

Environmental impact of incineration of calorific industrial waste in a rotary kiln and in a cement kiln. A comparison.

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1. Introduction

A scientific study (Vermeulen et al., 2009) compared the environmental impact of incineration of **high** to **medium calorific waste** in a specialised waste incinerator (usually a rotary kiln) with incineration in a cement kiln.

High calorific waste typically has a lower heating value (LHV) of above 16 MJ/kg, for **medium calorific waste** this is typically 11-16 MJ/kg.

These types of waste include:

- waste oil
- waste solvents
- refuse derived fuel: high calorific waste derived from municipal solid waste by mechanical separation combined with biological treatment
- carpet and textile waste
- plastic or mixed plastic waste
- automotive shredder residue, ASR: after removal of hazardous or reusable fluids and parts from an end-of-life vehicle, the remaining car hulk is shredded. Recyclable metals are removed and a residual mixed fraction is obtained. This residual fraction, together with the fluff collected by an air suction installation at the shredder is called ASR.
- meat and bone meal, MBM: a secondary product from the rendering of fat from unmarketable animal tissue

Some of these wastes may be hazardous (see below).

The current waste hierarchy is: material recycling > energy recovery > disposal. Plastic waste should according to this hierarchy, be subjected to a combination of separation and purification processes to obtain 'pure' plastics. However, the costs and the environmental impact of the separation/purification process must be weighed against the benefits of recycling. In practice therefore, energetic valorization (energy recovery) is usually preferred. Moreover, starting from impure and mixed plastics, mostly low quality end products are obtained at reasonable cost. Demand for such low quality end products is generally low. High or medium calorific waste is therefore usually incinerated or co-incinerated in view of energy recovery.

High or medium calorific wastes are not in the first place incinerated or co-incinerated to destroy them, but rather to substitute the fuel needed to operate the installations and to assure their **main functions**. This reduces resource (fuel) depletion and fuel costs. Although low calorific waste may be *thermally treated in both processes at a certain waste management cost*, the first intention is not to replace fuel. Indeed, to fully replace fuel, the calorific value of waste should at least exceed the required average calorific value of the incinerator (see below), otherwise fuel must be added to reach the required average calorific value. Therefore, incineration of low calorific waste was not included in this study.

The main function of a **hazardous waste incinerator** is to *incinerate hazardous and difficult to treat wastes* in the best environmental conditions, which constitutes a major service to society. Many such wastes (e.g. non-recyclable/heavily contaminated soil, some clinical & biohazard wastes, contaminated sludge, contaminated waste water, persistent organic pollutants or POPs) do not have a sufficient heating value or suitable combustion characteristics to be incinerated alone. Auxiliary **fuel** (usually fossil fuel) is therefore required to conduct the incineration. In general, to destroy the waste, a temperature of at least 850°C for at least 2 s is required; for high chlorine waste this is 1100°C for 2 s. For proper operation each incinerator requires input of a given *average calorific value*: for the rotary kilns at Indaver, Antwerp this is about 14MJ/kg. To obtain the needed average calorific value, high or sometimes medium calorific waste can be added to the input to substitute the auxiliary fuel. Process heat in the combustion gases is recovered in a boiler to give steam, which can be used in the process or in other waste treatment processes, or used to generate electricity to be delivered to the electric grid. The ashes (bottom ashes, fly ashes and flue gas cleaning residues) produced in the rotary kiln are disposed in a dedicated landfill.

Hazardous waste is generated by all sectors of society. Examples are:

- from industry and small businesses: wood preservatives, tar, spent activated carbon, certain organic solvents, certain filter cakes, contaminated sludge, oil waste (oils, emulsions), solvent-containing paint, varnish, ink, chlorofluorocarbons, contaminated soil, contaminated waste water, etc.
- from hospitals: sharps, body parts, some medicines, bandages, etc.
- from households: solvents, organic acids, etc.
- from farms: pesticides.

Large quantities of hazardous waste are generated. Although waste prevention reduces hazardous waste generation, many hazardous wastes cannot easily be substituted. Society must therefore assure proper end-of-life treatment or disposal of hazardous waste, to avoid introduction of hazardous components into the food or recycling chains. Proper treatment of hazardous waste should thus be considered a major service to society. Inorganic hazardous waste is disposed in controlled landfills. For combustible or partly combustible hazardous waste, incineration is to-date the only possible or the most acceptable treatment method. The rotary kiln is the incinerator of choice for the treatment of hazardous waste in all aggregation states: whether solid, paste or liquid (in bulk or in drums).

High to medium calorific waste can also be used to partly substitute fuel in a **cement kiln**. The function of a cement kiln is to *produce clinker* in the best process and environmental conditions. Inputs are raw materials, containing specific proportions of calcium oxide, silica, alumina, and iron oxide, and fossil fuel. Fuel is needed to heat the raw materials to the high temperature (1450°C), required for clinker production. Clinker production requires a given *average calorific value* of the fuel in order to ensure the continuity of the process, but in particular to guarantee the quality of the clinker: some cement kilns require an average calorific value of 21MJ/kg at the main burner. The cement kiln dust is to a large extent recycled into the process, depending on the heavy metal content, and when a part remains it is landfilled.

Several types of auxiliary fossil fuel can be used:

- Rotary kiln: fuel oil.
- Cement kiln: coal, petcoke or fuel oil Generally a mixture of coal and petcoke is used.

