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Comparison of the environmental impact of the incineration of calorific industrial waste in a rotary kiln and a cement kiln in view of fuel substitution.

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Management summary

Introduction

This project compares from an environmental point of view, the incineration of industrial waste (mainly high calorific, but also medium calorific waste) in a specialised waste incinerator (rotary kiln) and the co-incineration in a cement kiln (dry process)**.** In both cases, the objective is *substitution of fuel by calorific waste*, in order to avoid resource depletion and to save costs. The comparative study can help to decide in which type of installation, cement kiln or rotary kiln, a given amount of industrial calorific waste can best be incinerated from an environmental point of view.

The study starts from the (obvious) viewpoint that the *function* of a specialised rotary kiln incinerator is to *incinerate difficult industrial waste* (mainly toxic, medical, hazardous, and otherwise difficult to treat industrial waste) in the best environmental conditions. Moreover, it generates steam or electricity as a by-product. The function of a cement kiln, on the other hand, is to produce clinker, in the best possible process conditions. Both processes need large amounts of fuel to obtain the high temperatures required. Substitution of fuel in a rotary kiln by calorific industrial waste is considered comparable to substitution of fuel in a cement kiln, despite intrinsic differences between both processes.

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 calorific waste are considered: industrial sludge, automotive shredder residue and high calorific solvents. All three are currently used as fuel substitutes in both rotary kilns and cement kilns in Belgium and cover different calorific ranges and toxicity levels.

Methodology

In order to help judging in which type of installation a specific high or medium calorific industrial waste can best be incinerated from an environmental point of view, we consider the following 2 questions:

1. *What is the absolute environmental impact due to emissions (and avoided emissions) related to the incineration of 1 ton of such waste in a cement kiln and in a rotary kiln incinerator?*
   The outcome of this comparison reflects the effectiveness of the flue gas cleaning system, the capability of trapping heavy metals and SO_2 (in the clinker or the ashes) and the energy efficiency of the incinerator.

2. *When 1 ton of high or medium calorific waste replaces in each process an equivalent energetic amount of fossil fuel, how does the environmental impact of each process changes?*
   This problem is in the first place investigated for the current situation in Belgium: the actually used fuels, fuel oil (recycled oil to be precise) for rotary kilns and petcokes for cement kilns, are (partially) substituted by calorific waste. This approach is, however, biased: there is no guarantee that the actually used fuel is optimal from an environmental point of view, usually it has merely been selected based on price and availability. Therefore, in addition, the change of environmental impact when other types of fossil fuel would have been substituted is estimated.

As both processes have a different function, a simplified model is used to study the environmental impact of the emissions related to the incineration of 1 ton calorific waste in both kilns. Both processes are characterised by a *main function or product* (destruction of hazardous waste for the rotary kiln and clinker production for the cement kiln); due to these activities *pollutants* are emitted and *by-products* (heat and solid residues) are formed
Emissions due to the collection and transport of waste, investments in buildings, equipment or flue gas cleaning systems and pre-treatment of the waste were not taken into the scope of the study. Discharges of waste water were estimated; they are negligible compared to the impact of air emissions. The environmental impact of the landfill of the solid residues of both processes is not taken into account, as it is difficult to estimate it accurately.
The study was thus limited to the investigation of the environmental impact of direct emissions of the process and indirect emissions related to the production of by-products (steam and electricity).

The following 8 environmental impact categories were considered:

- global warming
- acidification
- photochemical ozone creation
- eutrophication
- human toxicity
- fresh water toxicity
- sea water toxicity
- terrestrial toxicity

Resource depletion as impact category was not studied, since the substitution and thus the saving of fossil fuels is equal for both processes.

The most important emissions to air and the corresponding impact categories are:

- CO_2 ~> global warming
- SO_2 ~> acidification and photochemical ozone creation
- Fuel NO_x ~> acidification, photochemical ozone creation and eutrophication
- Heavy metals ~> human toxicity, fresh water toxicity, sea water toxicity and terrestrial toxicity

The input specific emissions were estimated by the use of (linear) transfer coefficients, which give the ratio of the emissions of an element in one specific output flow, relative to the total amount of that element in the input. For the rotary kiln these transfer coefficients were deduced from online and offline measurements, performed at the rotary kiln 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 in order to obtain the transfer coefficients. The transfer coefficients from different sources agreed satisfactorily, so that the average values could be used. To estimate fuel-NO_x a semi-empirical model was used.
The environmental impact was subsequently deduced from the emissions using the characterisation factors from the CML-database.

Results

As an answer to *question 1,* the results showed that for 7 out of 8 of the considered impact categories, **the absolute environmental impact of emissions due to the incineration of calorific waste in the rotary kiln is considerably smaller than this of emissions due to incineration of the same waste in a cement kiln**. This can be attributed to the better flue gas cleaning of the specialised incinerator and also to some extent to the avoided emissions due to steam and electricity production in the specialised incinerator.

As to the change of the environmental impact (*question 2)*: when the actually used fossil fuels in Belgium are substituted by calorific waste, both systems show in general comparable changes. When, however, the same reference fuels are (hypothetically) substituted in both installations, substitution of fuel by calorific waste in a rotary kiln is in general more advantageous: for global warming the change is the same, for sea water toxicity the cement kiln is more advantageous, while for all other impact categories (acidification, photochemical ozone creation, eutrophication, human toxicity, fresh water toxicity and terrestrial toxicity) the rotary kiln is more advantageous. **The change of the environmental impact depends thus strongly on the choice of the reference fuel**. When in the incinerators fuel containing a high amount of carbon or impurities (e.g. the petcoke used as reference fuel in cement kilns), is substituted by a *cleaner (or lower carbon containing)* calorific waste, the environmental impact can be improved. Moreover, this relative improvement will be highest when the transfer coefficients of the pollutants are highest. On the other hand the installation with the highest transfer coefficient has also the highest absolute environmental impact (question 1).

Conclusions

It can be concluded that the *absolute environmental impact* of incineration of calorific waste in a rotary kiln is for all impact categories (except impact on sea water toxicity) lower than for a cement kiln. The *change of the environmental impact* of both installations, when a reference fuel is replaced by calorific waste, depends strongly on the selected reference fuel. **This shows clearly that the calculations of the absolute environmental impact and of the change of the environmental impact when fuel is substituted by calorific waste are complementary and are both required for this comparative study.**

Besides, we believe that in an installation first the flue gas cleaning system should be optimised to achieve a minimal absolute environmental impact. Only afterwards it makes sense to consider replacing fuel by waste in order to further improve the situation. Moreover, for such comparisons it is best to start from an optimal fuel from an environmental point of view, not from one containing much carbon per calorific value or producing a large quantity of pollutants.

1 Aim

This project compares from an environmental point of view the incineration of industrial waste (mainly high calorific, but also medium calorific waste) in a specialised waste incinerator (rotary kiln) and the co-incineration in a cement kiln (dry process). In particular the environmental impact of the emissions related to the incineration of industrial waste in both processes is considered. In both cases, the objective is *substitution of fuel by calorific waste*, in order to counteract resource depletion and to save costs. The comparative analysis facilitates deciding in which type of installation, cement kiln or rotary kiln, a given amount of industrial waste can best be incinerated from an environmental point of view.
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 calorific waste are considered:

- industrial sludge, typical calorific value of 7 – 16 MJ/kg
- automotive shredder residue (ASR), typical calorific value of 15 – 22 MJ/kg
- high calorific solvents, typical calorific value of 22 – 29 MJ/kg

All three waste types are currently used as fuel substitutes in both rotary kilns and cement kilns in Belgium and cover different calorific ranges and toxicity levels [Annex I].

2 Starting point

The study starts from the (obvious) viewpoint that the aim of a specialised rotary kiln incinerator is to *incinerate difficult waste* (mainly toxic, medical, hazardous, and otherwise difficult to treat industrial waste) in the best environmental conditions. In a lot of cases incineration is the only possible or the most acceptable treatment of these difficult waste streams. Moreover, it generates steam and electricity as a by-product. The major inputs are waste to be destroyed, and fuel (fossil fuels, possibly substituted by calorific waste).
The function of a cement kiln, on the other hand, is to *produce clinker*, in the best process conditions. In this case the product is thus clinker; inputs are raw materials which contain a specific proportion of calcium oxide (65%), silica (22%), alumina (6%) and iron oxide (3%) [van Oss and Padovani, 2003; Hewlett, 1998] and fuel (fossil fuels, possibly substituted by calorific waste).

For the execution of these processes large amounts of fuel are needed, to obtain the high temperatures required. Substitution of fuel in a rotary kiln by calorific industrial waste is considered comparable to substitution of fuel in a cement kiln, despite the intrinsic differences between both processes.

In both installations **fuel** is thus required:

- In the **rotary kiln incinerator**, fuel is necessary in order to conduct the destruction and combustion process at the lowest possible temperature, at which the waste can still be destroyed with an as low as possible environmental impact. In general flame temperatures between 850°C and 1200°C are required in the kiln. For waste containing high chlorine contents, temperature should minimally be 1200°C during at least 2 seconds.
  The input of fuel serves to obtain the necessary temperatures at start-up and to compensate for energy losses (mainly with the flue gases) during combustion. Moreover, to ensure the continuity of the process and a complete burnout of the waste, the incinerator requires a certain *average calorific value* provided by the fuel [Seyler et al., 2005; Pavlas and Tous, 2009]. For a specific rotary kiln this average calorific value depends on the waste that is destroyed and on the working conditions of the kiln. For instance the rotary kilns at the Indaver site require an average calorific value of 14MJ/kg. Process heat is recovered and transformed into steam and electricity that is partly reused in the process itself, and partly applied in other processes or delivered to the electrical grid. The ashes produced in the rotary kiln are disposed in a dedicated landfill.

- In the **cement kiln**, fuel is needed to heat the material to a high temperature (1400-1600°C), required for production of clinker. Especially the sinter process requires flame temperatures of 1800 – 2000 °C for a short time.
  The input of fuel serves thus to obtain the high temperatures for the clinker producing reactions and to compensate for energy losses. Also this type of process requires a certain *average calorific value* of the fuel in order to ensure the continuity of the process, but in particular to guaranty the quality of the clinker to be produced [Bolwerk, 2006; Alsop et al., 2007]. In this case not only the working conditions of the kiln, but also the type of process (wet or dry) and the place where the fuel is fed determine the calorific requirements of the fuel. Cement kilns in Belgium require for instance an average calorific value at the main burner of 21MJ/kg [Bolwerk, 2006]. In the cement kiln flue gases and load flow countercurrent; no excess heat is recovered. The ashes (or cement kiln dust) are to a large extent recycled into the process, depending on the heavy metal content. Part of the cement kiln dust is disposed in a dedicated landfill.

In practice the following types of fossil fuel can be used for the two processes discussed:

- Rotary kiln: coal, petcoke or fuel oil
  in Belgium, mostly recycled oil is used
- Cement kiln: coal (if necessary pulverised), petcoke or fuel oil
  in Belgium, a mixture of coal and petcoke is used

In order to save fossil fuel (in view of resource conservation and to save costs) part or all of the regular fuel needed may, in principle, in both types of installations be replaced by high or medium calorific waste. It is important to note that the fraction of fossil fuel that can effectively be substituted depends on the required calorific value for the incineration process, the type of fossil fuel substituted and the calorific value of the waste substituting the fossil fuel.

This study investigates the effects of substituting marginal amounts of fossil fuels by certain industrial waste types and takes thus not into account the energetic limitations of the kilns. If however large amounts of fossil fuels (several percentages) are being replaced in the kilns, these aspects should also be taken into account.

3 Methodology

In order to help judging in which type of installation a specific type of high or medium calorific waste can best be incinerated from an environmental point of view, we consider the following questions:

1. *What is the absolute environmental impact due to emissions (and avoided emissions) related to the incineration of 1 ton of such waste in a cement kiln and in a rotary kiln incinerator?*

   The outcome of this comparison reflects the effectiveness of the flue gas cleaning system, the capability of trapping heavy metals and SO_2 (in the clinker or the ashes) and the energy efficiency of the incinerator.

2. *When 1 ton of high or medium calorific waste replaces in each process an equivalent energetic amount of fossil fuel how does the environmental impact of each process changes?*

   On the one hand, this problem is investigated for the current situation in Belgium: the actually used fuels, fuel oil for rotary kilns and petcokes for cement kilns, are (partially) substituted by calorific waste. This approach is however biased: there is no guarantee that the actually used fuel is optimal from an environmental point of view. Therefore also the change of environmental impact when other types of fossil fuel would have been substituted is estimated.

As both processes have a different function, a simplified model is used [figure 1] to study the environmental impact of the emissions related to the incineration of 1 ton calorific waste (input) in both kilns. Both processes are characterised by a *main function or product*, being the destruction of hazardous waste for the rotary kiln and clinker production for the cement kiln; due to these activities *pollutants* are emitted and *by-products* (heat and solid residues) are formed. Heat and solid residue can be considered as a secondary output of the processes, without being the main aim. They can be recycled into the process itself, used in other applications or landfilled.

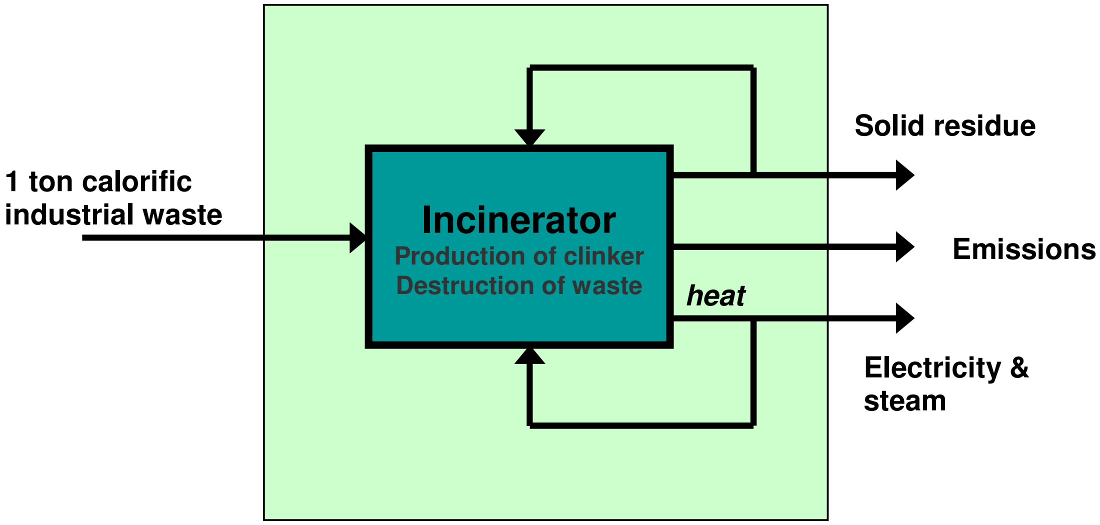

Figure 1: Inventory of the emissions and co-products caused by the incineration of 1 ton calorific industrial waste

The process heat recovered in the rotary kiln is partly used in the process itself and partly applied in other processes (at the same site or in surrounding companies) or fed as electricity to the electrical grid. When electricity and heat are applied in other processes or delivered to the electrical grid (as is the case for the rotary kiln), emissions that would occur when the same amount of steam or electricity is produced in natural gas or coal fired units (the marginal power source in Belgium and Europe [Finnveden, 2005]), are avoided. In the cement kiln, combustion gases and load flow countercurrent; no excess heat is recovered.

The ashes produced in the rotary kiln are disposed in a dedicated landfill, while the cement kiln dust is to a large extent recycled into the process, depending on the load of heavy metals. Part of the cement kiln dust is also landfilled. The environmental impact of the landfilling of the ashes of both processes (bottom ash, flue gas cleaning residues, cement kiln dust, …) is not taken into account, as the impact is uncertain [Hellweg, 2000; Bruder-Hubscher et al., 2001; Astrup et al., 2006; Obersteiner et al., 2007]. Moreover the possible environmental impact due to trapping pollutants (especially heavy metals) in clinker and thus the dispersion of these pollutants in cement is not taken into account.

Emissions due to collection and transport of waste, construction of buildings, equipments or flue gas cleaning systems and pre-treatment of waste are not taken into the scope of the calculations.

It is assumed that the transport and collection of the industrial waste is similar for both processes, so that it can be excluded in a comparative study. Besides, if the waste is not transported over long distances, the environmental impact of the transport is in general small in comparison to the actual incineration process [Rabl et al., 2008; Finnveden et al., 2007].

As this investigation is made for the situation in Belgium, where both incinerator types already exist, investment costs are not considered. For countries having only one of these processes available (or even none), taking into account the investment costs is mostly inevitable when making general waste management decisions.

Finally, it must be remarked that quality requirements for fuel for cement kilns, are higher than for specialised waste incinerators. A homogeneous input for the cement kiln often requires an intensive pre-treatment of the waste. In this study however only industrial waste streams, suitable for both processes, are considered. This way also pre-treatment could be excluded from this comparative study.

3.1 Inventory of emissions

Emissions of waste treatment processes can be classified into two groups: *input specific emissions* and *process specific emissions*. Some emissions however e.g. NO_x show characteristics of both categories: emissions of fuel-NO_x are input specific, while emissions of thermal NO_x are process specific [Miller and Bowman, 1989; Hill and Smoot, 2000; Glarborg et al., 2003]. The fuel NO_x and thermal NO_x were considered separately.

While it is obvious that input specific emissions are allocated to the input of the process, process specific emissions are in general allocated to the process and its function [Seyler et al., 2005]. In this study, *process specific emissions* are for the *rotary kiln* allocated to the *destruction of hazardous waste*, those of the *cement kiln* to the *production of clinker*.

Input specific emissions to air and impact categories:

- CO_2 ~> global warming
- SO_2 ~> acidification and photochemical ozone creation
- Fuel NO_x ~> acidification, photochemical ozone creation and eutrophication
- Heavy metals ~> human toxicity, ecotoxicity

Process specific emissions to air and impact categories:

- Thermal NO_x ~> acidification, photochemical ozone creation and eutrophication
- PCDDs and PCDFs ~> human toxicity, ecotoxicity
- PM_{10} or dust ~> human toxicity

Emissions to water and impact categories:

- Nitrogen-content ~> eutrophication
- Phosphorus-content ~> eutrophication
- Heavy metals ~> human toxicity and ecotoxicity

By-products

- Electricity
- Steam
- Solid residues

3.1.1 Input specific emissions to air

Input specific emissions are function of the composition of the input (calorific *waste and fuel)*. If the input is changed, these emissions will change as well. Input specific emissions are thus allocated to the input of the process. Therefore it is important to first obtain all the necessary data about the calorific waste, used for fuel substitution as considered in this study. The following data are needed to estimate the most relevant airborne emissions [Section 4.1]:

- Calorific value
- Water content
- Carbon content
- Sulphur content
- Nitrogen content
- Hydrogen content
- Heavy metal content (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn)

Annex I gives data for both the fossil fuels and the industrial calorific wastes considered. This data has been obtained from measurements at the Indaver site and literature search.

To estimate the fate of the elements in the input, usually linear transfer coefficients are used. This linear relation is however only valid within a reasonable interval [Abanades, 2001]. If large amounts of a certain element (e.g. carbon, sulphur, nitrogen, hydrogen or heavy metals) are fed into the kiln, it is possible that the neutralisation capacity of the kiln and its flue gas treatment is exceeded. In this case the emissions tend to increase rather exponentially than linearly.
The (linear) transfer coefficients give the ratio of the emissions of a specific element in one specific output flow relative to the total amount in the input of that element [Equation 1]

$$\text{transfer coefficient}_{\text{i, air}} = \frac{emission_{\text{i, air}}}{input_{\text{i, total}}} \qquad \textbf{[1]}$$

With: transfer coefficient $_{\text{i, air}}$ = fraction of pollutant i, emitted into the air
emission$_{\text{i, air}}$ = total emission of pollutant i to the air over a certain period (e.g. one year)
input$_{\text{i, air}}$ = total amount of pollutant i, fed to the incinerator over a certain period (e.g. one year)

To apply this method however, knowledge about the partitioning of the elements between flue gas, water and solid residue, is necessary). In general transfer coefficients of an element are primarily function of the physicochemical properties of the element, which determines the amount of evaporation, entrainment, …. In addition however also occurrence and distribution of other elements in the waste (e.g. chlorine, sulphur, …), physicochemical conditions of the incinerator (e.g. temperature, composition of the flue gas, type of incinerator, …) and combustion kinetics (e.g. retention time, mixing conditions, …) influence the partitioning to some extent.

Several studies have been conducted to investigate the exact influence of these parameters. Morf and Brunner [2000] and Belevi and Moench [2000] concluded that the transfer coefficients (especially those of heavy metals) were basically a function of the physicochemical properties of the elements and the working conditions of the incinerator. Since only marginal changes in normal operation of the incinerators are considered in this study, working conditions of the incinerators are assumed constant.

For this study, transfer coefficients for the rotary kiln were deduced from online and offline measurements performed for the rotary kiln at the Indaver site in Antwerp during normal operation. These were subsequently compared with literature data, in order to ensure an accurate and robust set of transfer coefficients. Annex II shows the transfer coefficients that have been used and compares these with literature data.

For cement kilns an extensive literature search has been conducted in order to make a good estimate of the transfer coefficients [Annex II]. In this study the average values have been used from different sources, showing good consistency (Denis, 1999; Ministerium fur UNLV, 2000; Seyler et al., 2005; Genon and Brizio, 2008 and data from CBR Lixhe).

For fuel-NO_x however, transfer coefficients for both processes are strongly dependent on process conditions and on the composition of the waste. As a consequence transfer coefficients cannot be assumed constant for every waste type, as it is the case for other pollutants such as CO_2, SO_2 and heavy metals. Based on literature research [Baumbach, 1996; Jones et al., 1999; Winter et al., 1999; Glarborg et al., 2003; Rogaume et al., 2005; Streibel et al., 2006; Chyang et al., 2007; Afsharvahid et al., 2008; Dagaut et al., 2008] and data from different incinerators a semi-empirical model was developed in order to make a crude estimate of transfer coefficients for fuel-NOx emissions. As can be seen in Annex III, not only the working conditions of the incinerator, but also the nitrogen and bounded hydrogen content (water content not taken into account) of the input will influence the specific transfer coefficients of the fuel-NOx. According to Chyang et al. (2007) the hydrogen content of the input will enhance the conversion of fuel nitrogen into NOx, while high levels of nitrogen will rather decrease the conversion into fuel-NO_x.

Beside the partitioning of the elements between flue gas, water residues or solid residues, also the *speciation* of the elements (chemical form of the elements in the residues) is determinant for the environmental impact of the incineration process. Most of the heavy metals (e.g. arsenic, selenium, chromium and mercury) exist in several oxidation states, whereas their toxicity is a strong function of the specific oxidation state at which they occur in the environment. Chromium for example is usually present as oxides of trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)). While Cr(III) is a natural compound of low toxicity (characterisation factor for human toxicity: $6.5\ 10^2$ kg $C_6H_4Cl_2$-equivalents per kg), hard to dissolve in water and hard to be absorbed by plants, Cr(VI) is a highly toxic industrial product (characterisation factor for human toxicity: $3.4\ 10^6$ kg $C_6H_4Cl_2$-equivalents per kg). Cr(VI) is soluble in water and can enter the body via inhalation, ingestion and contact with the skin.

The specific oxidation state of chromium depends largely on the working conditions of the incinerator, e.g. flame temperature and oxygen excess and the composition of the input [Chen et al., 1997; Kashireninov and Fontijn, 1998; Guo and Kennedy, 2001].

3.1.2 Process specific emissions to air

Process specific emissions are assumed to be independent of the input to the process (e.g. raw materials, fuel) and occur solely because of the execution of the process. They depend on the process and its operating conditions, e.g. temperature, oxygen content, … . As a consequence, changes in the input will not (or barely) alter these emissions. This assumption is reasonable for emissions that are completely determined and controlled by the technology and operation of the process like dust, dioxins and thermal NO_x. In order to make an accurate estimate of these emissions only data from processes and working conditions are necessary.

These emissions are for this reason related to the functionality of the kiln: the process specific emissions of the rotary kiln are allocated to the destruction of hazardous waste, those of the cement kiln to the production of clinker. This implies that these emissions will not be taken into account when the absolute environmental impact of 1 ton of high or medium calorific waste is determined [Section 3.2].

3.1.3 Emissions to water

An advantage of a cement kiln (especially the dry process) is that there are no or barely any discharges into water. Specialised incinerators however use water in the flue gas scrubber, which generates polluted wastewater. This wastewater however is treated intensively, so that the actual discharges are rather low and process dependent. In Annex IV the overall discharges into water from the rotary kiln at the Indaver site, after water treatment, are given and the environmental impact is compared to the environmental impact of the emissions to air. From this calculation it can be concluded that the environmental impact of the discharges into water can be neglected in comparison to the emissions into air, as it accounts for less than 1% of the total environmental impact.

In some specialised incinerators the water is re-circulated and evaporated completely in the process. This way zero discharge can be put into practice for specialised incinerators as well.

3.1.4 By-products

As stated before, both processes are characterised by a *main function* and *by-products* [Figure 1].

