varying from 1 to more than 50 percent. If the facility uses dry process kilns, this moisture is usually reduced to less than 1 percent before or during grinding. Drying alone can be accomplished in impact dryers, drum dryers, paddle-equipped rapid dryers, air separators, or autogenous mills. However, drying can also be accomplished (to a minor extend) during grinding in ball-and-tube mills or roller mills. While thermal energy for drying can be supplied by exhaust gases from separate, direct-fired coal, oil, or gas burners, the most efficient and widely used source of heat for drying is the hot exit gases from the pyroprocessing system.

Materials transport associated with dry raw milling systems can be accomplished by a variety of mechanisms, including screw conveyors, belt conveyors, drag conveyors, bucket elevators, air slide conveyors, and pneumatic conveying systems. The dry raw mix is pneumatically blended and stored in specially constructed silos until it is fed to the pyroprocessing system.

In the wet process, water is added to the raw mill during the grinding of the raw materials in ball or tube mills, thereby producing a pumpable slurry, or slip, of approximately 65% solids. The slurry is agitated, blended, and stored in various kinds and sizes of cylindrical tanks or slurry basins until it is fed to the pyroprocessing system.

The heart of the portland cement manufacturing process is the pyroprocessing system. This system transforms the raw mix into clinkers, which are gray, glass-hard, spherically shaped nodules that range from 0.32 to 5.1 centimeters (cm) (0.125 to 2.0 inches [in.]) in diameter. The chemical reactions and physical processes that constitute the transformation are quite complex, but they can be viewed conceptually as the following sequential events:

1. Evaporation of free water;
2. Evolution of combined water in the argillaceous components;
3. Calcination of the calcium carbonate ($CaCO_3$) to calcium oxide (CaO);
4. Reaction of CaO with silica to form dicalcium silicate;
5. Reaction of CaO with the aluminum and iron-bearing constituents to form the liquid phase;
6. Formation of the clinker nodules;
7. Evaporation of volatile constituents (e. g., sodium, potassium, chlorides, and sulfates, metals);
8. Reaction of excess CaO with dicalcium silicate to form tricalcium silicate.

This sequence of events may be conveniently divided into four stages, as a function of location and temperature of the materials in the rotary kiln.

1. Evaporation of uncombined water from raw materials, as material temperature increases to 100°C;
2. Dehydration, as the material temperature increases from 100°C to approximately 430°C to form oxides of silicon, aluminum, and iron;
3. Calcination, during which carbon dioxide (CO_2) is evolved, between 900°C and 982°C, to form CaO;
4. Reaction, of the oxides in the burning zone of the rotary kiln, to form cement clinker at temperatures of approximately 1450°C.

Rotary kilns are long, cylindrical, slightly inclined furnaces that are lined with refractory to protect the steel shell and retain heat within the kiln. The raw material mix enters the kiln at the elevated end, and the combustion fuels generally are introduced into the lower end of the kiln in a countercurrent manner. The materials are continuously and slowly moved to the lower end by rotation of the kiln. As they move down the kiln, the raw materials are changed to cementitious or hydraulic minerals as a result of the increasing temperature within the kiln. The most commonly used kiln fuels are coal, natural gas, and occasionally oil. The use of supplemental fuels such as waste solvents, scrap rubber, and petroleum coke has expanded in recent years, and can be as high as 100% substitution of fossile fuels.

Five different processes are used in the portland cement industry to accomplish the pyroprocessing step: the wet process (Ciment d'Obourg, Holcim), the dry process (long dry process), the semidry process, the dry process with a preheater, and the dry process with a preheater/precalciner (all other plants). Each of these processes accomplishes the physical/chemical steps defined above. However, the processes vary with respect to equipment design, method of operation, and fuel consumption. Generally, fuel

consumption decreases in the order of the processes listed. The paragraphs below briefly describe the process, starting with the wet process and then noting differences in the other processes.

In the wet process and long dry process, all of the pyroprocessing activity occurs in the rotary kiln. Depending on the process type, kilns have length-to-diameter ratios in the range of 15:1 to 40:1. While some wet process kilns may be as long as 200 m, many wet process kilns and all dry process kilns are shorter. Wet process and long dry process pyroprocessing systems consist solely of the simple rotary kiln. Usually, a system of chains is provided at the feed end of the kiln in the drying or preheat zones to improve heat transfer from the hot gases to the solid materials. As the kiln rotates, the chains are raised and exposed to the hot gases. Further kiln rotation causes the hot chains to fall into the cooler materials at the bottom of the kiln, thereby transferring the heat to the load.

Dry process pyroprocessing systems have been improved in thermal efficiency and productive capacity through the addition of one or more cyclone-type preheater vessels in the gas stream exiting the rotary kiln. This system is called the preheater process. The vessels are arranged vertically, in series, and are supported by a structure known as the preheater tower. Hot exhaust gases from the rotary kiln pass countercurrently through the downward-moving raw materials in the preheater vessels. Compared to the simple rotary kiln, the heat transfer rate is significantly increased, the degree of heat utilization is greater, and the process time is markedly reduced by the intimate contact of the solid particles with the hot gases. The improved heat transfer allows the length of the rotary kiln to be reduced. The hot gases from the preheater tower are often used as a source of heat for drying raw materials in the raw mill. Because the catch from the mechanical collectors, fabric filters, and/or electrostatic precipitators (ESP) that follow the raw mill is returned to the process, these devices are considered to be production machines as well as pollution control devices.

Additional thermal efficiencies and productivity gains have been achieved by diverting some fuel to a calciner vessel at the base of the preheater tower. This system is called the preheater/precalciner process. While a substantial amount of fuel is used in the precalciner, at least 40% of the thermal energy is required in the rotary kiln. The amount of fuel that is introduced to the calciner is determined by the availability and source of the oxygen for combustion in the calciner. Calciner systems sometimes use lower-quality fuels (e. g., less-volatile matter and higher impurities, such as chlorine and sulphur) as a means of improving process economics.

Preheater and precalciner kiln systems often have an alkali bypass system between the feed end of the rotary kiln and the preheater tower to remove the undesirable volatile constituents. Otherwise, the volatile constituents condense in the preheater tower and subsequently recirculate to the kiln. Buildup of these condensed materials can restrict process and gas flows. The alkali content of portland cement is often limited by product specifications because excessive alkali metals (i. e., sodium and potassium) can cause deleterious reactions in concrete. In a bypass system, a portion of the kiln exit gas stream is withdrawn and quickly cooled by air or water to condense the volatile constituents to fine particles. The solid particles, containing the undesirable volatile constituents, are removed from the gas stream and thus the process by fabric filters and ESPs.

The semidry process is a variation of the dry process. In the semidry process, the water is added to the dry raw mix in a pelletizer to form moist nodules or pellets. The pellets then are conveyed on a moving grate preheater before being fed to the rotary kiln. The pellets are dried and partially calcined by hot kiln exhaust gases passing through the moving grate.

Regardless of the type of pyroprocess used, the last component of the pyroprocessing system is the clinker cooler. This process step recoups up to 30% of the heat input to the kiln system, locks in desirable product qualities by freezing mineralogy, and makes it possible to handle the cooled clinker with conventional conveying equipment. The more common types of clinker coolers are

(1) reciprocating grate,
(2) planetary
(3) rotary.

In these coolers, the clinker is cooled from about 1100°C to 100°C by ambient air that passes through the clinker and into the rotary kiln for use as combustion air. However, in the reciprocating grate cooler, lower clinker discharge temperatures are achieved by passing an additional quantity of air through the clinker. Because this additional air cannot be utilized in the kiln for efficient combustion, it is vented to the atmosphere, used for drying coal or raw materials, or used as a combustion air source for the precalciner.

The final step in portland cement manufacturing, which is not incorporated in the LCA study, involves a sequence of blending and grinding operations that transforms clinker to finished portland cement. Up to 5% gypsum or natural anhydrite is added to the clinker during grinding to control the cement setting time, and other specialty chemicals are added as needed to impart specific product properties. This finish milling is accomplished almost exclusively in ball or tube mills. Typically, finishing is conducted in a closedcircuit system, with product sizing by air separation.

2.3 Emissions

Particulate matter (PM and PM-10), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbonmonoxide (CO), and carbondioxide (CO_2) are the primary emissions in the manufacture of portland cement. Small quantities of volatile organic compounds (VOC), ammonia (NH_3), chlorine, and hydrogen chloride (HCl), also may be emitted. Emissions may also include residual materials from the fuel and raw materials or products of incomplete combustion that are considered to be hazardous. Because some facilities burn waste fuels, particularly spent solvents in the kiln, these systems also may emit small quantities of additional hazardous organic pollutants. Also, raw material feeds and fuels typically contain trace amounts of heavy metals that may be emitted as a particulate or vapor.

Sources of PM at cement plants include (1) quarrying and crushing, (2) raw material storage, (3) grinding and blending (in the dry process only), (4) clinker production, (5) finish grinding, and (6) packaging and loading. The largest emission source of PM within cement plants is the pyroprocessing system that includes the kiln and clinker cooler exhaust stacks. Often, dust from the kiln is collected and recycled into the kiln, thereby producing clinker from the dust. However, if the alkali content of the raw materials is too high, some or all of the dust is discarded or leached before being

returned to the kiln. In many instances, the maximum allowable cement alkali content of 0.6% (calculated as sodium oxide) restricts the amount of dust that can be recycled. Bypass systems sometimes have a separate exhaust stack. Additional sources of PM are raw material storage piles, conveyors, storage silos, and unloading facilities.

Oxides of nitrogen are generated during fuel combustion by oxidation of chemically-bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. As flame temperature increases, the amount of thermally generated NO_x increases. The amount of NO_x generated from fuel increases with the quantity of nitrogen in the fuel. In the cement manufacturing process, NO_x is generated in both the burning zone of the kiln and the burning zone of a precalcining vessel. Fuel use affects the quantity and type of NO_x generated. For example, in the kiln, natural gas combustion with a high flame temperature and low fuel nitrogen generates a larger quantity of NO_x than does oil or coal, which have higher fuel nitrogen but which burn with lower flame temperatures. Also, the use of secondary fuel dramatically decreases the production rate of NO_x. The opposite may be true in a precalciner. Types of fuels used vary across the industry. Historically, some combination of coal, oil, and natural gas was used, but over the last 15 years, most plants have switched to coal, which generates less NO_x than does oil or gas. However, in recent years a number of plants have switched to systems that burn a combination of coal and waste fuel.

Sulfur dioxide may be generated both from the sulfur compounds in the raw materials and from sulfur in the fuel. The sulfur content of both raw materials and fuels varies from plant to plant and with geographic location. However, the alkaline nature of the cement provides for direct absorption of SO_2 into the product, thereby mitigating the quantity of SO_2 emissions in the exhaust stream. Depending on the process and the source of the sulfur, SO_2 absorption ranges from about 70% to more than 95%.

The CO_2 emissions from portland cement manufacturing are generated by two mechanisms. As with most high-temperature, energy-intensive industrial processes, combusting fuels to generate process energy releases substantial quantities of CO_2. Substantial quantities of CO_2 also are generated through calcining of limestone or other calcareous material. This calcining process thermally decomposes $CaCO_3$ to CaO and CO_2. Typically, portland cement contains the equivalent of about 63.5 percent CaO. Consequently, about 1.135 units of $CaCO_3$ are required to produce 1 unit of cement, and the amount of CO_2 released in the calcining process is about 500 kg per tonne of portland cement produced. Total CO_2 emissions from the pyroprocess depend on energy consumption and generally fall in the range of 0.85 to 1.35 tonne of CO_2 per tonne of clinker.

In addition to CO_2 emissions, fuel combustion at portland cement plants can emit a wide range of pollutants in far smaller quantities. If the combustion reactions do not reach completion, CO and volatile organic pollutants, typically measured as total organic compounds (TOC), VOC, or organic condensable particulate, can be emitted. Incomplete combustion also can lead to emissions of specific hazardous organic air pollutants, although these pollutants are generally emitted at substantially lower levels than CO or TOC.

Emissions of metal compounds from portland cement kilns can be grouped into three general classes: volatile metals, including mercury (Hg) and thallium (Tl); semivolatile metals, including antimony (Sb), cadmium (Cd), lead (Pb), selenium (Se), zinc (Zn),

potassium (K), and sodium (Na); and refractory or nonvolatile metals, including barium (Ba), chromium (Cr), arsenic (As), nickel (Ni), vanadium (V), manganese (Mn), copper (Cu), and silver (Ag). Although the partitioning of these metal groups is affected by kiln operating conditions, the refractory metals tend to concentrate in the clinker, while the volatile and semivolatile metals tend to be discharged through the primary exhaust stack and the bypass stack, respectively.

In the pyroprocessing units, PM emissions are controlled by fabric filters (reverse air, pulse jet, or pulse plenum) and electrostatic precipitators (ESP). Typical control measures for the kiln exhaust are reverse air fabric filters. Clinker cooler systems are controlled most frequently with pulse jet or pulse plenum fabric filters. A few gravel bed filters also have been used to control clinker cooler emissions. Typical outlet PM loadings are identical to those reported for kilns.

Cement kiln systems have highly alkaline internal environments that can absorb up to 95% of potential SO_2 emissions. However, in systems that have sulfide sulfur (pyrites) in the kiln feed, the sulfur absorption rate may be as low as 70% without unique design considerations or changes in raw materials. The cement kiln system itself has been determined to provide substantial SO_2 control. Fabric filters on cement kilns are also reported to absorb SO_2. Generally, substantial control is not achieved. An absorbing reagent (e. g., CaO) must be present in the filter cake for SO_2 capture to occur. Without the presence of water, which is undesirable in the operation of a fabric filter, $CaCO_3$ is not an absorbing reagent. It has been observed that as much as 50% of the SO_2 can be removed from the pyroprocessing system exhaust gases when this gas stream is used in a raw mill for heat recovery and drying. In this case, moisture and calcium carbonate are simultaneously present for sufficient time to accomplish the chemical reaction with SO_2.

2.4 Schematic overview of LCA concerned plants

In Figures 2 to 5 schematic overviews of the cement plants, that are under regard in the LCA, are shown. The schemes are printed as received from the project members. There is one wet production process (Ciments d'Obourg), whilest all other plants in Belgium are of the type preheater (4 or 5 stage) and precalciner.

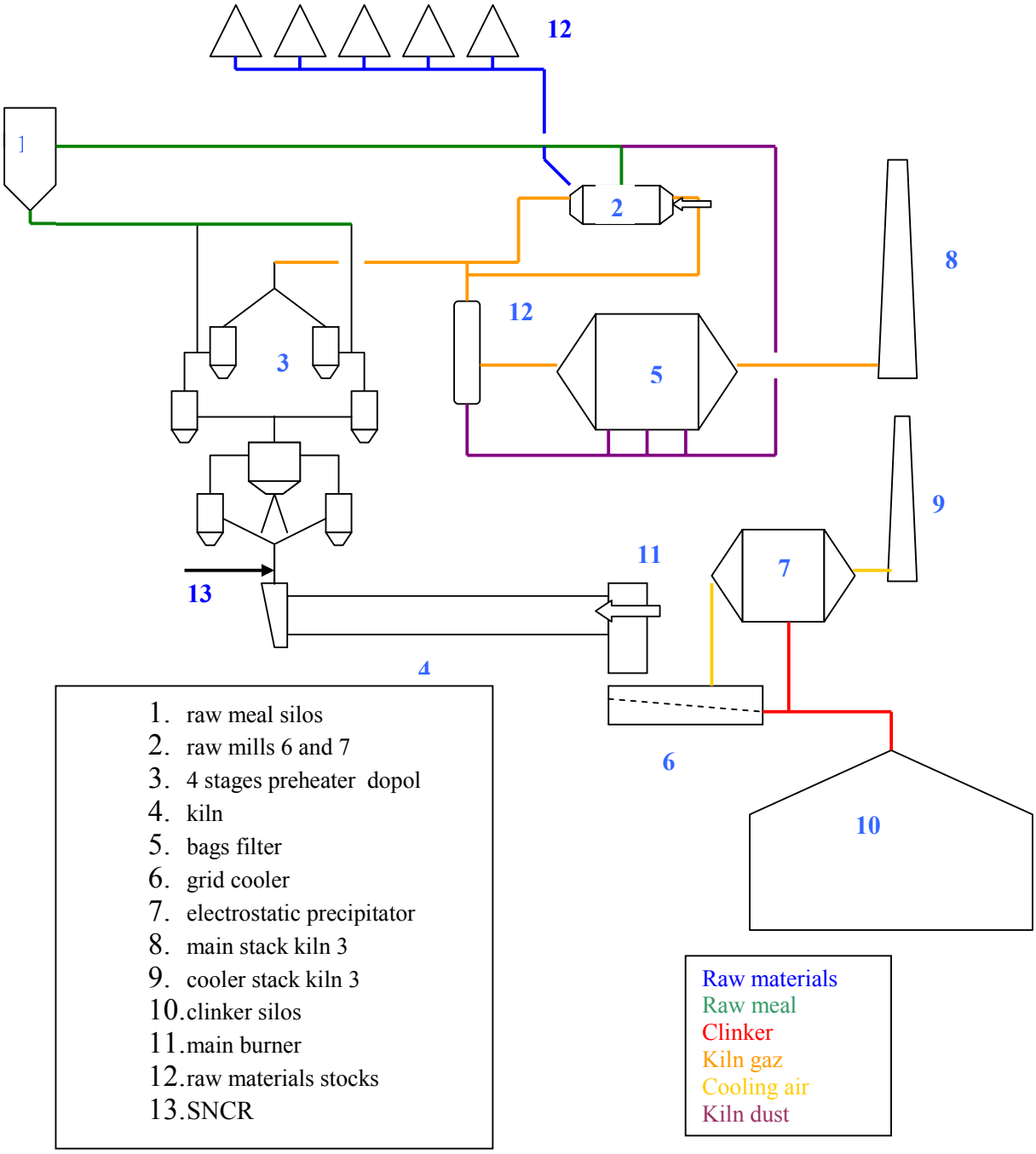


Figure 2 The production facility of CCB – Kiln-3.

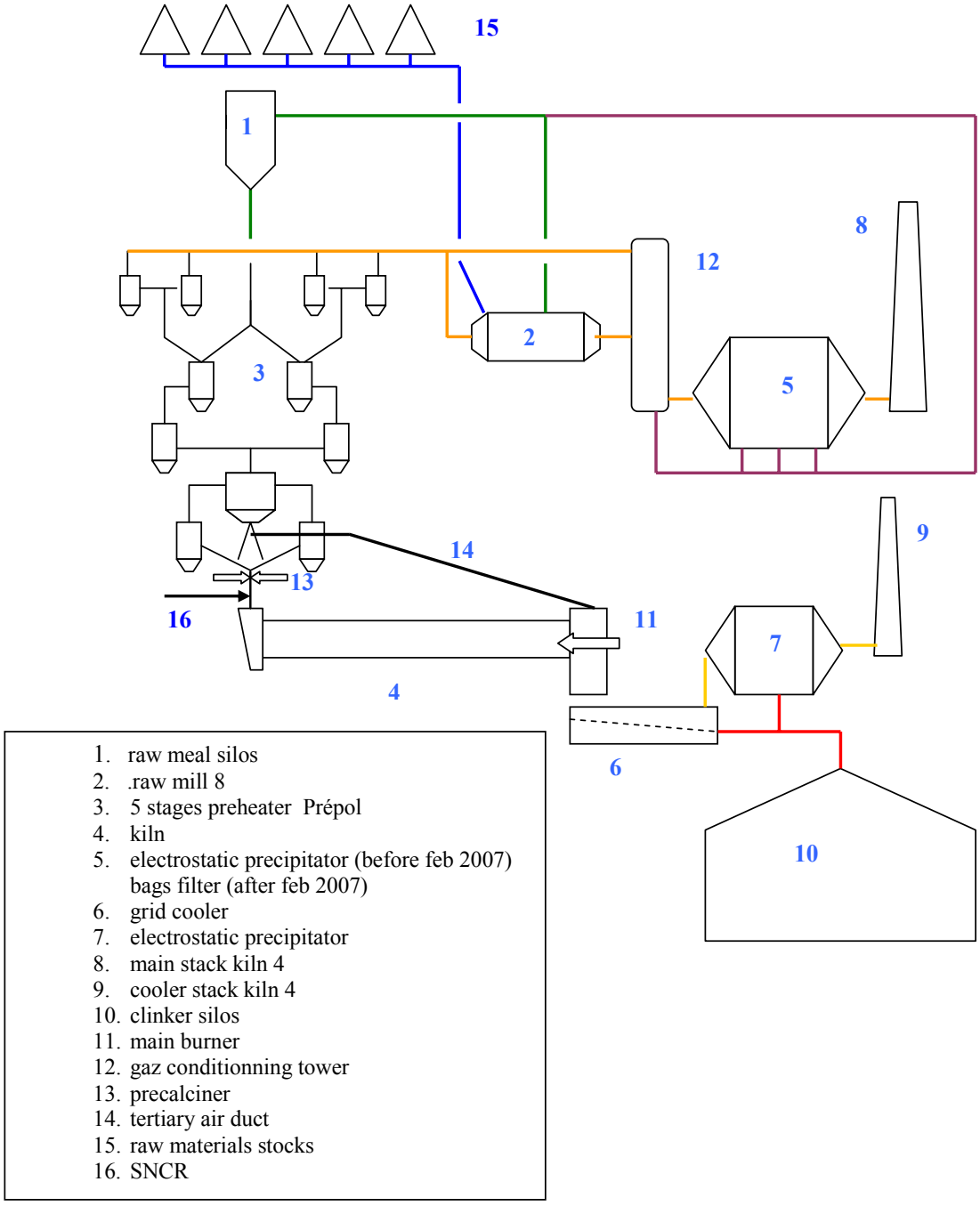


Figure 3 The production facility of CCB – Kiln-4.