2. Methodology

The *functional unit* of the study is the incineration of 1 ton of industrial high or medium calorific waste, which substitutes an equivalent energetic amount of fossil fuel. Three types of industrial high calorific waste are considered:

- automotive shredder residue, ASR
- meat and bone meal, MBM
- high calorific solvents.

Table 1 shows the composition and the calorific value (LHV) of these wastes. ASR has in general a much higher heavy metal concentration than the 2 other waste types.

Table 1: Composition and calorific value of the considered wastes

Parameter	Unit	ASR composition range	Average ASR composition	MBM composition range	Average MBM composition	Solvent composition range	Average solvent composition
C	kg/ton	279-627	410	333-557	369	305-477	411
N	kg/ton	8.8-45	19	68-96	83	10-20	15
S	kg/ton	1.9-5.6	3.7	1.0-12	4.0	7.0-10	8
Cal. value	GJ/ton	13-29	17	15-31	21	22-29	25
As	g/ton	1.2-69	30	0.3-25	0.5	2.0-2.9	2.5
Cd	g/ton	2.0-86	34	0.07-5.0	0.4	0.1-2.9	1.5

Cr	g/ton	17-7000	1120	1.0-6.00	3.5	1.9-17	9.3
Cu	g/ton	27-16600	4910	4.1-27	16	55-55	55
Hg	g/ton	0.2-14	4.1	0.003-0.2	0.1	0.1-0.5	0.3
Ni	g/ton	54-4000	734	0-7.80	2.9	2.1-6.3	4.3
Pb	g/ton	94-7000	2610	0.3-36	16	2.6-65	34
Zn	g/ton	1430-14100	8260	70-140	100	157-157	157

In order to compare the environmental impact of incineration of a given high calorific waste in a rotary kiln and in a cement kiln, the following 2 questions are answered:

1. *What is the direct environmental impact of the emissions related to the incineration of 1 ton of calorific waste in a cement kiln and in a rotary kiln incinerator?* In principle, the plant with the least environmental impact should be preferred.
2. *When 1 ton of calorific waste substitutes an equivalent energetic amount of fossil fuel in a rotary kiln or cement kiln, how does the environmental impact change compared to the original scenario?* It is already clear at this stage that the conclusion is highly dependent on the original scenario.

The following 8 environmental impact categories are considered:

- Global warming
- Acidification
- Photochemical ozone creation
- Eutrophication
- Human toxicity
- Fresh water toxicity
- Sea water toxicity
- Terrestrial toxicity

Resource depletion as impact category is only implicitly considered, as the definition of the functional unit assures equal savings of fossil fuel in the rotary kiln and the cement kiln.

Environmental impact categories

- Global warming: greenhouse gases (CO₂, CH₄, etc.) absorb IR radiation from the earth resulting in an increased atmospheric temperature. CO₂ is the most important emission contributing to global warming.
- Acidification: soil and water become more acidic due to the emission of gases (SO₂, NO_x) that react in the atmosphere to form acids (H₂SO₄, HNO₃) leading to acid precipitation. SO₂ and NO_x are the most important emissions contributing to acidification.
- Photochemical ozone creation or photochemical smog formation: ozone precursors such as NO_x, together with volatile organic compounds, under the influence of sunlight form ozone and oxidizing compounds that condense to give photochemical smog. NO_x and SO₂ are the most important contributors to photochemical ozone creation.
- Eutrophication: high concentration of nutrients (nitrate and phosphate) in surface water lead to enhanced algae growth. NO_x is the most important emission contributing to eutrophication.
- Human toxicity: impact of emission of toxic pollutants on human health
- Fresh water toxicity: impact of emission of toxic pollutants on fresh water ecosystems
- Sea water toxicity: impact of emission of toxic pollutants on sea water ecosystems
- Terrestrial toxicity: impact of emission of toxic pollutants on terrestrial ecosystems. Heavy metal emissions are the most important emissions contributing to the different toxicity impact categories.

Emissions of industrial production processes can be classified into *input specific emissions* and *process specific emissions*. Only the input specific emissions will be considered here, as process specific emissions do not change when fuel is substituted by calorific waste. The input specific emissions from calorific waste and fuel are estimated from the calorific value, water content, carbon, sulphur, nitrogen, hydrogen and heavy metal (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) concentrations, as obtained from measurements and literature, making use of *transfer coefficients*. To estimate fuel-NO_x emissions a semi-empirical model (Vermeulen et al., 2010) is used. The emissions of the relevant pollutants are translated into environmental impact in the considered impact categories using the characterisation factors from the CML-database. Environmental impact is expressed as kg of a representative pollutant (e.g. kg SO₂ for acidification).