The process heat, produced during incineration of the calorific waste can be recycled into the process or transformed into steam or electricity [Figure 1]. When electricity or steam is produced from an *excess of heat*, it can be applied in other processes (in or outside the waste treatment company) or delivered to the electrical grid. Consequently, this use of electricity or steam avoids certain emissions that would otherwise occur when the same amount of energy was produced in natural gas or coal fired units [Finnveden, 2005]. Based on data and literature, we assumed gas and coal fired power units to be the marginal power source in Belgium. Estimates of the avoided emissions from gas and coal fired power units are obtained from the Eco-invent database and extensive literature search. To estimate the avoided emissions, the calorific value of 1 ton of the considered industrial waste was multiplied by an *energy yield factor*. This yield factor was obtained as the fraction of the amount of energy applied in other processes or delivered to the electrical grid to the total energy input. This way process heat is allocated to the calorific value of the input [Seyler, 2005]. Depending on the calorific value of the input, more or less excess heat will be generated and thus more or less emissions will be avoided. Avoided emissions related to an excess process heat are thus allocated to the calorific value of the process input; they are different for different waste types.

The amount of ashes strongly depends on the waste to be incinerated and can also be recycled into the process, as is the case in the cement kiln. The environmental impact of the landfilling of the ashes of both processes (bottom ash, flue gas cleaning residues, cement kiln dust, …) is not taken into account, as the impact is uncertain [Hellweg, 2000; Bruder-Hubscher et al., 2001; Astrup et al., 2006; Obersteiner et al., 2007].

3.2 Estimation of the absolute environmental impact

In order to answer the first question: *'What is the environmental impact when 1 ton of high or medium calorific waste is incinerated in a rotary kiln incinerator or in a cement kiln?'*, the direct emissions of the process and indirect (avoided) emissions (related to the steam and electricity production from excess heat) when incinerating 1 ton of high calorific waste, will be translated into *environmental impacts* for the relevant impact categories:

- global warming
- acidification
- photochemical ozone creation
- eutrophication
- human toxicity
- ecotoxicity (respectively fresh water, sea water and terrestrial toxicity)

The environmental impacts for the relevant impact categories are subsequently determined using the characterisation factors from the CML-database [Annex V].
The results of these calculations are shown in Annex III in detail and discussed in Section 5.1.

Resource depletion was not studied, since the substitution and thus the saving of fossil fuels is equal in both options.
As explained in Section 4.1, on the one hand the discharges into water can be neglected in comparison to the emissions into air and on the other hand the process specific emissions to air will not be allocated to the fuel or its substitutes. In this way only the input specific emissions, and the avoided emissions due to the production of steam and electricity from excess heat will have to be considered.

3.3 Comparison of waste incineration scenarios relative to a reference scenario

This section aims at answering the question: '*When 1 ton of high or medium calorific waste replaces in each process an equivalent energetic amount of fossil fuel how does the environmental impact of each process changes?'*
This can be investigated in a 'business as usual scenario' where the actual fossil fuel, in this case used in Belgium, for the considered processes is replaced by calorific waste. In addition the change of environmental impact for different types of fossil fuel is estimated and compared.

As explained in Section 2, the two types of processes being compared, have several intrinsic differences. One of the most important is the difference in functionality which makes it particularly difficult to compare all the emissions of these two processes. Questions that arise are e.g. how must 'products' like clinker production or the destruction of low calorific, toxic waste be taken into account properly, since it is not easy to translate this into environmental impact categories.

These difficulties can be overcome by setting up hypothetical scenarios, with constant amounts of products generated in each scenario. In this way one can decide in which kiln specific high or medium calorific wastes cause the largest environmental improvement or the lowest environmental deterioration in comparison to the reference scenario.

The set up of these scenarios assumes that both specialised incinerators and cement kilns still have some capacity left for the substitution of fuel by high or medium calorific waste. In this way one can discuss whether 1 ton of a specific calorific waste, should rather be incinerated in a rotary kiln incinerator, substituting fossil fuel *(scenario 1)*; or whether it is better for environment to use the same amount of industrial waste as fuel substitute in a cement kiln *(scenario 2)*. By comparing these two scenarios with a reference scenario, where the energy for both processes is obtained only from fossil fuels, the environmental improvement or deterioration can be calculated for each impact category.

The light blue frame in Figures 2, 3 and 4 represents the boundaries of the scenarios. In the different scenarios emissions of a specialised incinerator and of a cement kiln are taken into account, along with the avoided emissions related to the formation of by-products.
We apply techniques of life cycle analysis, but do not have the aim to carry out an LCA.

3.3.1 Scenario 1

In this scenario the reference flow of 1 ton of calorific waste is incinerated in the specialised incinerator [Figure 2], substituting an equivalent energetic amount of fossil fuel (fuel oil for the case of Belgium), which would otherwise be used to generate the necessary heat for the destruction of low calorific and/or toxic waste.

3.3.2 Scenario 2

In scenario 2 the cement kiln incinerates the reference flow of 1 ton of calorific waste [Figure 3], substituting an equivalent energetic amount of fossil fuel (petcokes for the case of Belgium), which would otherwise be needed for the production of clinker.

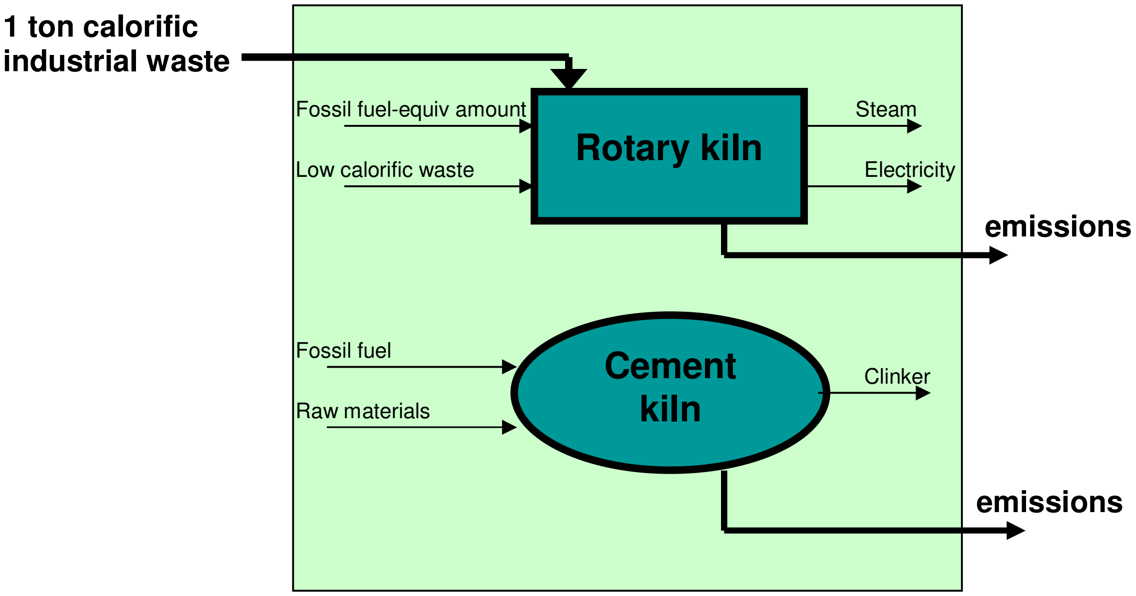

Figure 2: Scenario 1; 1 ton of calorific industrial waste is incinerated in a specialised incinerator

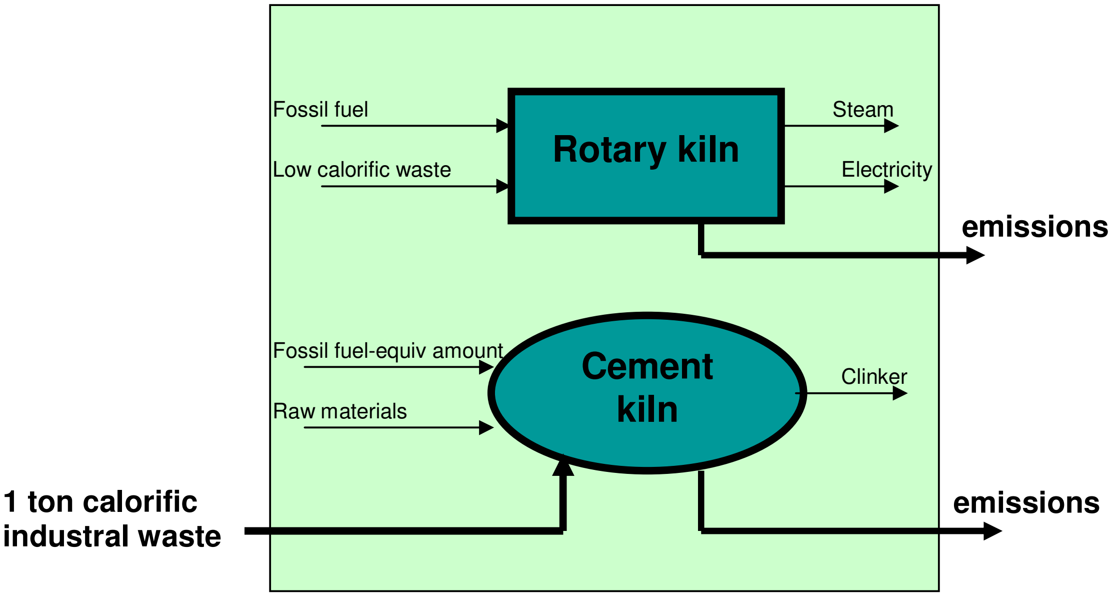

Figure 3: Scenario 2; 1 ton of calorific waste is incinerated in a specialised incinerator

3.3.3 Reference scenario

In order to determine the environmental effect of substituting fossil fuel with high or medium calorific industrial wastes, one has to make a comparison with the reference situation, where the total energy for both processes is obtained from fossil fuels only, instead of calorific waste [Figure 4].

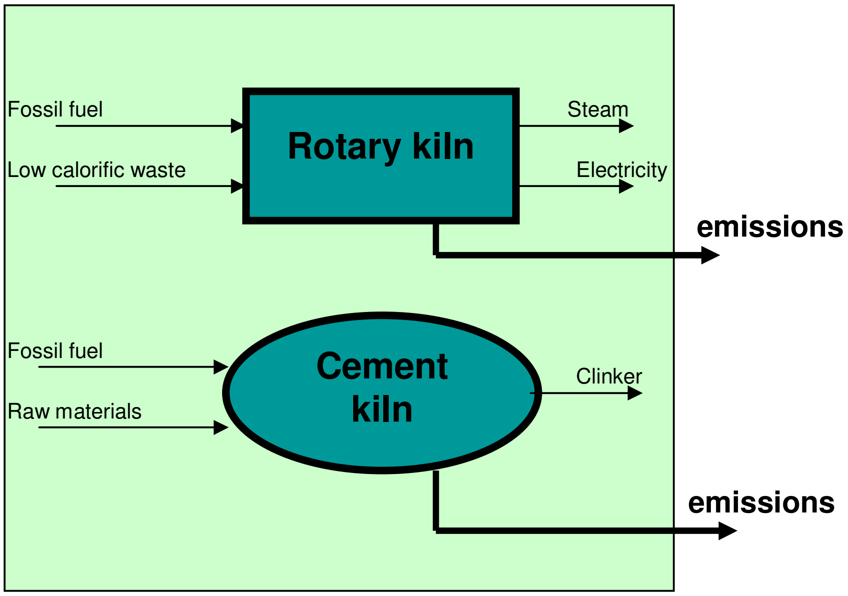

Figure 4: reference scenario

Each of the scenarios, as can be seen in Figure 2, 3 and 4, takes the most important inputs and outputs into account. It must be kept in mind that in each scenario the generation of products (clinker) and by-products (steam, and electricity) remains constant, since the input of raw material and the calorific value of the fuels also remains constant for each scenario. The light blue frames in the figures represent the boundaries of the scenario, which is clearly focused on the actual incineration processes.

The results of these calculations are discussed in Section 5.2 and shown in more detail in Annex III.

3.3.4 Actual comparison

The first two scenarios will give the absolute emissions of 1 ton of calorific waste in each hypothetical situation. As already stated, in order to know which is the best environmental option, incineration of calorific waste in a specialised incinerator or in a cement kiln, these scenarios will be compared with the reference scenario for the most important airborne emissions.

The difference between scenario 1 and the reference scenario will give an estimate of the *change of environmental impact* due to emissions of the incineration of 1 ton waste in a rotary kiln incinerator, substituting an equivalent energetic amount of fossil fuel. The difference between scenario 2 and the reference scenario will give an estimate of the *change of environmental impact* of the emissions due to the incineration of 1 ton waste in a cement kiln, substituting an equivalent energetic amount of fossil fuel.
These comparisons can help to make a decision about which situation is more favourable: using high or medium calorific wastes in a rotary kiln incinerators and using fossil fuels (e.g. coal, petcoke or fossil fuel) in cement kilns, or vice versa.

The current situation in Belgium will be investigated in a ‘business as usual scenario’ where the actually used fuels of both incinerators in Belgium are considered, namely fuel oil (recycled oil to be precise) for rotary kilns and petcokes for cement kilns. This gives however only a biased indication of the change of environmental impact, as it would be valid for Belgium but not necessarily for other countries and would assume that the existing fuel selection in Belgium is optimal from an environmental point of view, while this choice is in general based on price and availability. As a consequence also estimates are made of the changes in environmental impact when other types of fossil fuel would have been substituted. (Section 5.2, Annex III)

Due to the specific set up of these hypothetical scenarios, allocation problems of process specific emissions and difficulties with taking products properly into account can be overcome, as already stated. Indeed a suitable selection of the scenarios, which implies the same amount of products and by-products, makes that the products and by-products are cancelled out. In addition, only the input specific emissions have to be taken into account, since only those will differ due to a change of input, between scenario 1 and the reference scenario or between scenario 2 and the reference scenario, as follows directly from the definition of process specific emissions (Section 3.1.2)

Thus, only the following airborne emissions have to be considered:

- CO_2 ~> global warming
- SO_2 ~> acidification, photochemical ozone creation
- Fuel NO_x ~> acidification, photochemical ozone creation and eutrophication
- Heavy metals ~> human toxicity, ecotoxicity

4 Results and discussion

4.1 Estimation of the absolute environmental impact

As discussed in the previous section, first the absolute environmental impact of the incineration of 1 ton of high or medium calorific waste will be estimated. The input related emissions and the avoided emissions due to electricity or steam production will be taken into account, since the process related emissions are allocated to the main function of each process (respectively low calorific or toxic waste destruction and clinker production) and the discharges into water can be neglected in comparison to the airborne emissions, as discussed in Section 4. The data used to obtain the environmental impact due to the incineration of 1 ton of high or medium calorific waste can be found in Annex II, III and IV.

In some cases a general improvement of absolute environmental impact can be realized: when the direct emissions due to the incineration of the waste are lower than the avoided emissions due to electricity or steam production, a net negative value (= improvement) is obtained.

4.1.1 Global warming

As can be seen in Figure 5, the environmental impact due to global warming is less for the rotary kiln than for the cement kiln. Since the transfer coefficients for both incinerators are 100%, the only difference in environmental impact of these absolute emissions is caused by the avoided emissions due to steam and electricity production in the rotary kiln.

Sludge (e.g. from municipal wastewater treatment plants) contains almost only biogenic carbon, consequently its impact on global warming is not relevant . Due to the avoided CO_2 emissions, a negative environmental impact can be distinguished for the incineration of sludge in the rotary kiln, which means that a general avoidance of CO_2 emissions can be realised in this case.

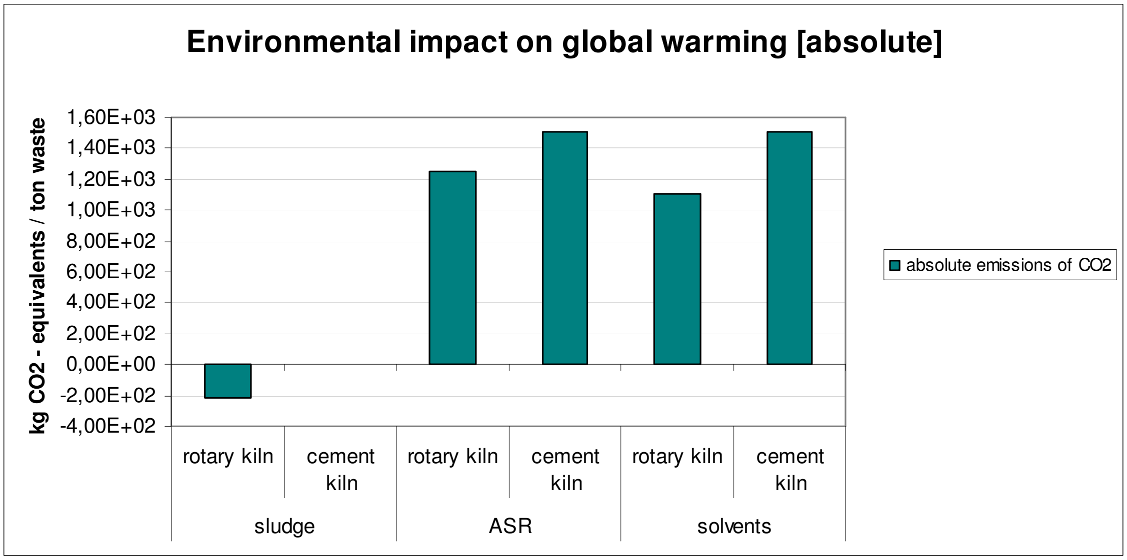

Figure 5: The environmental impact of the absolute CO_2 emissions on global warming

4.1.2 Acidification

For acidification both SO_2 and NO_x emissions are considered.

The environmental impact on acidification due to the SO_2 emissions is much higher in a cement kiln than in a specialised incinerator due to the large difference in transfer coefficients: 0.2% for the rotary kiln and 3.87% for the cement kiln [Annex II, Figure 6]. Moreover, the avoided SO_2 emissions in the rotary kiln, due to electricity and steam production, are for the three considered wastes higher than the direct emissions due to incineration, explaining the negative value (decrease in environmental impact) in Figure 6.

For the NO_x emissions only the fuel related NO_x emissions are considered. They are estimated using a semi-empirical model based on the process conditions and on the hydrogen and nitrogen content of the waste [Section 4.1.1]. From Figure 6 it is clear that the environmental impact on acidification of fuel-NO_x emissions is lower for a specialised incinerator than for a cement kiln, for all three waste types. This is due to the lack of DeNOx installations and, in a less extent, to the higher working temperature in most cement kilns, next to the avoided emissions (electricity and steam production) in the rotary kiln.

For all three types of calorific industrial waste the total contribution on acidification is significantly higher for the cement kiln than the rotary kiln. In a specialised incinerator even an overall decrease of impact on acidification is seen for ASR and solvents; the reasons are the low direct SO_2 and NO_x emissions due to the presence of a thorough flue gas cleaning, and the avoided emissions due to steam and electricity production.

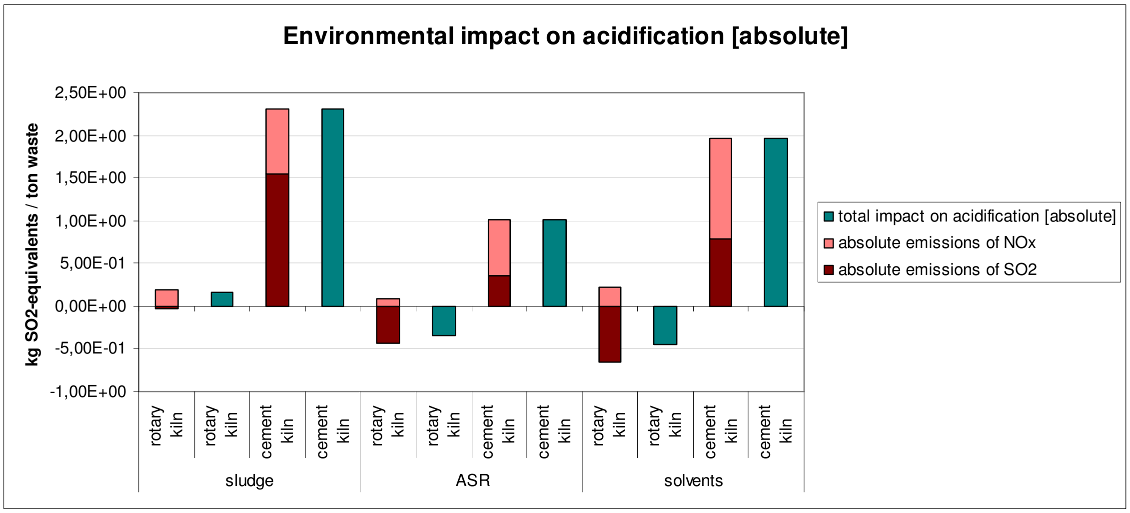

Figure 6: The environmental impact of the absolute NO_x and SO_2 emissions on acidification.

4.1.3 Photochemical ozone creation

As for acidification, also NO_x and SO_2 emissions contributes to photochemical ozone creation. The characterisation factors for both pollutants differ however for both impact categories . For photochemical ozone creation NO_x emissions have a higher environmental impact than SO_2 (4.27 10^{-1} vs. 4.8 10^{-2} C_2H_4-equivalents), while for acidification the opposite is true (5.1 10^{-1} vs. 1.2 SO_2-equivalents).

For all three types of calorific industrial waste the total contribution on photochemical ozone creation is higher for the cement kiln than the rotary kiln [Figure 7]. This can be attributed to the avoidance of SO_2 and NO_x emissions due to electricity and steam production in combination with a thorough flue gas cleaning system, resulting in very low transfer coefficients for the rotary kiln incinerator.

4.1.4 Eutrophication

For eutrophication only NO_x-emissions are considered.

The fuel-NO_x emissions are higher for the cement kiln than for the rotary kiln. This is due to the lack of DeNOx installations and the slightly higher working temperatures in most cement kilns compared to the rotary kiln, and to the avoided emissions (electricity and steam production) in the rotary kiln

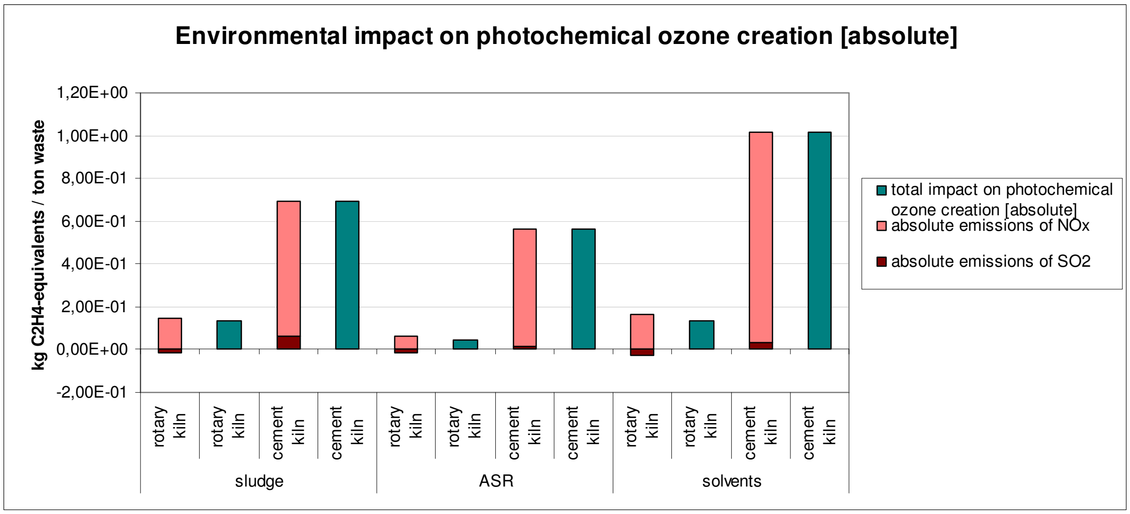

Figure 7: The environmental impact of the absolute NO_x and SO_2 emissions on photochemical ozone creation.

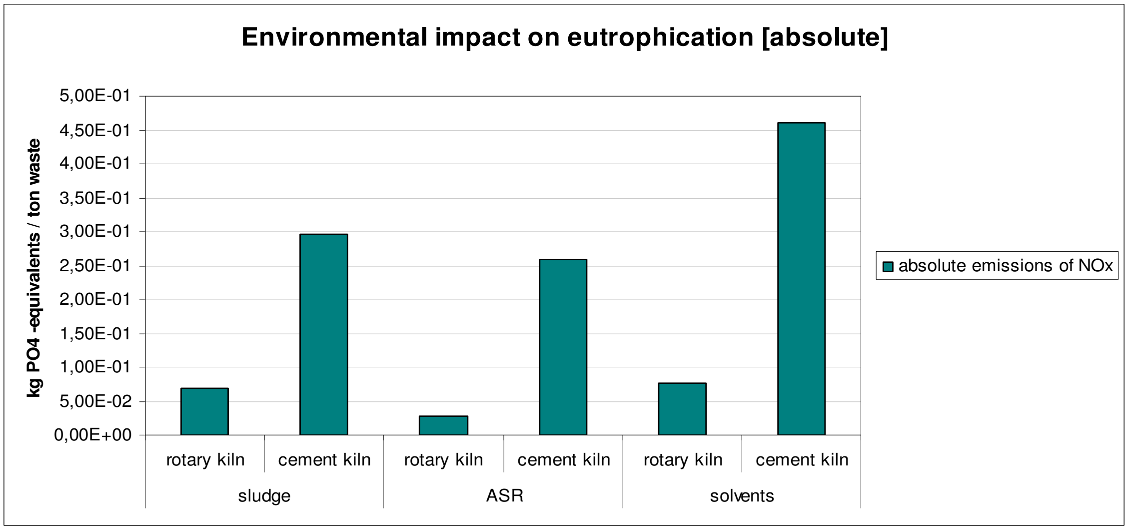

Figure 7: The environmental impact of the absolute NO_x emissions on photochemical ozone creation

4.1.5 Human toxicity and ecotoxicity

For human and eco toxicity the impact of a set of 8 heavy metals is investigated: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). These heavy metals were considered as the highest priority for toxicity calculations on the 'Derde Noordzeeconferentie' [www.milieurapport.be]. Moreover, also our calculations have pointed out that these metals are of most interest for the impact categories 'human and ecotoxicity', for the wastes considered. In extent, Thallium (Tl), Vanadium (V) and Cobalt (Co) can also be of some importance if present in rather large amounts in the industrial waste.