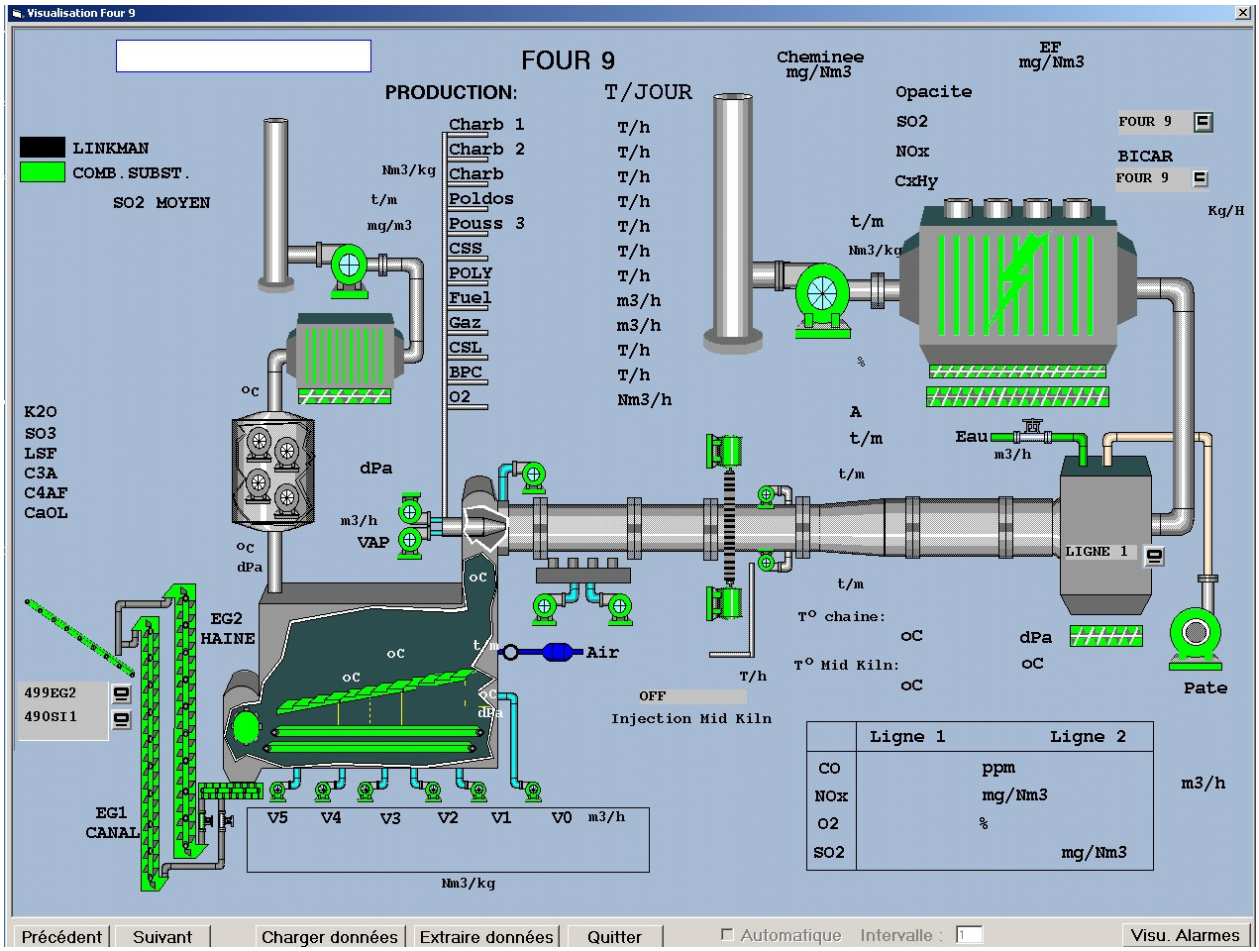


Figure 4 The production facility of Ciment d'Obourg.

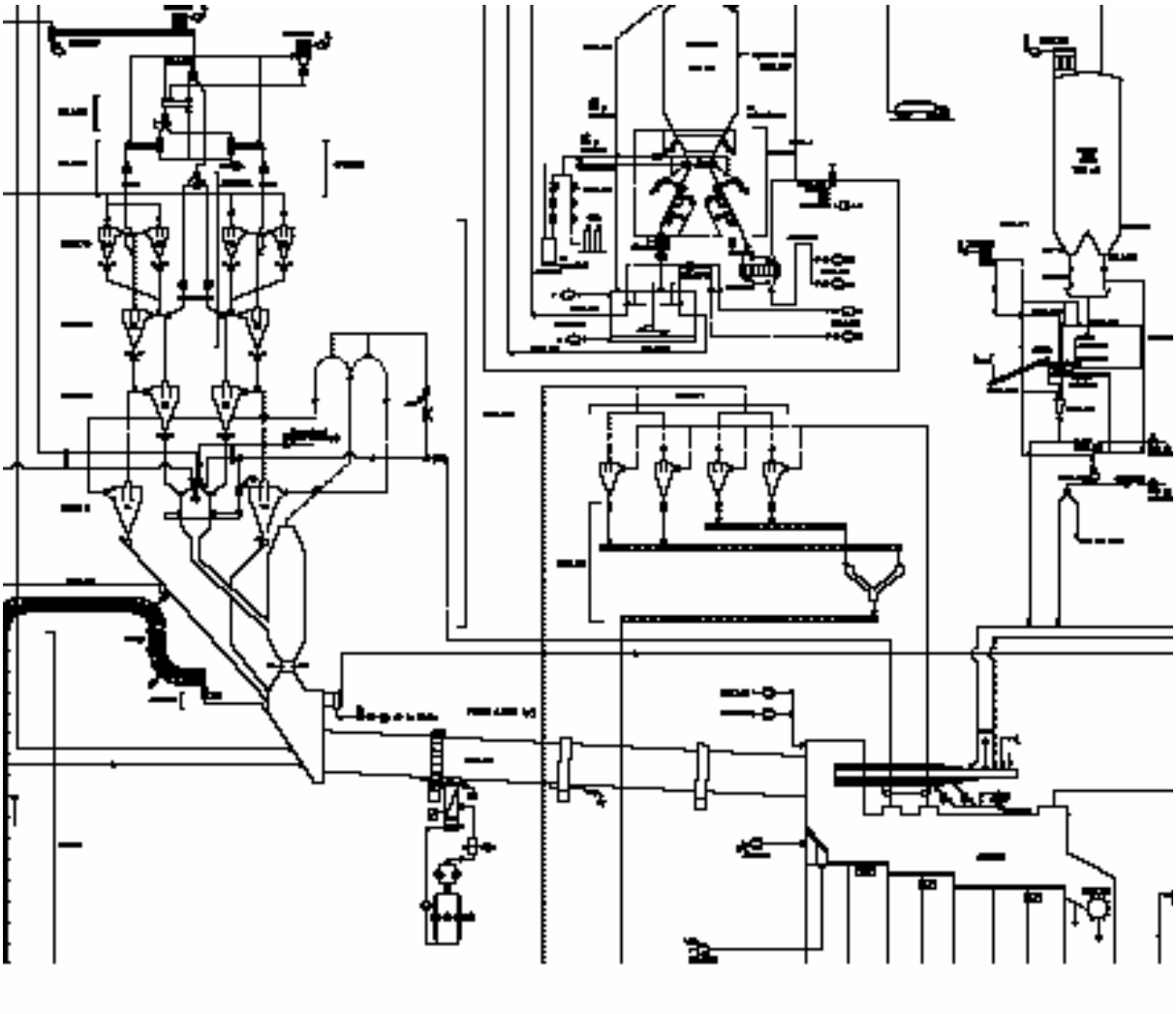


Figure 5 The production facility of CBR – Lixhe.

3 Waste incineration

Introduction

For the LCA study to Febelcem the environmental impact of (hazardous) waste treatment in the cement industry is compared with the environmental impact of the same wastes, when incinerated in the most suitable incineration system.
For the waste incineration part of the study, the following starting points were used:

- Five specific waste streams:
    1. Solvents and waste oils
    2. Filter cake
    3. Industrial sludge
    4. Paint, ink residues
    5. Fluff (plastics, textiles, RBA, etc)
- Based on the Belgian situation, using the processes at Indaver.

The goal of this Annex is to supply relevant process data of the waste incineration and the transfer coefficients to be used in the LCA study.

Hazardous waste incineration in Belgium

Indaver near Antwerp is the largest hazardous waste incinerator in Belgium and disposes of several (thermal) treatment systems for the selected five waste streams. Information about the Indaver plant, as presented below, is mainly derived from their internet site. In figure 1 an overview of the thermal treatment process of hazardous waste, as performed in a rotary kiln, is presented.

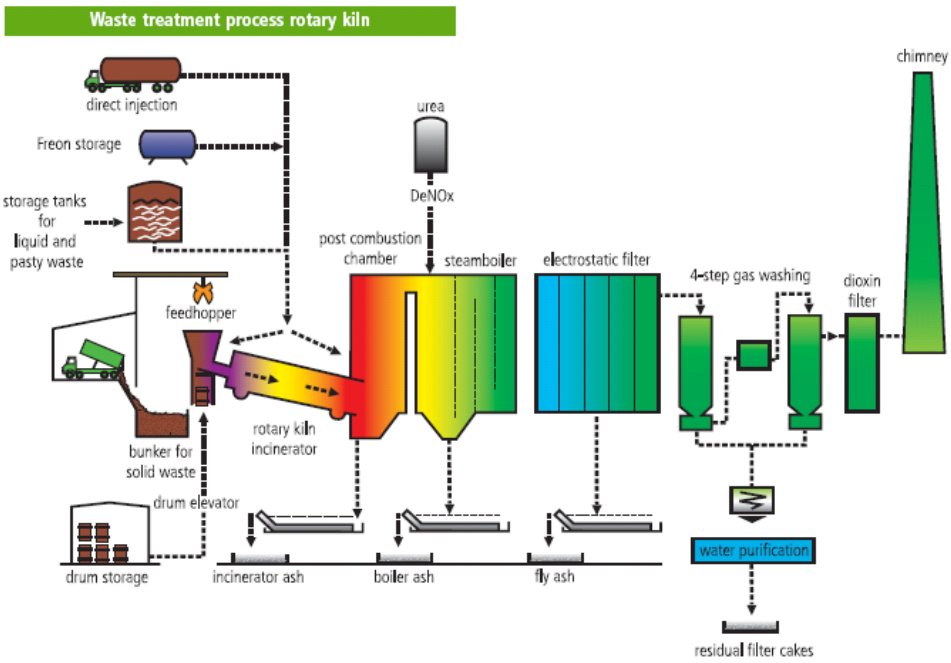


Figure 1 Typical incinerator for hazardous waste with rotary kiln and wet flue gas treatment system (Annual report of Indaver).

The most suitable incineration system for the indicated five waste streams is not in all cases the rotary kiln, but in some cases the FBC (Fluidised Bed Combustor). Based on specific (Mr. Wauters) information of Indaver it is assumed that the Rotary Kiln is most suitable to incinerate solvents and waste oils, and paint/ink residues and filter cake and the FBC process would be used for industrial sludges and fluff.
Figure 2 shows an overview of the FBC (Dutch: Wervelbed installatie), which is in operation since 2006.

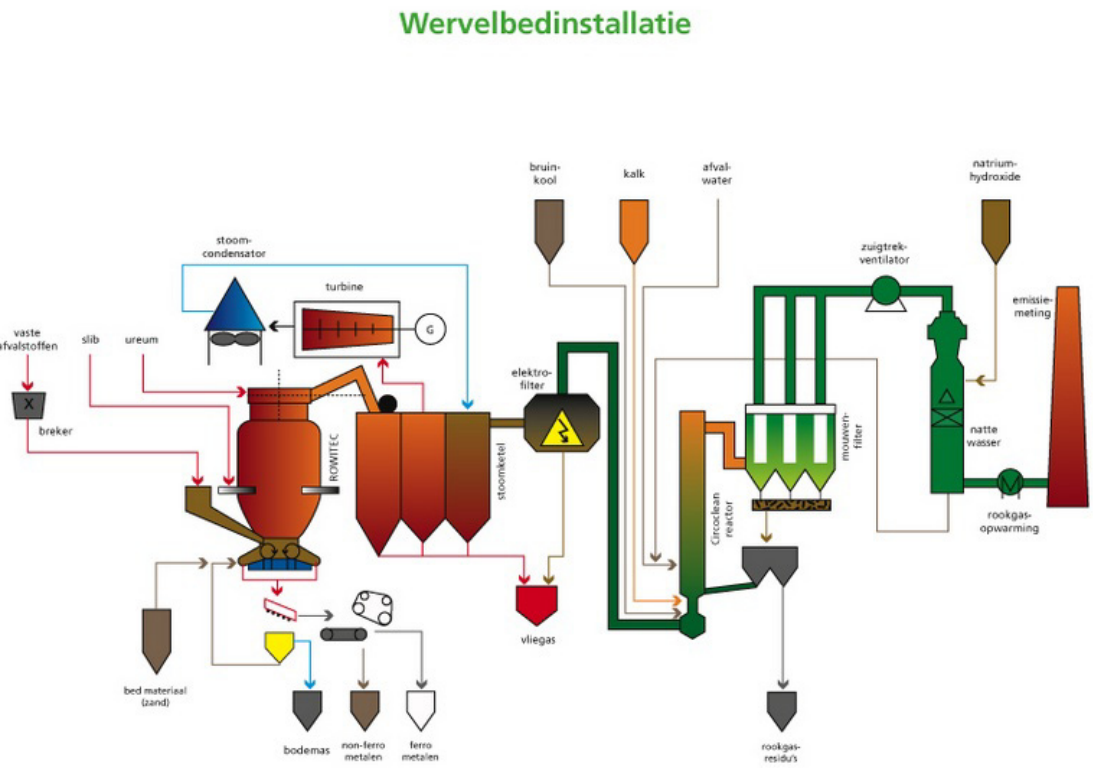


Figure 2. Overview of FBC at Indaver (Indaver).

The FBC consists of a fluidised bed with boiler, an Electro Static Precipitator, a Reactor, a Fabric Filter and a flue gas washer. The washing water is reused in the reactor (Semi Dry System).

Starting points for transfer coefficients
Indaver was not involved in the project and only wanted to deliver public data (Annual report 2005). For this reason other sources of data had to be used. An important source is an Eco-Invent study performed on Swiss incineration plants. The Swiss hazardous waste incinerator plant chosen as a representative of the rotary kiln is rather similar to the plant of Indaver. Both of the plants are equipped with Rotary Kilns with afterburners for fluid waste with high calorific values. Furthermore it is important that the flue-gas treatment in both cases is based on a wet system with wet scrubbers, resulting in emissions to the surface water. After passing the dust filters (ESP = Electro Static Precipitator) and wet scrubbers a pilot filter using brown coal is operational to clean the flue gasses to such a degree, that they can easily strike all threshold limits for

emissions to the air. Residues like slag (after treatment for removal of metals), boiler ash, ESP-ash and filter cake are solid residues that are landfilled.

As no direct information of transfer coefficients of FBC was available also for the FBC transfer coefficients from the Eco-Invents study were used, corrected with public data of Indaver, as far as they were available. Of main importance, compared to the DTO (Rotary Kiln), is that no emissions from the FBC take place to water, as a result of the semi dry flue gas treatment system. This results in transfer coefficients to air and solid residues only. Another important difference is the energy production, which is higher with the modern FBC.

Comparing the process of FBC with other combustion processes, like grate and rotary kiln, the following should be considered regarding this LCA study:
The behavior in a combustion system for a lot of components is the same. On the grate, in the rotary kiln or in the fluidised bed the waste stream is converted and split into two streams: a flue gas stream and a solid residue stream. The composition of those streams will not be quite different for a great number of components, starting from the same waste stream. A volatile component like mercury will in principle give the same behavior in al those combustion processes, resulting in a transfer of all the mercury into the flue gas stream. In the next phase of the process the flue-gasses will cool down in a boiler and are subsequently treated in a semi-dry flue gas treatment process. In the last mentioned step the mercury will be captured in the filters for ca 96% and subsequently transferred to the solid residue stream. The other ca 4% will be emitted to the air. It might be possible that some other components will evaporate on the grate or in the rotary kiln to an higher extent than in the fluid bed (due to possible higher temperatures in the grate furnace or rotary kiln), and will be captured in the flue gas treatment system, resulting in a slightly different solid residue stream. A number of combustion products, like dust, NO_x, CO and unburned components will behave different in the compared processes. This effect will be reduced by the flue-gas treatment system. For this components different transfer coefficient are used per process.

Transfer coefficients of hazardous waste incineration in a rotary kiln
Most of the transfer coefficients used for hazardous waste incineration in a rotary kiln are based on a Swiss study by Eco-Invent of a hazardous waste incineration plant, which is similar to the rotary kiln process of Indaver.
The rotary kiln hazardous waste incineration plant of Indaver has the following characteristics (figure 3):

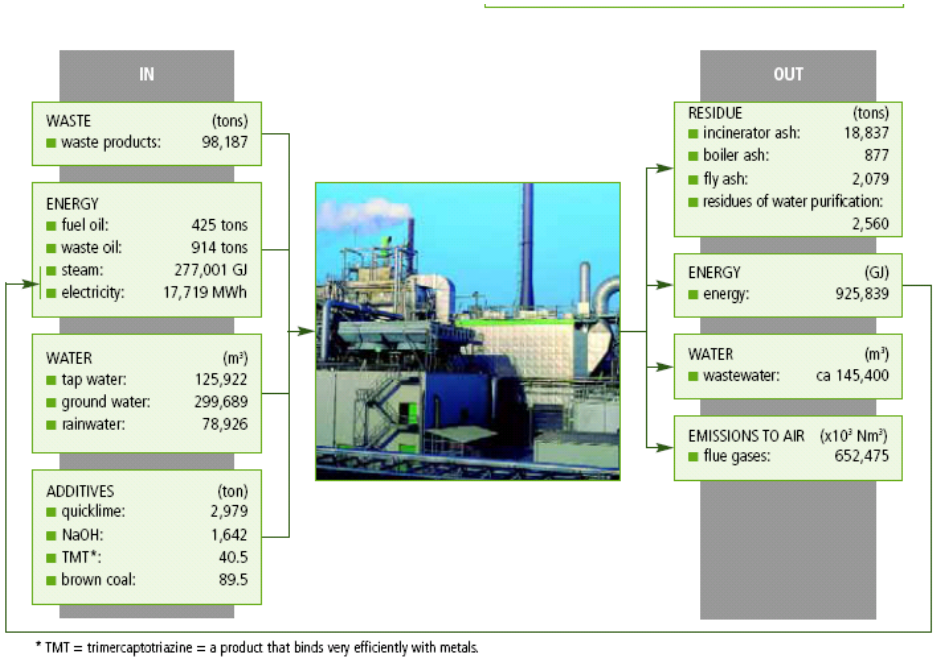


Figure 3 Main characteristics of a the rotary kiln hazardous waste incinerator of Indaver (annual report).

The consumables necessary for the incineration per ton of hazardous waste are presented in table 1. These figures are mostly based on chemical reactions and partly, expressed per ton waste, on figures of the annual report of Indaver.

Table 1 Specifications of consumables for hazardous waste incineration.

Input	Amount	Unit	Remark
NH_4	0.358	g NH_4 /MJ input	denox installation
Lime	1.41 0.71	kg lime /kg S-input; kg lime /kg Cl-input	Flue gas cleaning
NaOH (50%)	0.74 0.37	kg NaOH /kg S-input kg NaOH/kg Cl-input	scrubber
HCl (30%)	0.008	g HCl /MJ input	scrubber
Poly Electrolyte	0.03	kg/ton waste	water treatment
TMT 15	0.41	kg/ton waste	water treatment
Tap water	1.28	m^3/ton waste	
Ground water	3.05	m^3/ton waste	
Fuel oil	4.33	kg/ton waste	
Brown coal	0.91	kg/ton waste	dioxin filter material

Table 2 shows the products and residues of the incineration of hazardous waste in a rotary kiln, based on information of the Indaver Annual report 2005.

Table 2 Typical outputs of hazardous waste incineration in a rotary kiln (Indaver annual report 2005).