Input specific emissions depend on the input of the process (waste and fuel). Examples are CO₂, SO₂, fuel NO_x (the NO_x formed from nitrogen in the fuel) and heavy metals. **Process specific emissions** are typical for the process, irrespective of the specific input. Examples are thermal NO_x (the NO_x formed at high temperature from nitrogen and oxygen in the combustion air), dioxins (PCDDs) and furans (PCDFs), and PM₁₀ or dust (although the composition of the dust can be input specific)

Transfer coefficients give the ratio of the amount of an element or compound in a specific output flow, here flue gas, to the total amount in the input. The relation between the amount in the input and in the flue gas is, however, only linear in a reasonable concentration interval. If large amounts of a certain element or compound are fed into the kiln, the neutralisation capacity of the kiln or of the flue gas treatment may be exceeded and the emissions increase exponentially, rather than linearly. For the rotary kiln, transfer coefficients were deduced from online and offline measurements performed at the rotary kilns of Indaver, Antwerp. These were subsequently compared with literature data, in order to ensure an accurate and robust set of transfer coefficients. For the cement kiln an extensive literature search was conducted: transfer coefficients from different sources agreed satisfactorily, so that the average values were used.

Attention was also given to other contributions to the environmental impact, but it was shown that these are negligible. Therefore, only the environmental impacts of emissions to air from the incineration of the calorific waste and of the fuel are taken into account.

Other contributions to environmental impact

It was shown that emissions from transport of waste are only important (in a relative sense) at distances of about 1000km for the impact categories acidification, photochemical ozone creation and eutrophication; for the other impact categories (global warming, human toxicity and ecotoxicity) this is only for still larger distances. This contribution was neglected because transport of waste over long distances should be avoided, the transport distances are generally unknown, and there is no reason why transport distances would differ significantly for the 2 types of incinerators.

Rotary kiln incinerators are all equipped with flue gas cleaning systems, to reach the low emission standards for incineration of hazardous waste. In general, reagent and water consumption by the flue gas cleaning system would not change when fuel is substituted for waste. Cement kilns are only occasionally equipped with a dedicated flue gas cleaning system (deNO_x-installation). For all these reasons the contribution to the environmental impact of flue gas cleaning (reagent use, water use, etc.) was considered process related and was not included.

In rotary kiln incinerators wet scrubbing is often applied. This leads to waste water containing some of the impurities released from the incineration of the calorific waste. This waste water is extensively treated. The corresponding discharges were estimated, but their impact was in all impact categories negligible compared to the emissions to the air. The contribution of waste water discharge was therefore not further considered.

In general, incineration in a rotary kiln does not necessarily require sophisticated pretreatment of the wastes. For the cement kiln, on the contrary, in many cases some form of pretreatment (milling, addition of sorbent, etc.) is required. As the relevant data is not generally available, this aspect was not included in the study. However it would make the comparison more favourable for the rotary kiln.

Another important aspect to consider is that thermal treatment produces ashes. In the cement kiln, dust is to a large extent recycled into the process, and/or landfilled, depending on the concentration of heavy metals, chlorine, etc. The major part of the ashes is incorporated in the final product and the silicates, and aluminium, calcium, and iron compounds replace some mineral feedstock. In addition, however, concentrations of elements such as Cl, Pb, Cd, Cu and Zn may increase, so that product quality may decrease. Moreover, toxic elements from the waste may thus be spread over the technosphere and eventually the environment.

In the case of the rotary kiln, bottom ash is generally used for construction purposes on a class 1 landfill; fly ash and flue gas cleaning residue are used in waste-to-waste applications or stabilised/solidified and landfilled/backfilled to assure containment of the hazardous components. Spreading of toxic elements in the environment is thus excluded. These ash-related aspects are hard to quantify, but should in a comparison not be neglected.

3. Results and discussion

3.1 Direct environmental impact of high calorific waste incineration

3.1.1 Global warming

As can be seen in Figure 1, CO₂ emissions (and thus also the environmental impact due to global warming) are the same for the 3 wastes for both incineration in the rotary kiln and in the cement kiln. This is obvious as we assume that all carbon is completely combusted (converted into CO₂) and that all CO₂ is emitted with the flue gas.

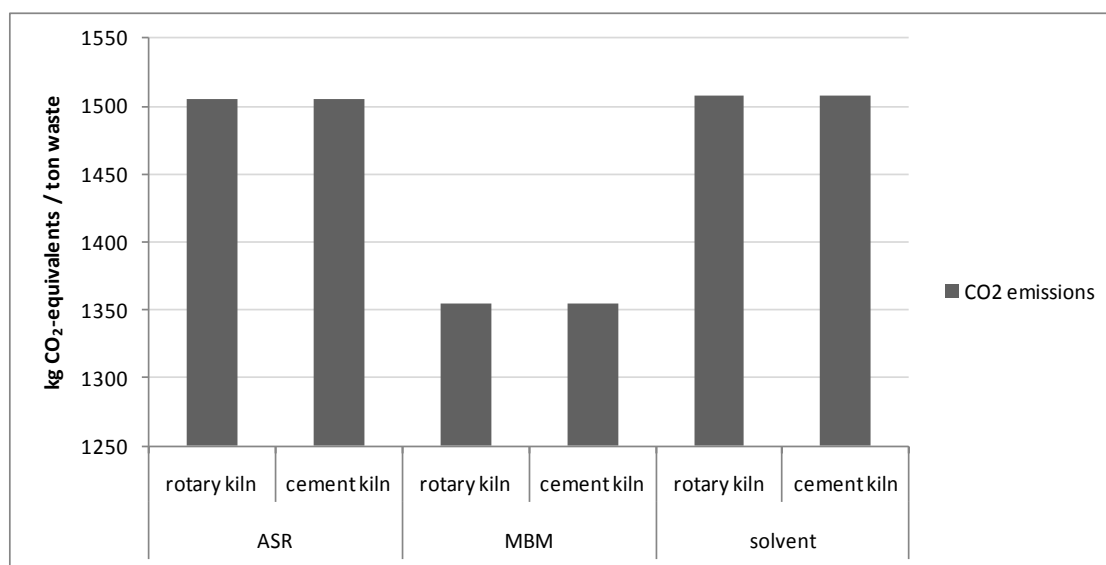


Figure 1: Environmental impact (global warming) of the CO₂ emissions from 1 ton of waste

3.1.2 Acidification

For acidification both SO₂ and NO_x emissions are considered.