For the different toxicity impact category different heavy metals are of main importance, as can be seen in Figures 8 to 11. For **human toxicity** one can distinguish chromium (Cr), nickel (Ni) and in addition also cadmium (Cd) and mercury (Hg) emissions are important for the cement kiln. For **fresh water toxicity** mercury (Hg) emissions are by far the most important. This is one of the greatest bottlenecks of the cement kilns [Figure 9], since the transfer of mercury into air is around 40% for cement kilns, while for a rotary kiln this is only 0.22%. For **sea water toxicity** the environmental impact is mainly caused by nickel (Ni), zinc (Zn) and copper (Cu), in addition also cadmium (Cd) can be considered important for the cement kiln. For **terrestrial toxicity** chromium (Cr) is the most important emission, with some minor influences of cadmium (Cd), zinc (Zn) and nickel (Ni).

The environmental impact of the heavy metal emissions in the categories human toxicity, terrestrial and fresh water toxicity are larger for a cement kiln than for a rotary kiln, for all three considered waste types . For sludge and ASR, the contributions to seawater toxicity are higher for a rotary kiln than for a cement kiln. This can largely be attributed to the higher transfer coefficients for nickel and copper in a rotary kiln.

In general it can be stated that rather less volatile elements, such as Cu, Ni and Cr are quite easily trapped into the clinker, explaining the low transfer coefficients for these elements [Shih et al, 2005]. For the cement kiln, transfer coefficients are ca. 0.02% for Cu, Ni and Cr, while for the rotary kiln at the Indaver Site, transfer coefficients of respectively 0.05%, 0.08% and 0.05% were measured.

For the environmental impact of chromium on the categories human and eco toxicity an important distinction must be made between the speciation of two oxidation states of chromium, Cr(III) and Cr(VI), the toxicity level of Cr (VI) is 4 orders of magnitude higher than that of Cr(III) [Section 4.1.1]. The specific oxidation state of chromium depends on several parameters, such as the flame temperature and the oxygen excess in the incinerator [Kashireninov and Fontijn, 1998]. In general higher working temperature of the incinerator and more excess of oxygen, will result in higher formation of Cr(VI). Besides the working parameters also the composition of the input waste plays an important role in the speciation of chromium, especially at lower temperatures in the post-flame gases. For a rough estimation however, it suffice to take only working temperature and oxygen excess into account [Kashireninov and Fontijn, 1998; Chen et al., 1997; Guo and Kennedy, 2001]. Combining these two parameters for both kilns a rough estimation can be made, concerning the amount of Cr(III) and Cr(VI) emitted during burning of the waste. The real amount of the Cr(VI) formed, will probably be even slightly higher, due to the presence chlorine in the post combustion chambers.

Considering this estimation, for a rotary kiln incinerator the contribution of Cr(VI) is estimated to be barely 1%, for the temperatures at which the cement kiln operates this share can easily exceed 10% [Kashireninov and Fontijn, 1998].

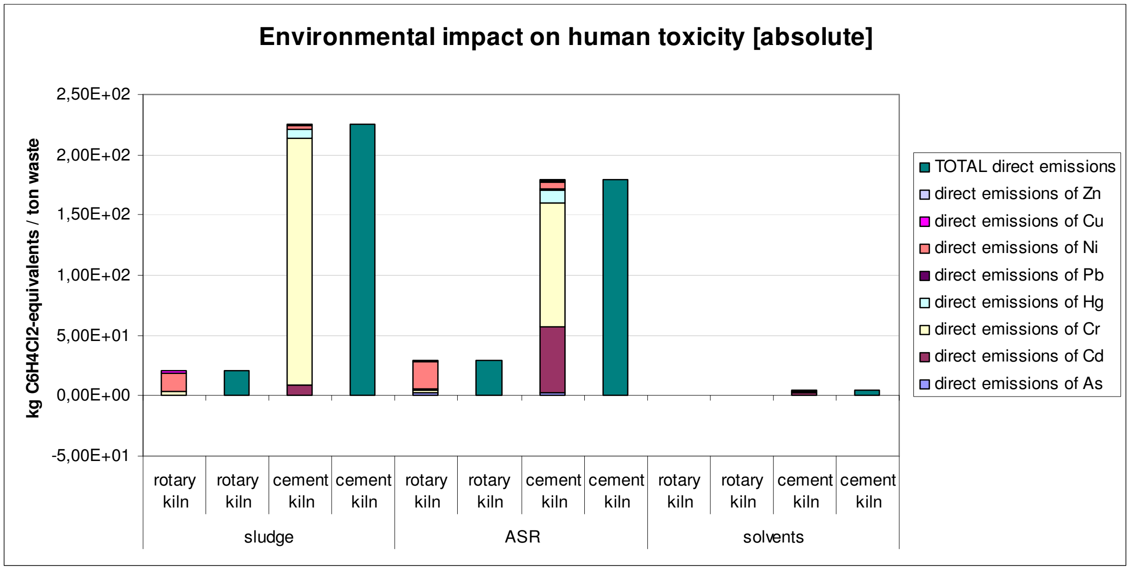

Figure 8: The environmental impact of the absolute emissions of heavy metals on human toxicity

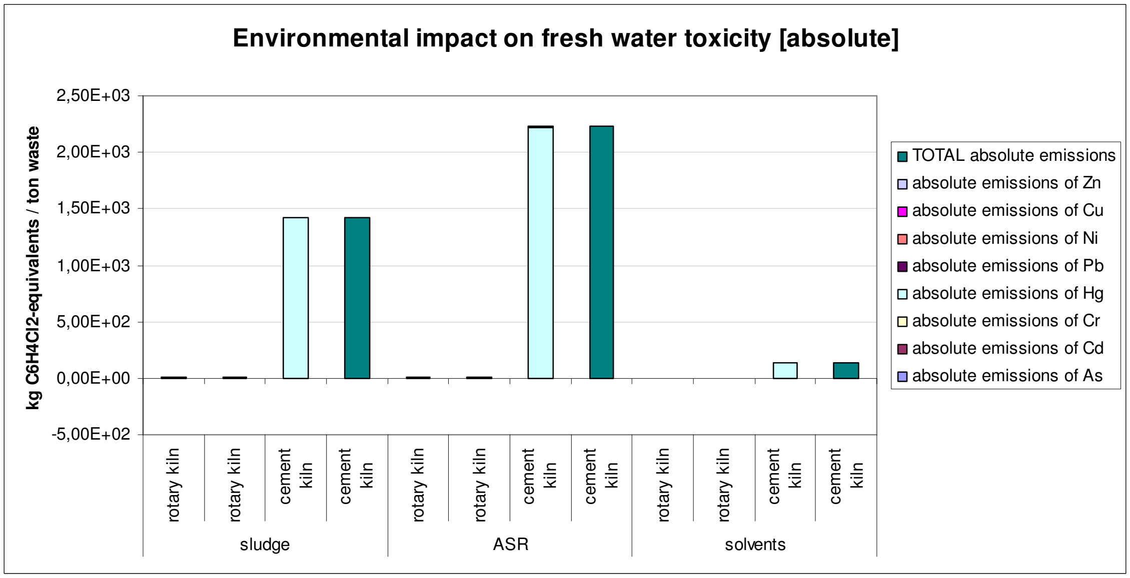

Figure 9: The environmental impact of the absolute emissions of heavy metals on fresh water toxicity

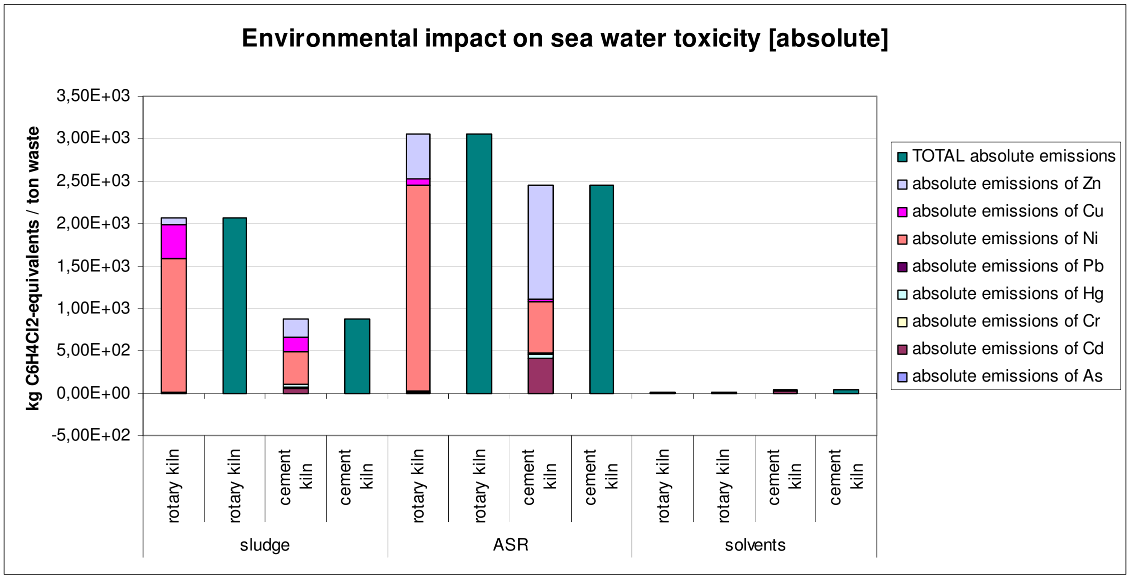

Figure 10: The environmental impact of the absolute emissions of heavy metals on sea water toxicity

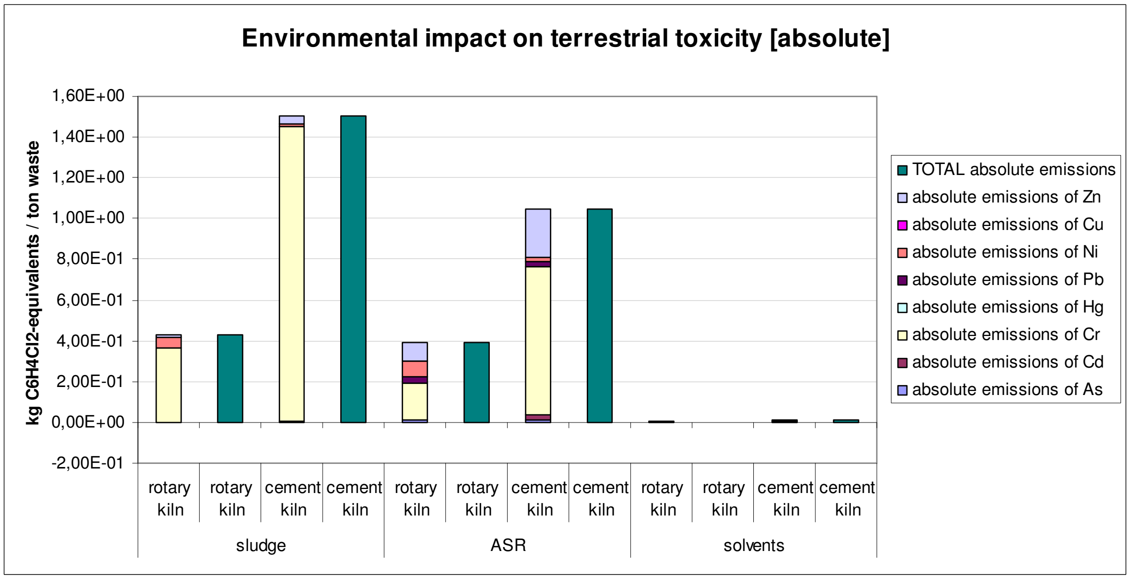

Figure 11: The environmental impact of the absolute emissions of heavy metals on terrestrial toxicity

4.1.6 Conclusions

When answering the question ‘what is the environmental impact when 1 ton of high or medium calorific waste is incinerated in a cement kiln or in a rotary kiln’, this study shows that for all environmental impact categories considered (except sea water toxicity) the impact of incinerating calorific industrial waste in the rotary kiln is considerably smaller than for a cement kiln.

This can mainly be attributed to the higher effectiveness of the flue gas cleaning of the rotary kiln in comparison to the cement kiln, causing (in general) smaller transfer coefficients for almost all elements considered [Annex II]. Moreover the higher energy efficiency of the rotary kiln, leading to recuperation of part of the calorific value of the waste as steam and/or electricity, makes it in some cases possible to even generate a general improvement in environmental impact when substituting fossil fuel with high calorific waste.

4.2 Comparison of waste incineration scenarios relative to a reference scenario

In this section the change of the environmental impact is investigated when 1 ton of high or medium calorific waste replaces an equivalent energetic amount of fuel.

First in ‘a business as usual’ scenario, the change of the environmental impact is studied, relative to the fossil fuel actually used in this type of kilns in Belgium (fossil fuel for the rotary kiln and petcoke for the cement kiln). For several impact categories however, the change of environmental impact is highly dependent on the actual fuel being substituted. Therefore the possible changes of environmental impact is also investigated and compared for different fossil fuel types in both kilns.

When in the incinerators fuel containing a high amount of carbon or impurities (e.g. the petcoke used as reference fuel in cement kilns), is substituted by a *cleaner* calorific waste, the environmental impact can be improved, resulting in a negative value. Moreover, this relative improvement will be highest for pollutants with high transfer.

4.2.1 Global warming

Since the transfer coefficients for carbon for both incinerators are 100%, the only difference in environmental impact of the absolute emissions is caused by the avoided emissions due to steam and electricity production in the rotary kiln [Section 5.1.1]. The change of environmental impact, substituting different fossil fuels for both incinerators is however the same [Figure 12], since an equal amount of steam and electricity is generated in both the substitution and the reference scenario. This implies that the energy efficiency of the incinerator and subsequently the efficiency of the generation of steam and electricity is not taken into account in this comparison.

All three waste types have a lower impact on global warming than the incineration of an equivalent energetic amount of coal or petcoke (negative values in figure 12). This can be attributed to their lower non-biogenic carbon content per calorific value. Automotive shredder residue (ASR) however contains more non-biogenic carbon per calorific value than fuel oil, which implies an increase of environmental impact on global warming (a positive value) as can be seen in Figure 12; for the other two waste types a reduction of environmental impact is observed compared to fuel oil.

If the comparison is made for the business as usual scenario [Figure 13], it is clear that the decrease of environmental impact on global warming for a cement kiln is larger than for a specialised incinerator. The reason is that fuel oil, normally used in the rotary kiln, contains less carbon per calorific value than petcoke, used in the cement kiln. This proves the significance of the choice of reference fuel and its impact on the overall results in such comparisons.

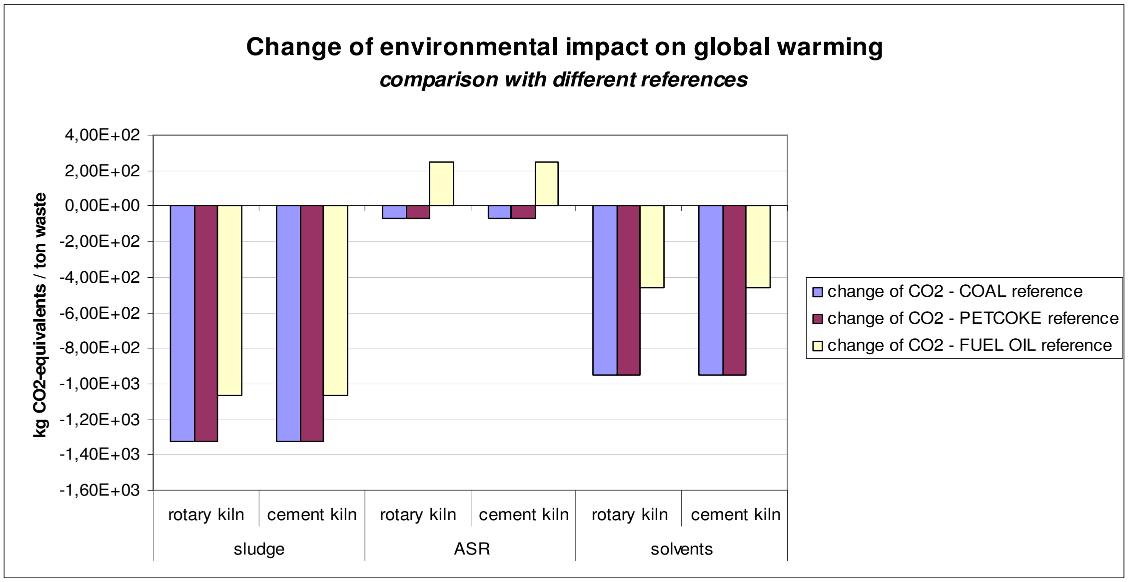

Figure 12: Possible change of environmental impact on global warming when fuel is substituted by calorific waste for different types of fuels

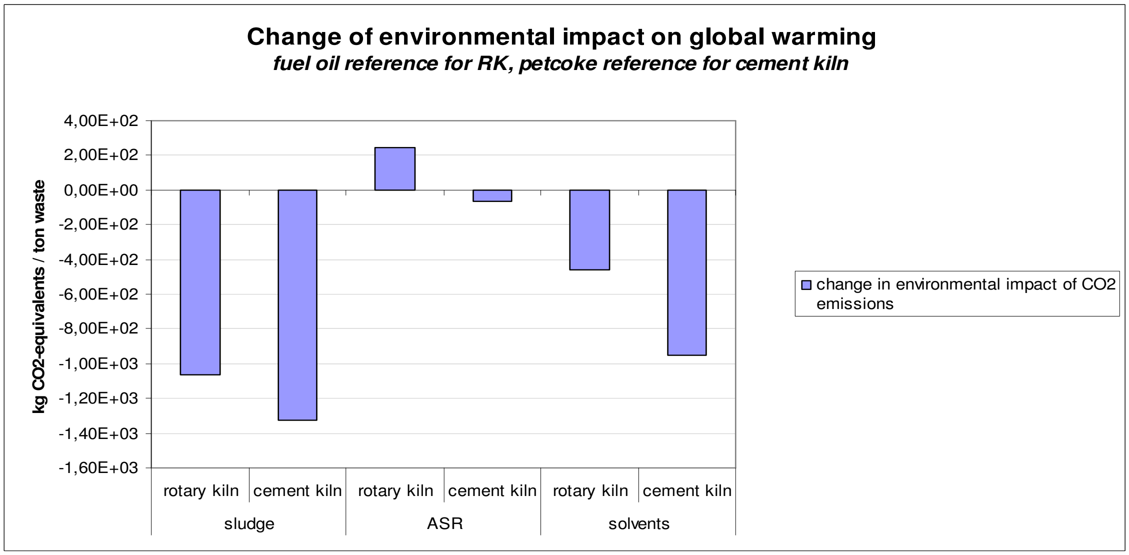

Figure 13: Change of impact on global warming when fuel is substituted by calorific waste in the business as usual scenario

4.2.2 Acidification

Figure 14 compares the change in environmental impact on acidification when substituting different reference fossil fuels in both processes by different waste types. Figure 15 gives the change in environmental impact of both emissions (SO_2 and NO_x) on acidification when substituting the currently used fossil fuels in Belgium.

The substitution of different reference fuels by waste increases the impact in the category ‘acidification’; exceptions are the substitution of petcoke by ASR and solvents in the cement kiln (Figure 14). For these substitutions an improvement in environmental impact is observed. This negative value is due to the decrease in SO_2 emissions when substituting petcokes by ASR or solvents in the cement kiln (Figure 15). Indeed, ASR and solvents have a lower content of sulphur than petcokes on the one hand and cement kilns have higher transfer coefficients for sulphur (2 orders of magnitude higher than for the rotary kiln).
The impact of fuel-NO_x emissions on acidification is smaller for the rotary kiln than for the cement kiln [Figure 15]. As was already stated before, this can be explained by the lack of DeNOx installations in most cement kilns, slightly to the higher working temperatures and also due to the avoided emissions (electricity and steam production) in a rotary kiln.

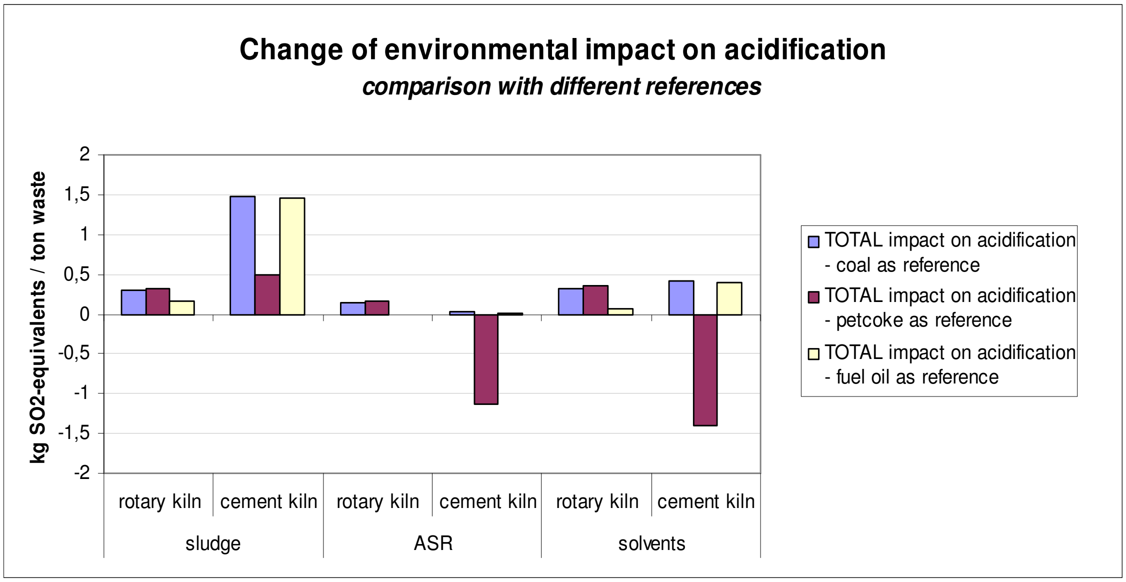

Figure 14: Possible change of environmental impact on acidification when fuel is substituted by calorific waste for different types of fuels

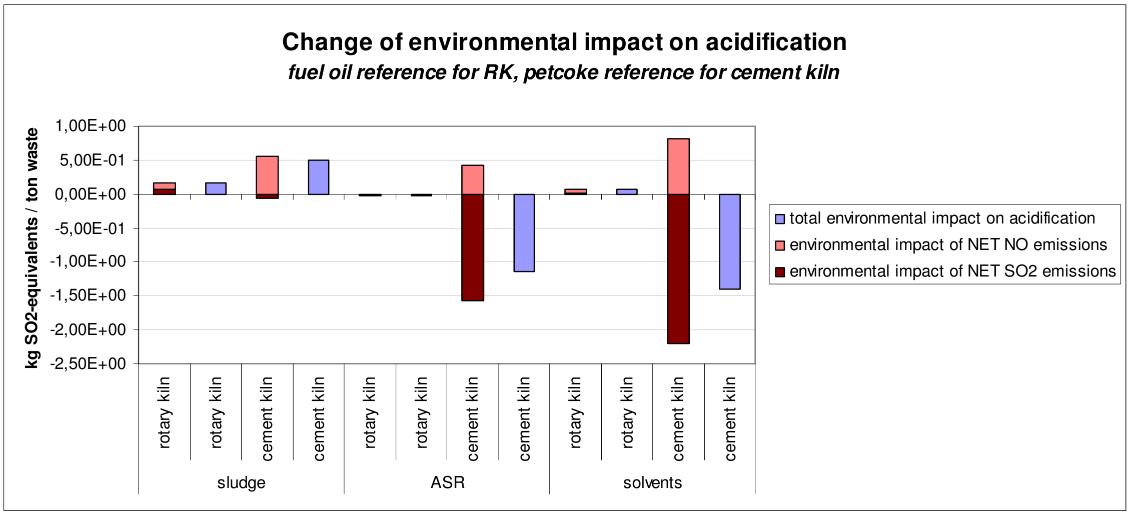

Figure 15: Change of impact on acidification when fuel is substituted by calorific waste in the business as usual scenario

4.2.3 Photochemical ozone creation

Substituting different reference fuels by waste increases the impact on photochemical ozone creation, with the exception of fuel oil substitution by ASR [Figure 16].
Substituting the currently used fuel in Belgium by waste, results in a lower increase of environmental impact for the rotary kiln compared to the cement kiln [Figure 17]. The contribution to photochemical ozone creation is larger for NO_x than for SO_2 for photochemical ozone creation. This results in a totally different general trend for photochemical ozone creation as for acidification, even though the same emissions (SO_2 and NO_x) are considered [Figure 16 vs. Figure 14].