Output DTO	Amount	Unit
Bottom ash	192	kg/ton
Boiler ash	8.9	kg/ton
Fly ash	21.2	kg/ton
Filter cake	26.1	kg/ton
Brown coal (Coal filter)	0.91	kg/ton
Waste water	1.48	m^3/ton
NO_x	1,965	g/ton
Dust	6.1	g/ton
CO	72	g/ton
C_xH_y	9.2	g/ton
TEQ (Dioxins)	162	ng/ton
Steam production	0.209	MJ/MJ
Electricity production	0.022	MJ/MJ

The transfer coefficients from the Swiss Eco-Invent study are presented in table 3. The sources of used data are presented in the second column and show that most of the sources are from MSWI (Municipal Solid Waste Incinerator).

Table 3 Transfer coefficients of typical hazardous waste incineration.

Element	Source	Air_emissions	Water_emissions	Solid residues
		%	%	%
H_2O	MSWI	100	0	0
O	MSWI	91.7	0	8.3
H	MSWI	100	0	0
C	UVB1988	100	0	0
S	Jahn2002	0.06	95.7	4.28
N1	UVB1988	4.6	7.93	0
P	Jahn2002	0.07	1.53	98.4
B	MSWI	12	15.1	72.9
Cl	Jahn2002	0.03	99.8	0.17
Br	Jahn2002	0.02	99.8	0.17
F	UVB1988	0.05	26.6	73.4
I	Jahn2002	0.02	99.8	0.21
Ag	MSWI	0.0013	0.0073	100
As	MSWI	1.02E-06	0.01	100
Ba	MSWI	0.1	0	99.9
Cd	UVB1988	0.899	10.2	88.9
Co	Jahn2002	0.07	99.9	0
Cr	MSWI	7.39E-06	0.32	99.7
Cu	Jahn2002	0.07	4.29	95.6
Hg	UVB1988	4.02	10.6	85.3
Mn	MSWI	5.45E-07	0.001	100
Mo	MSWI	0.02	0	99.8
Ni	Jahn2002	0.07	20.5	79.5
Pb	UVB1988	0.331	11.5	88.1
Sb	MSWI	3.89E-07	0.018	100
Se	MSWI	5.03E-07	0.0118	100
Sn	MSWI	0.133	0.00133	99.9
V	MSWI	0.01	0.001	100
Zn	Jahn2002	0.07	1.34	98.6
Be	MSWI	0.1	0	99.9
Sc	MSWI	0.05	0	100
Sr	MSWI	0.01	0	100
Ti	MSWI	0.1	0	99.9
Tl	MSWI	0.1	0	99.9
W	MSWI	0	0	100
Si	MSWI	0.233	0	99.8
Fe	Jahn2002	0.07	80.3	19.6
Ca	MSWI	0.167	0	99.8
Al	MSWI	0.156	0	99.8
K	MSWI	0.3	0	99.7
Mg	MSWI	0.138	0	99.9
Na	MSWI	0.941	0	99.1

Assessment of transfer coefficients for a Fluidised Bed Combustor (FBC)
To asses the transfer coefficients for FBC the same sources are used to air-emissions and solid residues.
This is demonstrated in table 4.

Table 4 Transfer coefficients for FBC.

Element	Source	Air_emissions	Solid Residues
		g/kg	g/kg
H_2O	MSWI	100	0
O	MSWI	91.7	8,3
H	MSWI	100	0
C	UVB1988	100	0
S	Jahn2002	0.06	99.94
N1	UVB1988	4.6	95.4
P	Jahn2002	0.07	99.93
B	MSWI	12	88
Cl	Jahn2002	0.03	99.97
Br	Jahn2002	0.02	99.98
F	UVB1988	0.05	99.95
I	Jahn2002	0.02	99.98
Ag	MSWI	0.0013	99.9987
As	MSWI	0.00000102	100
Ba	MSWI	0.1	99.9
Cd	UVB1988	0.899	99.101
Co	Jahn2002	0.07	99.93
Cr	MSWI	0.00000739	100
Cu	Jahn2002	0.07	99.93
Hg	UVB1988	4.02	95.98
Mn	MSWI	0.000000545	100
Mo	MSWI	0.02	99.98
Ni	Jahn2002	0.07	99.93
Pb	UVB1988	0.331	99.67
Sb	MSWI	0.000000389	100
Se	MSWI	0.000000503	100
Sn	MSWI	0.133	99.87
V	MSWI	0.01	99.99
Zn	Jahn2002	0.07	99.93
Be	MSWI	0.1	99.9
Sc	MSWI	0.05	99.95
Sr	MSWI	0.01	99.99
Ti	MSWI	0.1	99.9
Tl	MSWI	0.1	99.9
W	MSWI	0	100
Si	MSWI	0.233	99.77
Fe	Jahn2002	0.07	99.93
Ca	MSWI	0.167	99.83
Al	MSWI	0.156	99.84
K	MSWI	0.3	99.7
Mg	MSWI	0.138	99.86
Na	MSWI	0.941	99.06

Table 5 shows the difference of specific emission factors used for FBC compared to those of the DTO.

Table 5 Process data that are different for rotary kiln and FBC.

Output	DTO	FBC	Unit
Bottom ash	192	42	kg/ton waste
Boiler ash	8.9		
Fly ash	21.2	147	kg/ton waste
Filter cake	26.1	40	kg/ton waste
Brown coal (Coal filter)	0.91	0.9	kg/ton waste
Waste water	1.48	0	m^3/ton waste
NO_x	1,965	1,898	g/ton waste
Dust	6.1	16	g/ton waste
CO	72	93	g/ton waste
C_xH_y	9.2	11	g/ton waste
TEQ (Dioxins)	162	59	ng/ton waste
Steam production	0.209	0.254	MJ/MJ waste
Electricity production	0.022	0.102	MJ/MJ waste
Tap water	1.28	0.475	m^3/ton waste
Ground water	3.05	0.058	m^3/ton waste
Fuel oil	4.3	1.9	kg/ton waste
Activated Carbon	-	0.4	kg/ton waste
Brown coal	0.91	-	kg/ton waste

Check of process data with information in IPPC

In the 2006 document of waste incineration of IPPC "Reference document for best available techniques on Waste Incineration", data of an example of a hazardous waste incineration plant is presented in Annex 10.3.2.1. The plant involved is the hazardous waste incinerator in Vienna: Simmeringer Haide. The plant consists of a rotary kiln, a waste heat boiler, flue gas cleaning with: SNCR, ESP, four stage wet scrubber and activated carbon filter. The plant is considered to be rather similar to the Indaver plant in Antwerp. The produced energy is used in a district heating system. In table 6 a comparison is made of consumables between Indaver and Simmeringer Haide.

Table 6 Comparison of data from Indaver and Simmeringer Haide.

Input	Simmeringer Haide kg/ton	Indaver kg/ton	Remark
Lime	23	30	flue gas cleaning
NaOH (50%)	5.2	17	Scrubber
HCl (30%)	1		Scrubber
Tap water		1,280	
Ground water	6,158	3,050	
Fuel oil	40	4.3	
Brown coal	5	0.91	dioxin filter material

The most important differences in conversion factors between the two plants are caused in the use of brown coal and fuel oil. The oil consumption is dependent of the caloric value of the mixture of the wastes to be incinerated and the number of starts and stops. The use of coal in the pilot filter is dependent of the composition of the coal and the operational conditions (hot spots). In table 7 the outputs and some emissions of both plants are compared.

Table 7 Comparison of output streams and some emissions.

Output	Simmeringer Haide kg/ton	INDAVER DTO kg/ton
Incineration ash	190	192
Boiler ash		8.9
Fly ash	14.6	21.2
Filter cake	17 (55% H_2O)	26.1
Brown coal (Coal filter)	?	0.91
Waste water	1,657	1,480
NO_x	0.821	1.97
Dust	0.0004	0.0061
CO	0.26	0.072
C_xH_y	0.017	0.0092
TEQ (Dioxins)	12 (ng/ton)	162 (ng/ton)

The most important differences in conversion factors between the two plants in table 7 are in the emissions. These emissions are mostly dependent of the process conditions and can be influenced by temperatures, residence time, mixing with combustion air etc. Furthermore the selected flue gas purification can play an important role (NO_x and NH_4-injection).

Evaluation regarding the LCA study

One of the starting points of the LCA study is to calculate the environmental impact of incineration of one ton of the five selected waste streams. This means when incinerating solvents with a NCV (Net Calorific Value) of 22 MJ/kg will produce more electricity than incinerating filter cake with much water and a NCV of 5 MJ/kg and much solids (high ash content) producing high slag and dust loads in the process. The composition of these waste streams plays an important role, also in the actual output streams, and hence in the actual transfer coefficients. However, for the LCA study a fixed set of transfer coefficients per incinerator has to be used, in order to keep the calculations practicable.

Another factor is the behaviour of an element in the incineration process. If the specific chemical compound of the element evaporates at a lower temperature, it is most probable, that this element will not remain in the slag, but will act as a gas and end up partly in the water (scrubber and water treatment plant) or in the air. That means that the behaviour of an element in one of the five defined waste streams can differ from the behaviour of the same element in another waste stream. Starting point for the assessment of the transfer coefficients is that in principle all elements will behave the same as in the average waste composition.

For energy production the relation with the heating value is an important factor. Based on the Indaver annual report in 2005 the key factors are presented in table 8.

Table 8 Key factors for energy recovery in DTO en FBC.

Recovered energy to external users in MJ per MJ input	**DTO**	**FBC**
Steam	0.209	0.254
Electricity	0.022	0.102

After correction for own use, steam is used for heating of buildings and for recycling processes at the Indaver site. The rest of the steam is used for production of electricity. The figure for electricity production is corrected for own use including flue gas treatment systems.

4 Shadow Prices

This annex contains Chapter 2 of the TNO Report 'Toxicity has its price'[1].

Methodological background

Environmental costs are external costs

Economic activities are almost without exception accompanied by a certain stress on man or the environment. For man, this means an encroachment on health and safety, for the environment, the dislocation of ecosystems, often quantified by a reduction in stocks of clean air, water, soil and biotic and abiotic material [2]. The cost of stress on the environment and man are not discounted in the product price through the market. That is why they are called external charges, compared with internal production costs.

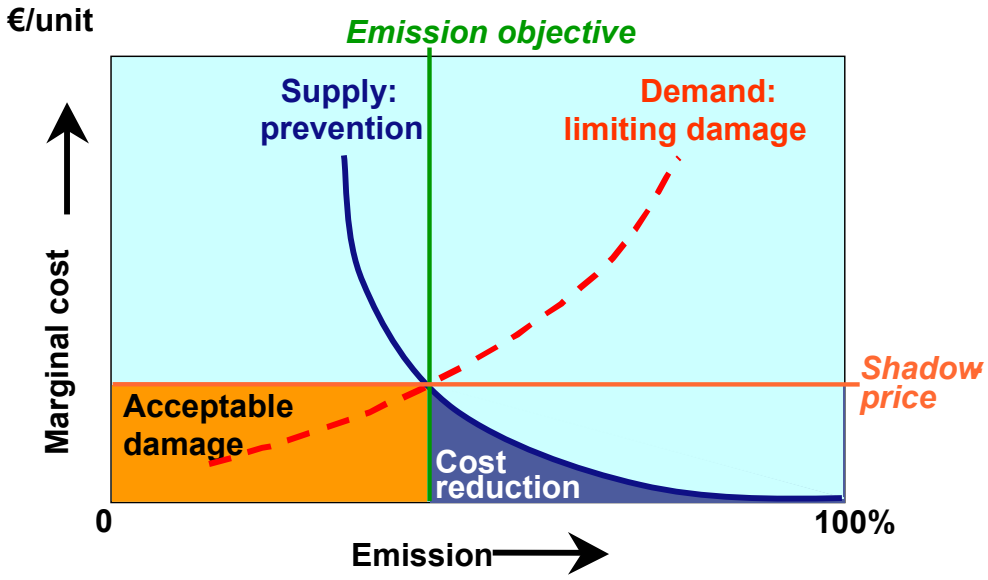


Fig. 1 Demand for limitation and supply of emission prevention on the virtual environmental market form an equilibrium price. If a government objective crosses the equilibrium point of demand and supply, the shadow price will under this objective be the same as the equilibrium price.

The cost of the environmental burden depends on the price that society is willing to pay for a clean environment and is related to the situation and moment. Generally speaking, the heavier the environmental burden, the greater the willingness to pay a higher price to limit environmental damage. In this way, a demand curve is created towards limiting environmental damage (see Fig. I).

A virtual environmental market

In addition to demand for emission restriction, there is a supply of emission prevention opportunities which also has a particular price for each level of prevention. Generally

[1] Harmelen, A.K. van, Ligthart, T.N., Leeuwen, S.M.H. van, Korenromp, R.H.J., Gijlswijk, R.N. van, 2004, Toxicity has its price. Shadow prices for eco and other toxicity and exhaustion of abiotic raw materials within DuboCalc. Commissioned by the Ministry of Transport, Public Works and Water Management, Building Department, Directorate-General for Water affairs.

speaking, the price increases the greater the reduction demanded. If there were to be a market for the environment, demand and supply would form an equilibrium price at the intersection of the curves of marginal damage limitation and marginal prevention cost.

Government restrictions on external effects provide a shadow price
Because external charges are not remunerated through the market, an authority will have to determine to what extent the damage must be limited. This can be done by formulating an emission objective. The point where this objective intersects the marginal damage curve is called the shadow price. This is the extent to which the total cost and benefit change as a result of a change in a limiting factor, in this case the emission limitation. In the present environmental example, the shadow price is in fact the highest permissible environmental cost level per unit of environmental damage that the government is still prepared to bear.

A cost-effective shadow price approximates the equilibrium price
A government that wishes to work cost-effectively positions its emission objective in such a way that it appears at the intersection so that demand and supply are in equilibrium. These total charges concern the cost of the preventive measures in question (the surface beneath the marginal prevention curve to the right of the emission objective) plus the environmental damage sustained as a result of unprevented emissions, the surface beneath the shadow price to the left of the objective. If the government discharges its task as a representative of society properly and works cost-effectively, it will ensure that the shadow price of its environmental objective coincides with the equilibrium price adopted in society. If this is in fact not the case, the perceived environmental damage will increase more strongly in relation to the market equilibrium than the prevention costs will reduce (if the reduction objective is positioned too low) or the prevention expenses will increase more sharply than the environmental damage avoided (if the reduction objective is excessive).

Charging through the shadow price creates an environmental market
However, because the damage is collective, benefits in the form of damage avoided often do not directly profit the investor in prevention costs. In fact, the equilibrium price is virtual. If, on the other hand, the external charges resulting from environmental damage are charged through to the polluter, investment in prevention will certainly result in benefits for the polluter. The damage can, for example, be internalised in the product price. This substantiates an essential criterion of present environmental policy, the "polluter pays" principle. This implies that every individual and every organisation is in principle responsible for the damage caused by him or her to the environment. Moreover, this is done in this manner in an economically cost-effective way. A price has thereby been set for the environment that plays a role in economic dealings. A polluter can decide for himself whether it is advantageous to pay the levy or to reduce his emissions himself and thereby incur additional cost for the reduction measures to be adopted. In either case, the environmentally polluting products will become more expensive and the environmentally friendly less so. This approach with the aid of market-conforming instruments has been the centre of attention in recent years. NO_x equalisation in heavy industry and the negotiable CO_2 emission rights are well-known examples of this.

Application of the shadow price
In addition to the actual charging through of the shadow price by means of e.g. an environmental levy, the shadow price, like the market price, is an easily interpreted

signal of economic scarcity. In studies with such varying subjects as life cycle analysis, technological development, sustainability strategies or environmentally friendly designs, in which environmental effects of different kinds must be compared with each other, the shadow price can be easily used to calculate the environmental damage. This is done by multiplying the emissions by the shadow price. The environmental damage calculated in this way, also known as environmental cost or shadow cost, provides an indication of the environmental losses pertaining to present or future emission objectives [5][6][7][8] and [10]. Some studies use the environmental burden calculated in this way in micro-economic cost-benefit analyses, while others do so in micro-economic studies to correct GNP in order thereby to calculate a green GNP [5].

Advantages of the shadow price method
The shadow price has a neutral unit with which various environmental effects can be gathered under a single denominator. Using the shadow price method, different environmental effect categories can be easily weighed up. The shadow price also has the advantage that it dovetails with the use of market-conforming instruments. It also matches the present economic reality in the business world since external charges are rendered visible. It supports integral analyses in order to provide transparent results wherein policy and business can recognise their own activities and the relationship with environmental topics.

Conditions for applying the shadow price method
The shadow price approach is especially suitable for calculating through the present policy or present collective preferences and not for long-term sustainable solutions, because the shadow price of these long-term objectives is difficult to establish. The present collective preferences differ per country [4]. This implies that the use of shadow costs is meaningful at national or European level, where environmental pressure and environmental desires are more or less of a comparable order. This is not the case on a world scale.

Two possible routes for determining the shadow price
The shadow price can be determined firstly by estimating the environmental damage associated with the established emission objectives. Secondly, assuming that the government works cost-effectively, the shadow price can also be derived by combining the prevention cost with the emission objectives adopted.

Environmental damage is difficult to establish
The value (monetary) of environmental damage is difficult to establish. An approach for this is the “willingness-to-pay” principle, whereby the amount is established that society (or groups in society) can pay to avoid particular environmental damage. This can be done directly (“stated preferences”) by enquiries (contingent valuation method) or by inferring the revealed influence of the environmental burden on market prices (“revealed preferences”). The disadvantage of these methods of willingness to pay is that they are very moment-related and must be implemented simultaneously for all environmental effect categories if comparable results are to be obtained. One wonders in particular whether, for the alleged preferences, obstruction is correctly estimated, in other words in the right relationship with real investment decisions [11].

Emission prevention costs can be established more accurately
The emission prevention costs or combating costs can be established more accurately. The highest permissible cost for preventing certain environmental effects, the so-called

marginal cost that society must incur if the emission objective desired by government is to be achieved, can be used as a basis. An alternative method is to resort to price elasticities, but these are available only to a limited extent. In fig. 2.1 it is assumed that the government or society is sufficiently rational to position its objective at the point of the equilibrium price *and* that the location of this point is known. In other words, that the marginal environmental damage has been quantified. This is not in fact the case, so that the shadow price derived from the present policy objective and marginal prevention curve must be interpreted more as a yardstick of present policy preferences. The shadow price is above all an estimate of the equilibrium price by present policy. Since policy-makers wish to set to work cost effectively, the consequence of the present objective is that the marginal damage is evidently estimated at the shadow price level. The actual environmental damage as perceived in society may lie at a completely different level.

CE has established the shadow prices within the Netherlands [11] for the environmental effect categories of the CML-2 method, except for six categories in the area of human toxicity, ecotoxicity and abiotic raw material depletion. It should be mentioned here that CE in fact establishes the shadow price for emission objectives for the year 2010. This can be done because the environmental effect categories that CE deals with are properly worked out and documented in policy plans and measures. This is not the case with the other topics, where objectives, insofar as they are set, often influence more than one environmental effect category. An analysis of the present situation is therefore more opportune, so the shadow price of present policy can be derived from it on the basis of the steps taken.

Overview of steps taken

The shadow prices to be used in the weighing up method for the environmental effect categories of abiotic raw materials depletion and toxicity are worked out by five stages:

1. determining present policy for the various environmental effect categories;
2. selecting relevant guide substances, sectors and firms for the policy to be implemented;
3. collecting cost data for measures by means of literature research and telephone interviews of firms, licensors and experts;
4. calculating the shadow price on the basis of the cost estimates of the measures;
5. calibrating the shadow price on the basis of environmental costs actually incurred.

Determining present policy

The present policy that is relevant to the environmental effect categories investigated is analysed to see how society is stimulated to take steps, so that they can be taken into account when selecting guide substances, sectors and measures. A look is taken here at policy: concentration standard, emissions standard, objective for emissions, concentrations or reduction in use, for firm, sector or country. Particular reference is made to national and European laws and regulations.

Selecting guide substances, sectors and firms

With this step, the relevant substances and sectors are selected where it is anticipated that measures have been adopted to comply with present policy. This selection is made with the aid of the data from Emission registration (Collective and Individual firms) coordinated by TNO each year [1]. These are converted for each environmental effect category into equivalent emissions with the aid of characterising factors in accordance with CML-2 [3].

The 1.4-dichloro-benzene equivalents used for toxicity and ecotoxicity are not comparable for the toxic environmental effect categories because the significance of the effects of a unit of 1.4-dichloro-benzene differs per environmental effect category. Dichloro-benzene equivalents of various environmental effect categories cannot therefore be aggregated. Guide substances are consequently selected separately for each environmental effect category. A selection of guide substances and sectors is made for each environmental effect category on the basis of three criteria for each substance:

1. share in national and sectoral equivalent emission;
2. historical change in equivalent emission;
3. present policy pressure to take steps.

By selecting the substances contributing most to the national or sectoral total per environmental effect category, the likelihood is enhanced that these substances will be important for the measures within a certain environmental effect category.

Substances and sectors have also been selected where an appreciable reduction has already been made and where the policy pressure to take steps is appreciable, so that we may assume that the best progress on the marginal reduction cost curve has been made here (in other words the marginal costs are high). A link is made here with the collected data on policy measures for the environmental topic concerned. A number of firms have been chosen from the selected sectors where data on the cost of measures per substance have been collected.