SO₂ emissions are significantly higher in a cement kiln than in a specialised incinerator due to the higher transfer coefficient for S in the cement kiln.

For the NO_x emissions only the fuel-NO_x emissions are considered. These are estimated using a semi-empirical model (Vermeulen et al., 2010) based on the process conditions and on the nitrogen, hydrogen and carbon concentration of the waste. From Figure 2 it appears that for all 3 wastes fuel-NO_x emissions (and thus also their environmental impact due to acidification) are lower for the rotary kiln than for a cement kiln. Explanations are that cement kilns are mostly not equipped with a deNO_x installation and that the working temperature of the cement kiln is higher, leading to slightly higher fuel NO_x production.

For the three types of calorific industrial waste, the total contribution to acidification of the cement kiln thus significantly exceeds that of the rotary kiln.

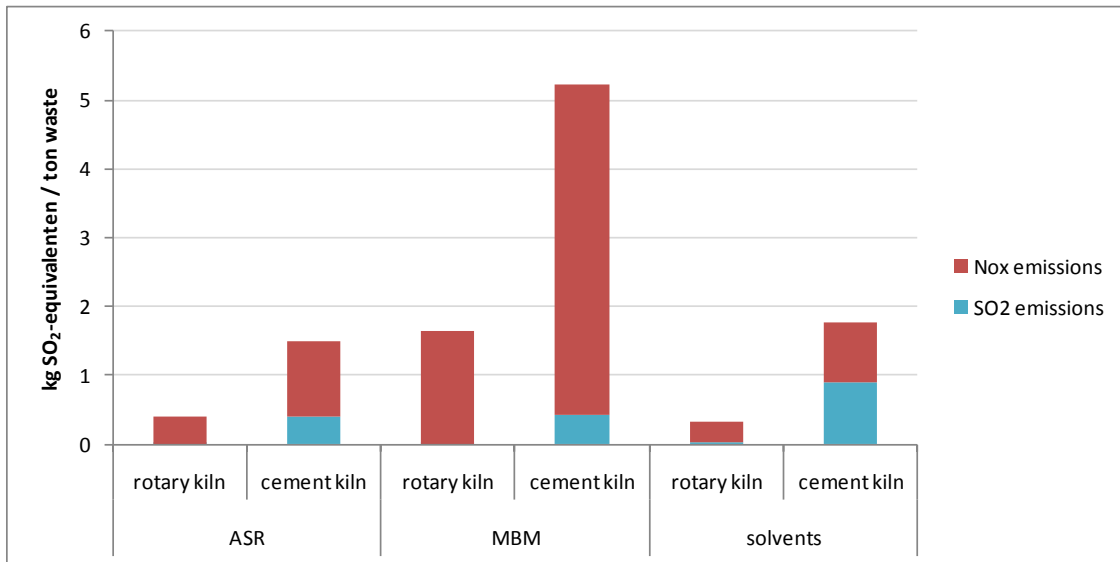


Figure 2: Environmental impact (acidification) of the NO_x and SO₂ emissions from 1 ton of waste

3.1.3 Photochemical ozone creation

NO_x and SO₂ contribute most to photochemical ozone creation, as is the case for acidification. The total contribution to photochemical ozone creation (Figure 3) is for all 3 wastes higher for the cement kiln than for the rotary kiln.

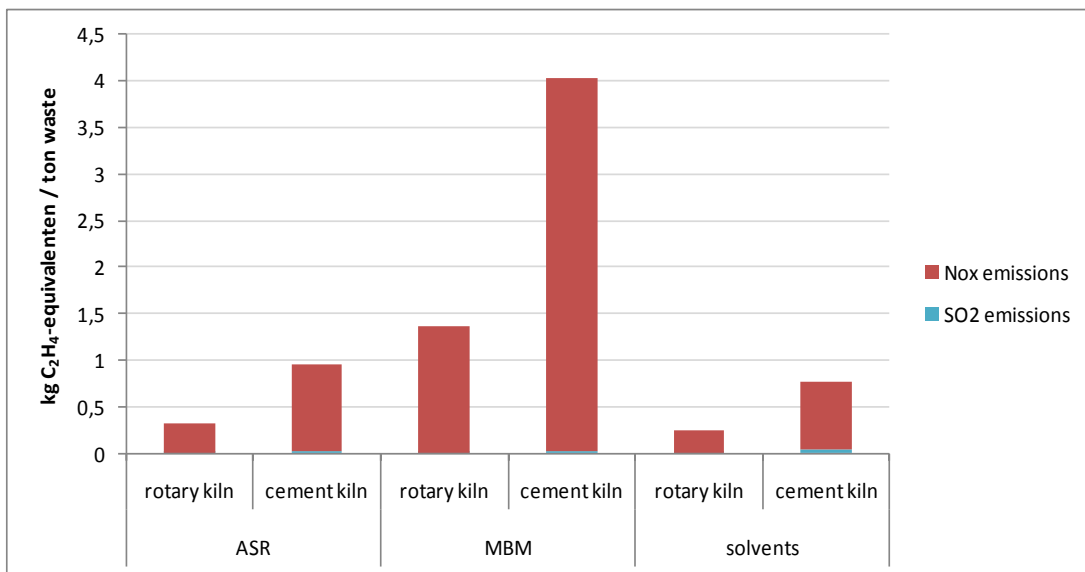


Figure 3: Environmental impact (photochemical ozone creation) of the NO_x and SO₂ emissions from 1 ton of waste