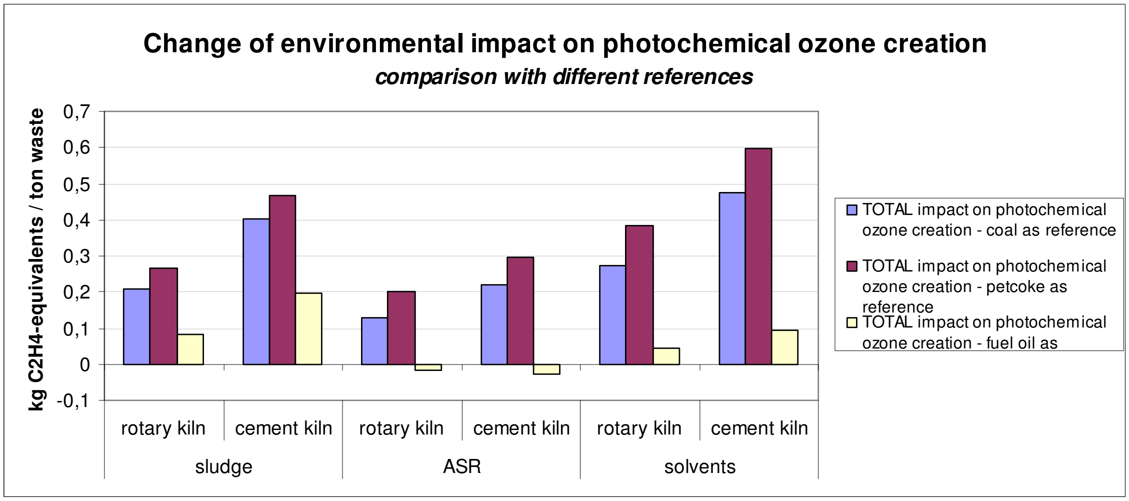

Figure 16: Possible change of environmental impact on photochemical ozone creation when fuel is substituted by calorific waste for different types of fuels

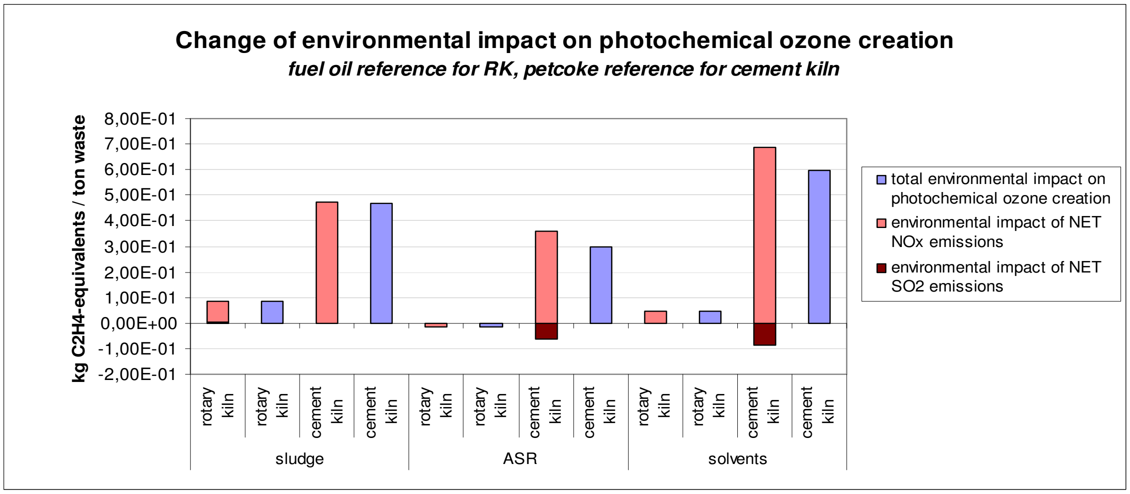

Figure 17: Change of impact on photochemical ozone creation when fuel is substituted by calorific waste in the business as usual scenario

4.2.4 Eutrophication

For eutrophication only the fuel-NO_x emissions are of importance within this study. The general trend for this impact category is thus comparable to that of photochemical ozone creation, where fuel-NO_x is also the most important emission [Figure 16 vs. Figure 18].

For the business as usual scenario the increase of environmental impact is much lower for the incineration of waste in a rotary kiln than in a cement kiln [Figure 19]. This can be attributed to the lower working temperature, the presence of a DeNOx-installation.

Decrease of the environmental impact on eutrophication can be realised by substituting fuel oil by ASR in the rotary kiln.

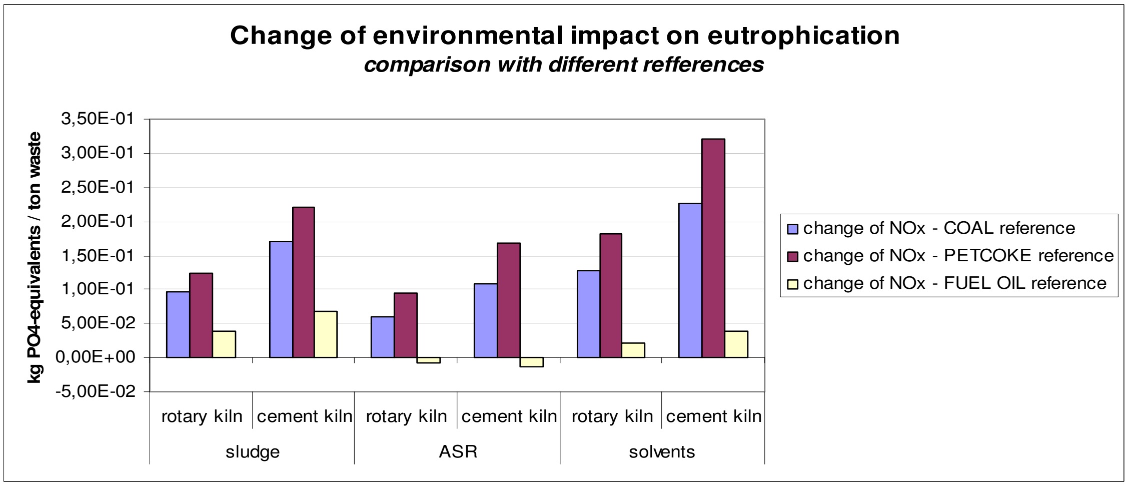

Figure 18: Possible change of environmental impact on eutrophication when fuel is substituted by calorific waste for different types of fuels

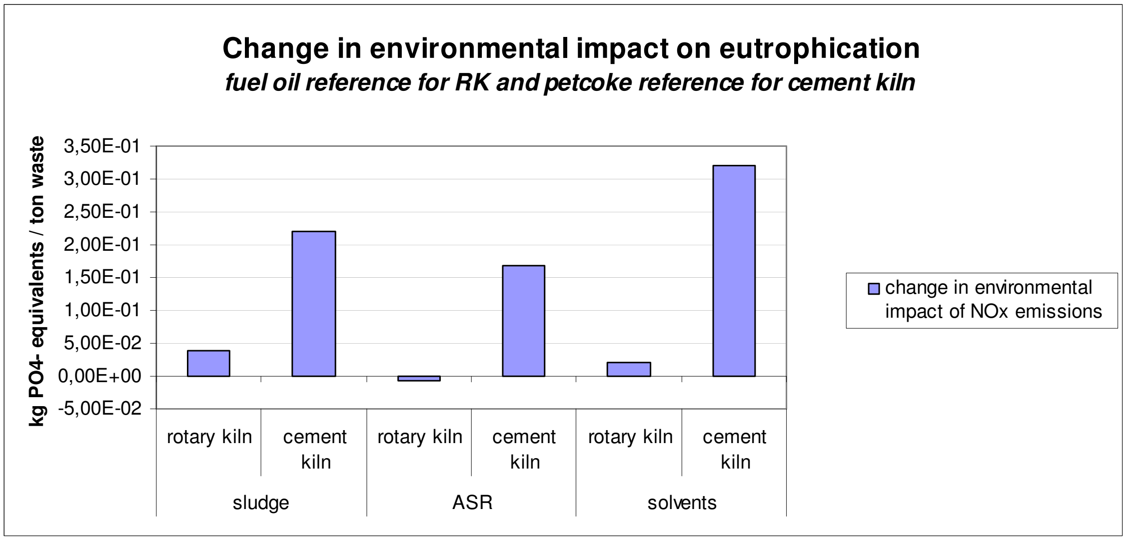

Figure 19: Change of impact on eutrophication when fuel is substituted by calorific waste in the business as usual scenario

4.2.5 Human toxicity and ecotoxicity

Industrial wastes (high or medium calorific) contain in general higher amounts of heavy metals than fossil fuels, resulting in a general increase in environmental impact on toxicity impact categories when 1 ton of these wastes replace an equivalent energetic amount of fossil fuel.

Specialised incinerators such as rotary kilns are in general equipped with a thorough flue gas cleaning system. This makes that the transfer coefficients of a rotary kiln are in general lower than those of a cement kiln as can bee seen in Annex II. Less volatile heavy metals however, such as copper (Cu), chromium (Cr) and nickel (Ni) can be trapped quite efficiently into the clinker, resulting in rather low transfer coefficients for these heavy metals in cement kilns [Section 5.1.5].

In general the substitution of different reference fuels by waste results in a lower impact on **human toxicity** for the rotary kiln, compared with the cement kiln [Figures 20 and 21]. The decrease of environmental impact on human toxicity when coal is substituted by solvents can be attributed to the high content of arsenic in coal[Figure 20].

For a specialised incinerator emissions of nickel (Ni) are of most importance along with those of chromium (Cr). For a cement kiln, next to these, also the emissions of the more volatile heavy metals cadmium (Cd) and mercury (Hg) have to be considered for the environmental impact on human toxicity.

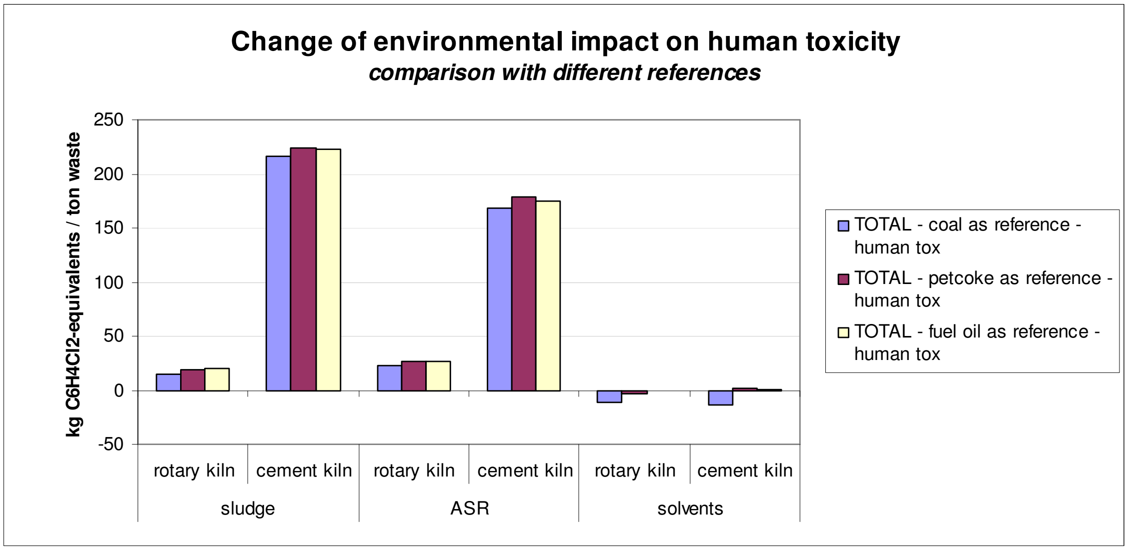

Figure 20: Possible change of environmental impact on human toxicity when fuel is substituted by calorific waste for different types of fuels

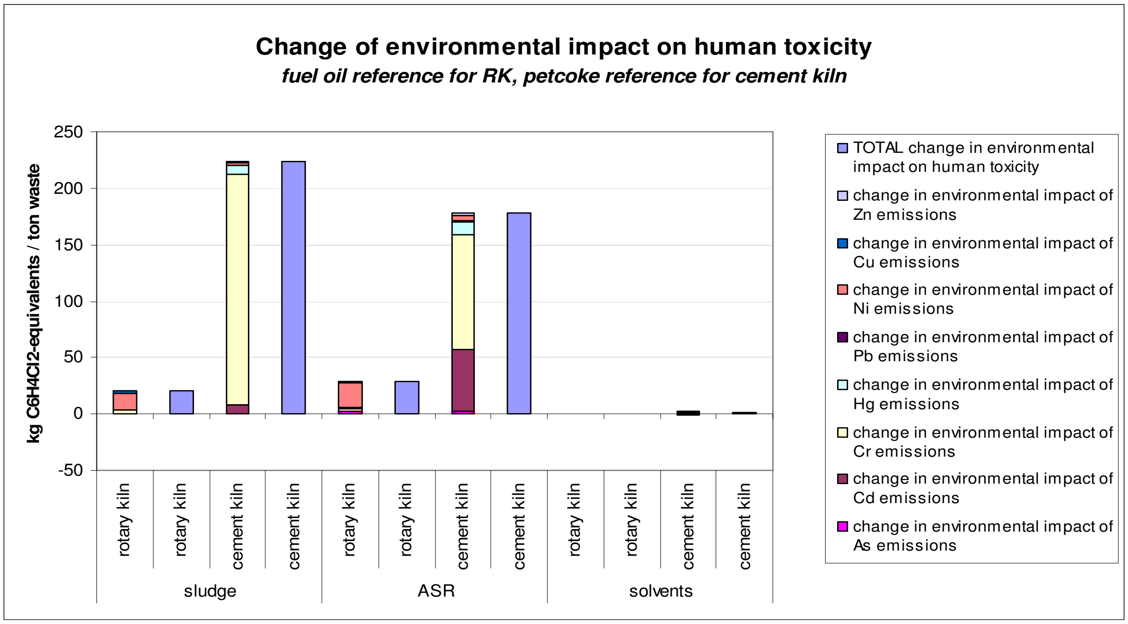

Figure 21: Change of impact on human toxicity when fuel is substituted by calorific waste in the business as usual scenario

For **freshwater toxicity** the emissions of mercury (Hg) are by far the most important ones. The transfer coefficient for mercury is much higher for a cement kiln than for a rotary kiln (38.7% vs. 0.2%), explaining the large increase in environmental impact for the cement kiln in practically all cases [Figure 22 and 23].

Decrease of the impact of fresh water toxicity can be realised by substituting fuel oil by solvents in a cement kiln [Figure 22]. This can be contributed to the lower mercury content of solvents compared to fossil fuel and the large transfer coefficient for mercury in the cement kiln.

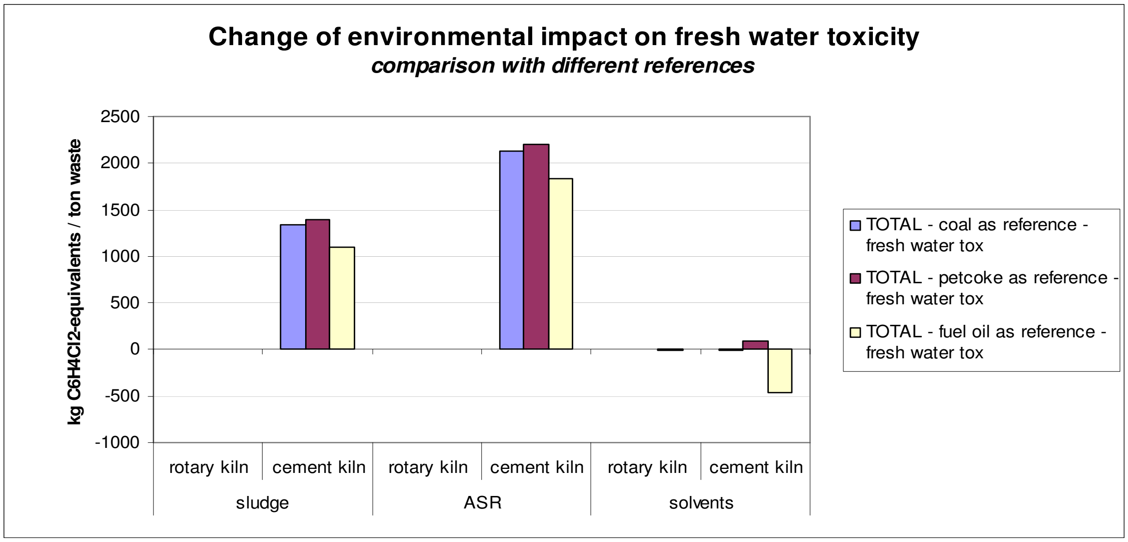

Figure 22: Possible change of environmental impact on freshwater toxicity when fuel is substituted by calorific waste for different types of fuels

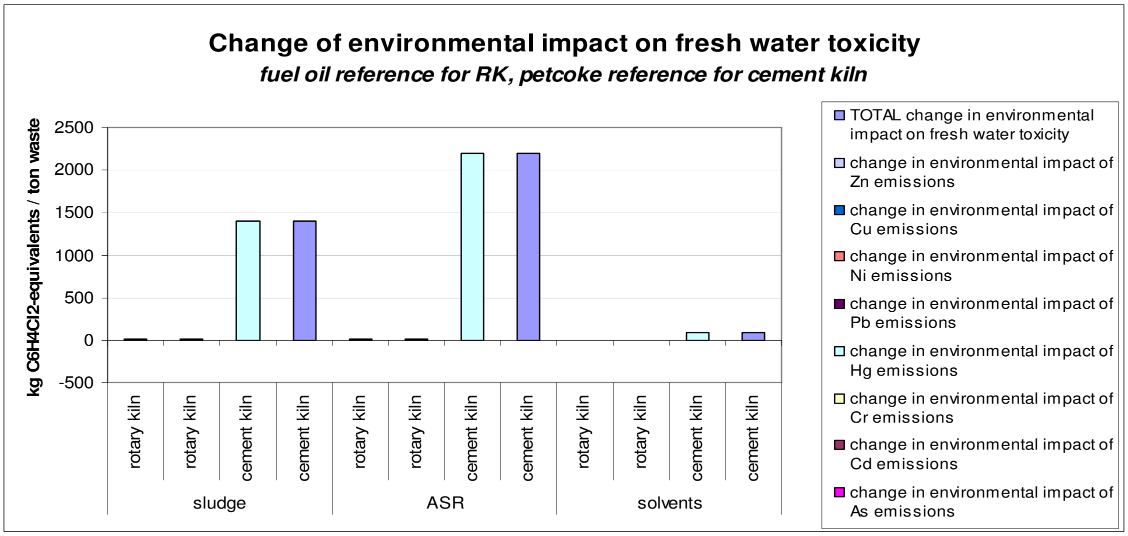

Figure 23: Change of impact on freshwater toxicity when fuel is substituted by calorific waste in the business as usual scenario

For the impact category **seawater toxicity**, the increase of the environmental impact is in general smaller for the cement kiln than for the rotary kiln when substituting the different fuels by sludge and ASR waste. Substitution of coal and petcoke by solvents gives a larger decrease in environmental impact for the rotary kiln than for the cement kiln [Figure 24]. This is due to the lower nickel content of the solvents in comparison to the fossil fuels and the higher transfer coefficients of nickel in the rotary kiln (0.08%, vs. 0.02% in a cement kiln) as is already discussed in Section 5.1.5.

From the business as usual scenario can be deduced that for the rotary kiln especially nickel (Ni), copper (Cu) and zinc (Zn) emissions have to be considered, while for a cement kiln also cadmium (Cd) emissions are important.

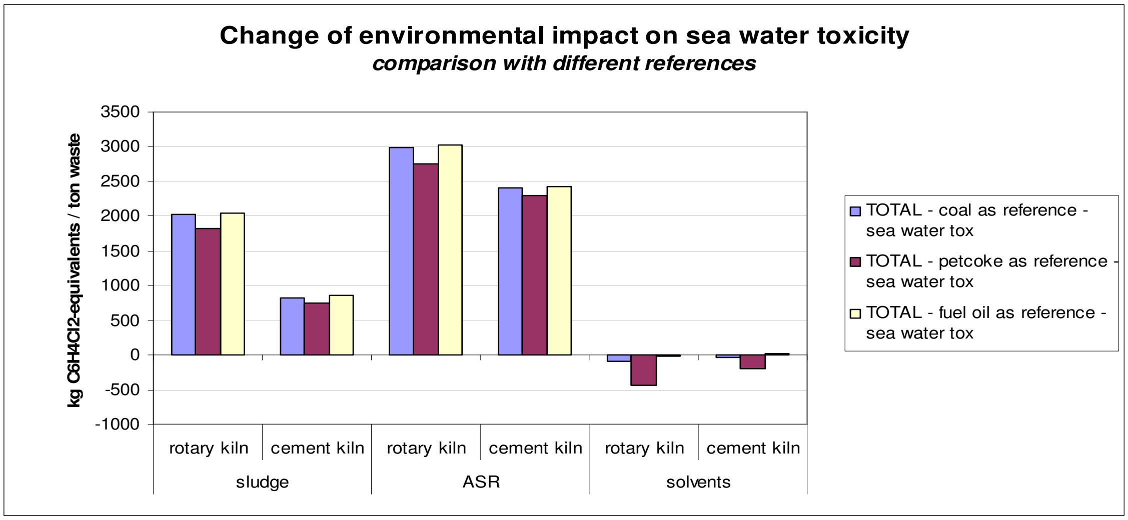

Figure 24: Possible change of environmental impact on seawater toxicity when fuel is substituted by calorific waste for different types of fuels

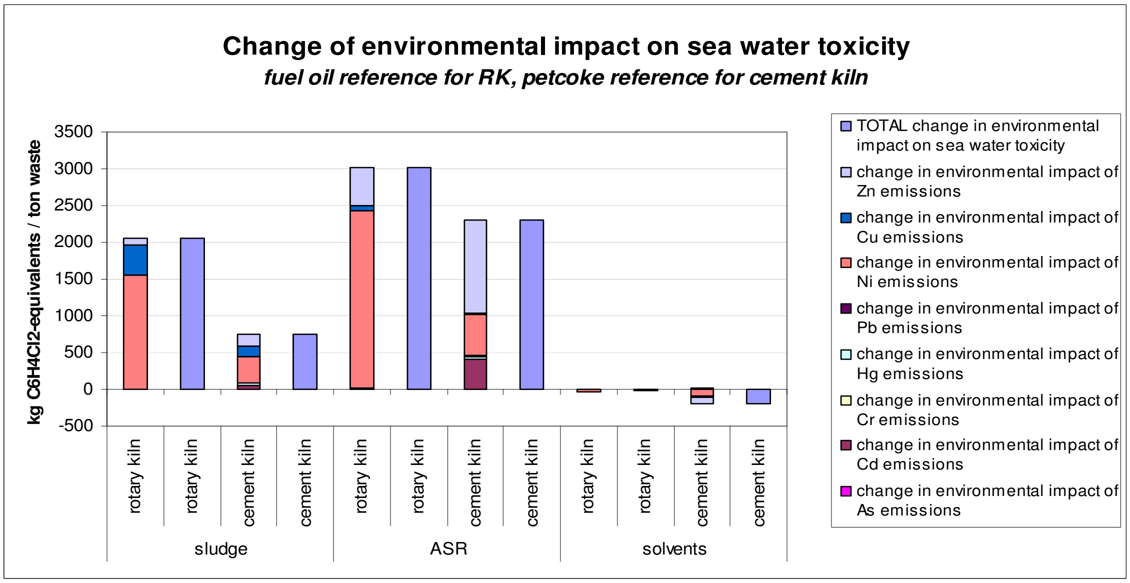

Figure 25: Change of impact on seawater toxicity when fuel is substituted by calorific waste in the business as usual scenario

The last impact category to be discussed is **terrestrial toxicity**. In general the increase of environmental impact is lower for a rotary kiln than for the cement kiln, chromium being the most important emissions to be considered [Figure 26 and 27]. Emissions of nickel (Ni) and zinc (Zn) are also important for both rotary and cement kiln, in addition also cadmium (Cd) is of importance for the cement kiln.

A decrease in environmental impact can be obtained when substituting coal and petcoke by solvents in both kilns.