Collecting cost data for measures

As a third step, data were collected regarding costs and emission reductions under the measures by means of literature research and telephone interviews with selected firms, provincial authorities and experts. The ultimate objective is to establish the marginal prevention costs or the most expensive measure being introduced to achieve a reduction or equivalent reduction, because this is the shadow price.

We have had to rely heavily on the data in the international literature because telephone enquiries amongst firms did not produce a great deal. Firms do not wish to let go of their data on competition grounds, have had enough of surveys or do not wish to cooperate for other reasons.

Calculating the shadow price

As a fourth step, the shadow price for a particular environmental effect category was estimated on the basis of cost data and emission reductions through measures, obtained from the literature and interviews. These are the marginal prevention costs or the most expensive emission reduction measure adopted to comply with policy. These cost data were converted to Euros per equivalent reduction.

Because many measures cover more than one environmental effect category, reduction costs in € per equivalent reduction can be calculated only if cost allocation is arranged by environmental effect categories. The following cost allocation method was therefore developed for options that influence more than one environmental effect category:

1. initial weighing up of environmental effect categories that reflect the priority of the present policy is necessary for these or the equivalents to be compared;
2. the reduction cost must effectively be allocated on the basis of the relative importance that a measure has for an environmental effect category;
3. minor environmental effects within an environmental effect category are ignored on account of their disruptive effect.

Calibrating the shadow price

Shadow prices established by the method described above for toxic environmental effect categories have proved inadequate in practice. The main reason for this is that the present toxicity policy is inconsistent with the CML-2 method used. The policy does not work precisely according to the characterisation factors of CML, partly because local and practical aspects play a role (rightly). This can reduce the cost effectiveness of measures in terms of CML characterisation factors. The shadow prices calculated are consequently not the "revealed collective preferences" of present policy. The result is that the shadow prices are so high that any application is overshadowed by the shadow cost of toxicity.

In order nonetheless to calculate a viable shadow price in DuboCalc and other instruments and analyses, the shadow prices for the various environmental effect categories have been calibrated on the basis of the expenditure incurred on distributing toxic substances according to Milieubalans (Environmental Balance) [9]. The shadow prices calculated are consequently more representative of the present policy approach.

Impact category	**Abbre-viation**	**Unit**	Shadow price [€/kg eq.]
Abiotic Depletion	ADP	kg Sb eq.	0
Global Warming	GWP	kg CO_2 eq.	0,05
Ozone Depletion	ODP	kg CFC-11 eq.	30
Human Toxicity	HTP	kg $C_6H_4Cl_2$ eq.	0,084
Freshwater Aquatic Ecosystem Toxicity	FAETP	kg $C_6H_4Cl_2$ eq.	0,04
Terrestrial Ecosystem Toxicity	TETP	kg $C_6H_4Cl_2$ eq.	1,28
Marine Aquatic Ecosystem Toxicity	MAETP	kg $C_6H_4Cl_2$ eq.	0,00001
Photochemical Oxidant Creation	POCP	kg C_2H_4 eq.	2
Acidification	AP	kg SO_2 eq.	4
Eutrophication	EP	kg PO_4^{3-} eq.	9

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5 LCA results

5.1 Results for Clinker kilns

Table 1 Environmental results for 1 ton of solvents/waste oils in clinker kiln, analyzed with CML and shadow prices.

	Chararcterisation					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	9.3E-01	0.0E+00	0.0E+00	9.3E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.4E+02	1.1E+03	1.1E+03	1.3E+03	kg CO2 eq	6.9E+00	5.6E+01	5.6E+01	6.3E+01	€
ozone layer depletion	4.8E-05	0.0E+00	0.0E+00	4.8E-05	kg CFC-11 eq	1.5E-03	0.0E+00	0.0E+00	1.5E-03	€
human toxicity	5.3E+01	1.5E+00	7.0E+00	5.5E+01	kg 1,4-DB eq	4.4E+00	1.3E-01	5.9E-01	4.6E+00	€
fresh water aquatic ecotox.	9.2E+00	7.9E-03	1.4E+00	9.2E+00	kg 1,4-DB eq	3.7E-01	3.2E-04	5.6E-02	3.7E-01	€
marine aquatic ecotoxicity	1.7E+05	5.7E+01	1.3E+04	1.7E+05	kg 1,4-DB eq	1.7E+00	5.7E-04	1.3E-01	1.7E+00	€
terrestrial ecotoxicity	4.8E-01	3.0E-01	3.8E-01	7.8E-01	kg 1,4-DB eq	6.2E-01	3.8E-01	4.9E-01	1.0E+00	€
photochemical oxidation	7.1E-02	8.7E-05	1.6E-02	8.7E-02	kg C2H4	1.4E-01	1.7E-04	3.2E-02	1.7E-01	€
acidification	6.2E-01	2.2E-03	4.0E-01	1.0E+00	kg SO2 eq	2.5E+00	8.7E-03	1.6E+00	4.0E+00	€
eutrophication	3.8E-02	0.0E+00	0.0E+00	3.8E-02	kg PO4--- eq	3.4E-01	0.0E+00	0.0E+00	3.4E-01	€
Total						**1.7E+01**	**5.7E+01**	**5.9E+01**	**7.5E+01**	€

Table 2 Environmental results for 1 ton of solvents/waste oils in clinker kilns, analyzed with Eco-indicator 99.

	Chararcterisation					Eco-indicator 99 [Pt]				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
Carcinogens	9.9E-06	1.4E-07	2.6E-06	1.0E-05	DALY	2.7E-01	3.8E-03	6.8E-02	2.8E-01	Pt
Resp. organics	6.1E-08	0.0E+00	0.0E+00	6.1E-08	DALY	1.8E-03	0.0E+00	0.0E+00	1.8E-03	Pt
Resp. inorganics	6.0E-05	9.8E-08	1.8E-05	7.8E-05	DALY	1.7E+00	2.6E-03	4.7E-01	2.1E+00	Pt
Climate change	2.9E-05	2.4E-04	2.4E-04	2.6E-04	DALY	7.6E-01	6.1E+00	6.1E+00	6.9E+00	Pt
Radiation	6.5E-06	0.0E+00	0.0E+00	6.5E-06	DALY	1.7E-01	0.0E+00	0.0E+00	1.7E-01	Pt
Ozone layer	5.1E-08	0.0E+00	0.0E+00	5.1E-08	DALY	2.0E-03	0.0E+00	0.0E+00	2.0E-03	Pt
Ecotoxicity	1.7E+01	1.9E+00	5.1E+00	2.0E+01	PAF*m2yr	1.6E-01	1.5E-02	4.0E-02	1.8E-01	Pt
Acidification/ Eutrophication	1.8E+00	1.9E-03	3.5E-01	2.2E+00	PDF*m2yr	1.5E-01	1.5E-04	2.7E-02	1.8E-01	Pt
Land use	8.0E+00	0.0E+00	0.0E+00	8.0E+00	PDF*m2yr	6.4E-01	0.0E+00	0.0E+00	6.4E-01	Pt
Minerals	9.1E-02	0.0E+00	0.0E+00	9.1E-02	MJ surplus	1.7E-01	0.0E+00	0.0E+00	1.7E-01	Pt
Fossil fuels	1.1E+02	0.0E+00	0.0E+00	1.1E+02	MJ surplus	2.7E+00	0.0E+00	0.0E+00	2.7E+00	Pt
Total						**6.7E+00**	**6.1E+00**	**6.7E+00**	**1.3E+01**	Pt

Table 3 Environmental results for 1 ton of sludges in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	1.3E+00	0.0E+00	0.0E+00	1.3E+00	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.5E+02	0.0E+00	0.0E+00	1.5E+02	kg CO2 eq	7.7E+00	0.0E+00	0.0E+00	7.7E+00	€
ozone layer depletion	1.8E-05	0.0E+00	0.0E+00	1.8E-05	kg CFC-11 eq	5.3E-04	0.0E+00	0.0E+00	5.3E-04	€
human toxicity	1.7E+01	6.0E+00	5.8E+01	3.4E+01	kg 1,4-DB eq	1.4E+00	5.0E-01	4.8E+00	2.8E+00	€
fresh water aquatic ecotox.	3.8E-01	5.0E-02	2.9E+00	7.5E-01	kg 1,4-DB eq	1.5E-02	2.0E-03	1.2E-01	3.0E-02	€
marine aquatic ecotoxicity	1.3E+04	3.0E+02	1.0E+05	3.9E+04	kg 1,4-DB eq	1.3E-01	3.0E-03	1.0E+00	3.9E-01	€
terrestrial ecotoxicity	3.2E-02	8.0E-01	1.0E+00	1.0E+00	kg 1,4-DB eq	4.1E-02	1.0E+00	1.3E+00	1.3E+00	€
photochemical oxidation	7.1E-02	1.1E-04	2.0E-02	7.5E-02	kg C2H4	1.4E-01	2.2E-04	4.0E-02	1.5E-01	€
acidification	2.4E-01	2.7E-03	5.1E-01	3.3E-01	kg SO2 eq	9.5E-01	1.1E-02	2.0E+00	1.3E+00	€
eutrophication	3.2E-02	0.0E+00	0.0E+00	3.2E-02	kg PO4--- eq	2.9E-01	0.0E+00	0.0E+00	2.9E-01	€
Total						**1.1E+01**	**1.5E+00**	**9.4E+00**	**1.4E+01**	€

Table 4 Environmental results for 1 ton of paint, ink in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	9.5E-01	1.2E+01	0.0E+00	9.5E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.4E+02	8.6E+02	8.6E+02	1.0E+03	kg CO2 eq	7.2E+00	4.3E+01	4.3E+01	5.0E+01	€
ozone layer depletion	4.9E-05	0.0E+00	0.0E+00	4.9E-05	kg CFC-11 eq	1.5E-03	0.0E+00	0.0E+00	1.5E-03	€
human toxicity	6.0E+01	3.0E+00	6.0E+00	6.5E+01	kg 1,4-DB eq	5.1E+00	2.5E-01	5.0E-01	5.4E+00	€
fresh water aquatic ecotox.	9.4E+00	2.7E-02	5.9E-02	9.4E+00	kg 1,4-DB eq	3.7E-01	1.1E-03	2.4E-03	3.8E-01	€
marine aquatic ecotoxicity	1.7E+05	1.4E+02	1.8E+04	1.8E+05	kg 1,4-DB eq	1.7E+00	1.4E-03	1.8E-01	1.8E+00	€
terrestrial ecotoxicity	4.9E-01	6.4E-01	8.1E-01	1.2E+00	kg 1,4-DB eq	6.2E-01	8.1E-01	1.0E+00	1.5E+00	€
photochemical oxidation	1.0E+01	3.6E-04	6.6E-02	1.0E+01	kg C2H4	2.0E+01	7.1E-04	1.3E-01	2.0E+01	€
acidification	6.4E-01	8.9E-03	1.6E+00	1.6E+00	kg SO2 eq	2.6E+00	3.6E-02	6.6E+00	6.3E+00	€
eutrophication	4.3E-02	0.0E+00	0.0E+00	4.3E-02	kg PO4--- eq	3.9E-01	0.0E+00	0.0E+00	3.9E-01	€
Total						**3.8E+01**	**4.4E+01**	**5.2E+01**	**8.6E+01**	€

Table 5 Environmental results for 1 ton of fluff in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	3.0E-01	0.0E+00	0.0E+00	3.0E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	4.5E+01	2.3E+03	2.3E+03	2.3E+03	kg CO2 eq	2.2E+00	1.2E+02	1.2E+02	1.2E+02	€
ozone layer depletion	1.5E-05	0.0E+00	0.0E+00	1.5E-05	kg CFC-11 eq	4.5E-04	0.0E+00	0.0E+00	4.5E-04	€
human toxicity	1.6E+01	4.1E+00	3.4E+01	2.4E+01	kg 1,4-DB eq	1.3E+00	3.4E-01	2.8E+00	2.0E+00	€
fresh water aquatic ecotox.	2.7E+00	1.7E-02	4.5E-01	2.7E+00	kg 1,4-DB eq	1.1E-01	7.0E-04	1.8E-02	1.1E-01	€
marine aquatic ecotoxicity	5.1E+04	6.7E+03	5.0E+04	5.8E+04	kg 1,4-DB eq	5.1E-01	6.7E-02	5.0E-01	5.8E-01	€
terrestrial ecotoxicity	1.4E-01	2.6E-01	5.2E-01	4.3E-01	kg 1,4-DB eq	1.8E-01	3.3E-01	6.7E-01	5.5E-01	€
photochemical oxidation	3.3E-02	3.4E-05	1.9E-03	3.3E-02	kg C2H4	6.6E-02	6.9E-05	3.9E-03	6.7E-02	€
acidification	2.2E-01	8.6E-04	4.8E-02	2.3E-01	kg SO2 eq	8.9E-01	3.4E-03	1.9E-01	9.1E-01	€
eutrophication	2.1E-02	0.0E+00	0.0E+00	2.1E-02	kg PO4--- eq	1.9E-01	0.0E+00	0.0E+00	1.9E-01	€
Total						**5.5E+00**	**1.2E+02**	**1.2E+02**	**1.2E+02**	€

Table 6 Environmental results for 1 ton of filtercake in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	9.1E-02	0.0E+00	9.1E-02	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.4E+01	2.4E+02	2.5E+02	kg CO2 eq	7.1E-01	1.2E+01	1.3E+01	€
ozone layer depletion	1.8E-06	0.0E+00	1.8E-06	kg CFC-11 eq	5.4E-05	0.0E+00	5.4E-05	€
human toxicity	1.6E+00	6.2E+00	7.8E+00	kg 1,4-DB eq	1.3E-01	5.2E-01	6.5E-01	€
fresh water aquatic ecotox.	1.2E-01	3.9E-02	1.6E-01	kg 1,4-DB eq	4.9E-03	1.6E-03	6.5E-03	€
marine aquatic ecotoxicity	4.6E+02	2.2E+03	2.7E+03	kg 1,4-DB eq	4.6E-03	2.2E-02	2.7E-02	€
terrestrial ecotoxicity	9.2E-03	4.7E-01	4.8E-01	kg 1,4-DB eq	1.2E-02	6.0E-01	6.2E-01	€
photochemical oxidation	2.4E-02	1.3E-04	2.4E-02	kg C2H4	4.8E-02	2.7E-04	4.8E-02	€
acidification	8.4E-02	3.3E-03	8.7E-02	kg SO2 eq	3.4E-01	1.3E-02	3.5E-01	€
eutrophication	1.7E-02	0.0E+00	1.7E-02	kg PO4--- eq	1.6E-01	0.0E+00	1.6E-01	€
Total					**1.4E+00**	**1.3E+01**	**1.5E+01**	€

Table 7 Environmental results for 1 ton of petcokes in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation, CML					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	2.7E+01	0.0E+00	0.0E+00	2.7E+01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	5.4E+02	3.1E+03	3.1E+03	3.6E+03	kg CO2 eq	2.7E+01	1.5E+02	1.5E+02	1.8E+02	€
ozone layer depletion	5.3E-04	0.0E+00	0.0E+00	5.3E-04	kg CFC-11 eq	1.6E-02	0.0E+00	0.0E+00	1.6E-02	€
human toxicity	2.8E+02	1.8E+00	9.0E+00	2.8E+02	kg 1,4-DB eq	2.3E+01	1.5E-01	7.5E-01	2.4E+01	€
fresh water aquatic ecotox.	2.6E+01	2.5E-02	4.8E-01	2.7E+01	kg 1,4-DB eq	1.1E+00	1.0E-03	1.9E-02	1.1E+00	€
marine aquatic ecotoxicity	1.7E+05	5.9E+02	2.1E+04	1.7E+05	kg 1,4-DB eq	1.7E+00	5.9E-03	2.1E-01	1.7E+00	€
terrestrial ecotoxicity	1.4E+00	1.5E-01	2.5E-01	1.6E+00	kg 1,4-DB eq	1.8E+00	1.9E-01	3.2E-01	2.0E+00	€
photochemical oxidation	1.8E+00	2.5E-04	4.6E-02	1.9E+00	kg C2H4	3.7E+00	5.0E-04	9.2E-02	3.7E+00	€
acidification	8.1E+00	6.2E-03	1.1E+00	8.5E+00	kg SO2 eq	3.3E+01	2.5E-02	4.6E+00	3.4E+01	€
eutrophication	7.5E-01	0.0E+00	0.0E+00	7.5E-01	kg PO4--- eq	6.8E+00	0.0E+00	0.0E+00	6.8E+00	€
Total						**9.8E+01**	**1.5E+02**	**1.6E+02**	**2.5E+02**	€

Table 8 Environmental results for 1 ton of coal in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation, CML					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	1.9E+01	0.0E+00	0.0E+00	1.9E+01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	2.5E+02	3.1E+03	3.1E+03	3.4E+03	kg CO2 eq	1.2E+01	1.6E+02	1.6E+02	1.7E+02	€
ozone layer depletion	2.1E-05	0.0E+00	0.0E+00	2.1E-05	kg CFC-11 eq	6.3E-04	0.0E+00	0.0E+00	6.3E-04	€
human toxicity	8.0E+01	1.7E+00	1.3E+01	8.6E+01	kg 1,4-DB eq	6.7E+00	1.5E-01	1.1E+00	7.2E+00	€
fresh water aquatic ecotox.	5.0E+00	1.6E-02	5.1E-01	5.2E+00	kg 1,4-DB eq	2.0E-01	6.5E-04	2.0E-02	2.1E-01	€
marine aquatic ecotoxicity	7.4E+04	6.1E+02	3.0E+04	8.6E+04	kg 1,4-DB eq	7.4E-01	6.1E-03	3.0E-01	8.6E-01	€
terrestrial ecotoxicity	2.8E-01	2.3E-01	4.0E-01	5.6E-01	kg 1,4-DB eq	3.6E-01	3.0E-01	5.1E-01	7.2E-01	€
photochemical oxidation	3.6E-01	5.1E-05	9.4E-03	3.7E-01	kg C2H4	7.3E-01	1.0E-04	1.9E-02	7.4E-01	€
acidification	2.8E+00	1.3E-03	2.4E-01	2.9E+00	kg SO2 eq	1.1E+01	5.1E-03	9.4E-01	1.2E+01	€
eutrophication	3.1E-01	0.0E+00	0.0E+00	3.1E-01	kg PO4--- eq	2.7E+00	0.0E+00	0.0E+00	2.7E+00	€
Total						**3.5E+01**	**1.6E+02**	**1.6E+02**	**1.9E+02**	€

Table 9 Environmental results for 1 ton of raw meal in clinker kilns, analyzed with CML and shadow prices.

	Chararcterisation, CML					Shadowcosts				
	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit	Transport and pre-treatment	Emissions (min)	Emissions (max)	Total	Unit
abiotic depletion	6.7E-02	0.0E+00	0.0E+00	6.7E-02	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.0E+01	3.4E+02	4.4E+02	3.7E+02	kg CO2 eq	5.0E-01	1.7E+01	2.2E+01	1.8E+01	€
ozone layer depletion	5.7E-07	0.0E+00	0.0E+00	5.7E-07	kg CFC-11 eq	1.7E-05	0.0E+00	0.0E+00	1.7E-05	€
human toxicity	2.8E+00	8.9E-02	1.6E+01	8.9E+00	kg 1,4-DB eq	2.3E-01	7.5E-03	1.3E+00	7.4E-01	€
fresh water aquatic ecotox.	1.2E-01	2.2E-03	1.2E+00	6.0E-01	kg 1,4-DB eq	4.8E-03	8.6E-05	4.9E-02	2.4E-02	€
marine aquatic ecotoxicity	6.5E+03	7.8E+01	1.2E+04	1.1E+04	kg 1,4-DB eq	6.5E-02	7.8E-04	1.2E-01	1.1E-01	€
terrestrial ecotoxicity	8.1E-03	6.9E-04	3.0E-01	1.5E-01	kg 1,4-DB eq	1.0E-02	8.8E-04	3.8E-01	1.9E-01	€
photochemical oxidation	1.2E-02	6.7E-05	8.4E-03	1.5E-02	kg C2H4	2.5E-02	1.3E-04	1.7E-02	3.1E-02	€
acidification	6.3E-02	1.7E-03	2.1E-01	1.3E-01	kg SO2 eq	2.5E-01	6.7E-03	8.4E-01	5.4E-01	€
eutrophication	9.7E-03	0.0E+00	0.0E+00	9.7E-03	kg PO4--- eq	8.7E-02	0.0E+00	0.0E+00	8.7E-02	€
Total						**1.2E+00**	**1.7E+01**	**2.5E+01**	**2.0E+01**	€

5.2 Results for Waste incineration

Table 10 Environmental results for 1 ton of solvents/waste oils in waste incineration, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	3.0E-02	0.0E+00	3.0E-02	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	4.6E+00	5.9E+01	6.4E+01	kg CO2 eq	2.3E-01	5.9E+01	5.9E+01	€
ozone layer depletion	5.8E-07	1.5E-04	1.5E-04	kg CFC-11 eq	1.7E-05	1.5E-04	1.7E-04	€
human toxicity	5.1E-01	1.2E+00	1.7E+00	kg 1,4-DB eq	4.3E-02	1.2E+00	1.2E+00	€
fresh water aquatic ecotox.	4.0E-02	4.5E-02	8.5E-02	kg 1,4-DB eq	1.6E-03	4.5E-02	4.7E-02	€
marine aquatic ecotoxicity	1.5E+02	1.2E-01	1.5E+02	kg 1,4-DB eq	1.5E-03	1.2E-01	1.2E-01	€
terrestrial ecotoxicity	3.0E-03	1.1E+00	1.1E+00	kg 1,4-DB eq	3.8E-03	1.1E+00	1.2E+00	€
photochemical oxidation	7.8E-03	1.7E-01	1.8E-01	kg C2H4	1.6E-02	1.7E-01	1.9E-01	€
acidification	2.7E-02	4.6E+00	4.7E+00	kg SO2 eq	1.1E-01	4.6E+00	4.7E+00	€
eutrophication	5.7E-03	2.4E+00	2.4E+00	kg PO4--- eq	5.1E-02	2.4E+00	2.5E+00	€
Total					**4.6E-01**	**6.9E+01**	**6.9E+01**	€

Table 11 Environmental results for 1 ton of solvents/waste oils in waste incineration, analyzed with Eco-indicator 99.