3.1.4 Human toxicity

For human toxicity the impact of a set of 8 heavy metals was investigated: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). Calculations pointed out that, for the wastes considered, these metals are of most interest for all 'toxicity' impact categories. As shown in Figure 4, the heavy metal emissions of a cement kiln exceed these of a rotary kiln, for the 3 wastes types. As expected, the impact for ASR is much larger than the one for MBM and solvents.

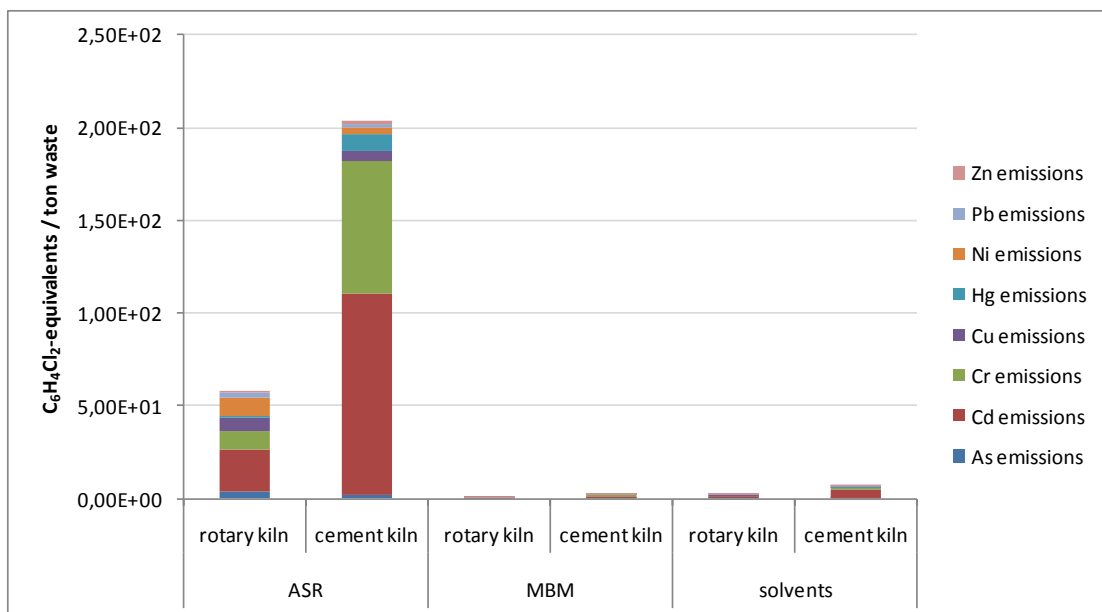


Figure 4: Environmental impact (human toxicity) of heavy metal emissions from 1 ton of waste

3.1.5 Other impact categories

The major contributor to eutrophication is NO_x . Again, as NO_x emissions are higher for the cement kiln than for the rotary kiln, the total contribution to eutrophication is for all 3 wastes higher for the cement kiln than for the rotary kiln.

For ecotoxicity (fresh water toxicity, sea water toxicity, terrestrial toxicity) the same heavy metals as for human toxicity play a role, albeit with a different weight. For all 3 subcategories and all 3 waste types the impact of incineration in a cement kiln exceeds that of incineration in a rotary kiln.

3.2 Effect on environmental impact when calorific waste substitutes fuel

In this section it is investigated how the environmental impact changes, when 1 ton of high calorific waste substitutes an equivalent energetic amount of fuel, both for the cement kiln and the rotary kiln.

The change of the environmental impact is obviously highly dependent on which fuel is substituted. Therefore, for both kilns the change is investigated for 3 scenarios where calorific waste substitutes coal, petcoke or fuel oil, respectively.

3.2.1 Global warming

Figure 5 shows that the environmental impact decreases (negative change), when petcoke or coal is substituted by calorific waste, as the three waste types considered emit less CO_2 than the equivalent energetic amount of petcoke or coal. The same is true when fuel oil is substituted by MBM or solvents, but not when fuel oil is substituted by ASR. For all waste/reference fuel combinations the impact change is obviously the same for the two incinerators.

If we consider a scenario (which is realistic in certain EU countries) in which fuel oil for the rotary kiln and petcoke for the cement kiln are substituted by calorific wastes, the environmental impact due to global warming decreases more for the cement kiln than for the rotary kiln. The reason is simply that fuel oil emits less CO_2 per calorific value than petcoke.