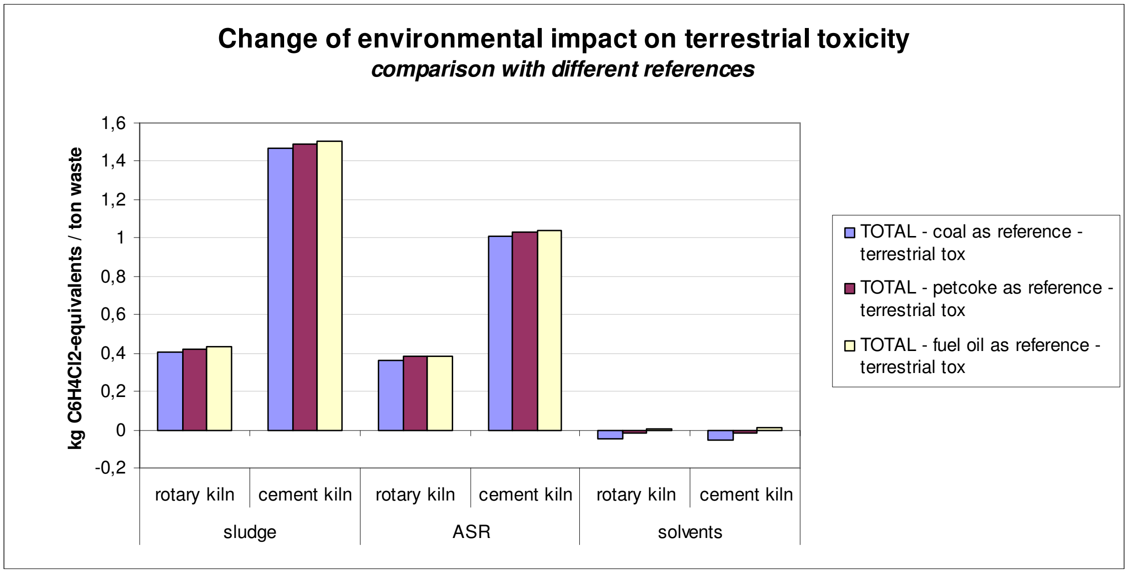

Figure 26: Possible change of environmental impact on terrestrial toxicity when fuel is substituted by calorific waste for different types of fuels

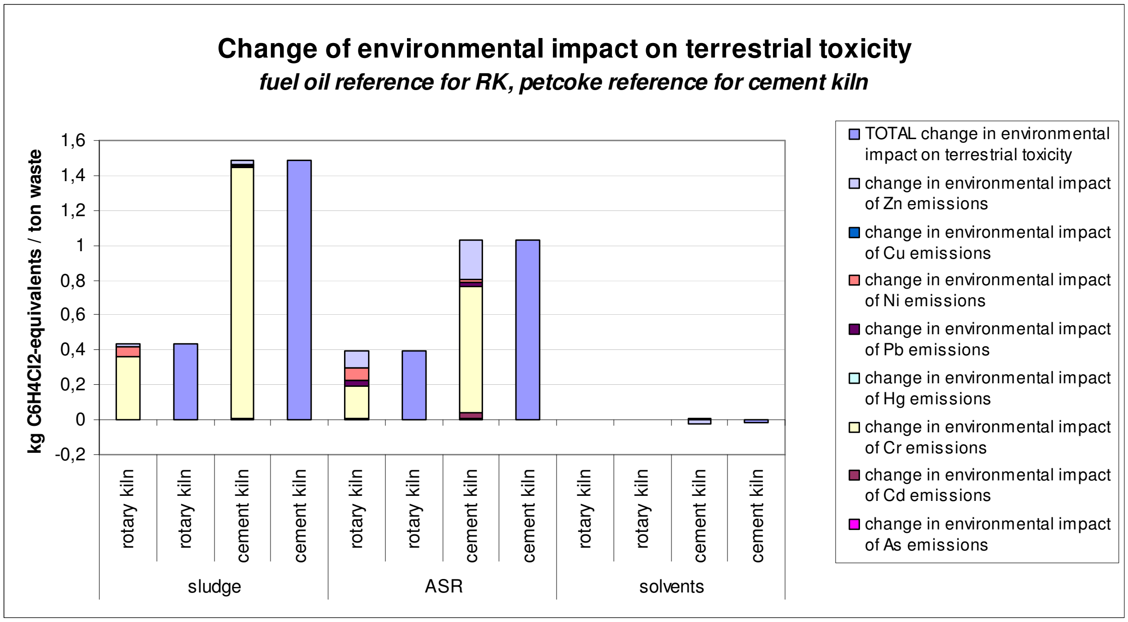

Figure 27: Change of impact on terrestrial toxicity when fuel is substituted by calorific waste in the business as usual scenario

4.2.6 Conclusions

From the point of view of resource conservation both systems show in general comparable changes when the actually used fuels in Belgium are substituted by calorific waste in both kilns. When, however, the same reference fuels are (hypothetically) substituted by waste in both installations, substitution of the fuel by calorific waste in a rotary kiln is in general more advantageous: for global warming the improvement is the same, for sea water toxicity the cement kiln is more advantageous and for all other impact categories (acidification, photochemical ozone creation, eutrophication, human toxicity, fresh water toxicity and terrestrial toxicity) the rotary kiln scores better. The results of the comparison of both kilns depends thus strongly on the choice of the reference fuel. When fuels containing a high amount of carbon or impurities, are substituted by a rather *clean* industrial waste, there is an improvement of the environmental impact. Moreover, this improvement will be the highest when the transfer coefficients of the pollutants are the highest. It should be kept in mind that the highest transfer coefficients also result in the highest absolute environmental impact (Section 3.1 and 4.1).

5 General conclusion

In this study a methodology has been developed to investigate the environmental impact when substituting fuel by medium and high calorific industrial waste (sludge, ASR and solvents) in a rotary kiln and in a cement kiln. Despite their intrinsic differences we have considered the substitution of fuel by industrial waste in a rotary kiln as an activity, comparable to the substitution in a cement kiln, for these industrial waste types. The impact categories global warming, acidification, photochemical ozone creation, eutrophication, human toxicity, fresh water toxicity, sea water toxicity and terrestrial toxicity are considered.

In our opinion two aspects must be considered:
The absolute environmental impact when incinerating 1 ton of industrial waste, reflects the effectiveness of the flue gas cleaning systems of the incinerators, the capability of trapping heavy metals or SO_2 in the clinker or the ashes and the energy efficiency of the incinerator, including the avoided emissions due to electricity and steam generation. It is clear that the process yielding the least environmental impact should in principle be preferred.

The second important aspect is *the change of environmental impact* when substituting an equivalent amount of fossil fuel by 1 ton calorific industrial waste. First the current situation in Belgium was investigated, considering the substitution of the actually used fuels in both processes in Belgium, namely fuel oil (recycled oil to be precise) for rotary kilns and petcokes for cement kilns. Next to this also the change in environmental impact, when (hypothetically) substituting other types of fossil fuels (coal, petcoke, fuel oil) in both kilns, was estimated [Section 5.2, Annex III]. 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 this choice is in general merely based on prise and availability.

It may be concluded that considering *the absolute emissions*, for almost each impact category (except for sea water toxicity) the impact of incinerating calorific waste in the rotary kiln is considerably smaller than for a cement kiln. This can mainly be explained by the higher effectiveness of the flue gas cleaning of the rotary kiln and to some extent also by the avoided emissions due to steam and electricity generation.

When considering the *change of environmental impact* when replacing the actually used fossil fuels in Belgium (*business as usual scenario*), both systems show in general comparable changes. When, however, the same reference fuels are (hypothetically) substituted in both installations, the substitution of fuel by calorific waste is in general more advantageous in a rotary kiln. The incineration of the industrial waste in the rotary kiln results indeed in a lower impact for all impact categories, with exception for the category global warming, giving the same result for both processes

The specific results when comparing both kilns are thus strongly dependent on the choice of reference fuel and the specific characteristics of the calorific waste. When fuels containing a higher amount of carbon or impurities are substituted by a rather *clean* calorific waste, there is an improvement of the environmental impact. For instance, if a calorific waste contains less contaminants than the fuel, it can be noticed that substitution of the most carbon containing, impure fossil fuel results in the highest environmental improvement. Moreover, the improvement will be highest when the transfer coefficients of the pollutants (for both fuel and the calorific waste) are highest, while it is obvious that the latter causes also the highest absolute environmental impact.

This shows clearly that the calculations of the *absolute environmental impact* and of the *change of the environmental impact* when fuel is substituted by calorific waste in different kilns, are complementary and are both required. Besides environmental aspects, also social and economical consequences are of great importance when making general waste management decisions. They are however out of the scope of this study.

From this study can be concluded that cement kilns show opportunities in improving their environmental impact when substituting their currently used fuels by high or medium calorific wastes. These are rather short term solutions for a lot of high or medium calorific wastes, since the transfers of sulphur, nitrogen and (volatile) heavy metals into air remain relatively high for cement kilns. Besides, we believe that in an installation first the flue gas cleaning should be optimised to achieve a minimal absolute environmental impact. Only then it makes sense to consider the replacement of fuel by waste in order to further improve the situation and conserve resources. Moreover for such comparisons it is best to start from an optimal fuel, not from one containing much carbon per calorific value or a lot of pollutants.

6 References

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7 Annex

7.1 Annex I: Characteristics of the input

SLUDGE

		De Vos (2007) **Table 1; ANNEX**	Velden (2007) **Table2; p98**	Ragosnig [2005] **Table 3 ; p 450**	Conesa [2008] **Table 1, p3, sludge 1**	Conesa [2008] **Table 1, p 3, sludge 2**	Werther [1999] **Table 3, p 62**	Leckner [2004] **Table 1; p 478 gedroogd**	Canonico [2000] **Table 1, p 2**	Indaver [2006] **Internal ommunication**	Gálvez [2007] **Table 1, p 388**	Elled [2007] **Table 1; p845 MSS Ryaverket**	Elled [2007] **Table 1; p845 MSS Nolhagaverket**	Nadziakiewecz [2003] **Table 1, p243**
wt%	C	0						53,2				52,6	50,2	20,5
wt%	H							7,1				7,2	7,3	3,1
wt%	N						3,8	7,11				5,4	5	0,45
wt%	S	1,5			1,24	1,78		1,9		4,2		1,4	1,2	0,9
wt%	O							30,6				33,3	36,2	14,6
MJ/kg	Cal. value	8,24			16,99	11,77		9,8			16,98	20,5	19,5	7
ppm	Cl	5000		1774	1840	3890				4	1804	1000	1000	
ppm	As	10	10,5	0,68	<0,5	2,4						5,9	5,2	0,0062 - 0,0153
ppm	Cd	9	4,5	0,45	13,4	2,9	3,8		4		13,4	0,86	0,53	1,36 - 20,0
ppm	Cr	308,3	85	13,6	178,1	572,7	91		13	19,9	178	31	43	106,2 - 380
ppm	Hg	1,3		0,68	<0,5	1,2	2,7		0,04	13,6	<0,5	1,2	0,77	1,99- 2,5
ppm	Sb	40,1	1,1		4,2	0,15				17,2	4,2	13	15	
ppm	Co	30,9		0,9	1,6	4,5					1,6	6,9	2,8	10,9 - 40,0
ppm	Se	3,1								1,2		13	15	1,2 - 1,3
ppm	V	123,5			11,3	17,4					11,3	23	23	34,1 - 36,4
ppm	Ni	334,5	38,7	10,1	35,8	223,2	39		140	41,3	35,8	21	13	16 - 50
ppm	Pb	208,8	162	45,2	69	72	159		32	35,1	69	38	17	20,0 - 49,5
ppm	Tl	7			<0,5	0,1					<0,5	9,4	10	
ppm	Cu	416,3	300		217,7	562,3	330		31	12,6	318	394	266	80-800
ppm	Zn	2742	1581	167			1318		420		568	652	385	2432-6100

SLUDGE

Average value of data from LITERATURE

	Font_2001 **Sludge 1 Table 2, p 931**	Font_2001 **Sludge 2 Table 2, p 931**	Font_2001 **Sludge 3 Table 2, p 931**	Font_2001 **Sludge 4 Table 2, p 931**	Font_2001 **Sludge 5 Table 2, p 931**	Font_2001 **Sludge 6 Table 2, p 931**	Font_2001 **Sludge 7 Table 2, p 931**	Spliethoff **Table 1, p35**		**AVG**	**STDEV**
C	29,6	29,2	30,6	33,6	35,3	33,6	32,2	24,4	C	32,69	14,27
H	4,7	4,7	4,9	5,1	5,5	5,2	5,3	4,3	H	5,367	1,265
N	1,4	2,9	3	5,4	6,2	4,2		3,54	N	4,033	1,937
S	1	<1	1	<1	3	<1	<1	0,94	S	1,672	0,989
O								19	O	26,74	9,417
Cal. value	15,24	11,5	9,92	12,6	14,9	13,7	15,5	10	Cal. value	13,38	3,957
Cl									Cl	2039	1633
As									As	5,78	3,947
Cd									Cd	5,284	4,958
Cr	100	4700	4600	400	34000	600	4000		Cr	2774	7962
Hg									Hg	2,686	4,475
Sb									Sb	11,87	13,13
Co									Co	7,029	10,73
Se									Se	8,075	6,934
V									V	34,92	43,71
Ni		1900	500	600	400	5400			Ni	608,3	1362
Pb		100	1700	100	1400		300		Pb	281,7	503,7
Tl									Tl	6,625	4,539
	200	2200	2900	300	400	2800	5700			1020	1525
		680	3200	3300	800	7100	2600			1822	1876

SLUDGE

Average value of data from INDAVER

Indaver meetcampagne **sludge, used for FB combustion**			**AVG**	**STDEV**
19/11/2008	**20/11/2008**	**21/11/2008**		
3720	1767	1653	2380	1161,873
<100	<100	<100		
<100	<100	<100		
176	236	181	197,6667	33,29164
3	< 50	6	4,5	2,12132
14	18	37	23	12,28821
80	<300	<300	80	0
4	3	3	3,333333	0,57735
<500	<500	<500		
65	41	48	51,33333	12,34234
156	280	185	207	64,86139
<100	<100	<100		
274	294	349	305,6667	38,83727
1446	1715	1225	1462	245,3915

Average value of data from BOTH SOURCES

		AVG	**STDEV**
wt%	C	32,69231	14,27244
wt%	H	5,366667	1,265151
wt%	N	4,033333	1,937263
wt%	S	1,671667	0,989305
wt%	O	26,74	9,4169
MJ/kg	Cal. value	13,38313	3,95655
ppm	Cl	2132,009	1470,121
ppm	As	5,779667	3,946958
ppm	Cd	5,2842	4,95779
ppm	Cr	2406,027	7398,772
ppm	Hg	3,0488	4,081426
ppm	Sb	14,90455	13,34077
ppm	Co	16,1505	27,64504
ppm	Se	6,042857	5,529273
ppm	V	34,91667	43,71121
ppm	Ni	520,3346	1260,364
ppm	Pb	269,9	461,203
ppm	Tl	6,625	4,538998
ppm	Cu	913,245	1424,171
ppm	Zn	1758,796	1699,36

	ASR		*fluff*												*Average value of data from LITERATURE*	
		De Vos [2007] **Table 1; ANNEX**	Nourredine [2006] en [2007] **[ASR]**	Börjeson [2000] **[ASR]** **mixed cars, Table 5 e.v.**	Börjeson [2000] **[ASR]** **mixed waste, Table 5, e.v.**	Börjeson [2000] **[ASR]** **industrial waste, Table 5, e.v.**	Boughton [2007] **[ASR]** **Table 8, fuel fraction**	ASR WRc [2003] **Table 4.4, p 69**	Roy [2001] **table 4, p 10, A**	Roy [2001] **table 4, p 10, B**	Roy [2001] **table 4, p 10, C**	Roy [2001] **table 4, p 10, D**	Roy [2001] **table 4, p 10, E**	Roy [2001] **table 4, p 10, F**	**AVG**	**STDEV**
wt%	C	62,67	49,5							27,9	30,1	29,7	46,2		41,01	14,05
wt%	H		5,3							4	3,74	4	6,3		4,668	1,097
wt%	N		4,5					2		0,88	1,32	0,9	1,9		1,917	1,352
wt%	S	0,5	0,2	0,65	0,45	0,4		0,32		0,28	0,38	0,3	0,3		0,378	0,13
wt%	O		6,9												6,9	0
MJ/kg	Cal. value	21,57	16,7	25,8	14,7	16,45	19	18,3	12,4	12,8	11,1	10,2	16,5	19	16,5	4,377
ppm	Cl	7000	5000	21500	17000	37500		12000	35000	5000	57200	5000	7000	35000	20350	17128
ppm	As	69,6					1,2	10,6							27,13	37,08
ppm	Cd	6,6		32	26,5	17,5	2	31,9	65	50					28,94	21,12
ppm	Cr	196,9	800				17	489	420	230	400			7000	1194	2357
ppm	Hg	0,4		0,35	3,75	1,3	1								1,36	1,395
ppm	Sb	223,9		0,35	3,75	1,3									57,33	111,1
ppm	Co	22,6					24								23,3	0,99
ppm	Se	0,2													0,2	0
ppm	V	34,3					6								20,15	20,01
ppm	Ni	54,1	700				98	366			690			4000	984,7	1503
ppm	Pb	361,1	2000	2390	2455	1567	94	2710	2800	2400	4100			7000	2534	1856
ppm	Tl	1,9													1,9	0
ppm	Cu	185,5													185,5	
ppm	Zn	1433													1433	

ASR

Average value of data from INDAVER

		Indaver meetcampagne sludge, used for FB combustion		AVG	STDEV
		car shredder 1	**car shredder 2**		
wt%	C				
wt%	H				
wt%	N				
wt%	S				
wt%	O				
MJ/kg	Cal. value				
ppm	Cl	12450	6335	9393	4324
ppm	As	52	29	40,5	16,3
ppm	Cd	30	86	58	39,6
ppm	Cr	2134	351	1243	1261
ppm	Hg	12	14	13	1,41
ppm	Sb	40	69	54,5	20,5
ppm	Co	174	118	146	39,6
ppm	Se	<100	3	3	0
ppm	V	<500	<500		
ppm	Ni	278	209	244	48,8
ppm	Pb	1789	1455	1622	236
ppm	Tl	<100	<100		
ppm	Cu	>9274	>2604		
ppm	Zn	9616	10150	9883	378

Average value of data from BOTH SOURCES

		AVG	STDEV
wt%	C	41,01167	14,049826
wt%	H	4,668	1,097324
wt%	N	1,916667	1,3524151
wt%	S	0,378	0,1296834
wt%	O	6,9	0
MJ/kg	Cal. value	16,50231	4,3765457
ppm	Cl	18784,64	16293,924
ppm	As	32,48	28,408661
ppm	Cd	34,75	25,912342
ppm	Cr	1203,79	2121,151
ppm	Hg	4,685714	5,821563
ppm	Sb	56,38333	86,525838
ppm	Co	84,65	74,440737
ppm	Se	1,6	1,979899
ppm	V	20,15	20,011122
ppm	Ni	799,3875	1315,913
ppm	Pb	2393,931	1729,7334
ppm	Tl	1,9	0
ppm	Cu	185,5	
ppm	Zn		

SOLVENTS

		De Vos (2007) **general solvents**	Seyler (2005) chem **waste solvents incinerators**	Seyler (2005) Cem **waste solvents cement**	Hofstetter [2003] **average waste solvent in incinerator**
wt%	C	30,52	47,7		45
wt%	H		8,2		8,5
wt%	N		1		2
wt%	S	1	0,7		0,83
wt%	O		20		41
MJ/kg	Cal. value	29,15	21,7		
ppm	Cl	0	24000		230000
ppm	As	2,9		2	
ppm	Cd	2,9		0,1	
ppm	Cr	16,7		1,9	
ppm	Hg	0,5		0,1	
ppm	Sb	3			
ppm	Co	6,6	4,1	2,5	
ppm	Se	0,1			
ppm	V	4,5			
ppm	Ni	6,3	4,6	2,1	
ppm	Pb	65,2		2,6	
ppm	Tl	3	57	18	
ppm	Cu	54,8			
ppm	Zn	156,6			

		AVG	**STDEV**
wt%	C	41,073	9,2386
wt%	H	8,35	0,2121
wt%	N	1,5	0,7071
wt%	S	0,8433	0,1504
wt%	O	30,5	14,849
MJ/kg	Cal. value	25,425	5,2679
ppm	Cl	84667	126433
ppm	As	2,45	0,6364
ppm	Cd	1,5	1,9799
ppm	Cr	9,3	10,465
ppm	Hg	0,3	0,2828
ppm	Sb	3	0
ppm	Co	4,4	2,0664
ppm	Se	0,1	0
ppm	V	4,5	0
ppm	Ni	4,3333	2,1127
ppm	Pb	33,9	44,265
ppm	Tl	26	27,875
ppm	Cu	54,8	0
ppm	Zn	156,6	0

COAL

average value of data from LITERATURE

		De Vos (2007) **Table 1 Coal**	Seyler 2005 (cem) **Table 6; p124**	Denis (1999) **Annex VII**	Vouk (1983) **Table 1; p 203**		Leckner [2004] and [2007] **Table 1; p478**	Gieré [2006] **Table 2, p 2281**	Nadziakiewicz [2003] **Table 1, p243**	Werther_1999 **table 18, p 93**	McIlveen-Wright **Table 3, p 2035**	**AVG**
			AVG		**MIN**	**MAX**				**Bituminous coal**		
wt%	C	85,6286	73	78,83			84,9	75	52,9	79,2	84	76,6823
wt%	H						5		4,1	4,7	5,7	4,875
wt%	N		1,3				1,6		0,24	1,8	1,5	1,288
wt%	S	0,7		0,875			0,7	1,5	0,8	0,9	2,6	1,15357
wt%	O						7,7		7,7	7,6	6,06	7,265
MJ/kg	Cal. value	33,84	25,8	27			33,4		21,6		35,64	29,5467
ppm	Cl	0		500			800	215		7000	1400	1652,5
ppm	As	2,7	30	3,72	5	45		7	0 - 0,170	5		14,06
ppm	Cd	0,1	0,24	2,79	0,5			14	0,1 - 3	<1		3,526
ppm	Cr	19	43	36,705	10			12	0 - 60	<2		24,141
ppm	Hg	0,1	0,42	0,365	0,012	0,15			0,02 - 1	<2		0,2094
ppm	Sb	0,6			1,4			0,3				0,76667
ppm	Co	5,6			5	25		10	0 - 140	<2		11,4
ppm	Se	1,7			3			2,9	0,2 - 10			2,53333
ppm	V	29			25			33	2 - 100			29
ppm	Ni	16	50	16,965	15			43	0 - 130	3		23,9942
ppm	Pb	8,8	140	16,665	25			12	2 - 370	20		37,0775
ppm	Tl	1	0,63					<0,5				0,815

COAL

average value of data from KULeuven thesis

average value of data from BOTH SOURCES

	Block_1975 **Table 2, p148**				**AVG block**		**AVG**	**STDEV**
	home heating	**electric power**	**coke production**	**industrial proc.**				
C						C	76,68232	10,65065
H						H	4,875	0,665207
N						N	1,288	0,61296
S						S	1,153571	0,694086
O	4,4 - 7,9	21,3	8,86	6,45	12,203	O	9,381429	5,335061
Cal. value						Cal. value	29,54667	5,551255
Cl						Cl	1652,5	2665,021
As	0,5 - 2,3 - 6,3	3,9 - 6,6 - 24,9	5	1,2	3,1	As	11,62444	15,22916
Cd	4	<5	2		3	Cd	3,375714	4,90465
Cr	12	55	14,2	24,5	26,425	Cr	25,15611	16,11163
Hg	0,5	0,6	0,5	0,6	0,55	Hg	0,360778	0,221027
Sb	0,5 - 1,0	2	1,6	1	1,5333	Sb	1,15	0,637966
Co	8,9	13,9	8,9	12,7	11,1	Co	11,25	6,344627
Se	1	2	1	1,2	1,3	Se	1,828571	0,84993
V	19,5	72	22,9	57,6	43	V	37	19,90988
Ni	60	55	33	40	47	Ni	33,1965	19,49568
Pb						Pb	37,0775	50,74587
Tl						Tl	0,815	0,26163

PETCOKE

		Chen (2006) Table 2, p 211	De Vos (2007)	Nagpal [2005]	Kääntee_2004 Table 2, p295
wt%	C	81,00 - 89,5	83,719662	89,23	89,5
wt%	H	3,5 - 5,5		3,59	3,08
wt%	N	1,30 - 1, 80		1,35	1,71
wt%	S	4,50 - 5,50	3,4	5,22	4
wt%	O	0,50 - 2,00		0,1	1,11
MJ/kg	Cal. value	30 - 34,5			33,7
ppm	Cl		2000		
ppm	As		0,9		
ppm	Cd		1,4		0,46
ppm	Cr		9		1,30E-07
ppm	Hg		0,2		5,00E-02
ppm	Sb		1,3		
ppm	Co		5,2		1,00E-08
ppm	Se		0,2		
ppm	V		1094,7		9,06E-06
ppm	Ni		334,3		4,32E-06
ppm	Pb		2,4		0,00053
ppm	Tl		2		

		AVG	STDEV
wt%	C	87,48322	3,262132
wt%	H	3,335	0,360624
wt%	N	1,53	0,254558
wt%	S	4,206667	0,927434
wt%	O	0,605	0,714178
MJ/kg	Cal. value	33,7	0
ppm	Cl	2000	0
ppm	As	0,9	0
ppm	Cd	0,93	0,66468
ppm	Cr	4,5	6,363961
ppm	Hg	0,125	0,106066
ppm	Sb	1,3	0
ppm	Co	2,6	3,676955
ppm	Se	0,2	0
ppm	V	547,35	774,0698
ppm	Ni	167,15	236,3858
ppm	Pb	1,200265	1,696682
ppm	Tl	2	0