	Chararcterisation				Eco-indicator 99 [Pt]			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
Carcinogens	4.8E-08	5.0E-06	5.1E-06	DALY	1.3E-03	1.3E-01	1.3E-01	Pt
Resp. organics	8.2E-09	3.2E-08	4.1E-08	DALY	2.1E-04	8.4E-04	1.1E-03	Pt
Resp. inorganics	5.8E-06	2.2E-04	2.3E-04	DALY	1.5E-01	5.7E+00	5.9E+00	Pt
Climate change	9.7E-07	2.5E-04	2.5E-04	DALY	2.5E-02	6.5E+00	6.5E+00	Pt
Radiation	1.2E-09	3.4E-07	3.4E-07	DALY	3.0E-05	8.7E-03	8.8E-03	Pt
Ozone layer	6.1E-10	5.3E-09	5.9E-09	DALY	1.6E-05	1.4E-04	1.5E-04	Pt
Ecotoxicity	1.8E+00	2.0E+01	2.2E+01	PAF*m2yr	1.4E-02	1.5E-01	1.7E-01	Pt
Acidification/ Eutrophication	2.4E-01	1.2E+01	1.2E+01	PDF*m2yr	1.8E-02	9.3E-01	9.4E-01	Pt
Land use	1.8E-04	4.6E-02	4.6E-02	PDF*m2yr	1.4E-05	3.6E-03	3.6E-03	Pt
Minerals	3.5E-05	1.7E-02	1.7E-02	MJ surplus	8.2E-07	4.1E-04	4.1E-04	Pt
Fossil fuels	9.1E+00	6.4E+01	7.3E+01	MJ surplus	2.2E-01	1.5E+00	1.7E+00	Pt
Total					**4.3E-01**	**1.5E+01**	**1.5E+01**	Pt

Table 12 Environmental results for 1 ton of sludges in waste incineration, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	1.0E-01	0.0E+00	1.0E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.6E+01	7.0E-01	1.6E+01	kg CO2 eq	7.8E-01	7.0E-01	1.5E+00	€
ozone layer depletion	2.0E-06	4.4E-05	4.6E-05	kg CFC-11 eq	5.9E-05	4.4E-05	1.0E-04	€
human toxicity	1.7E+00	2.3E+00	4.0E+00	kg 1,4-DB eq	1.5E-01	2.3E+00	2.5E+00	€
fresh water aquatic ecotox.	1.4E-01	1.9E-02	1.5E-01	kg 1,4-DB eq	5.4E-03	1.9E-02	2.4E-02	€
marine aquatic ecotoxicity	5.1E+02	8.5E-02	5.1E+02	kg 1,4-DB eq	5.1E-03	8.5E-02	9.0E-02	€
terrestrial ecotoxicity	1.0E-02	2.0E+00	2.0E+00	kg 1,4-DB eq	1.3E-02	2.0E+00	2.0E+00	€
photochemical oxidation	2.7E-02	2.2E-02	4.8E-02	kg C2H4	5.3E-02	2.2E-02	7.5E-02	€
acidification	9.3E-02	2.3E-01	3.2E-01	kg SO2 eq	3.7E-01	2.3E-01	6.0E-01	€
eutrophication	1.9E-02	6.4E-02	8.3E-02	kg PO4--- eq	1.7E-01	6.4E-02	2.4E-01	€
Total					**1.5E+00**	**5.4E+00**	**7.0E+00**	€

Table 13 Environmental results for 1 ton of paint, ink in waste incineration, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	3.3E-02	2.9E-01	3.2E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	5.0E+00	9.2E+02	9.3E+02	kg CO2 eq	2.5E-01	4.6E+01	4.6E+01	€
ozone layer depletion	6.4E-07	5.1E-06	5.8E-06	kg CFC-11 eq	1.9E-05	1.5E-04	1.7E-04	€
human toxicity	5.6E-01	2.6E+02	2.6E+02	kg 1,4-DB eq	4.7E-02	2.2E+01	2.2E+01	€
fresh water aquatic ecotox.	4.4E-02	5.2E+01	5.2E+01	kg 1,4-DB eq	1.7E-03	2.1E+00	2.1E+00	€
marine aquatic ecotoxicity	1.6E+02	3.5E+06	3.5E+06	kg 1,4-DB eq	1.6E-03	3.5E+01	3.5E+01	€
terrestrial ecotoxicity	3.3E-03	1.7E+00	1.7E+00	kg 1,4-DB eq	4.2E-03	2.1E+00	2.1E+00	€
photochemical oxidation	8.6E-03	8.9E-02	9.8E-02	kg C2H4	1.7E-02	1.8E-01	2.0E-01	€
acidification	3.0E-02	1.2E+00	1.2E+00	kg SO2 eq	1.2E-01	4.7E+00	4.8E+00	€
eutrophication	6.2E-03	2.7E-01	2.8E-01	kg PO4--- eq	5.6E-02	2.4E+00	2.5E+00	€
Total					**5.0E-01**	**1.1E+02**	**1.2E+02**	€

Table 14 Environmental results for 1 ton of fluff in waste incineration, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	3.0E-01	6.9E-02	3.7E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	4.5E+01	2.3E+03	2.4E+03	kg CO2 eq	2.2E+00	1.2E+02	1.2E+02	€
ozone layer depletion	1.5E-05	1.4E-06	1.6E-05	kg CFC-11 eq	4.5E-04	4.3E-05	4.9E-04	€
human toxicity	1.6E+01	1.5E+01	3.1E+01	kg 1,4-DB eq	1.3E+00	1.3E+00	2.6E+00	€
fresh water aquatic ecotox.	2.7E+00	2.4E+00	5.1E+00	kg 1,4-DB eq	1.1E-01	9.8E-02	2.1E-01	€
marine aquatic ecotoxicity	5.1E+04	5.8E+03	5.7E+04	kg 1,4-DB eq	5.1E-01	5.8E-02	5.7E-01	€
terrestrial ecotoxicity	1.4E-01	4.9E-01	6.4E-01	kg 1,4-DB eq	1.8E-01	6.3E-01	8.1E-01	€
photochemical oxidation	3.3E-02	1.0E-02	4.3E-02	kg C2H4	6.6E-02	2.0E-02	8.6E-02	€
acidification	2.2E-01	4.9E-02	2.7E-01	kg SO2 eq	8.9E-01	1.9E-01	1.1E+00	€
eutrophication	2.1E-02	8.6E-03	2.9E-02	kg PO4--- eq	1.9E-01	7.7E-02	2.6E-01	€
Total					**5.5E+00**	**1.2E+02**	**1.2E+02**	€

Table 15 Environmental results for 1 ton of filtercake in waste incineration.

	Chararcterisation				Shadowcosts			
	Transport and pre-treatment	Emissions	Total	Unit	Transport and pre-treatment	Emissions	Total	Unit
abiotic depletion	9.1E-02	3.5E+01	3.5E+01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	1.4E+01	0.0E+00	1.4E+01	kg CO2 eq	7.1E-01	1.5E+01	1.6E+01	€
ozone layer depletion	1.8E-06	1.5E+01	1.5E+01	kg CFC-11 eq	5.4E-05	1.5E-04	2.1E-04	€
human toxicity	1.6E+00	1.5E-04	1.6E+00	kg 1,4-DB eq	1.3E-01	4.5E+00	4.7E+00	€
fresh water aquatic ecotox.	1.2E-01	4.5E+00	4.7E+00	kg 1,4-DB eq	4.9E-03	2.1E+00	2.1E+00	€
marine aquatic ecotoxicity	4.6E+02	2.1E+00	4.6E+02	kg 1,4-DB eq	4.6E-03	4.3E+00	4.3E+00	€
terrestrial ecotoxicity	9.2E-03	4.3E+00	4.3E+00	kg 1,4-DB eq	1.2E-02	1.4E+00	1.4E+00	€
photochemical oxidation	2.4E-02	1.4E+00	1.4E+00	kg C2H4	4.8E-02	1.8E-01	2.2E-01	€
acidification	8.4E-02	1.8E-01	2.6E-01	kg SO2 eq	3.4E-01	4.7E+00	5.0E+00	€
eutrophication	1.7E-02	4.7E+00	4.7E+00	kg PO4--- eq	1.6E-01	2.5E+00	2.6E+00	€
Total					**1.4E+00**	**3.5E+01**	**3.6E+01**	€

Table 16 Environmental results for substitution in waste incineration (per MJ caloric content of waste), analyzed with CML and shadow prices.

	Chararcterisation, CML				Shadowcosts			
	Electricity & heat [MJ], fluidised bed	Electricity & heat [MJ], rotary kiln	Avoided fuel [MJ]	Unit	Electricity & heat [MJ], fluidised bed	Electricity & heat [MJ], rotary kiln	Avoided fuel [MJ]	Unit
abiotic depletion	0.000219226	0.00014028	0.0005426	kg Sb eq	0	0	0	€
global warming	0.028693145	0.01771752	0.0838411	kg CO2 eq	0.001434657	0.00088588	0.0041921	€
ozone layer depletion	2.75877E-09	2.0223E-09	1.063E-08	kg CFC-11 eq	8.2763E-08	6.067E-08	3.188E-07	€
human toxicity	0.00653446	0.00393719	0.0077327	kg 1,4-DB eq	0.000548895	0.00033072	0.0006495	€
fresh water aquatic ecotox.	0.00045328	0.00026476	0.000679	kg 1,4-DB eq	1.81312E-05	1.0591E-05	2.716E-05	€
marine aquatic ecotoxicity	9.7039867	3.4282406	3.6460917	kg 1,4-DB eq	9.70399E-05	3.4282E-05	3.646E-05	€
terrestrial ecotoxicity	0.000107603	8.2327E-05	5.525E-05	kg 1,4-DB eq	0.000137732	0.00010538	7.072E-05	€
photochemical oxidation	1.14269E-05	7.0053E-06	3.806E-05	kg C2H4	2.28537E-05	1.4011E-05	7.612E-05	€
acidification	7.91604E-05	4.3987E-05	0.0002134	kg SO2 eq	0.000316642	0.00017595	0.0008535	€
eutrophication	4.92388E-06	2.4926E-06	1.865E-05	kg PO4--- eq	4.43149E-05	2.2433E-05	0.0001678	€
Total	**9.7E+00**	**3.5E+00**	**3.7E+00**		**2.6E-03**	**1.6E-03**	**6.1E-03**	**€**

5.3 Net impact

5.3.1 Summary results

Table 17 Comparison of thermal treatment in cement kilns avoiding petcokes and raw meal with thermal treatment in waste incinerators, analyzed with CML and shadow prices [results in € shadowcosts].

	Solvents in cement kilns (pet coke, raw meall)	Solvents in rotary kiln (electricity, heat)	Solvents in rotary kiln (supportive fuel)	Sludge in cement kilns (petcoke, raw meal)	Sludge in fluidised bed (electricity, heat)	Paint/ink in cement kilns (pet coke, raw meal)	Paint, ink in rotary kiln (electricity, heat)	Fluff in cement kilns (pet coke, raw meal)	Fluff in fluidised bed (electricity, heat)	Filter in cement kilns (pet coke, raw meal)	Filtercake in rotary kiln (electricity, heat)
global warming	-1.3E+02	3.4E+01	-6.3E+01	-41.883581	-3.4E+00	-3.3E+01	20.261211	-2.3E+00	8.7E+01	-1.7E+01	11.599894
ozone layer depletion	-1.3E-02	-1.6E-03	-9.1E-03	-0.0034698	-1.1E-04	-5.6E-03	-0.0003422	-1.0E-02	-1.3E-03	-2.2E-03	-7.844E-05
human toxicity	-1.6E+01	-7.0E+00	-1.6E+01	-3.128147	-8.0E-01	-4.9E+00	10.081085	-1.3E+01	-9.3E+00	-2.7E+00	3.1015061
fresh water aquatic ecotox.	-5.5E-01	2.9E-01	-2.0E-01	-0.2373779	-1.2E-01	-8.9E-02	1.1148792	-5.8E-01	-1.9E-01	-1.4E-01	2.0325607
marine aquatic ecotoxicity	2.7E-01	1.7E+00	1.6E+00	-0.0652532	-5.8E-01	1.1E+00	20.151552	-5.1E-01	-1.5E+00	-2.3E-01	4.1768265
terrestrial ecotoxicity	-6.7E-01	-1.9E+00	-8.5E-01	0.766548	9.3E-01	6.2E-01	0.46218504	-7.3E-01	-2.2E+00	3.3E-01	0.94080349
photochemical oxidation	-3.2E+00	-2.2E-01	-2.0E+00	-0.7862629	-2.4E-02	1.9E+01	0.01019078	-2.3E+00	-4.1E-01	-4.8E-01	0.15829729
acidification	-2.8E+01	-3.9E-01	-2.0E+01	-7.126806	-1.4E+00	-9.4E+00	1.5050983	-2.0E+01	-5.7E+00	-4.3E+00	4.1611335
eutrophication	-5.6E+00	1.8E+00	-2.4E+00	-1.4224027	-9.5E-03	-2.6E+00	1.2729552	-4.2E+00	-6.9E-01	-8.1E-01	2.5081757

Table 18 Comparison of thermal treatment in cement kilns avoiding petcokes and raw meal with thermal treatment in waste incinerators, analyzed with Eco-indicator 99 [results in Eco-indicator Points].

	Solvents in cement kilns (pet coke, raw meall)	Solvents in rotary kiln (electricity, heat)	Solvents in rotary kiln (supportive fuel)	Sludge in cement kilns (petcoke, raw meal)	Sludge in fluidised bed (electricity, heat)	Paint/ink in cement kilns (pet coke, raw meal)	Paint, ink in rotary kiln (electricity, heat)	Fluff in cement kilns (pet coke, raw meal)	Fluff in fluidised bed (electricity, heat)	Filter in cement kilns (pet coke, raw meal)	Filtercake in rotary kiln (electricity, heat)
Carcinogens	-8.0E-02	1.3E+01	1.3E+01	-0.0298696	2.2E-01	9.7E-02	21.348433	-1.6E-01	1.3E-01	-1.3E-02	43.853392
Resp. organics	-4.5E-02	-4.5E-03	-2.9E-02	-0.0112686	-8.8E-05	3.1E-01	-0.0007462	-3.4E-02	-5.4E-03	-6.9E-03	0.00062391
Resp. inorganics	-1.5E+01	2.4E+00	-7.2E+00	-3.7497619	-6.0E-02	-5.6E+00	2.53976	-1.1E+01	-3.3E+00	-2.3E+00	5.6483521
Climate change	-1.4E+01	3.7E+00	-6.9E+00	-4.5769303	-3.7E-01	-3.6E+00	2.2180586	-2.3E-01	9.5E+00	-1.8E+00	1.2697197
Radiation	1.3E-01	-6.6E-02	-7.4E-03	0.00529197	-7.5E-02	1.5E-01	-0.01357	1.7E-02	-2.0E-01	-9.0E-03	-0.0031972
Ozone layer	-1.1E-02	-1.5E-03	-8.3E-03	-0.0031598	-9.9E-05	-5.1E-03	-0.000314	-9.1E-03	-1.2E-03	-2.0E-03	-7.276E-05
Ecotoxicity	-5.7E-01	-8.5E-02	-6.8E+00	0.02296336	6.6E-01	-1.1E-01	0.82850234	-4.5E-01	6.9E-02	1.8E-02	1.4539265
Acidification/ Eutrophication	-1.4E+00	6.6E-01	-4.6E-01	-0.3198207	-2.0E-02	-5.6E-01	0.47554173	-1.0E+00	-3.2E-01	-1.9E-01	0.93834414
Land use	5.4E-01	-1.2E-02	-4.0E-03	-0.0228846	-2.8E-02	3.9E+00	-0.0004613	1.1E-01	8.9E-02	-1.6E-02	0.00274191
Minerals	1.7E-03	-5.6E-04	5.2E-06	1.6569E-05	-1.1E-02	2.0E-03	-6.157E-06	-3.6E-04	-2.8E-02	-1.7E-04	0.00025642
Fossil fuels	-1.7E+02	-2.4E+01	-1.1E+02	-40.975814	-1.7E+00	-8.3E+01	-5.4412985	-1.3E+02	-2.5E+01	-2.7E+01	-1.9739308

5.3.2 Net results for the 5 selected wastes

Table 19 Net environmental results for 1 ton of solvents/waste oils, analyzed with CML and shadow prices.

	Chararcterisation					Shadowcosts				
	Cement: Solvents-petcoke-raw meal.	Cement: Solvents-coal-raw meal	Waste: Solvents-energy	Waste-Solvents-fuel	Unit	Cement: Solvents-petcoke-raw meal.	Cement: Solvents-coal-raw meal	Waste: Solvents-energy	Waste-Solvents-fuel	Unit
abiotic depletion	-2.3E+01	-1.5E+01	-2.0E+01	-1.5E+01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	€
global warming	-1.9E+03	-1.6E+03	-2.9E+03	-1.3E+03	kg CO2 eq	-9.6E+01	-7.8E+01	-1.4E+02	-6.3E+01	€
ozone layer depletion	-4.2E-04	3.1E-05	-2.2E-04	-3.0E-04	kg CFC-11 eq	-1.3E-02	9.2E-04	-6.5E-03	-9.1E-03	€
human toxicity	-1.9E+02	-1.4E+01	-3.4E+02	-1.9E+02	kg 1,4-DB eq	-1.6E+01	-1.2E+00	-2.8E+01	-1.6E+01	€
fresh water aquatic ecotox.	-1.4E+01	4.9E+00	-2.7E+01	-4.9E+00	kg 1,4-DB eq	-5.6E-01	2.0E-01	-1.1E+00	-2.0E-01	€
marine aquatic ecotoxicity	2.8E+04	1.1E+05	-2.1E+05	1.6E+05	kg 1,4-DB eq	2.8E-01	1.1E+00	-2.1E+00	1.6E+00	€
terrestrial ecotoxicity	-5.8E-01	5.4E-01	-2.9E+00	-6.6E-01	kg 1,4-DB eq	-7.4E-01	7.0E-01	-3.7E+00	-8.5E-01	€
photochemical oxidation	-1.6E+00	-2.3E-01	-1.1E+00	-1.0E+00	kg C2H4	-3.2E+00	-4.6E-01	-2.3E+00	-2.0E+00	€
acidification	-7.0E+00	-1.5E+00	-2.8E+00	-5.0E+00	kg SO2 eq	-2.8E+01	-6.1E+00	-1.1E+01	-2.0E+01	€
eutrophication	-6.2E-01	-2.2E-01	1.8E+00	-2.7E-01	kg PO4--- eq	-5.6E+00	-2.0E+00	1.6E+01	-2.4E+00	€
Total						**-1.5E+02**	**-8.6E+01**	**-1.8E+02**	**-1.0E+02**	€

Table 20 Net environmental results for 1 ton of solvents/waste oils, analyzed with Eco-indicator 99.