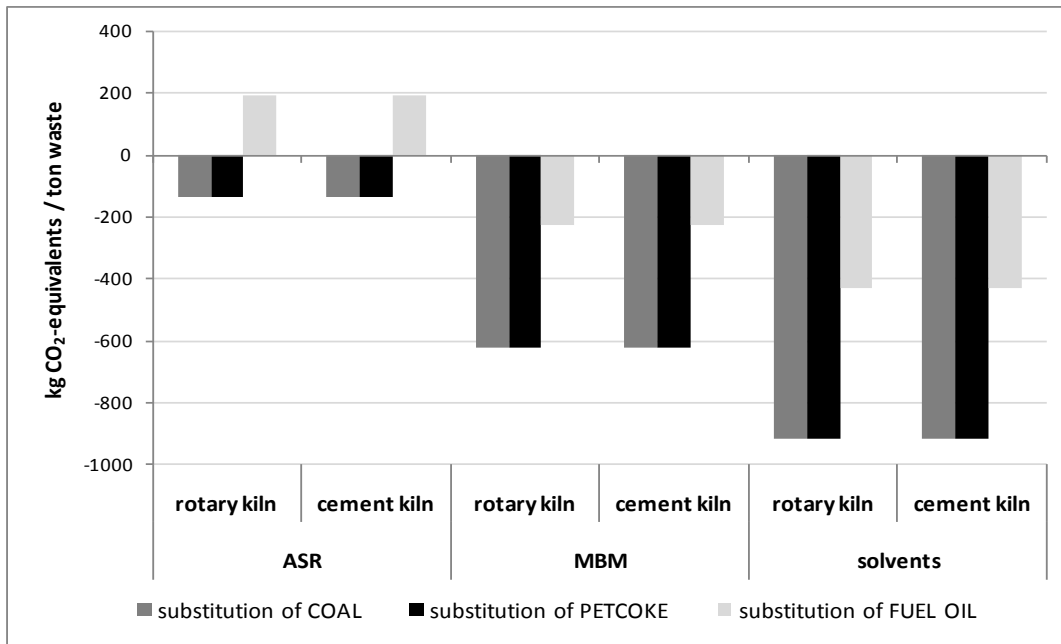


Figure 5: Change of environmental impact (global warming) when fossil fuels are substituted by calorific wastes

3.2.2 Acidification

Figure 6 gives the change in environmental impact (acidification) when different reference fossil fuels are substituted by calorific waste. Substitution of the reference fuels by waste increases the impact, except when petcoke (high sulphur content, thus large SO₂ emission) is substituted by ASR or by solvents in the cement kiln. Except in these 2 cases, for all reference fuel/waste combinations the environmental impact increases less for the rotary kiln than for the cement kiln. The large increase of the environmental impact for MBM is a result of its high nitrogen content.

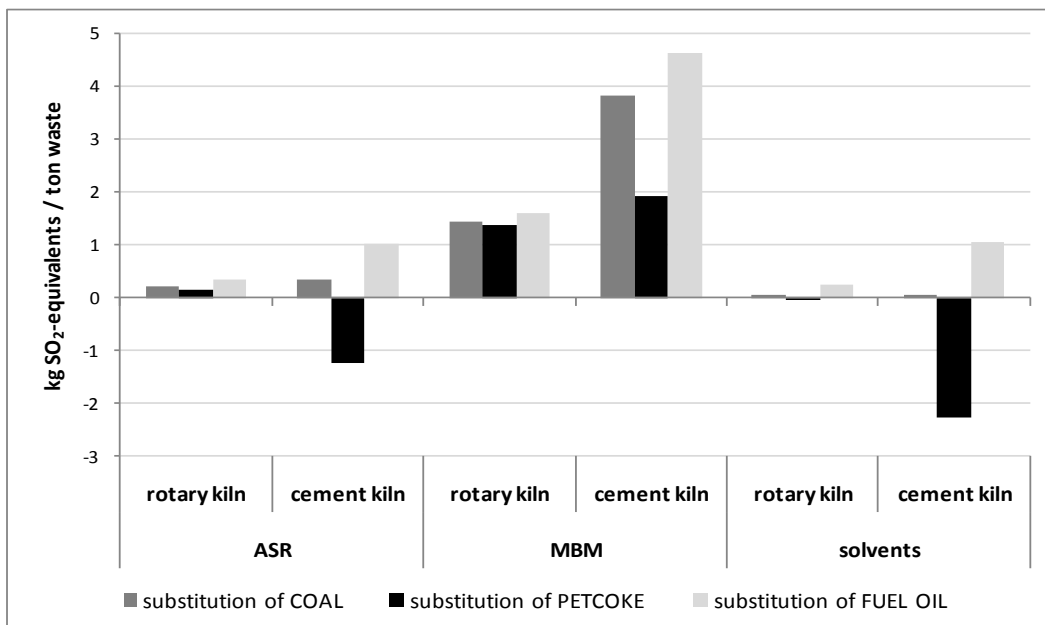


Figure 6: Change of environmental impact (acidification) when fossil fuels are substituted by calorific waste.

3.2.3 Photochemical ozone creation

Substitution of the 3 reference fuels by each of the 3 waste types considered increases the environmental impact (photochemical ozone creation) as shown in Figure 7. The increase of the environmental impact is in each case higher for the cement kiln than for the rotary kiln. The large increase of the environmental impact for MBM is again a result of its high nitrogen content.