FUEL OIL

		Seyler [2005] cem **Table 6; p124 [HEAVY]**	Barros [2005] and Hofstetter [2003] **Fuel oil**	Canonico [2000] **Fuel oil n°6**	Turunen [1995] **Table 4; p90; sample 1**	Turunen [1995] **heavy oil, sample 2**	Turunen [1995] **heavy oil, sample 3**	Block [1976] **light**	Block [1976] **mid heavy**	Block [1967]	Vouk [1983] **fuel oil**	Vouk [1983] **gasoline**
wt%	C	84										
wt%	H											
wt%	N	0,44										
wt%	S	0,83						0,45 - 1,08	1,9 - 2,8	1,5 - 2,4		
wt%	O											
MJ/kg	Cal. value	40,4										
ppm	Cl	20						0,2 - 5,1	10,0 - 17,0	22,0 - 97		
ppm	As	0,8	<0,03			0,1		0,012 - 0,013	0,01 - 0,07	0,01 - 0,03	0,42	0,0015
ppm	Cd	2	<0,01	0,3	0,031	0,01	0,025				0,01	0,015
ppm	Cr	1	0,46	0,005	0,058	0,04	0,062	<0,010	<0,050	0,030 - 0,11	1,3	0,017
ppm	Hg	0,006		0,005	0,008	0,01		<0,02	<0,03	<0,05	10	
ppm	Sb		0,028					<0,0009	0,003 - 0,010	<0,020 - 0,22	0,12	0,025
ppm	Co		0,58		0,289	0,18	0,185	0,0013 - 0,0014	0,03 - 0,07	0,02 - 0,09	0,2	
ppm	Se		<0,004					0,8 - 1,4	4,0 - 6,0	2,4 - 6,4	0,07	<0, 06
ppm	V		113		21,9	19,2	18	<0,004 - 0,25	39 - 54	33 - 103	82	0,0015
ppm	Ni	15	12,5	37,5	13,1	12,9	9,8	<0,2	15 - 18	8,0 - 33	55	0,086
ppm	Pb	3,5	0,16	1	0,206	0,3	0,41				2,3	400
ppm	Tl											

FUEL OIL

		Barros (2005) and Hofstetter [2003] crude oil	Barros (2005) and Hofstetter [2003] medium	Barros (2005) and Hofstetter (2003) heavy oil			AVG	STDEV
wt%	C				wt%	C	84	0
wt%	H				wt%	H		0
wt%	N				wt%	N	0,44	0
wt%	S				wt%	S	0,83	0
wt%	O				wt%	O		0
MJ/kg	Cal. value				MJ/kg	Cal. value	40,4	0
ppm	Cl				ppm	Cl	20	0
ppm	As	0,39	0,07	<0,03	ppm	As	0,29625	0,302005
ppm	Cd	0,073	0,005	0,01	ppm	Cd	0,2482	0,621959
ppm	Cr	13	0,62	0,72	ppm	Cr	1,570636	3,816769
ppm	Hg				ppm	Hg	2,0052	4,469229
ppm	Sb	0,032	0,024	<0,02	ppm	Sb	0,0458	0,041596
ppm	Co	4,5	6,3	3,3	ppm	Co	1,942	2,425647
ppm	Se	0,46	<0,004	0,06	ppm	Se	0,196667	0,228108
ppm	V	15	225	250	ppm	V	82,67794	95,19353
ppm	Ni	20	16	39	ppm	Ni	20,98964	16,05414
ppm	Pb	9,2	0,18	0,28	ppm	Pb	37,95782	120,1061
ppm	Tl				ppm	Tl		

7.2 *Annex II : Transfer coefficients*

rotary kiln

in %	Indaver_2006 **internal communication**	Wauters_1997 **special project**	De Vos_2007 - TNO **table 4; p22**	Saft_2007 **Table 5, p 235**	Seyler_2005 **Table 8; p 1222**	Ministerium fur UNLV **Anhang II,01 e.v.**		**AVG TFC**	**ST.DEV**
O			91,7				O	91,7	0
H			100				H	100	0
C	100	100	100		100		C	100	0
S	0,059	0,2	0,06		0,06		S	0,09475	0,07017
Cl	0,2	0,005	0,03		0,03	0,015	Cl	0,056	0,08119
As	<0,733	0,02	1,02E-06	0,063529		0,00007	As	0,0209	0,02994
Cd	<0,133	0,01	0,899	0,684615		0,009	Cd	0,400654	0,46007
Co	<0,0902		0,07	0,063707	0,07	0,000053	Co	0,05094	0,03405
Cr	<0,0493	0,005	7,39E-06	0,063592		7,90E-07	Cr	1,72E-02	0,03105
Hg	<0,157	0,22	4,02	0,272857		0,4	Hg	1,228214	1,86272
Sb	<0,0826		3,89E-07	0,063651			Sb	0,031826	0,04501
Se			5,03E-07				Se	5,03E-07	0
V	<0,0507		1,00E-02			1,30E-06	V	0,005001	0,00707
Ni	<0,0564	0,08	7,00E-02	0,063684	0,07	2,60E-07	Ni	5,67E-02	0,03225
Pb	<0,0272	0,09	3,31E-01	0,157011		0,004	Pb	0,145503	0,13862
Tl	<0,271		1,00E-01			0,00016	Tl	0,05008	0,0706
Cu	<0,00558		7,00E-02	<63,7	0,07	8,00E-08	Cu	0,046667	0,04041
Zn			7,00E-02	0,063691	0,07		Zn	0,067897	0,00364

Transfer coefficients, measured at the Indaver site are “Indaver_2006” and “Wauters_1997”;
for Cu and Zn of which data from the Indaver site lacked, the average value from literature data was used.

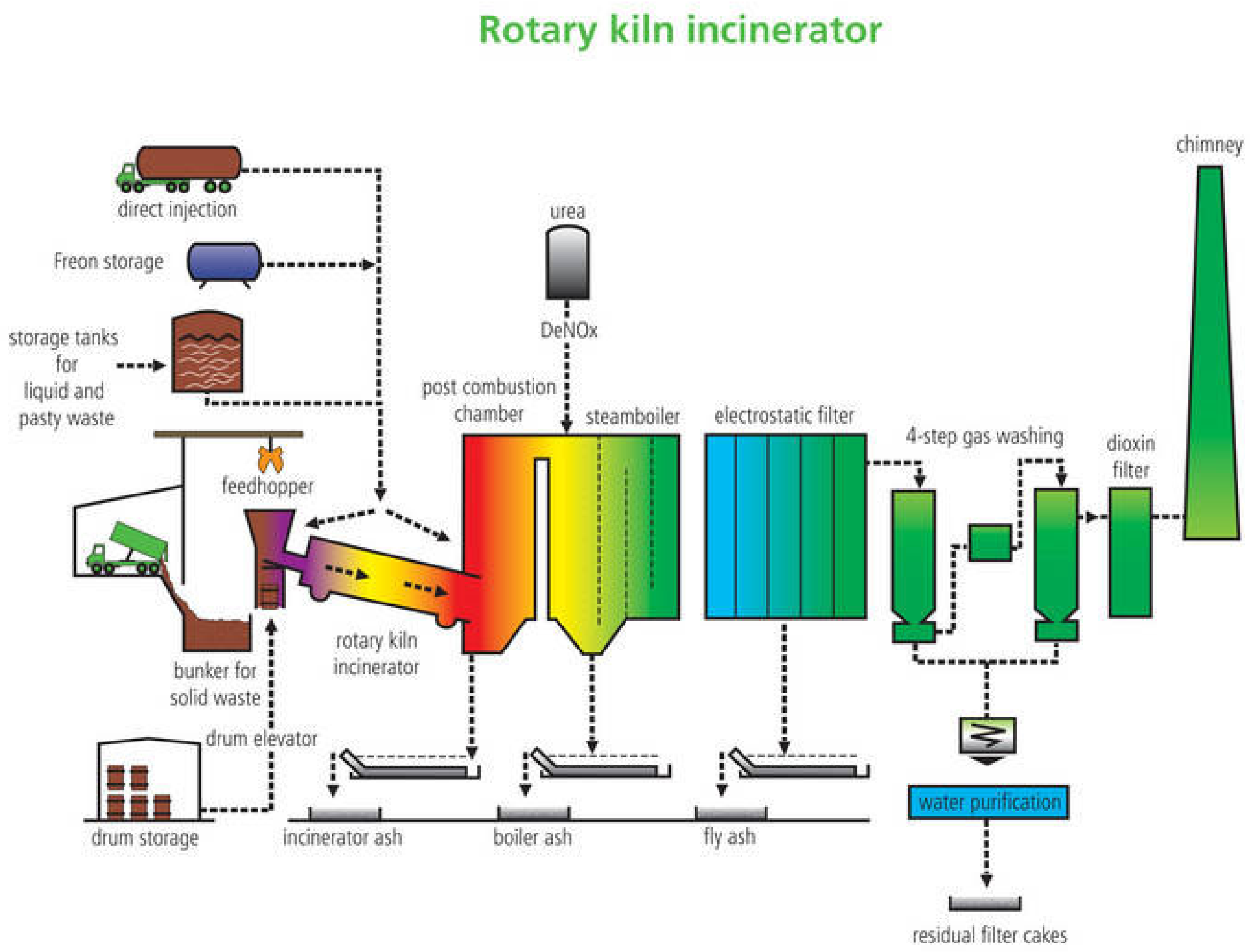


Figure 28: schematic presentation of the rotary kiln at the Indaver site, Antwerp

cement kiln

in %	Seyler_2005 **Table 8; p 1222**	CBR Lixhe	Denis [1999] **Table 3; p161 TEST 2a**	Denis [1999] **Table 3 p161 TEST 2b**	Ministerium fur UNLV **Anhang II,01 e.v.**	Genon[2008] **Table 2, p2379**		**AVG TFC**	**ST.DEV**
O							O		
H							H		
C	100	100	100	100	100	100	C	100	0
S		6,2	2,67	2,75			S	3,873333	2,01535
Cl		3,344			2,00E-02	3,4	Cl	2,254667	0
As	0,01	0,02	0,02	0,02	0,023	0,02	As	0,018833	0,00498
Cd	4,23	0,03	0,04	0,01	0,17	1,873	Cd	1,058833	1,86483
Co			0,02		0,019	0,014	Co	0,017667	0,00071
Cr	0,01	0,02	0,02	0,02	0,012	0,018	Cr	0,016667	0,00498
Hg	24,96	27,5	48	48	40	49	Hg	39,57667	10,9979
Sb			0,14	0,08			Sb	0,11	0,04243
Se			0,1	0,7			Se	0,4	0,42426
V			0,01	0,012	0,052	0,05	V	0,031	0,02369
Ni	0,001	0,03	0,03		0,03	0,019	Ni	0,022	0,0145
Pb	0,21	0,06	0,07	0,04	0,05	0,015	Pb	0,074167	0,07021
Tl	2,81				1,3	0,875	Tl	1,661667	1,06773
Cu	0,01		<0,02	<0,013	9,30E-03	0,04	Cu	0,019767	0,00049
Zn	0,18		8,00E-03		7,40E-02	0,437	Zn	0,17475	0,08677

For cement kilns the average value from literature data was used, since exact information from specific kilns in Belgium could not be obtained. However it can be seen that there is quite some consistency between the different references from literature.

7.3 Annex III: Calculation of environmental impacts

In this Annex all the input data into the excel files are given, along with the most important results, graphically presented, for all impact categories considered.

Global warming

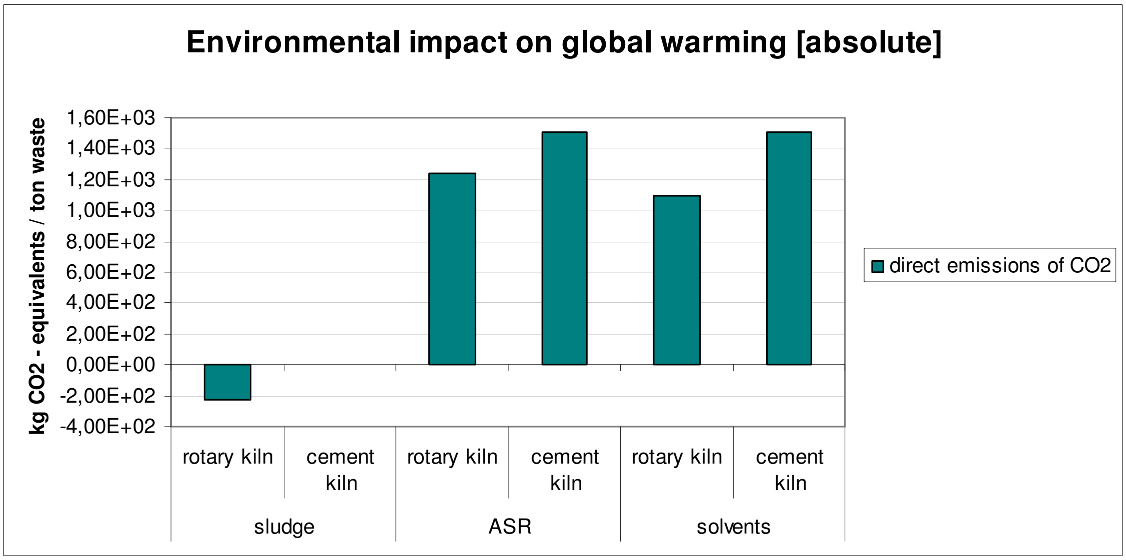
furnace type	**transfer coefficient**	**CO2/C**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	1	3,66667		14,7	0,026	0,131
cement kiln	1	3,66667		21	0	0

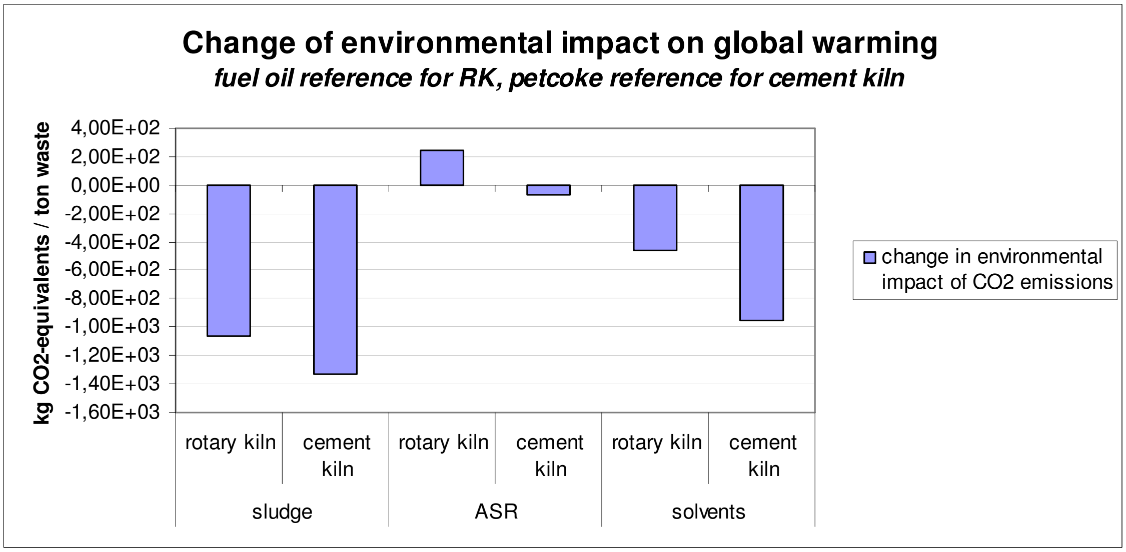
fuel type	**energetic value** **[MJ/kg]**	**carbon content** **[kg/ton]**
coal	29,55	7,67E+02
fuel oil	40,4	8,40E+02
petcoke	33,7	874,8

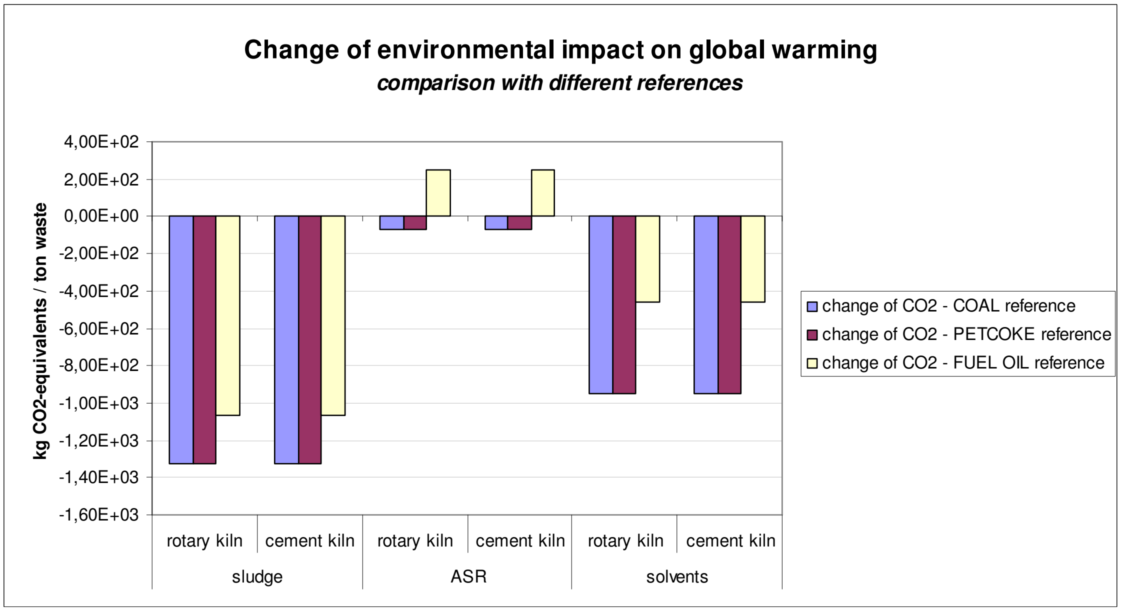
waste type	**energetic value** **[MJ/kg]**	**carbon content** *non-biogenic* **[kg/ton]**	*biogenic*	**functional unit** **[ton]**
sludge	13,95	0	326,9	1
ASR	16,5	410	0	1
solvents	25,8	410,7	0	1

electricity production avoided emissions	**average emissions CO2** [kg/GJ]
gas	176,9
coal	2,75E+02
energetic mixture [BE]	**1,96E+02**

steam production avioded emissions	**average emissions CO2** [kg/GJ]
gas	70,76
coal	110
energetic mixture [BE]	7,83E+01


Environmental impact on global warming [absolute]
kg CO2 - equivalents / ton waste
1,60E+03
1,40E+03
1,20E+03
1,00E+03
8,00E+02
6,00E+02
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
-4,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
direct emissions of CO2


Change of environmental impact on global warming
fuel oil reference for RK, petcoke reference for cement kiln
kg CO2-equivalents / ton waste
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
-4,00E+02
-6,00E+02
-8,00E+02
-1,00E+03
-1,20E+03
-1,40E+03
-1,60E+03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of CO2 emissions


Change of environmental impact on global warming
comparison with different references
kg CO2-equivalents / ton waste
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
-4,00E+02
-6,00E+02
-8,00E+02
-1,00E+03
-1,20E+03
-1,40E+03
-1,60E+03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of CO2 - COAL reference
change of CO2 - PETCOKE reference
change of CO2 - FUEL OIL reference

Acidification → SO_2

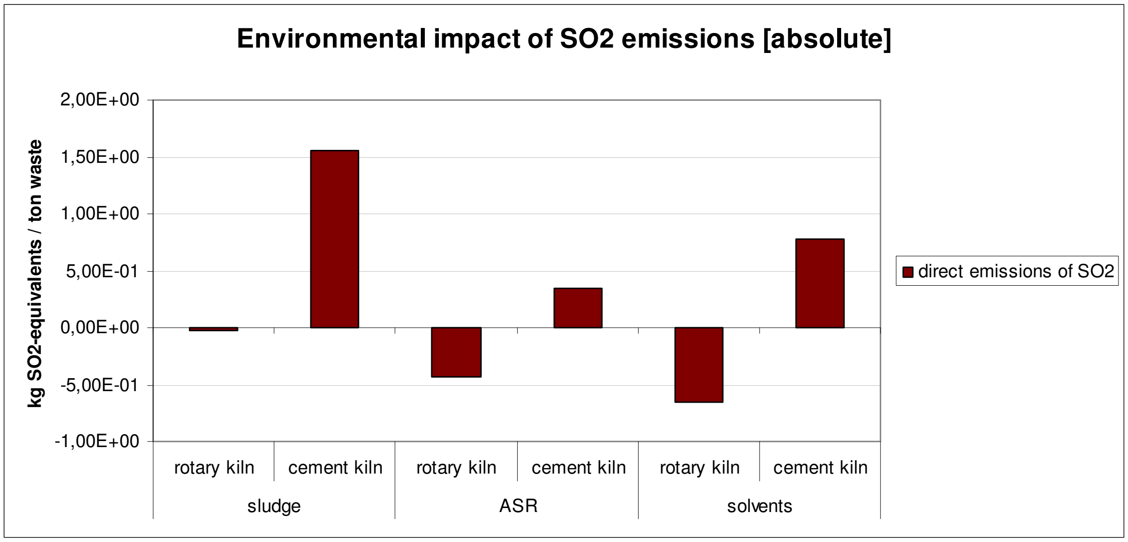
furnace type	transfer coefficient	SO2/S		minimal energy demand	electrical yield	steam yield
rotary kiln	0,002	2		14,7	0,026	0,131
cement kiln	0,0387	2		21	0	0

fuel type	energetic value [MJ/kg]	sulphur content [kg/ton]
coal	29,55	1,15E+01
fuel oil	40,4	8,30E+00
petcoke	33,7	42,1

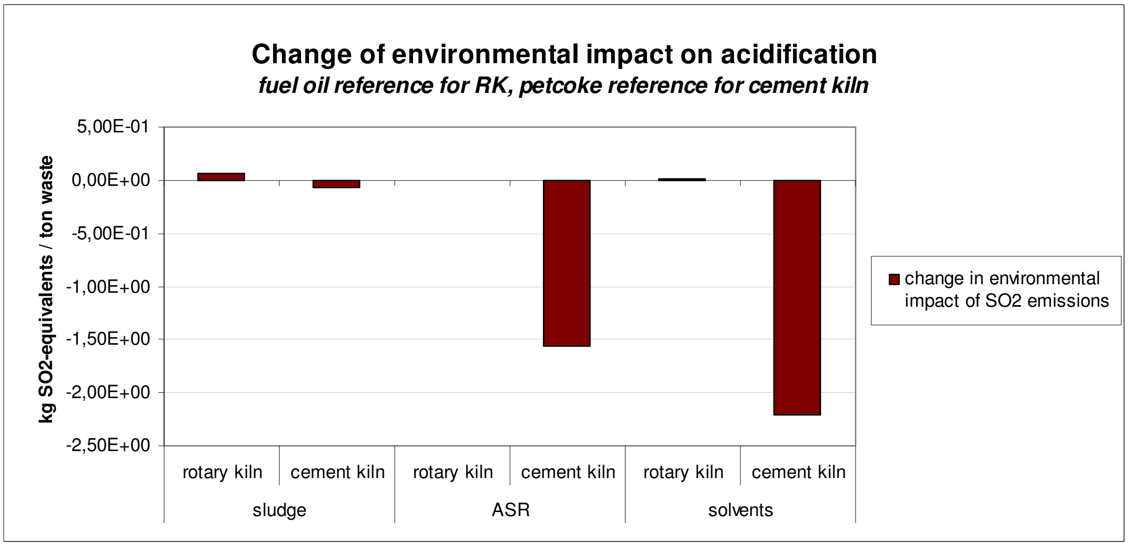
waste type	energetic value [MJ/kg]	sulphur content [kg/ton]		functional unit [ton]
sludge	13,95	16,7		1
ASR	16,5	3,78		1
solvents	25,8	8,43		1

electricity production avoided emissions	**average emissions SO2** [kg/GJ]
gas	0,06
coal	1,25
energetic mixture [BE]	**0,288599**

steam production avioded emissions	**average emissions SO2** [kg/GJ]
gas	0,024
coal	0,5
energetic mixture [BE]	0,1154396

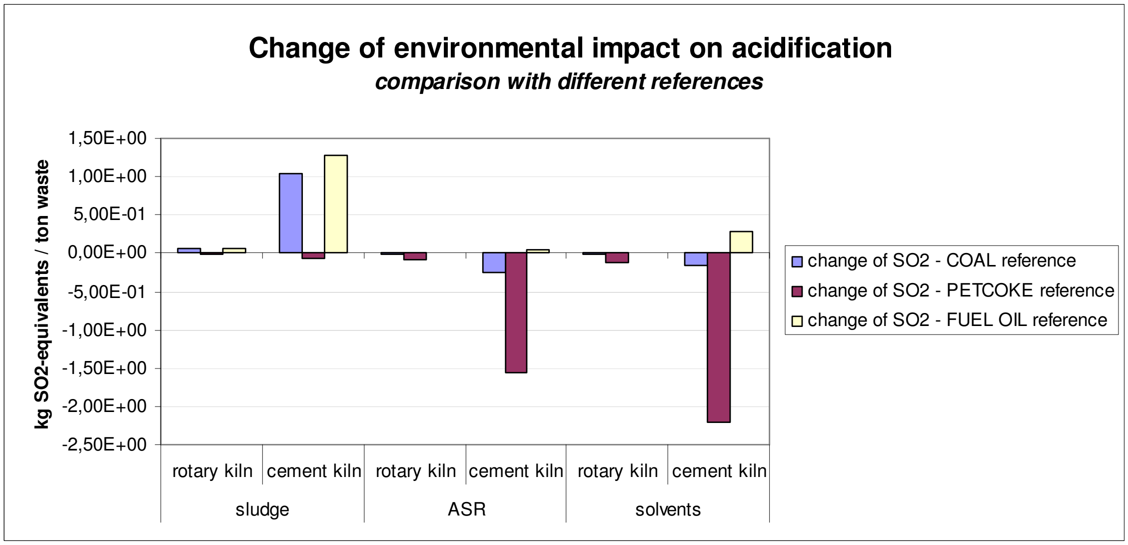


Environmental impact of SO2 emissions [absolute]