	Chararcterisation					Eco-indicator 99 [Pt]				
	Cement: Solvents-petcoke-raw meal.	Cement: Solvents-coal-raw meal	Waste: Solvents-energy	Waste-Solvents-fuel	Unit	Cement: Solvents-petcoke-raw meal.	Cement: Solvents-coal-raw meal	Waste: Solvents-energy	Waste-Solvents-fuel	Unit
Carcinogens	-3.5E-06	5.5E-06	-2.5E-06	-3.6E-06	DALY	-7.7E-02	1.6E-01	-6.5E-02	-9.3E-02	Pt
Resp. organics	-1.7E-06	-2.0E-07	-1.7E-07	-1.1E-06	DALY	-4.7E-02	-5.4E-03	-4.5E-03	-2.9E-02	Pt
Resp. inorganics	-5.7E-04	-1.9E-04	9.1E-05	-2.8E-04	DALY	-1.7E+01	-5.3E+00	2.4E+00	-7.2E+00	Pt
Climate change	-4.0E-04	-3.5E-04	1.4E-04	-2.6E-04	DALY	-1.7E+01	-8.6E+00	3.7E+00	-6.8E+00	Pt
Radiation	4.8E-06	5.2E-06	-2.5E-06	-2.9E-07	DALY	-4.3E-02	1.3E-01	-6.6E-02	-7.4E-03	Pt
Ozone layer	-4.4E-07	3.3E-08	-5.6E-08	-3.2E-07	DALY	-1.3E-02	1.5E-03	-1.5E-03	-8.3E-03	Pt
Ecotoxicity	-7.4E+01	-2.3E+01	-4.9E+01	-9.1E+02	PAF*m2yr	1.9E+01	-1.5E-01	-3.8E-01	-7.1E+00	Pt
Acidification/ Eutrophication	-1.8E+01	-9.6E+00	8.5E+00	-6.0E+00	PDF*m2yr	6.0E-01	-7.9E-01	6.6E-01	-4.7E-01	Pt
Land use	6.9E+00	-2.5E+00	-1.5E-01	-5.2E-02	PDF*m2yr	7.9E+00	-2.1E-01	-1.2E-02	-4.1E-03	Pt
Minerals	7.2E-02	-8.9E-02	-2.4E-02	2.2E-04	MJ surplus	9.0E-02	1.7E-01	-5.6E-04	5.8E-06	Pt
Fossil fuels	-7.1E+03	-3.0E+02	-1.0E+03	-4.8E+03	MJ surplus	-6.1E+01	-7.3E+00	-2.4E+01	-1.1E+02	Pt
Total						**-6.8E+01**	**-2.2E+01**	**-1.8E+01**	**-1.3E+02**	Pt

Table 21 Net environmental results for 1 ton of sludges, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Cement: Sludge-petcoke-Raw meal	Cement: Sludge-coal-Raw meal	Waste: Sludge-energy	Unit	Cement: Sludge-petcoke-Raw meal	Cement: Sludge-coal-Raw meal	Waste: Sludge-energy	Unit
abiotic depletion	-5.5E+00	-3.3E+00	-1.7E+00	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	-8.5E+02	-7.6E+02	-2.2E+02	kg CO2 eq	-4.2E+01	-3.8E+01	-1.1E+01	€
ozone layer depletion	-1.2E-04	1.3E-05	2.3E-05	kg CFC-11 eq	-3.5E-03	3.8E-04	7.0E-04	€
human toxicity	-3.7E+01	1.2E+01	-5.0E+01	kg 1,4-DB eq	-3.1E+00	1.0E+00	-4.2E+00	€
fresh water aquatic ecotox.	-5.9E+00	-5.6E-01	-3.6E+00	kg 1,4-DB eq	-2.4E-01	-2.2E-02	-1.4E-01	€
marine aquatic ecotoxicity	-6.2E+03	1.6E+04	-7.9E+04	kg 1,4-DB eq	-6.2E-02	1.6E-01	-7.9E-01	€
terrestrial ecotoxicity	6.1E-01	9.1E-01	1.1E+00	kg 1,4-DB eq	7.8E-01	1.2E+00	1.5E+00	€
photochemical oxidation	-3.9E-01	-1.7E-02	-4.6E-02	kg C2H4	-7.9E-01	-3.4E-02	-9.2E-02	€
acidification	-1.8E+00	-3.8E-01	-3.3E-01	kg SO2 eq	-7.1E+00	-1.5E+00	-1.3E+00	€
eutrophication	-1.6E-01	-4.3E-02	4.3E-02	kg PO4--- eq	-1.4E+00	-3.9E-01	3.8E-01	€
Total					**-5.4E+01**	**-3.7E+01**	**-1.6E+01**	€

Table 22 Net environmental results for 1 ton of paint, ink, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Cement: Paint,ink-petcoke-raw meal	Cement: Paint,ink-coal-raw meal	Waste: Paint,ink-energy	Unit	Cement: Paint,ink-petcoke-raw meal	Cement: Paint,ink-coal-raw meal	Waste: Paint,ink-energy	Unit
abiotic depletion	-1.1E+01	-7.2E+00	-7.0E-01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	-6.5E+02	-5.2E+02	8.0E+02	kg CO2 eq	-3.3E+01	-2.6E+01	4.0E+01	€
ozone layer depletion	-1.9E-04	4.0E-05	-9.0E-06	kg CFC-11 eq	-5.6E-03	1.2E-03	-2.7E-04	€
human toxicity	-5.8E+01	2.9E+01	2.3E+02	kg 1,4-DB eq	-4.9E+00	2.4E+00	1.9E+01	€
fresh water aquatic ecotox.	-2.2E+00	7.2E+00	5.0E+01	kg 1,4-DB eq	-8.9E-02	2.9E-01	2.0E+00	€
marine aquatic ecotoxicity	1.1E+05	1.5E+05	3.5E+06	kg 1,4-DB eq	1.1E+00	1.5E+00	3.5E+01	€
terrestrial ecotoxicity	4.8E-01	1.0E+00	1.1E+00	kg 1,4-DB eq	6.1E-01	1.3E+00	1.4E+00	€
photochemical oxidation	9.3E+00	9.9E+00	4.7E-02	kg C2H4	1.9E+01	2.0E+01	9.3E-02	€
acidification	-2.3E+00	2.8E-01	8.9E-01	kg SO2 eq	-9.2E+00	1.1E+00	3.6E+00	€
eutrophication	-2.9E-01	-9.0E-02	2.6E-01	kg PO4--- eq	-2.6E+00	-8.1E-01	2.3E+00	€
Total					**-2.9E+01**	**-1.6E-01**	**1.0E+02**	€

Table 23 Net environmental results for 1 ton of fluff, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Cement: Fluff-petcoke-raw meal	Cement: Fluff-coal-raw meal	Waste: Fluff-energy	Unit	Cement: Fluff-petcoke-raw meal	Cement: Fluff-coal-raw meal	Waste: Fluff-energy	Unit
abiotic depletion	-1.7E+01	-1.2E+01	-4.4E+00	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	-4.6E+01	1.4E+02	1.7E+03	kg CO2 eq	-2.3E+00	6.9E+00	8.7E+01	€
ozone layer depletion	-3.3E-04	1.5E-06	-4.3E-05	kg CFC-11 eq	-1.0E-02	4.4E-05	-1.3E-03	€
human toxicity	-1.6E+02	-2.9E+01	-1.1E+02	kg 1,4-DB eq	-1.3E+01	-2.5E+00	-9.3E+00	€
fresh water aquatic ecotox.	-1.4E+01	-5.3E-01	-4.6E+00	kg 1,4-DB eq	-5.8E-01	-2.1E-02	-1.9E-01	€
marine aquatic ecotoxicity	-5.2E+04	5.7E+03	-1.5E+05	kg 1,4-DB eq	-5.2E-01	5.7E-02	-1.5E+00	€
terrestrial ecotoxicity	-5.8E-01	2.0E-01	-1.7E+00	kg 1,4-DB eq	-7.5E-01	2.6E-01	-2.2E+00	€
photochemical oxidation	-1.2E+00	-2.0E-01	-2.0E-01	kg C2H4	-2.3E+00	-4.0E-01	-4.1E-01	€
acidification	-5.1E+00	-1.6E+00	-1.4E+00	kg SO2 eq	-2.0E+01	-6.4E+00	-5.7E+00	€
eutrophication	-4.7E-01	-1.8E-01	-7.7E-02	kg PO4--- eq	-4.2E+00	-1.6E+00	-6.9E-01	€
Total					**-4.4E+01**	**-3.6E+00**	**6.7E+01**	€

Table 24 Net environmental results for 1 ton of filtercake, analyzed with CML and shadow prices.

	Chararcterisation				Shadowcosts			
	Cement: Filtercake-petcoke-raw meal	Cement: Filtercake-coal-raw meal	Waste: Filtercake-energy	Unit	Cement: Filtercake-petcoke-raw meal	Cement: Filtercake-coal-raw meal	Waste: Filtercake-energy	Unit
abiotic depletion	-3.7E+00	-2.6E+00	3.4E+01	kg Sb eq	0.0E+00	0.0E+00	0.0E+00	€
global warming	-3.4E+02	-3.0E+02	-4.6E+02	kg CO2 eq	-1.7E+01	-1.5E+01	-2.3E+01	€
ozone layer depletion	-7.3E-05	-1.3E-06	1.5E+01	kg CFC-11 eq	-2.2E-03	-3.8E-05	4.5E+02	€
human toxicity	-3.2E+01	-4.5E+00	-5.3E+01	kg 1,4-DB eq	-2.7E+00	-3.8E-01	-4.5E+00	€
fresh water aquatic ecotox.	-3.6E+00	-5.7E-01	2.0E-01	kg 1,4-DB eq	-1.4E-01	-2.3E-02	8.2E-03	€
marine aquatic ecotoxicity	-2.3E+04	-1.1E+04	-3.3E+04	kg 1,4-DB eq	-2.3E-01	-1.1E-01	-3.3E-01	€
terrestrial ecotoxicity	2.6E-01	4.3E-01	3.7E+00	kg 1,4-DB eq	3.3E-01	5.5E-01	4.7E+00	€
photochemical oxidation	-2.4E-01	-3.0E-02	1.2E+00	kg C2H4	-4.8E-01	-6.0E-02	2.5E+00	€
acidification	-1.1E+00	-3.2E-01	-9.5E-01	kg SO2 eq	-4.3E+00	-1.3E+00	-3.8E+00	€
eutrophication	-9.0E-02	-2.8E-02	4.6E+00	kg PO4--- eq	-8.1E-01	-2.5E-01	4.1E+01	€
Total					**-2.5E+01**	**-1.7E+01**	**4.7E+02**	€

5.3.3 Eco-indicator 99 results for solvents/waste oils

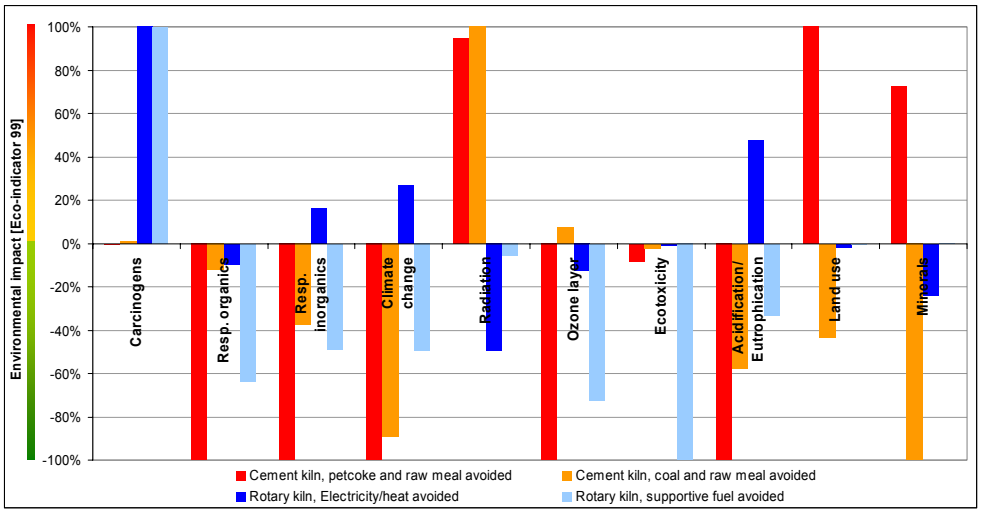


Figure 1 Eco-indicator 99 results for solvents/waste oils treatment in cement kiln with petcoke, coal and raw meal avoided, and for the rotary kiln with electricity/heat and supportive fuel avoided.

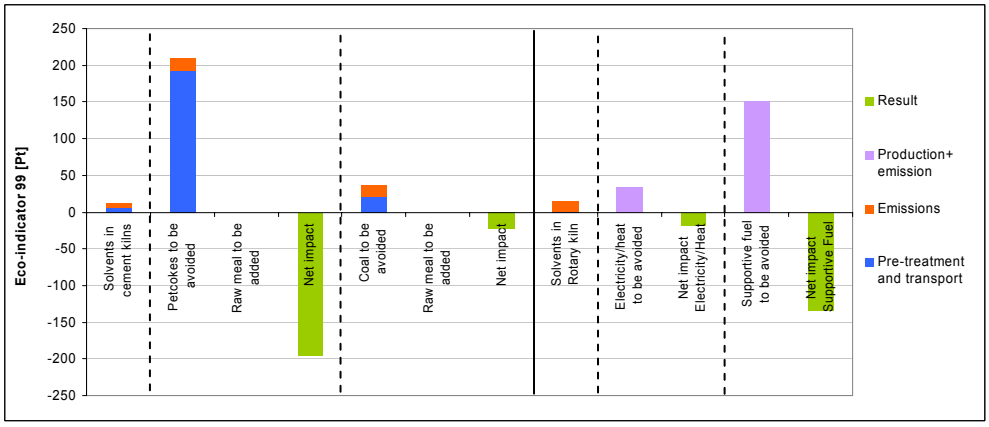


Figure 2 Eco-indicator 99 results for solvents/waste oils treatment in cement kiln rotary kiln with the contribution of pre-treatment/transport and emissions for incineration of solvents/waste oils and for the substitution.

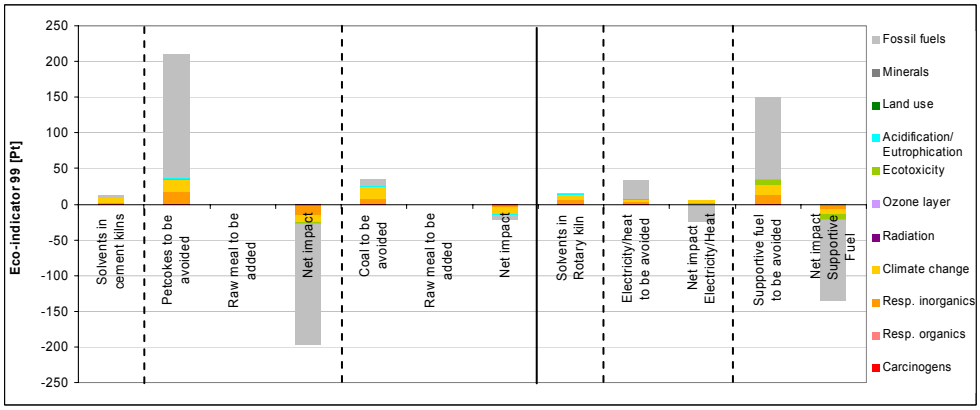


Figure 3 Eco-indicator 99 results for solvents/waste oils treatment in cement kiln rotary kiln with the contribution of each environmental impact category.

6 Comments of reviewer and panel members

In this Annex the comments are given of the reviewer (Jürg Liechti of Neosys), and of two of the expert panel members (Luk Umans of OVAM and Katleen Briffaerts of VITO) respectively. Besides, general remarks of Febelcem are included, as well as their reaction on some of the comments of OVAM. The other expert panel members had no comments any more after processing the comments on the first draft.

LCA comparison analysis of the thermal processing of waste streams in the clinker production vs. incineration of these waste streams in belgian waste incinerators4

Comments of the first rewiewer

0. Goal and scope of these comments

TNO, the Netherlands organisation for applied scientific research, and Neosys have been contacted in order to provide a study to both FEBELCEM and the Flemish regional authorities which should be the common objective and scientific basis allowing the comparison of incineration and co-processing of waste from an environmental perspective.

TNO and Neosys agreed on a common idea of how to elaborate such a study and of an internal distribution of the necessary work. In this collaboration TNO has done the LCA modelling, the data collecting and the calculations and written the necessary reports. Neosys has contributed to the LCA work by continuously discussing and questioning the different results achieved. Thus, Neosys acts as a first reviewer of the study and states a kind of quality assurance.

Neosys has been contacted because of its specific experiences in this kind of study and because of its geographical and political distance to the problem. Combining the high scientific reputation of TNO and the independency of Neosys seems to be an attractive formula to win a high acceptance of the results of the study.

The following comments refer to the study in its state of July 31st 2007 (Draft report D04).

1. General LCA approach

The chosen LCA approach is correct and according to standards. The phases:

- Goal and scope definition;
- Gathering and analysis of the inventory
- Impact assessment
- Weighing
- Interpretation and reporting

are worked out in a clear and transparent way. The definition of the boundary conditions and the compensation effects in order to obtain a correct comparison has been made very carefully and we agree to it.

The choice of CML2 as the method of impact assessment seems suitable to us. However, as we do not have much experience with CML2, we apreciated much the performed parallel calculation with EcoIndicator 99 which showed the same results. This gives a very high confidence in the correctness of the chosen method.

2. Weighing and the conformity of the study with ISO 14044

During the project sessions there was an intense debate on the conformity of the study to ISO 14044 if a method of weighing of the different impact indicators is applied. We repeat here our statements:

- A method of aggregation of the different indicators must be applied to make the study comprehensible. A decision about the application or not of a tax to waste coprocessing must be based on an aggregated judgement on the overall ecological performance of waste coprocessing. It could not be based on a comparison of 9 different indicator results which are hardly understandable for the decisionmaker.
- The chosen method of shadow cost is very suitable for the given problem because it takes as a base the situation of environmental action in a country. Since taxation of a certain handling of waste is actually a way of realizing an environmental policy the chosen aggregation reflects exactly the problem to decide on: If e.g. the study shows that coprocessing of a certain waste saves X Euro per ton shadow cost compared to incineration, this can be directly taken into account to decide on applying a tax of Y Euro per ton to one or the other method of waste elimination.
- Since any kind of aggregation / weighing is always subjective it must be made explicitly and transparently and the results of the analysis before weighing must be given in the study. This has been done correctly.
- ISO 14044 explains weighing and clearly allows it as a method to facilitate the interpretation of the results of an LCA study. As VITO argued in the discussions ISO 14044 prohibits weighing if a comparative LCA study is addressed to a general public. The idea behind is to prevent for the abuse of LCA studies which could occur when results are given to an uncritical public which doesn't have the means for independent interpretation. We think that this does not apply to our situation. This LCA comparison is not addressed to a general public but to decisionmakers for a tax, i.e. to people that have enough means to interprete the study independently.

As a result we think that the study is conform to ISO 14044 and that weighing has been applied correctly and in a very suitable way.

3. Choice of the waste. Representativity

There was a big debate on the representativity of the chosen waste streams. Finally, 5 waste streams have been chosen, which cover 91% of the mass input or 83% of the caloric input of wastes in Belgian cement kilns. We acknowledge that the question of representativity of the analysed wastes with respect to all wastes burned in the cement plants is important for the decisionmakers if you start from the idea that the tax would be applied equally to all wastes being burned there. However, the question of representativity does not affect the LCA study itself. The LCA study gives a comparative result to any waste given as an input if only it is clear to which incinerator the comparison has to be done.

Thus, we do not comment the representativity of the chosen waste steams. We would rather advise the decisionmakers to discuss the question of taxation for different wastes seperately and depending on their individual result out of the LCA comparison analysis.

4. Modeling of the inventory

The basic principle applied to obtain an inventory of relevant environmental impacts is the idea of marginal changes. Following this idea one additional ton of waste is used in the analysed process and replaces there an equivalent amount of fuels and/or raw materials. The impact is then calculated from a comparison of the emissions in both cases. We agree generally with this approach. However, it must be clear that the emissions regarded really depend on the input. This is not so for several substances. E.g. for NO2, the NO2 emission of the cement kiln does mainly not come from oxidation of the N-Input, but from oxidation of air-nitrogen in the high-temperature flame. Therefore the NO2 emission is much more dependent on the flame temperature than on the nitrogen input via fuels. So the replacement of a fuel by a waste can lead to lower NO2-emissions even if the N-content of the waste is higher, because of a lower flame temperature. For NO2 this effect has been taken into account in a good and conservative way. A similar effect applies for SO2: The SO2 emission of the cement plant is strongly dependent on the sulphur content of the raw material and not so much on the sulphur content of the fuels. This is because the fuel-sulphur is transferred into SO4 due to the high temperatures and oxigen content in the kiln. It remains afterwards in form of sulphates in the clinker. On the other hand sulphur in the raw material is slowly heated in the preheater cascade and will eventually oxidize and evaporate in form of SO2 before it enters the kiln. For SO2 we can not reproduce the reported transfer coefficient, however it seems plausible to us.

There are some other transfer coefficients we could not reproduce or not identify in the reported data. These are the coefficients for mercury, for VOC's and for the carbon content of the waste transferring into CO2.
For these transfer coefficients clarification requests are presently still pending.