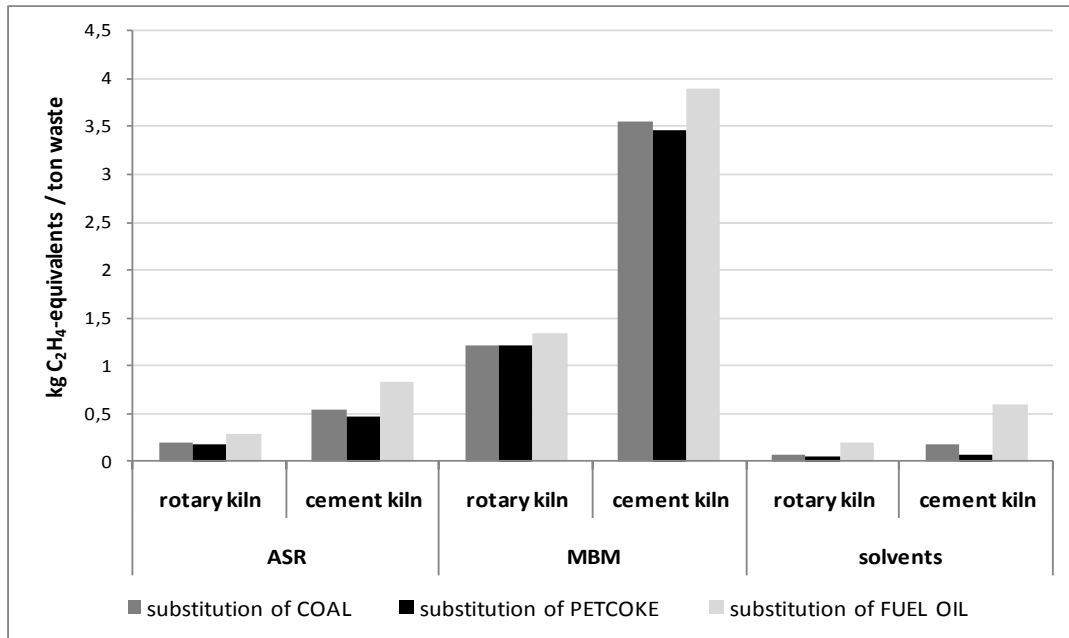


Figure 7: Change of environmental impact (photochemical ozone creation) when fossil fuels are substituted by calorific waste.

3.2.4 Human toxicity

For some high calorific industrial wastes such as ASR, heavy metal emissions have more impact (human toxicity) than for fossil fuels. The environmental impact due to human toxicity therefore increases when these wastes substitute an equivalent energetic amount of fossil fuel (Figure 8). Specialised incinerators such as rotary kilns are in general equipped with a high performance flue gas cleaning system. The transfer coefficients for heavy metals are therefore in general lower for a rotary kiln than for a cement kiln. Therefore, substitution of different reference fuels by ASR increases the environmental impact (human toxicity) for the rotary kiln less than for the cement kiln.

As heavy metal emissions from MBM and solvents are less important, the impact (human toxicity) changes only relatively little, when these wastes substitute the reference fuels. For coal as reference fuel, the environmental impact decreases, since heavy metal emissions from coal are more important than from MBM or solvents.

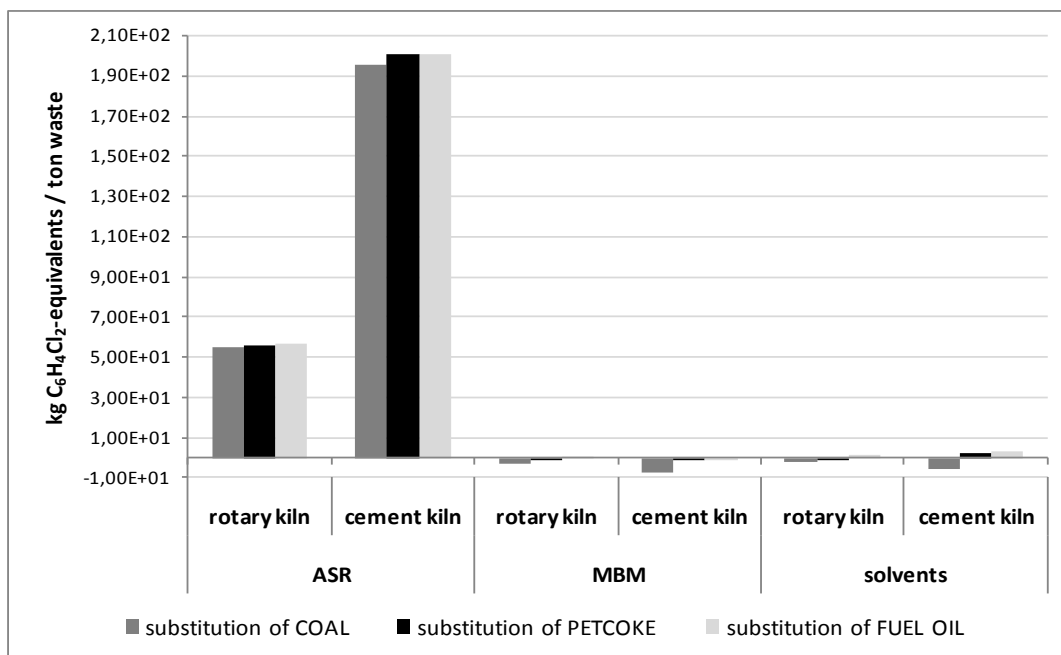


Figure 8: Change of environmental impact (human toxicity) when fuel is substituted by calorific waste

3.2.4 Other impact categories

Substitution of the 3 reference fuels by each of the 3 waste types considered increases the environmental impact (photochemical ozone creation). The increase of the environmental impact is in each case higher for the cement kiln than for the rotary kiln.