Change of environmental impact on acidification

fuel oil reference for RK, petcoke reference for cement kiln



Change of environmental impact on acidification

comparison with different references

Acidification → NO_x

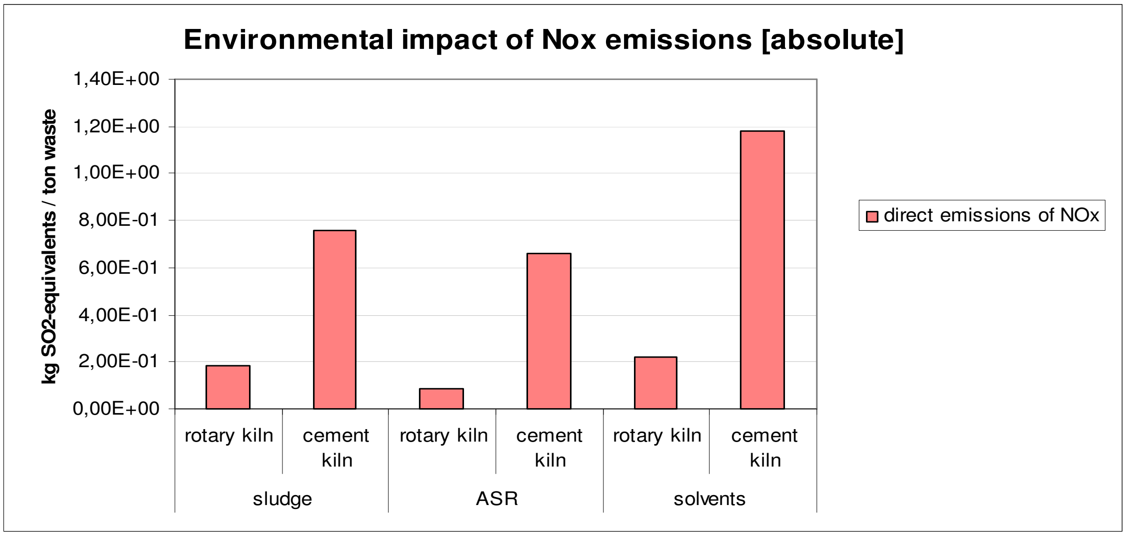
furnace type	**transfer FACTOR**	**NOx/N**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	**0,0073**	2,143		14,7	0,026	0,131
cement kiln	**0,0129**	2,143		21	0	0

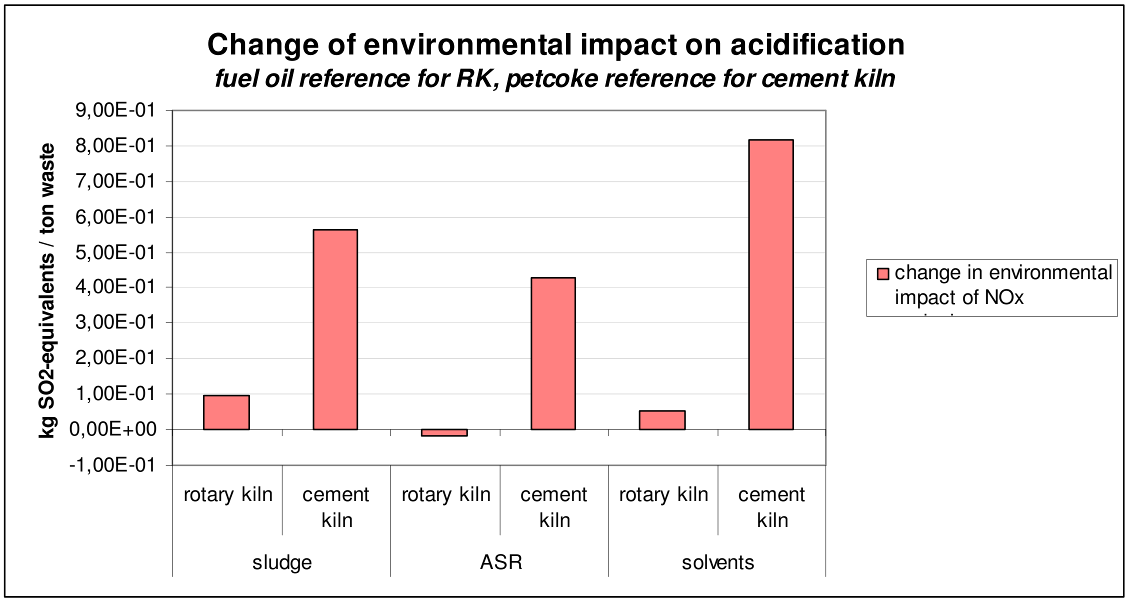
fuel type	**energetic value** [MJ/kg]	**nitrogen content** [kg/ton]	**hydrogen content** [kg/ton]	**transfercoëfficient** rotary kiln	cement kiln
coal	29,55	1,29E+01	48,75	0,0276	4,88E-02
fuel oil	40,4	4,40E+00	120	0,1991	3,52E-01
petcoke	33,7	15,3	33,35	0,0159	2,81E-02

waste type	**energetic value** [MJ/kg]	**nitrogen content** [kg/ton]	**hydrogen content** [kg/ton]	**functional unit** [ton]	**transfercoëfficient** rotary kiln	cement kiln
sludge	13,95	40,3	53,7	1	0,009727295	0,0171893
ASR	16,5	19,2	46,7	1	0,017755729	0,0313766
solvents	25,8	15	83,5	1	0,040636667	0,07181

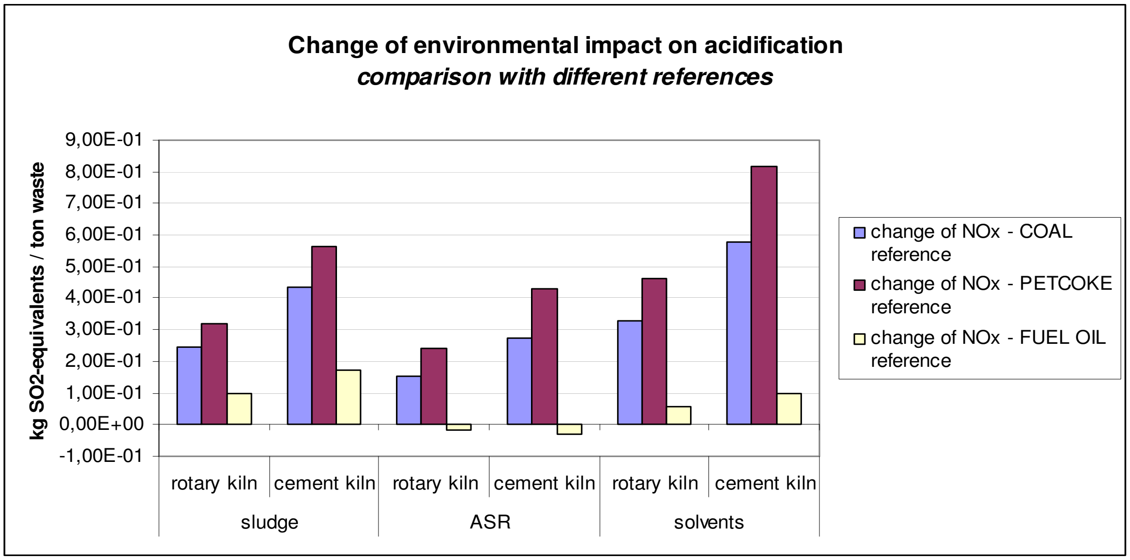
electricity production avoided emissions	**average emissions NOx** [kg/GJ]
gas	0,352
coal	0,783
energetic mixture [BE]	**0,4347951**

steam production avioded emissions	**average emissions NOx** [kg/GJ]
gas	0,1408
coal	0,3132
energetic mixture [BE]	0,17391804


Environmental impact of Nox emissions [absolute]

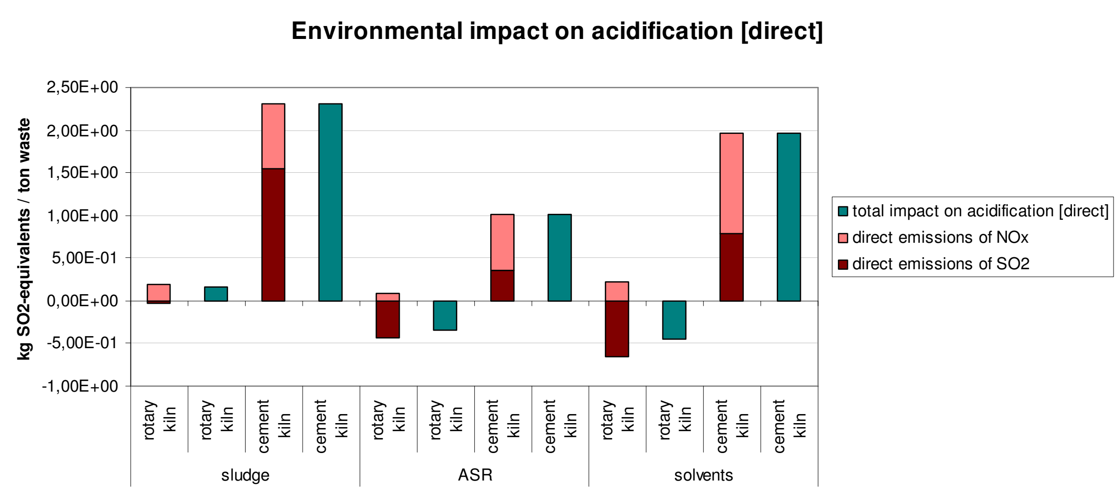

Change of environmental impact on acidification

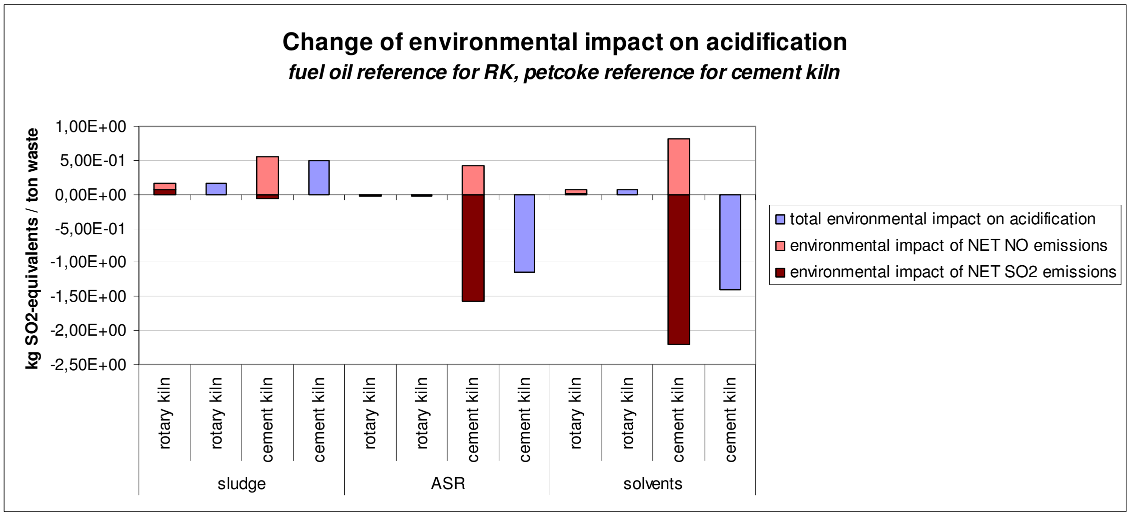
fuel oil reference for RK, petcoke reference for cement kiln

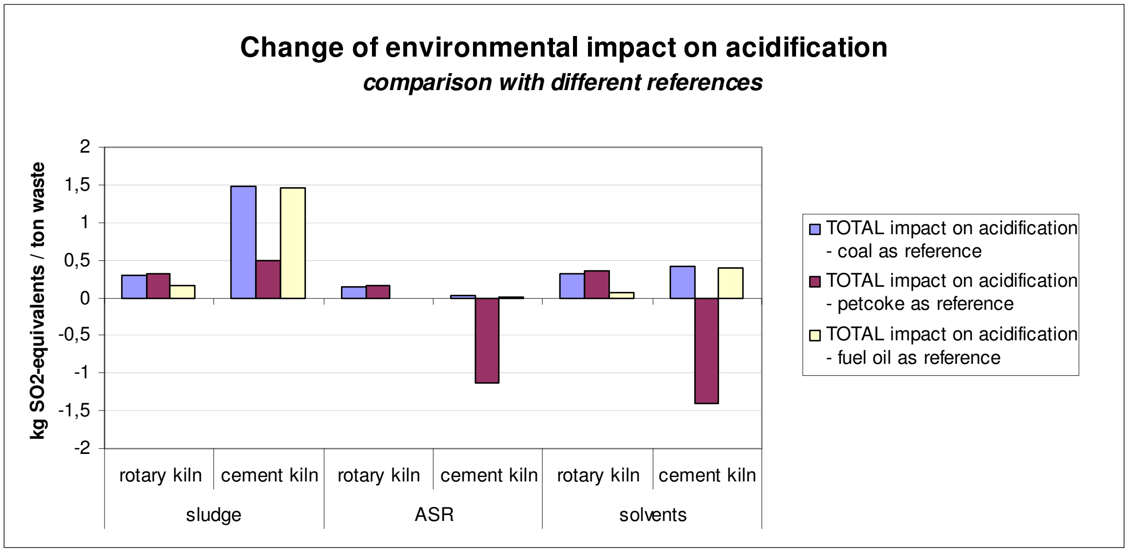

Change of environmental impact on acidification

comparison with different references

Acidification → TOTAL







Photochemical ozone creation → SO_2

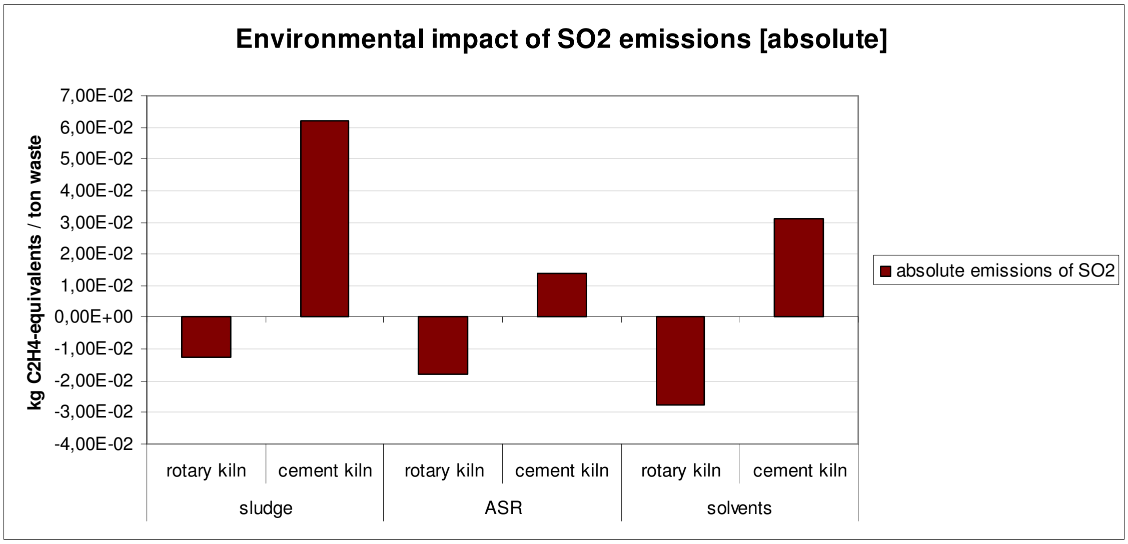
furnace type	**transfer coefficient**	**SO2/S**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,002	2		14,7	0,026	0,131
cement kiln	0,0387	2		21	0	0

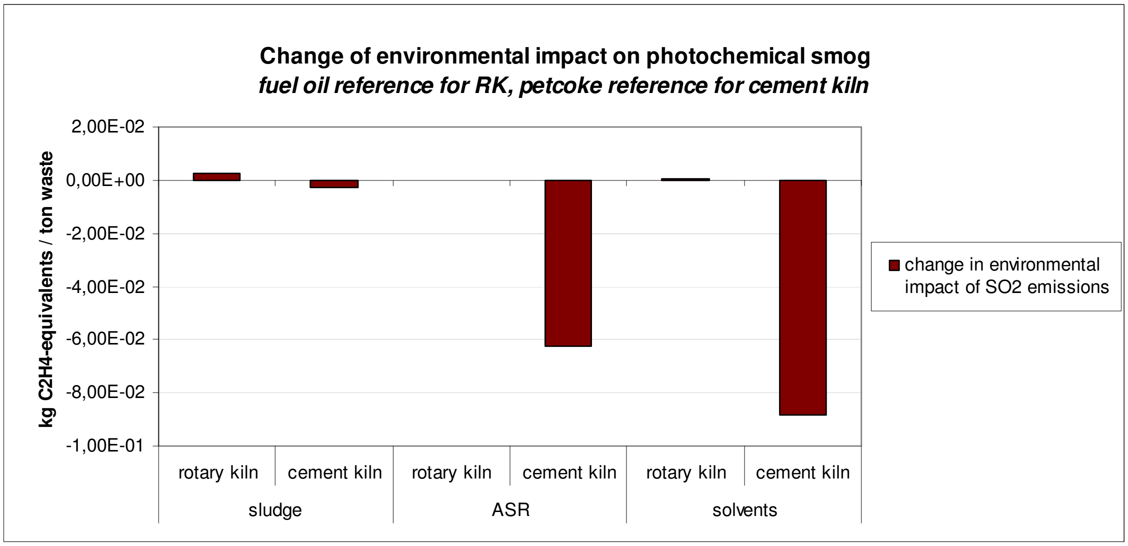
fuel type	**energetic value [MJ/kg]**	**sulphur content [kg/ton]**
coal	29,55	1,15E+01
fuel oil	40,4	8,30E+00

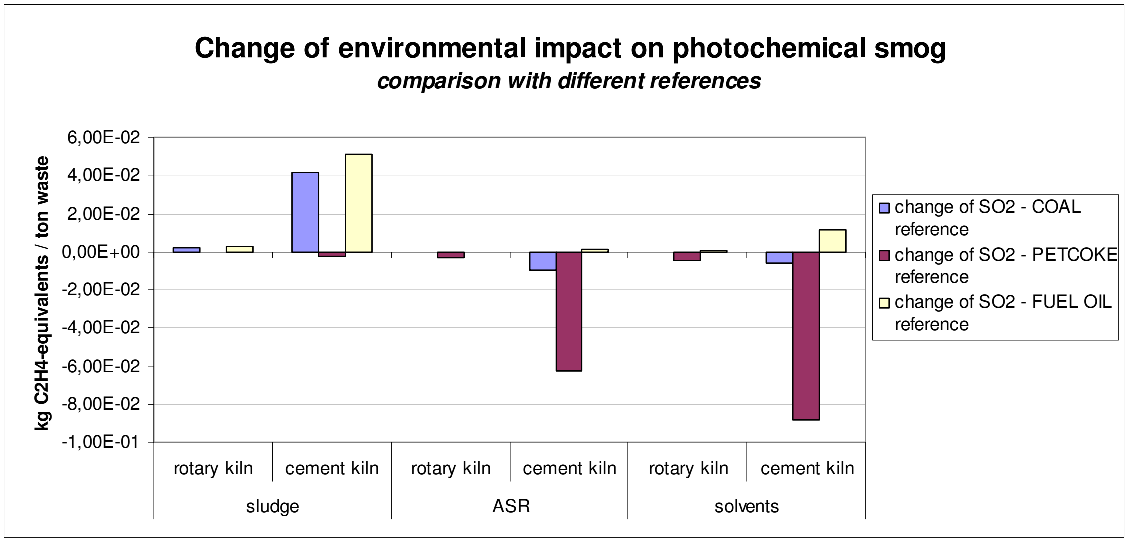
petcoke	33,7	42,1

waste type	**energetic value [MJ/kg]**	**sulphur content [kg/ton]**		**functional unit [ton]**
sludge	13,95	16,7		1
ASR	16,5	3,78		1
solvents	25,8	8,43		1

electricity production avoided emissions	**average emissions SO2** [kg/GJ]
gas	0,06
coal	1,25
energetic mixture [BE]	**0,288599**
steam production avioded emissions	**average emissions SO2** [kg/GJ]
gas	0,024
coal	0,5
energetic mixture [BE]	0,1154396


Environmental impact of SO2 emissions [absolute]
kg C2H4-equivalents / ton waste
7,00E-02
6,00E-02
5,00E-02
4,00E-02
3,00E-02
2,00E-02
1,00E-02
0,00E+00
-1,00E-02
-2,00E-02
-3,00E-02
-4,00E-02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
■ absolute emissions of SO2


Change of environmental impact on photochemical smog
fuel oil reference for RK, petcoke reference for cement kiln
kg C2H4-equivalents / ton waste
2,00E-02
0,00E+00
-2,00E-02
-4,00E-02
-6,00E-02
-8,00E-02
-1,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
■ change in environmental impact of SO2 emissions


Change of environmental impact on photochemical smog
comparison with different references
kg C2H4-equivalents / ton waste
6,00E-02
4,00E-02
2,00E-02
0,00E+00
-2,00E-02
-4,00E-02
-6,00E-02
-8,00E-02
-1,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
□ change of SO2 - COAL reference
■ change of SO2 - PETCOKE reference
□ change of SO2 - FUEL OIL reference

Photochemical ozone creation → NO_x

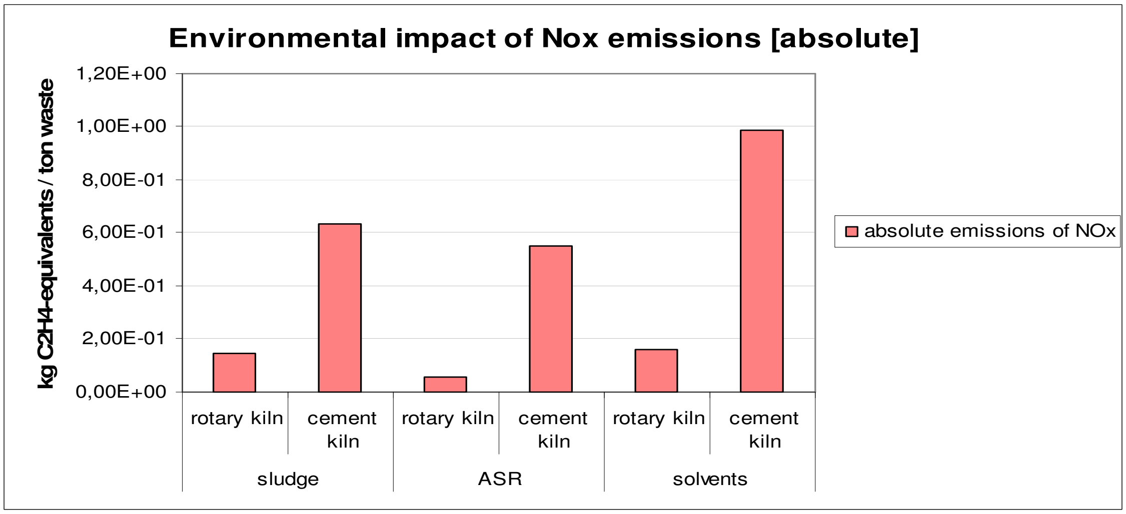
furnace type	**transfer FACTOR**	**NOx/N**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	**0,0073**	2,143		14,7	0,026	0,131
cement kiln	**0,0129**	2,143		21	0	0