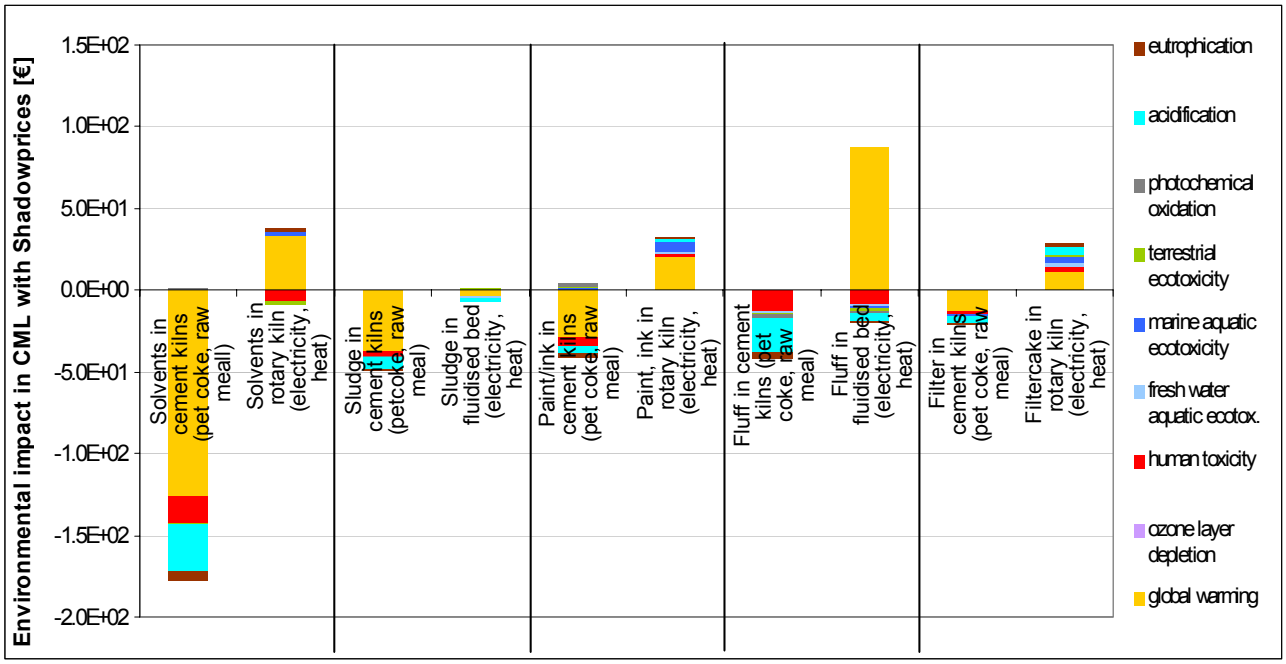
TNO: The transfer coefficients for the cement industry have been sent under the confidentiality agreement. These factors will not be published as febelcem whishes to keep these confidential.
The emission of VOC as a result of pre-treatment of waste is described in paragraph 3.2 in the report
The CO2 emissions per waste type are added to table 2 in Annex 1.

5. Plausibility Check of the results based on a Neosys model (2004)

For a rough estimation of the plausibility of the TNO results – especially for the chosen inventory model – we have made a test run of our 2004 transfer model / Eco-Indicator 99 impact calculation with the given data of the 5 waste categories. The result and its comparison to the TNO result is shown in the table on the following page. There is a generally very good confirmation of the TNO results.

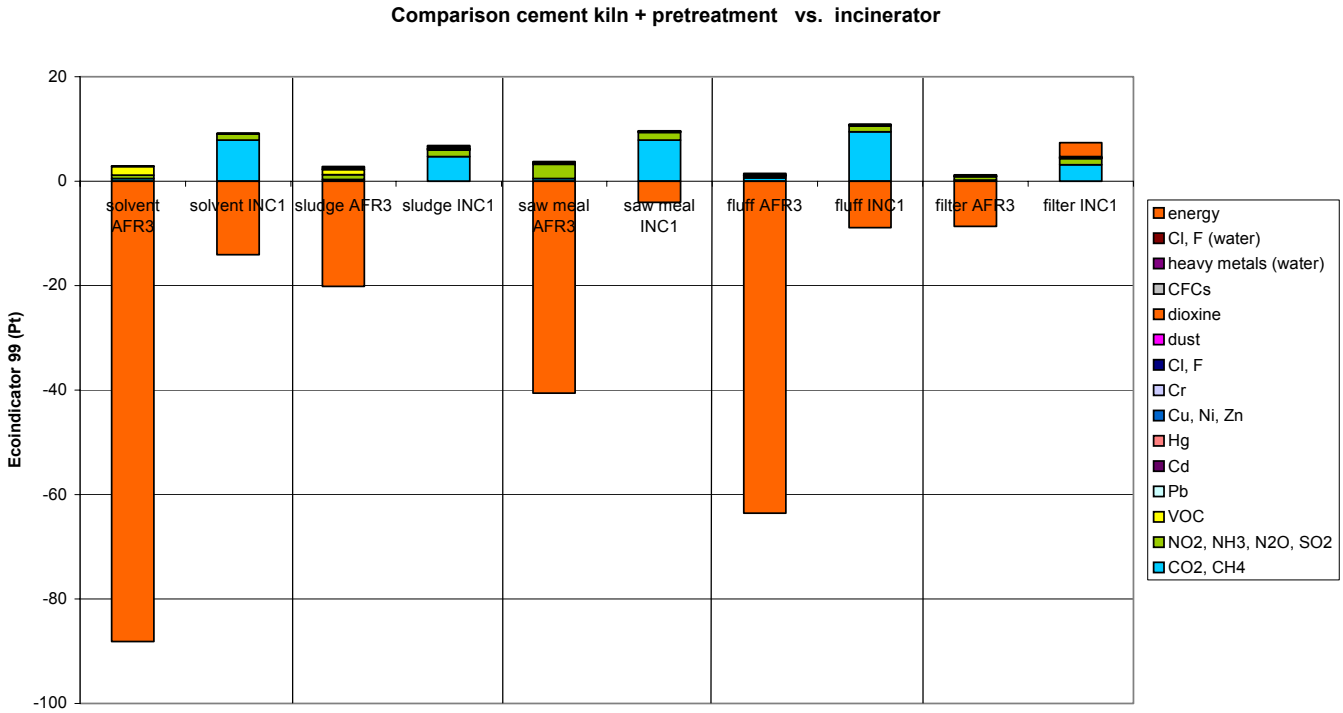
There are some methodological differences which lead to an other scaling and we do not show the contributions of the different impact parameters but the contributions of the different emissions and consumptions. We used a Lepol cement kiln and a pretreatment facility of which we adapted the VOC-emission to be what we expect approximately from the Geocycle plant. We used a rotary waste incinerator kiln type Indaver. As for the wastes we used the given input information of the 5 waste categories and we added estimated values for the VOC and C content of the wastes. On the other hand our model did not make use of the informations about the elements As, Sb, V and Tl.

Apart from our discussions with the TNO representatives and the feeling that we got a common understanding of the problem this check-up with its very well reproduced results gives us a strong confidence in the correctness of the assumptions and calculations in the TNO model and therefore in the accuracy of the results.



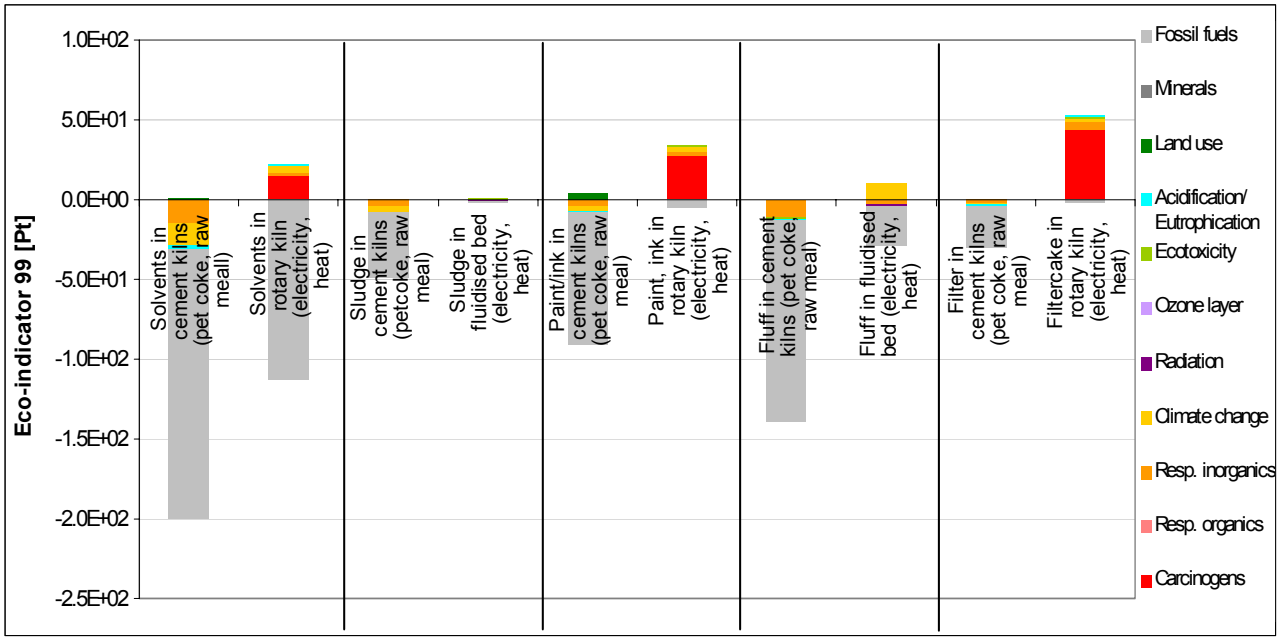
LCA result for 5 waste categories. Calculation witht **TNO inventory**, **CML2 impact assessment** and **weighing with 'shadow cost'**.

Left column is always co-processing in the cement system, right column is incineration in the corresponding Belgian incinerator.



LCA result for 5 waste categories. Calculation with **Neosys 2004 inventory**, **Ecoindicator 99 impact assessment** and **weighing according to Ecoindicator 99: 40:40:20**.

Left column is always coprocessing in the cement system, right column is incineration in an 'Indaver-type' rotary kiln.



LCA result for 5 waste categories. Calculation with **TNO inventory**, **Ecoindicator 99 impact assessment** and **weighing according to Ecoindicator 99: 40:40:20**.

Left column is always co-processing in the cement system, right column is incineration in the corresponding Belgian incinerator.

6. Sensitivity analysis

A sensitivity analysis has been applied to the results of the LCA. The variations of input data and system parameters have been chosen carefully and according to the uncertainties of the system. Especially we appreciate that the following parameters have been variated and the sensitivity of the system to these variations have been evaluated:

- the contents of heavy metals, halogenes and sulphur in the waste
- the carbon content and the caloric content of the waste (applied to fluff)
- the VOC content of the waste (applied to paint/ink/impregnated saw dust) resp. the transfer coefficient of VOC of the pretreatment

The LCA results of the variation cases show no significant difference. This means that the basic conclusions that are taken from the study are stable and that one can have confidence in them even if the uncertainties in the data and system parameters are taken into account.

7. Summary

We believe that the results of the LCA comparison analysis given in the draft report of july 31st are generally accurate and correct.

This belief is based on:

- Good discussions with the authors which led to a common understanding of the problems
- Agreement with the principles and methods chosen to perform the analysis
- Taking into account of our remarks by the authors during the establishment of the analysis

- Very good global reproduction of the results by a run of our own and independent LCA method

For economical reasons we did not checkup every single point or calculation from bottom to top. We checked points of crucial influence and points where mistakes seemed more likely than elsewhere.

Some of our clarification requests are still pending and we would like to comment on the transfer coefficients once more, after annex 2 is finalized.

July 31st 2007

Dr. Jürg Liechti

OPENBARE VLAAMSE AFVALSTOFFENMAATSCHAPPIJ

Comment the TNO-report "LCA of Thermal treatment of waste streams in the clinker production in Belgium" d.d. 31.07.2007

1 General comment on the document :

1. Philippe Decornet and M. Calozet will be mentioned "in the expert panel", while they were only present in the last meeting.
   Phillippe Decornet was the independent chair person of the expert panel, and will be referred to as such. Michel Calozet and Benoit Lussit will be mentioned together as representatives of Febelcem.
2. The letter of the Minister of 30.01.2007 (KAB/HG/bp/2007-011; KO2.4-U-07-0353) suggested that both emissions and energy performance should be researched. This study does not give any information concerning energy performance. E.g. the differences between wet cement process and dry cement process towards energy efficiency is not mentioned in the study.
   This question will be answered by Febelcem apart from this report. This project was performed and this report was written to answer the first question only. Besides, it does not make sense to assess energy performance in this respect, because the energy performance of a cement kiln (or other installation) is exactly the same in case primary fuels are used, and in case secondary fuels are used; there is no discrimination.
3. In the document itself, in the conclusions (or at least as a very clear footnote in the conclusion) , has to *be added that the OVAM does not agree* with certain points of departure and for that reason can not subscribe the results based on the following remarks:
   In the conclusions a footnote is placed, in which your constraints are mentioned and a reference is made to this Annex and this remarks.
   - The study examines only the environmental aspects of the input of waste in both processes; not the energetic aspects. The fact that the amount of used energy/ton produced clinker is significantly different and the fact that there is a lot more loss of energy in the cement industry in comparison with the incineration plant have not been discussed.
     As stated above (comment no 2), energy efficiency was outside the scope of the project, and in the goal and scope of the report it is explained in more detail that this is not relevant, because in this study the thermal treatment of 1 ton of waste is the functional unit, and not the production of 1 ton of cement clinker.
   - The study makes a environmental comparison based on a set of environmental parameters. In the report the most important environmental effect in the LCA has been generated by "global warming". Most important factor on this one is emission of CO2. There is a different energy requirement between the wet cement kilns and the dry cement kilns; this means that there will be a difference in CO2-emission (and on *global warming)* in the wet and the dry cement plants.
     The functional unit in this study is the input of one additional ton waste and the related change as a result of the energy content of the waste. The change in CO2 emission is related to characteristics of the waste and not to the characteristics of the kiln (see also the response on the bullet above on energetic aspects).
   - If two different treatment technologies (e.g. cement plants and waste incineration plants) will be compared, the same reference situation has to be used : e.g. the same energy source, and not two different energy sources with a completely different environmental impact.
     The focus of this study is a realistic change for the 2006 situation in Belgium. Waste incineration plants generate electricity, avoiding electricity production by power plants. Cement kilns use both waste and fossil fuel. Input of additional waste will reduce the input from petcokes (or coal) as reported by the cement industry in Belgium. It is not realistic to assume that the same fuels are avoided in 2006. Such analysis would have a highly theoretical character instead of a realist one, which is not desired for this study.
   - The fact that some emission level values are more strick for the waste incineration plants in comparison with the cement industry has never been valorized in the LCA.

The LCA study is based on real emissions as a result of the input of one ton waste, based on the elemental waste composition and transfer coefficients. Legal limits are not relevant for the calculation of the realistic emissions.

- Unless the fact that the cement industry is a severe emittor of NOx these emission of NOx have not taken into account in the LCA.
  Based on the fact that not the clinker production, but the treatment of waste is the basic subject of the study, using the approach of ***marginal change***, only changes in environmental burden, caused by the use of extra secondary fuels, are relevant. An explanation on the NO_x emissions is given in chapter 3.3.
- Furthermore OVAM does not agree with the approach that the capture of heavy metals in the flue gas cleaning, immobilization and controlled landfill (in case of waste incineration) is considered negative (whereas from environmental point of view it is positive) and at the same time the effect of dilution of heavy metals in the cement is considered to be negligible.
  In the case of immobilization and land filling of highly contaminated flue gas cleaning residues, a potential environmental risk exists, and can be measured by means of leaching tests. The heavy metals that remain in the cement clinker are also immobilized during the hardening of the cement, but the concentrations are in this case that low, that the leaching of these elements cannot be quantitatively measured. This is the reason that we state in chapter 2.1 of the report that the ***impact thereof*** in the framework of this study will be surely negligible.

4. Emission of pollutants to water are taken into account for the waste incineration plants. Are the used data for the LCA data of pollutants *before* waste water treatment or *after* ?
   The emission to water as calculated using the transfercoefficients are based on release to surface water after neutralisation and precipitation of pollutants, in other words, after waste waste water treatment
5. Are the changes as marginal as stated ? The input of more or less than 500 000 tons of waste is not that marginal any more.
   Again, in both cases (cement clinker production and waste treatment) minor changes in emissions, due to the treatment of ***one extra ton of waste,*** are compared with each other in this study. And not the absolute changes, caused by the fact that the two systems are intrinsically different. This is explained in chapter 2.1 and in chapter 3.5.
6. OVAM seriously regrets that no representative of the incineration plants was permitted in the expert panel.
   From OVAM's point of view, TNO can understand this. However, the study was commissioned by Febelcem, and not by the waste incinerators.
7. Emission values are not always realistic or are dated.
   - Hg-emissions of 4 % towards the air are not realistic in the actual situation. In this study TNO refers to a study on the emission of heavy metals (Theunis et al., 2003) : in that document it is stated that the actual treatment facilities can clean the fluegasses up to 99,99 % for Hg.
   - Some data in tabel 3 & 4 date from 1988 !

   To know the effect of using (outdated) transfercoefficients for incineration, an additional sensitivity analysis is made in paragraph 4.3.7
8. The OVAM received general data (5 streams) of the input of waste (tons) in de cement industry after the last meeting. This information was more general than the one repeatedly asked in the different meetings (and asked in the excel-sheet that has been sent around). The data of the origin of the sludges and filter cakes have never been given.
   This question will be answered separately by Febelcem. TNO does not have that detailed information either. For the purpose of this study this information was not required.
9. This document still is not complete : annex 2 was not included in the document. We would like to see the *completed document* which includes *all* remarks before it will be spread.
   In the last expert panel meeting it was decided that the final version of the report would not be sent around again. We regret that Annex 2 was not completed in time. However, this Annex only comprises a description of the cement clinker production process.

2 Specific comment on the report

- 5/37 : It was agreed in de the meeting of 10 July that the fact that OVAM does not agree with the results is written in the report, not in the annex. !!
  It will be mentioned in the conclusions and in the goal and scope, as a footnote.
- 6/37 : energy efficiency is excluded from the study
  This is mentioned explicitly.
- 7/37 : tabel 2 : negative value for the substitution of petcoke by solvents ?
  This is explained in the paragraph above the table.
- 7/37 : reference of table 2 + 3
  This information was provided by the cement producers, the stakeholders of Febelcem.
- 10/37 : Are there no min/max values for fluff and filter cake ?
  In Annex 1 it is explained that in these cases only one value was available.
- 13/37 : 3,5 GJ/ton produced clinker (dry process); how much energy (in GJ/ton) is necessary for the wet process ?
  For the wet process this is approximately 5 GJ/ton clinker produced.
- 13/37 : “marginal changes”; the substitution of 500 ktons is not very marginal anymore…
  Not the total substitution is studied in this report, only the marginal change of 1 ton. This will be mentioned in the chapters 3.3 and 3.5 more explicitly.
- 13/37 “as agreed” : it was decided by the cement producers; the OVAM wanted figures of each plant (as mentioned in several meetings). OVAM does not subscribe “as agreed”
  OK, not all members of the expert panel were happy with that, but from confidentiality viewpoint this was the only practical solution. We will make a footnote in the report.
- 14/37 : effect of waste on NOx : reference of this proof ? Emissions of NOx by the cement industry are significantly higher than the NOx-emissions of the waste incinerator.
  The measurements mentioned, were done at the ENCI plant in Maastricht (Netherlands). However, the actual data are confidential. As is explained in the report, most of the NO_x produced in a clinker kiln is not caused by the nitrogen from the raw materials or the fuels, and is therefore process intrinsic. This means that it will not change as a consequence of the marginal change of 1 ton of fuel. This will be explained more extensively in the report.
- 14/37 “streams not leaving the plant” e.g. heavy metals in cement
  Actually it concerns the fine particles (dust) from the E-filter. This will be added in the report.
- 14/37 and the following pages : Indaver is mentioned, while they were not allowed to participate in the steering committee
  See the reaction on general remark, no 6.
- 17/37 : Is this a different figure than figure 6 ?
  No, the figure exists 2 times; one of them is removed.
- 23/37 : not correct : there is no pretreatment for the sludges in case of a waste incinerator (fluidised bed incinerator - FBI)
  This is adapted in the report
- 24/37 : it is written that there will be an *avoided production* of petcoke. This is not realistic. Petcoke is not produced in behalf of the cement industry. It is a by-product of the petrochemistry in the production of petrochemical products.
  The approach of avoided (by) products is common practice in the LCA field. In the LCA study a second scenario is calculated where coal is avoided instead of petcokes. Coal is not a by product. The results for coal point in the same direction nfor each waste stream and do not change the conclusions.
- 24/37 : there is no pretreatment of sludges in FBI.
  This is adapted in the report
- 24/37 : the actual used fluegas cleaning for the FBI allows a better Hg-captation than the technique used in the cement industry. Why should the result of the cement industry be better ?
  The transfer coefficients for the cement industry are calculated for the real, measured 2006 emissions. This has resulted in a transfer coefficient for Hg emissions to air of 2%-4%. The used data for the incinerators are indeed a little outdated. We therefore have made an additional sensitivity analysis on this point, with a transfer coefficient of 0,05% Hg to air for waste incineration – see paragraph 4.3.7. However Hg and other metal

emissions have a limited contribution to the results, and other impacts (CO2 emissions) and the avoided energy determine the outcomes.