For eutrophication the result is similar as for photochemical ozone creation: The environmental impact for the cement kiln was higher than for the rotary kiln.

For ecotoxicity (subcategories: fresh water toxicity, sea water toxicity, terrestrial toxicity) the same heavy metals play the same role as for human toxicity, albeit with a different weight. For all subcategories the result is similar as for human toxicity: for ASR the environmental impact increases less for the rotary kiln than for the cement kiln, while only small changes occur for MBM and solvents.

4 Summary and conclusion

The environmental impact of the incineration of high and medium calorific industrial waste (ASR, MBM and solvents) in a rotary kiln and in a cement kiln was investigated. The waste substitutes the fuel needed to assure the primary function of the incinerators (destruction of hazardous waste, production of clinker). The impact categories global warming, acidification, human toxicity, photochemical ozone creation, eutrophication, and ecotoxicity were taken into account.

Two aspects were considered:

1. *The direct environmental impact* of incinerating 1 ton of calorific waste. This reflects mainly the effectiveness of the flue gas cleaning systems of the incinerators and the capability of trapping heavy metals or SO₂ in the clinker or the ashes. The process with the least environmental impact should in principle be preferred.
2. *The change of environmental impact* when 1 ton of calorific industrial waste substitutes an equivalent amount of fossil fuel, both in the rotary kiln and in the cement kiln. For each waste, we compared the change in both kilns for each of the 3 reference fuels (coal, petcoke, fuel oil). Indeed, simply making the calculation for the currently used fuel would give a biased analysis as it

assumes that the selection of this fuel would be optimal from an environmental point of view, while it is in general merely based on cost and availability.

For all environmental impact categories considered, the direct impact of emissions from incineration of calorific industrial waste in the rotary kiln is considerably smaller than for a cement kiln, except for climate change where the impact is the same. The lower environmental impacts can mainly be attributed to the better flue gas cleaning of the rotary kiln.

The change in the environmental impact depends strongly on the choice of reference fuel. When the same reference fuels are substituted by waste in both installations, the results shown in table 2 are obtained. The numbers indicate in how many fuel/waste combinations (out of 9) each of the 2 kilns is most advantageous (smaller increase or larger decrease). Incineration in a rotary kiln is, for each impact category, in the majority of cases more advantageous than incineration in a cement kiln.

Table 2: Effect on environmental impact, when 1 ton of waste substitutes an equivalent amount of fuel

	Rotary kiln	Cement kiln
Global warming	=	=
Acidification	7	2
Photochemical ozone creation	9	0
Human toxicity	5	4
Eutrophication	9	0
Ecotoxicity	6	3

The numbers indicate in how many fuel/waste combinations (out of 9) each of the 2 kilns is most advantageous (smaller increase or larger decrease).

TNO (De Vos et al., 2007 and <http://www.coprocessing.info/>) compared treatment of various calorific wastes in a cement kiln and in a rotary kiln and arrived at different conclusions: according to the TNO study, for most impact categories incineration in a cement kiln is 'better for the environment'. In the TNO study it was assumed that calorific waste is incinerated in a rotary kiln with the sole purpose of destroying it and to generate steam and electricity. The main function of a rotary kiln incinerator, to incinerate a wide range of hazardous and difficult to treat wastes (also low calorific) in the best environmental conditions, is completely neglected. Indeed, to conduct the incineration of these wastes under proper conditions auxiliary fuel is required. High calorific waste is incinerated in the rotary kiln to substitute this auxiliary fuel. The cement kiln and the rotary kiln thus practice to the same extent energetic valorization of waste. Moreover, TNO defines 'better for the environment' as giving the most advantageous impact change (smallest increase or largest decrease) when 1 ton of waste replaces an equivalent amount of fuel in the cement kiln or is 'destroyed' in the rotary kiln to generate steam and electricity. As petcoke, which has the highest environmental impact of all considered fuels in all impact categories except human toxicity and ecotoxicity, is considered as reference fuel in the cement kiln, substituting it by calorific waste often improves the environmental impact. Because of the high transfer coefficients, changes are generally large. In a wider life-cycle perspective one could also ask what will happen to the petcoke, if it is not used in the cement kilns. For the rotary kiln TNO takes into account only that generation of steam and electricity reduces the total need of steam or electricity generated by other energy sources, so that emissions to the atmosphere from these other energy sources are avoided. The TNO conclusion under these assumptions appears rather obvious.

This shows clearly that the calculations of the direct environmental impact and of the change of the environmental impact when fuel is substituted by calorific waste in different kilns are complementary and both are required. Moreover, substitution of several possible fuel types must be considered, as otherwise biased conclusions may be made. Besides, we believe that in an installation the flue gas cleaning should be optimised to achieve a minimal direct environmental impact and that low emission fuel should be incinerated. Only then does it makes sense to consider the effect upon the impact when fuel is replaced by calorific waste.

5 References

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