- 27/37 : last paragraph is not clear.
  The paragraph is adapted to improve understanding
- 28/37 : wrong basic assumption : fluff will not be incinerated in a rotary kiln
  Filtercake is treated in the rotary kiln (see paragraph 4.2.5.) and fluff in a fluidised bed (see paragraph 4.2.4)
- 28/37 : 4.2.5 : filter cakes : “treatment of fluff”
  We have erased the sentence on fluff in the paragraph on filtercake
- 29/37 : this paragraph suggests that there are no significant NOx-emissions in the cement industry, while the rotary kiln causes NOx-emissions (with impact on toxicity, acidification, eutrofication). OVAM disagrees.
  What is meant is that the NOx emission caused by one ton of secondary fuel is supposed to be equally high as the NOx emission caused by one ton of substitute (pet coke or coal). This will be clarified. This is also more extensively explained in chapter 3.3.
- annex 3 : reference of tables 3,4 5 ? What are the capacities of the installations ? It is not clear which technique is used in the scenarios (Swiss or Austrian) ? Are those data still representative (1988) ? Incineration plants became more performant
  TNO preferred to use recent data from Indaver, but as these data were not available public data on waste incineration were used. A sensitivity analysis is made using more lower transfer coefficients for emissions to air and waste water – see paragraph 4.3.7
- annex 3 : we never discussed *the behaviour of Hg in a waste incineration plant*. What about this behaviour in the cement kilns ?
  Most of the Hg is caught in the E-filter in a cement kiln, and is recycled internally in the plant, or added to the end product (see the remark on the comment on page 14/37).

Luk Umans
(24.07.2007)
Evert Mulder and Suzanne de Vos
(26.09.2007)

Datum : 24/08/2007 **Ref.** :

Van : VITO **Bijlage(n)** :

Aan : TNO

Kopie :

Betreft: Comments of final draft report LCA of thermal treatment of waste streams in the clinker production in Belgium

- Titel: better to say "LCA of thermal treatment of waste streams in clinker kilns in Belgium", since the methodology makes abstraction of the fact that clinker is produced.
  Good point; we will change the title.
- Summary: "A second positive effect is the fact that cement kilns do not have emissions of toxic substances to the water, whereas rotary kilns do have such emissions": the rotary kiln has a wet flue gas cleaning system followed by a waste water treatment removing these toxic substances from the water. Emissions to water are clearly overestimated by using very old LCA data (part of these data go back to 1988). In the previous LCA by TNO, about 10 years ago, specific distribution factors were used for the Indaver rotary kiln. These show emissions that are much lower (air and water). Why are these not used? We already questioned the results for incineration in the previous comments, but there was no reaction to this? See further on
  It was preferred to use 2006 data from Indaver, however as these data were not available for this study, it was agreed to use ecoinvent data as a startingpoint for the calculations. Nevertheless, we agree that the used data for the incinerators partly are a little outdated. We therefore have made an additional sensitivity analysis on this point – see paragraph 4.3.7. However Hg and other metal emissions have a limited contribution to the results, and other impacts (CO2 emissions) and the avoided energy determine the outcomes.
- The method used was not questionable by the expert panel. On different occasions, comments were made pointing out that the energy efficiency of the cement process is not taken into account, while the efficiency of energy recovery for the waste incinerators is determining the outcome of the LCA. At least, these issues could be addressed in the report. The study concludes that more CO_2 is saved by incinerating the waste in the cement kilns compared to the incinerators. This could be misleading. The reduction potential for CO2 will probably be much higher if the energy efficiency of the cement kilns is considered. The results suggest that CO2 emissions are reduced by treating the waste in a cement kiln in stead of an incinerator. But, maybe more CO2 emissions could be reduced by improving the average energy efficiency of Belgian cement kilns ... These issues are not addressed in the report.
  That is right; energy efficiency was outside the scope of the project. In the goal and scope of the report it is explained in more detail that energy efficiency is not relevant in this study, because in this study the thermal treatment of 1 ton of waste is the functional unit, and not the production of 1 ton of cement clinker. What is relevant in this study for clinker production, is the difference in CO2 emission between the treatment of 1 ton of waste and the use of a comparable amount of primary fuel (pet coke or coal). And for waste incinerators this is the difference in CO2 production between the incineration of one ton of waste and the production of an amount of electricity / heat in a Belgian power plant, equivalent to the amount of electricity / heat that is produced in the incinerator, when treating 1 ton of waste. (As was already explained on pages 5 and 6 of the report).

- The aggregation of the results is done, even though OVAM and VITO did not agree. There is no clear distinction between the ISO-conform LCA and the aggregation, although this was agreed upon earlier on in the project. This is not necessary after all, according to TNO and Neosys, because the report is intended for a limited public. VITO does not agree with this. If Febelcem is the only reader and user of the report, the argument holds, otherwise not.
  The study-approach is largely in harmony with ISO guidelines for LCA. A review panel has followed the study as it is a (public) LCA comparison. Any LCA needs interpretation of the results. LCA experts within the review panel have different interpretations on ISO guidelines as to what is allowed in a public comparison study. According to VITO weighting is not allowed, according to Neosys wighting needs to be transparent but is necessary for interpretation.
  In the Annex TNO publishes the
  - unweighted characterised results and
  - the procedure (or method) that is used to derive weighting factors
  - the weighting factors per impact category and
  - the weighted results

  By including this information in the report, we believe we are in line with the ISO descriptions on interpretation of LCA for comparative assertions disclosed to the public (requirements following from grouping or weighing of the results) - as there is transparancy on the selected weighting method, the weighting factors and the influence of weigthing on the (unweighted) results.
- p.6: To follow the guidelines for LCA and to ensure the quality of the LCA study, the study is conducted in consultation with an expert panel. This sentence should be removed from the report. The report could say that there was an expert team and could then refer directly to the annex. This way, all relevant information on the expert team and their comments are collected. The composition of the expert panel could then be listed in this annex. Our conclusion is that:
  - Deadline for serious comments on draft report was 19/07. Since the expert of VITO was absent from 9-13 /07, it was not feasible to do this. This deadline was decided on in the absence of VITO.
  - Distribution coefficients for incinerators were only available on 31/07, more than 10 days after the deadline to formulate fundamental comments. These data (and other) were asked by VITO for a long time. By sending them too late, the ISO-guidelines were not followed and the expert panel could not help to ensure the quality of the LCA.

  Leaving that sentence and the following in the goal and scope of the study would be misleading for the public reading the document. We really want to avoid such misunderstanding, because the report would be different if we were really consulted during the study.
  The sentence in the report will be revised. Furthermore in the report there is a reference to this Annex with your comments. It is right that the study had to be performed in a stringent time frame. However, all experts were in the opportunity to bring in comments. Nevertheless, not all comments of individual experts led to changes in the report.
- Several comments and recommendations from VITO were not taken into account although (for example, NO_x emissions are not taken into account in de emissions of the cement kilns and the emissions of petcokes or coal = misleading and incorrect: this should have been corrected on the figures). This is only one example. Stating that our presence in the expert panel ensures the quality of the LCA is incorrect.
  We are not in the position to assess the added value of the presence of VITO in the expert panel. We will therefore change that part of the sentence in the report, and state that the aim of consulting the expert panel was to improve the quality of the study.
- The report repeats on several occasions that it is not realistic to assume that solvents/waste oils replace light oil in waste incinerators. We have repeated on several occasions that these waste products are used to obtain the right process conditions. If they were not available, light oil would be used. So, they avoid the use of light oil. They are not used for starting up, as is suggested on many occasions in the report. We have provided different references. Indaver would certainly confirm this, if they were to be contacted. Still, no corrections are made to the report?

Starting point is (and was) the actual situation in 2006. Furthermore, in the goal and scope it is explained that the approach to compare both systems is that of ***marginal change***. From the year report of Indaver it can be learned that they already use waste oils as a supportive fuel. This is explained in chapter 2.2 of the report. So, if one ton of solvents / waste oils would be supplied extra to Indaver (a marginal change), this would most probably replace a ton of waste oil (as supportive fuel). This does nog lead to any change in environmental impact. We do not believe that light fuel could be replaced; otherwise in practice Indaver would already have replaced all light fuel by waste oil.

- For the cement industry, one could also argue that waste is replaced by waste if the maximum amount of waste (according to the permit) is already being treated. In those circumstances, petcoke could not be replaced any further by waste.
  Once again, the approach to compare the systems is that of marginal change. In case of the cement producers we asked them what they would replace if more waste materials would be supplied. Indeed, in one specific case, that of hazardous sludge, it would replace non-hazardous sludge (being more or less the samen material, resulting in no change in environmental impact). In all other cases the waste would replace pet cokes or (in less cases) coal.
- Petcoke:
  - This is in fact a by-product or waste product from refining activities; Even if the petcoke is not used, these activities will continue and petcoke is still produced. Therefore, it does not seem correct to assign part of the environmental impact of the refining proces to the petcoke? The use of petcokes will surely not result in a depletion of fossil fuels.
  - If it is not used by the cement industry, is it used elsewhere? Where? What emissions would these other processes produce

  The approach of substitution of by-products like petcoke is often applied in the LCA field. Even though it is a by-product, it has an economic value, and in that sense it is correct to assign part of the environmental impact of the refining process to the petcoke.
  Beside a substitution of petcoke, each waste stream is also analysed for a scenario where coal is substituted. Coal is a product, and no by-product. The results of the calculation with coal substitution point in the same direction as the calculations with petcoke substitution. The results are less positive, but the conclusions do not change.
- Filter cake: we repeat our question: why is it not dried before treatment? What's the difference with sludge? Filter cake has a lower heating value and a higher moisture content?
  This is clearly explained in chapter 3.2. One sentence in chapter 4.2.2. mistakingly was nog changed; this is done now.
- Comparison of Indaver transfer coefficients from previous LCA study and used transfer coefficients in current LCA.

Table 3 Transfer coefficients of typical hazardous waste incineration

Element	Source	Air_emissions	Water_emissions	Solid residues
		%	%	%
H2O	MSWI	100	0	0
O	MSWI	91,7	0	8,3
H	MSWI	100	0	0
C	UVB1988	100	0	0
S	Jahn2002	0,06/0.66%	95,7/17.9%%	4,28/81.44%
N1	UVB1988	4,6	7,93	0
P	Jahn2002	0,07	1,53	98,4
B	MSWI	12	15,1	72,9
Cl	Jahn2002	0,03/0.03%	99,8/96.7%	0,17/3.27%
Br	Jahn2002	0,02	99,8	0,17
F	UVB1988	0,05	26,6	73,4
I	Jahn2002	0,02	99,8	0,21
Ag	MSWI	0,0013	0,0073	100

As	MSWI	1,02E-06	0,01/0%	100/100%
Ba	MSWI	0,1	0	99,9
Cd	UVB1988	0,899/0%	10,2/0%	88,9/100%
Co	Jahn2002	0,07/0%	99,9/0%	0/100%
Cr	MSWI	7,39E-06/0%	0,32/0%	99,7/100%
Cu	Jahn2002	0,07/0.03%	4,29/0%	95,6/99.9%
Hg	UVB1988	4,02/0.05%	10,6/0.07%	85,3/99.88%
Mn	MSWI	5,45E-07	0,001	100
Mo	MSWI	0,02	0	99,8
Ni	Jahn2002	0,07/0.08%	20,5/0.00%	79,5/99.92%
Pb	UVB1988	0,331/0.09%	11,5/0.03%	88,1/99.88%
Sb	MSWI	3,89E-07	0,018	100
Se	MSWI	5,03E-07/0%	0,0118/0%	100/100%
Sn	MSWI	0,133	0,00133	99,9
V	MSWI	0,01	0,001	100
Zn	Jahn2002	0,07/0.02%	1,34/0.01%	98,6/99.97%
Be	MSWI	0,1	0	99,9
Sc	MSWI	0,05	0	100
Sr	MSWI	0,01	0	100
Ti	MSWI	0,1	0	99,9
Tl	MSWI	0,1	0	99,9
W	MSWI	0	0	100
Si	MSWI	0,233	0	99,8
Fe	Jahn2002	0,07	80,3	19,6
Ca	MSWI	0,167	0	99,8
Al	MSWI	0,156	0	99,8
K	MSWI	0,3	0	99,7
Mg	MSWI	0,138	0	99,9
Na	MSWI	0,941	0	99,1

10 years ago, less pollutants were taken into account. Concerning HF, such emissions are not measured (below measure limits) by Indaver, so it is not realistic to assume that these emissions would have such an important impact on the LCA results. Part of this information dates from 1988 (or older). This is very old. For the cement kilns, it was very important to use recent (2006) emission data. Why follow a different approach for both systems?

It was preferred to use 2006 data from Indaver, however as these data were not available for this study, it was agreed to use ecoinvent data as a startingpoint for the calculations. Nevertheless, we agree that the used data for the incinerators partly are a little outdated. We therefore have made an additional sensitivity analysis on this point – see paragraph 4.3.7. Even though we cannot justify the data (because there is no reference), we have used your data for that purpose. The results show that Hg and other metal emissions only have a limited contribution to the results, and other impacts (CO2 emissions) and the avoided energy determine the outcomes.

The main difference between 10 years ago and now for Indaver is the fact that they added a deNOx installations. Minor differences are not known by VITO, but they may exist. The performance could only be improved, but not worsened.

As we have no data from Indaver(except the public data), TNO cannot judge the environmental performance of Indaver

Concerning the Hg emissions, special care is taken by Indaver: Hg is removed in the wet cleaning and then removed from the water by complexing the Hg into insoluble products. The last traces of Hg in the waste gas are removed by the dioxin filter. The same is true for other pollutants. They are removed from the waste gas and then removed from the water (that's why

they use the TMT and FeCl3).
See comment above (just underneath the table).
The Cl emissions to water should be seen in the particular context of Indaver. They discharge into brak (semi salt) water in the Schelde. Therefore, they discharge NaCl without impacting that particular environment. Is this fact taken into account in the LCA calculations?
Chloride emissions to water do not contribute to the environment impact assessment with CML or Eco-indicator 99
All calculations should be adapted. We can only make this comment now, since these transfer coefficients were not sent to us before.
See comment above (just underneath the table).

- Similar information for the cement kilns is not available and can therefore not be evaluated by VITO. We are not able to play our role as independant expert.
  As was accepted by the expert panel, from an confidentiality point of view, the data of the individual cement producers were sent to TNO en Neosys only. The transfer coefficients calculated by TNO were reviewed by Neosys. Average environmetal impact data are presented in Annex 5.
- Transport: the subject of the study is -in our opion- the treatment of Flemish waste. It is not correct to use the same tranport distances for both systems (cement kiln and incineration)
  Transport is taken into account. Travelling distances for the thermal treatment of the wastes in cement kilns were determined, based on the real sources, specified by the cement producers. The used wastes mainly come from Belgium (all directions) and the North of France, the west of Germany (close to Belgium) and the South of the Netherlands. The transport distance from France to Indaver is slightly longer, from the Netherlands slightly shorter compared to the distance to the cement kilns. The difference for transports from Germany depends on the location of the cement kiln. The average net result is more or less the same for waste treatment at Indaver and for waste treatment in the cement kilns. For transparency reasons we have taken the same distance and transport means. Travel distances cannot be left out, however, because of the fact that the transport distances for the substituted fuels are not the same.
- In the report there are copy paste mistakes. Also for the sludge it is stated that the same pre-treatment is assumed for the cement kilns and the incinerator. But, this was adjusted, no? So, this should be removed from the report.
  These mistakes are adapted in the report.
- Why would the use of waste streams lead to a decrease of NOx emissions. Is there a scientific hypothesis or explanation? Please explain?
  This is known from measurements in practice, and also from modelling excercises. The measurements mentioned in the report, were done at the ENCI plant in Maastricht (Netherlands). However, the actual data are confidential. As is explained in the report (chapter 3.3), most of the NO_x produced in a clinker kiln is not caused by the nitrogen from the raw materials or the fuels, and is therefore process intrinsic. This means that it will not change as a consequence of the marginal change of 1 ton of fuel. This will be explained more extensively in the report.
- How are the NOx emissions for the incineration kilns calculated? Use of an emission factor per ton waste (same value for each waste)? Or, are they calculated in function of the caloric value of the waste? Not clear from the report, so we cannot evaluate the method ...
  The emission of NOx is based on the NOx reported by Indaver: 1,8 g per ton waste.
- Based on the results of a comparative LCA alone, it is not allowed to conclude that the environmental performance of one treatment is superior to another one. This is clearly stated in the ISO-guidelines.
  The conclusions are based on this LCA study and not on other studies.
- Sensitvity analysis: only the aggregated results are shown. Better would be to only show graphs with the real LCA resuts with min and max and to explain. Because the shadow prices are completely dominated by greenhouse gases, of course you cannot see differences in the other impact categories. There may be significant differences however. Please change this presentation, at least if your intention is to inform us through the report.
  For the sensitivity analysis the same holds as for the LCA results themselves, that it is quite

impossible to interpret them and to draw conclusions without aggregation. For almost every reader it will be difficult to interpret tables with real LCA-data. Besides, in most of the figures (24, 25 and 27), pre-treatment and transport, emissions, production and emissions have been distinguished.

- Annex with results showing min and max. The min and max from coal and petcoke results are not given seperately. This is not very clear for the public. It is not clear which results are presented in the tables?
  The minimum and maximum results related to emissions of petcokes and coal in cement kilns are listed separately in table 7 and 8 of Annex 5 LCA Results.
- A new draft final report should be made with the necessary corrections. This should be distributed to the expert panel and evaluated again, before the final report can be made.
  In the last meeting of the expert panel it was unanimously agreed that the final report would not be distributed once again, but that a reaction would be given on the comments and that both of them would be included in the report as an Annex.

FEBELCEM's comments and remarks

1. General remarks about the study

We feel that globally the study answers correctly to the question raised i.e.. the difference between environmental of incineration and co-incineration in cement kiln in Belgium.

We feel that the results of the study are robust: two LCA methods and two methods of aggregation have been used, a nearly-complete representativeness of the waste used as fuel in cement kiln in Belgium is assured and the sensitivity tests confirm the main conclusions.

However, we would like to highlight the fact that in many respects this study considers the worst case for the cement kilns, a.o.:

- The way of calculating NO_X emissions (as mentioned in chapter 3.3);
- Presentation of a non representative scenario for solvent (supportive fuel in a rotary kiln);
- Sensitivity tests present unfavorable situation for the cement kiln: a.o. on shadowprice on CO_2 and SO_X and on transfer coefficients for waste incineration. Besides, from our point of view, the values used in this later test are poorly justified.
- The selection of the incineration techniques for each of the five waste streams is made on the basis of technical considerations. We accept that choice but we stress this does not necessary correspond to the actual practice (one single installation (rotary kiln) in Flanders is currently allowed to treat hazardous waste). The scenario for hazardous sludge's is therefore favorable to the incinerators.

We feel that the report and its conclusions are conservative and that these elements are to be kept in mind for any interpretation of the results.

2. General remarks about OVAM's contribution to the study

TNO, Neosys and/or Febelcem have already answered most of remarks of OVAM. Among others, this is the case for: the substitution scenarios (use of petcoke and coal), difference between dry and wet processes, NOx emissions, capitation of heavy metals, methods of marginal change, representation of the incineration plants, information about the waste streams.

We deplore the fact that OVAM does not want to accept the scientific answers previously given and never gave any scientific basis justifying these refusals.

3. Energy performance (OVAM's remarks 2 and 3)

We never had the opportunity to answer the question about the energy performance. The mail of OVAM state the following:

- *"The letter of the Minister of 30.01.2007 […] suggested that both emissions and energy performance should be researched."* and
- *"The fact that the amount of used energy/ton produced clinker is signifanctly different and the fact that there is a lot more loss of energy in the cement industry in comparison with the incineration plant have not been discussed."*

We feel that these statements are not correct:

- It has never been suggest that this study should analyze the energy performance but the sustainability of two processes. The letter of the Minister states indeed the following:

"Ik kan instemmen met uw voorstel om gezamelijk een college van international erkende deskundigen aan te duiden om een analyse te maken van de globale duurzaamheidsbalans van enerzijds de verbranding van afvalstoffen en anderzijds de meeverbranding als nuttige toepassing in de Belgische cementovens" (§5)

The only reference to the energy performance is related to an OVAM's advice and not to the study.

- The energy loss is independent of the use (or not use) of waste in a cement kiln.

Consequently, the energy loss issue is not relevant in this debate.

In addition we would be interested to know what are the basis that allow OVAM to state that *there is a lot more loss of energy in the cement industry in comparison with the incineration plant.*

4. INDAVER (OVAM's remark 6)

This has already been answered in the beginning of the study.

The study has been commissioned in order to tackle a controversy between the Flemish Region and FEBELCEM about the environmental performance of incineration and co-incineration.

The review panel is composed of scientific bodies and of the two parties (OVAM standing for the Flemish region as stated in the letter of Minister Peeters of January 30 2007). There is no need to extend this panel to other parties.

In addition, we note that

- The participation of INDAVER is not needed in regard with the ISO standards (as mentioned during our first meeting)
- TNO took contact with Indaver in order to collect the data's (unfortunately with no success)
- OVAM did not agree to approach Indaver in order to ask them to cooperate to the data acquisition, despite our request.

5. Data asked by OVAM (OVAM's remark 8)

The information requested is of confidential nature. In addition, it is not required in order to perform an LCA analysis (as confirmed by TNO) nor to assess the representativeness.

We therefore do not understand the rational behind this request and do not see the relevance of disclosing such information.

We also stress that OVAM did not sign any confidentiality clause that is an additional reason to not disclose this information.