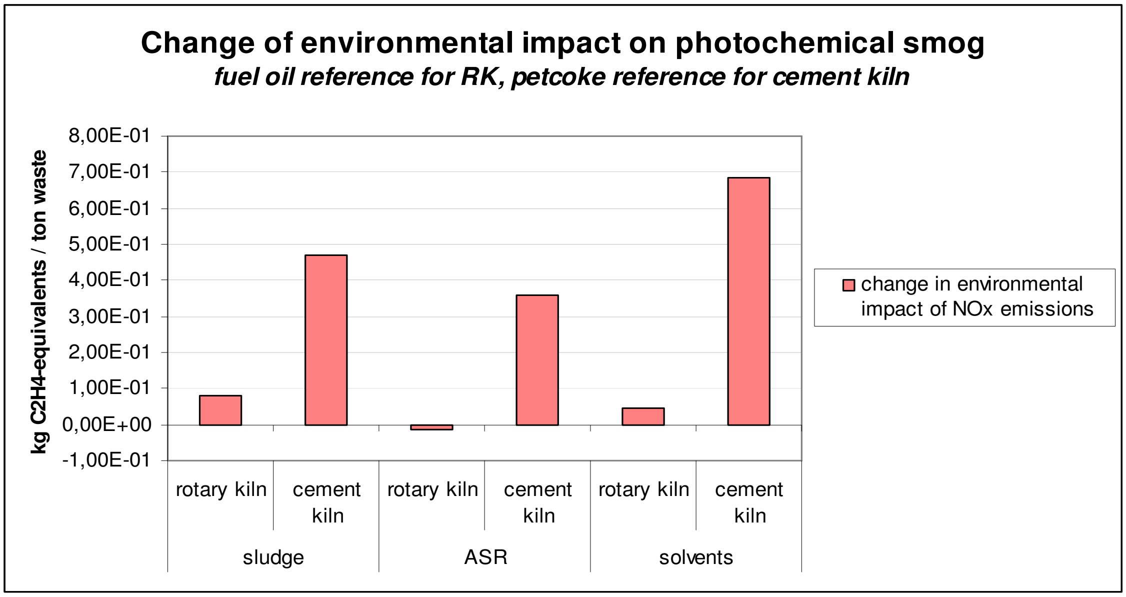
fuel type	**energetic value** [MJ/kg]	**nitrogen content** [kg/ton]	**hydrogen content** [kg/ton]	**transfercoëfficient** rotary kiln	cement kiln
coal	29,55	1,29E+01	48,75	0,0276	4,88E-02
fuel oil	40,4	4,40E+00	120	0,1991	3,52E-01
petcoke	33,7	15,3	33,35	0,0159	2,81E-02

waste type	**energetic value** [MJ/kg]	**nitrogen content** [kg/ton]	**hydrogen content** [kg/ton]	**functional unit** [ton]	**transfercoëfficient** rotary kiln	cement kiln
sludge	13,95	40,3	53,7	1	0,009727295	0,017189
ASR	16,5	19,2	46,7	1	0,017755729	0,031377
solvents	25,8	15	83,5	1	0,040636667	0,07181

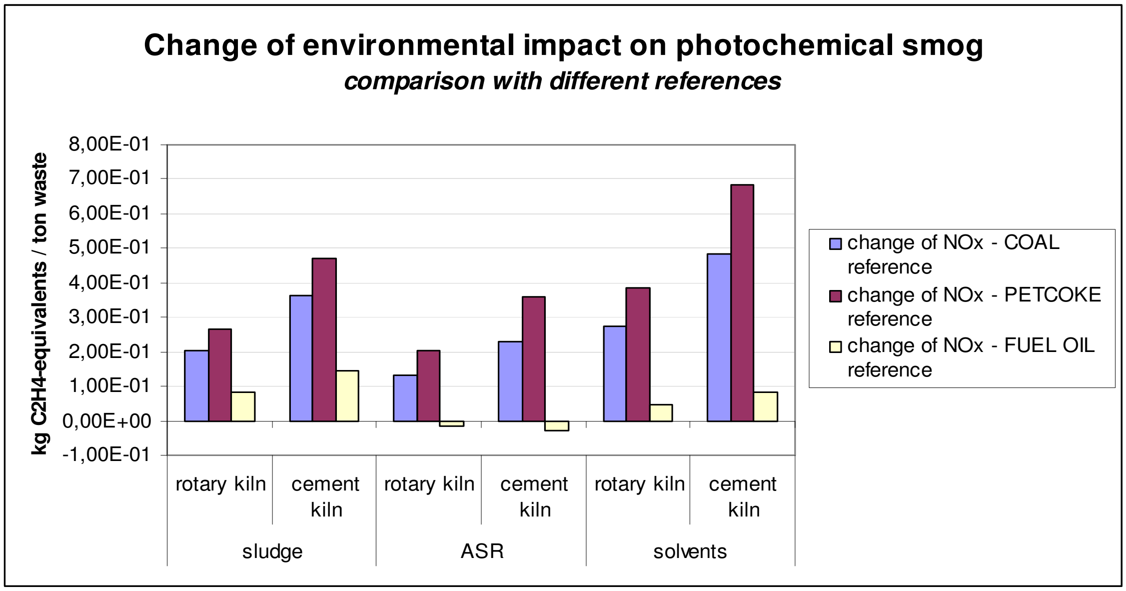
electricity production avoided emissions	**average emissions NOx** [kg/GJ]
gas	0,352
coal	0,783
energetic mixture [BE]	**0,4347951**

steam production avioded emissions	**average emissions NOx** [kg/GJ]
gas	0,1408
coal	0,3132
energetic mixture [BE]	0,17391804


Environmental impact of Nox emissions [absolute]

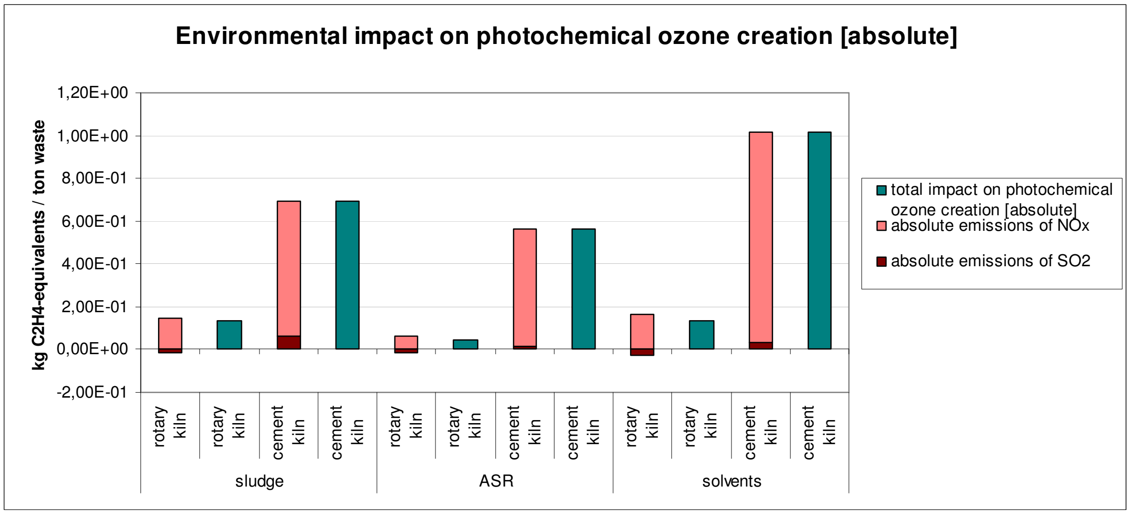

Change of environmental impact on photochemical smog

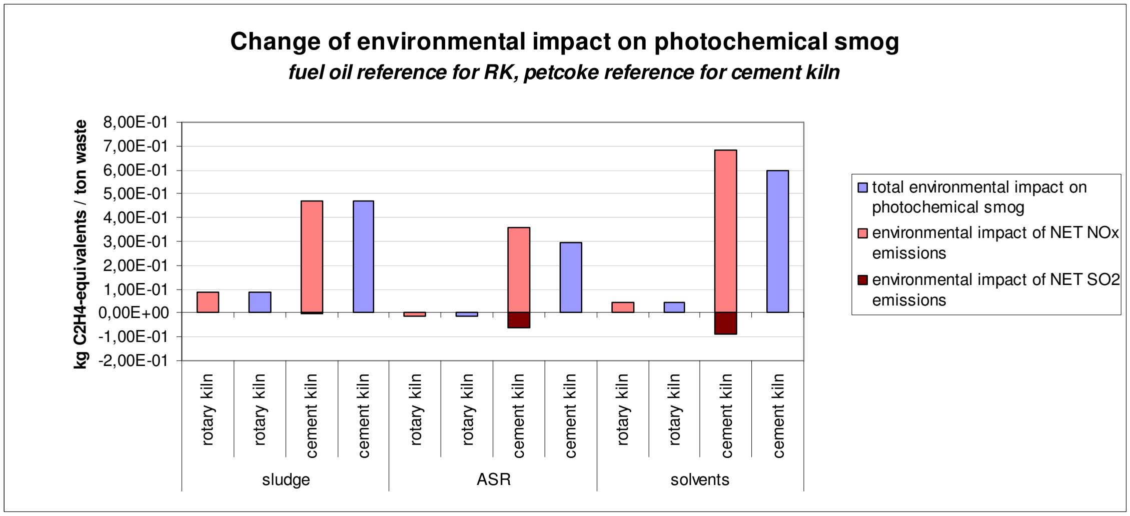
fuel oil reference for RK, petcoke reference for cement kiln

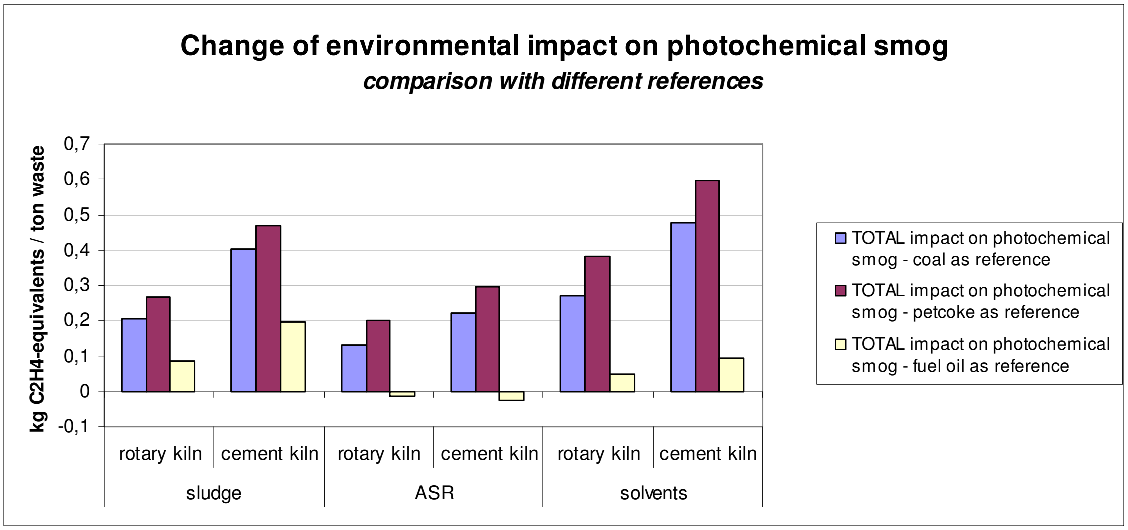

Change of environmental impact on photochemical smog

comparison with different references

Photochemical ozone creation → TOTAL







Eutrophication

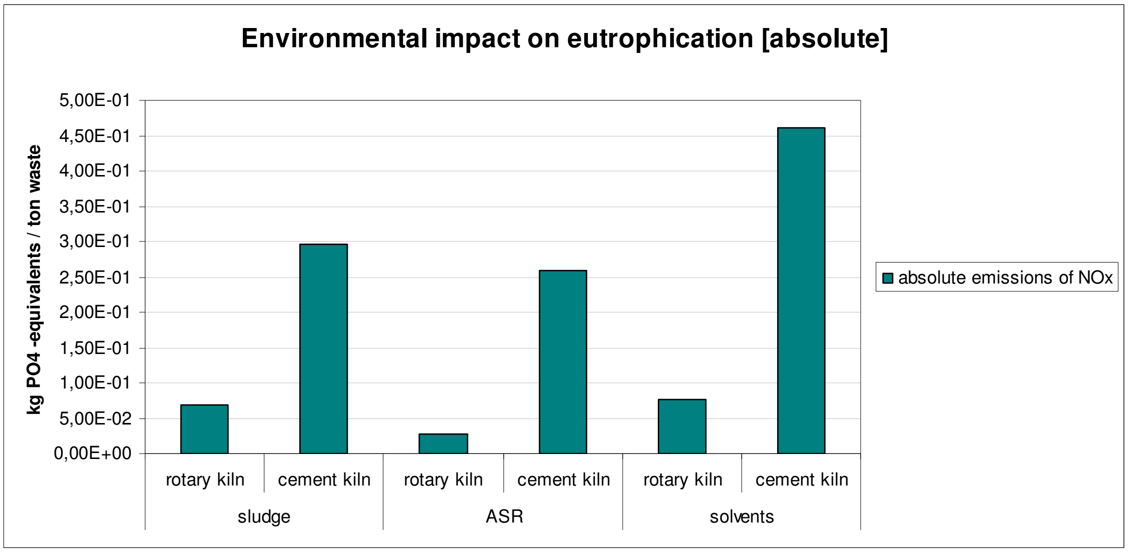
furnace type	transfer FACTOR	NOx/N		minimal energy demand	electrical yield	steam yield
rotary kiln	**0,0073**	2,143		14,7	0,026	0,131
cement kiln	**0,0129**	2,143		21	0	0

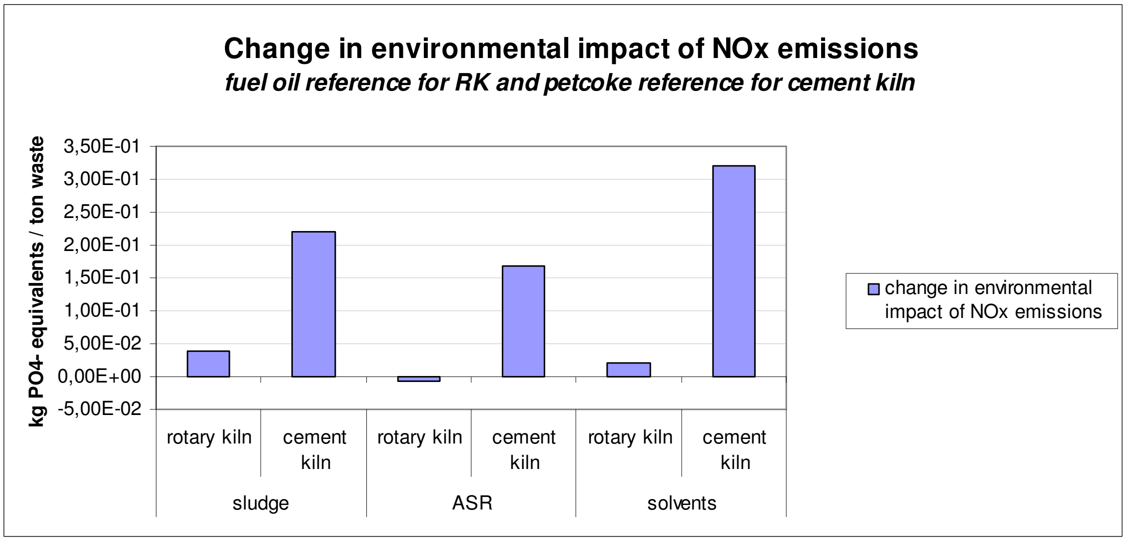
fuel type	energetic value [MJ/kg]	nitrogen content [kg/ton]	hydrogen content [kg/ton]	transfercoëfficient rotary kiln	transfercoëfficient cement kiln
coal	29,55	1,29E+01	48,75	0,0276	4,88E-02
fuel oil	40,4	4,40E+00	120	0,1991	3,52E-01
petcoke	33,7	15,3	33,35	0,0159	2,81E-02

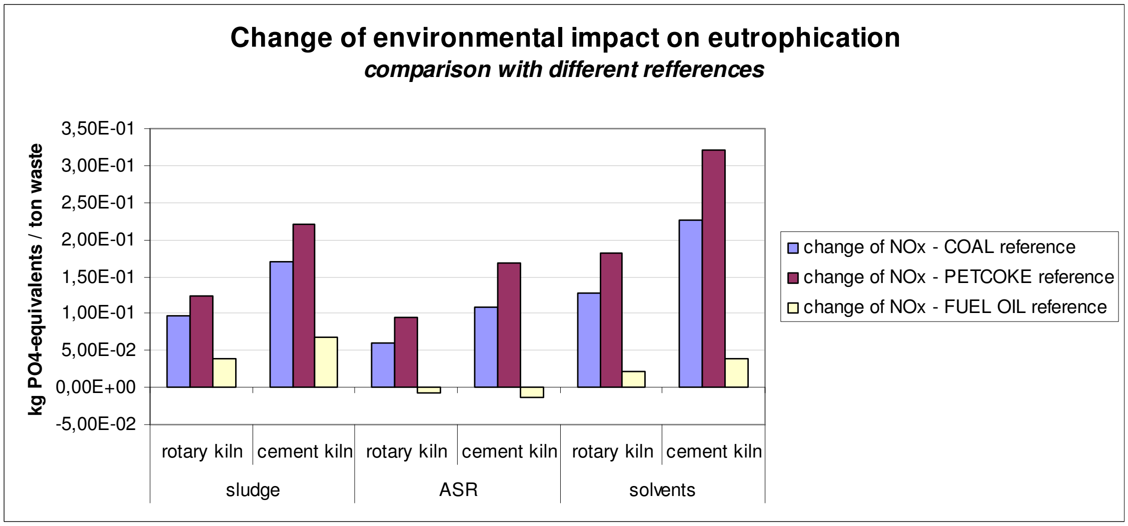
waste type	energetic value [MJ/kg]	nitrogen content [kg/ton]	hydrogen content [kg/ton]	functional unit [ton]	transfercoëfficient rotary kiln	transfercoëfficient cement kiln
sludge	13,95	40,3	53,7	1	0,009727295	0,017189
ASR	16,5	19,2	46,7	1	0,017755729	0,031377
solvents	25,8	15	83,5	1	0,040636667	0,07181

electricity production avoided emissions	average emissions NOx [kg/GJ]
gas	0,352
coal	0,783
energetic mixture [BE]	**0,4347951**

steam production avioded emissions	average emissions NOx [kg/GJ]
gas	0,1408
coal	0,3132
energetic mixture [BE]	0,17391804


Environmental impact on eutrophication [absolute]
kg PO4 -equivalents / ton waste
5,00E-01
4,50E-01
4,00E-01
3,50E-01
3,00E-01
2,50E-01
2,00E-01
1,50E-01
1,00E-01
5,00E-02
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of NOx


Change in environmental impact of NOx emissions
fuel oil reference for RK and petcoke reference for cement kiln
kg PO4- equivalents / ton waste
3,50E-01
3,00E-01
2,50E-01
2,00E-01
1,50E-01
1,00E-01
5,00E-02
0,00E+00
-5,00E-02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of NOx emissions


Change of environmental impact on eutrophication
comparison with different refferences
kg PO4-equivalents / ton waste
3,50E-01
3,00E-01
2,50E-01
2,00E-01
1,50E-01
1,00E-01
5,00E-02
0,00E+00
-5,00E-02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of NOx - COAL reference
change of NOx - PETCOKE reference
change of NOx - FUEL OIL reference

Human toxicity →As

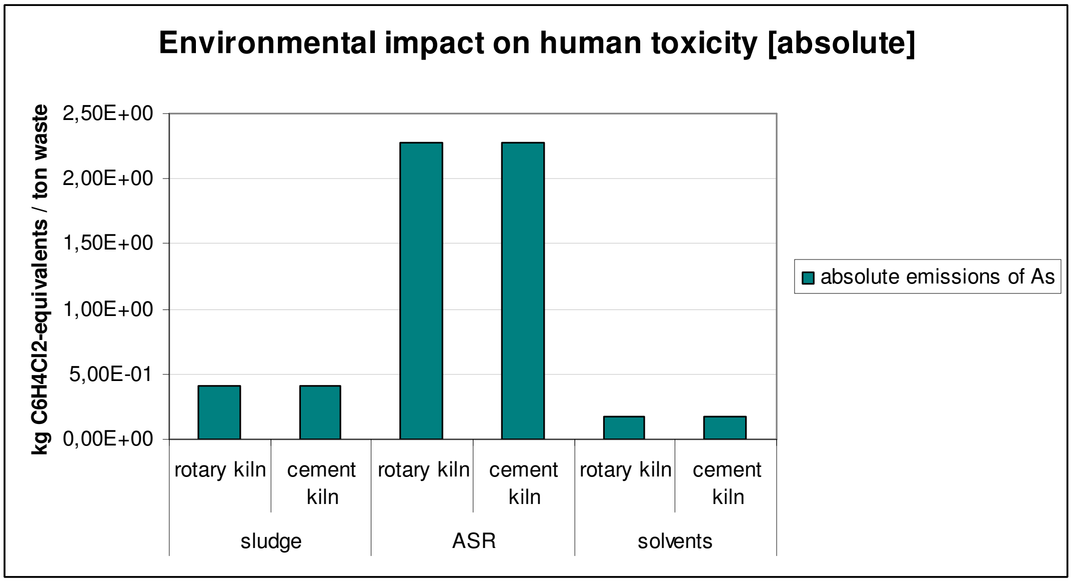
furnace type	transfer coefficient]	As/As		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0002	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

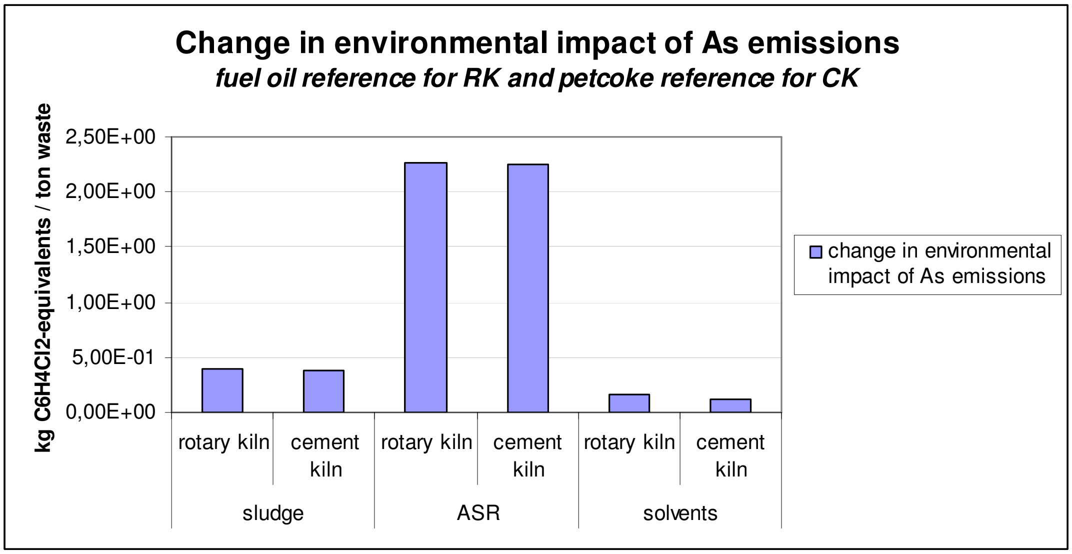
fuel type	energetic value [MJ/kg]	arsenic content [kg/ton]
coal	29,55	1,62E-01
fuel oil	40,4	3,00E-04

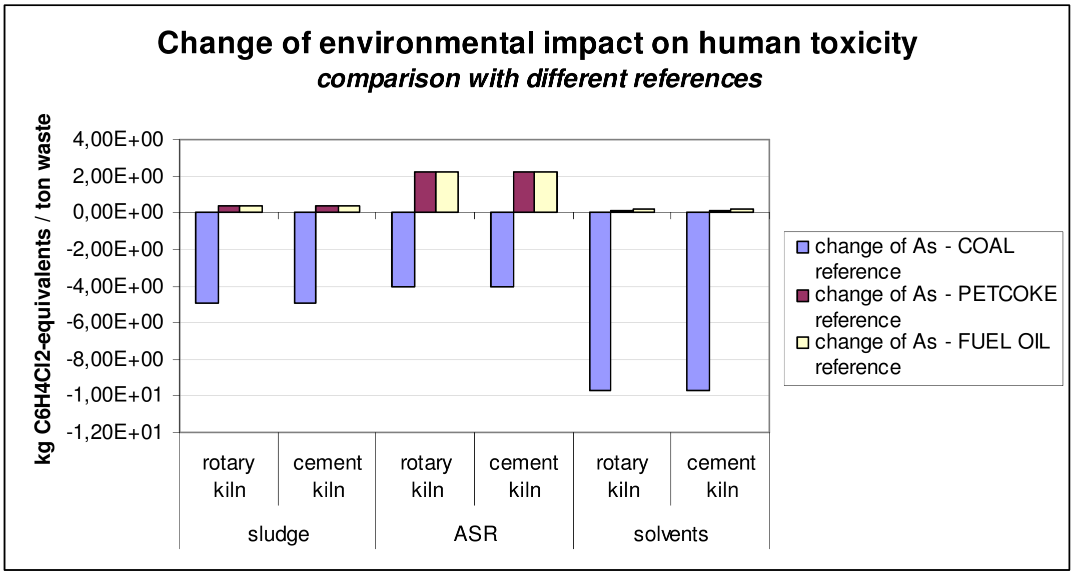
petcoke	33,7	0,0009

waste type	energetic value [MJ/kg]	arsenic content [kg/ton]		functional unit [ton]
sludge	13,95	0,0058		1
ASR	16,5	0,0325		1
solvents	25,8	0,00245		1

electricity production avoided emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
2,50E+00
2,00E+00
1,50E+00
1,00E+00
5,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of As


Change in environmental impact of As emissions
fuel oil reference for RK and petcoke reference for CK
kg C6H4Cl2-equivalents / ton waste
2,50E+00
2,00E+00
1,50E+00
1,00E+00
5,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of As emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
4,00E+00
2,00E+00
0,00E+00
-2,00E+00
-4,00E+00
-6,00E+00
-8,00E+00
-1,00E+01
-1,20E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of As - COAL reference
change of As - PETCOKE reference
change of As - FUEL OIL reference

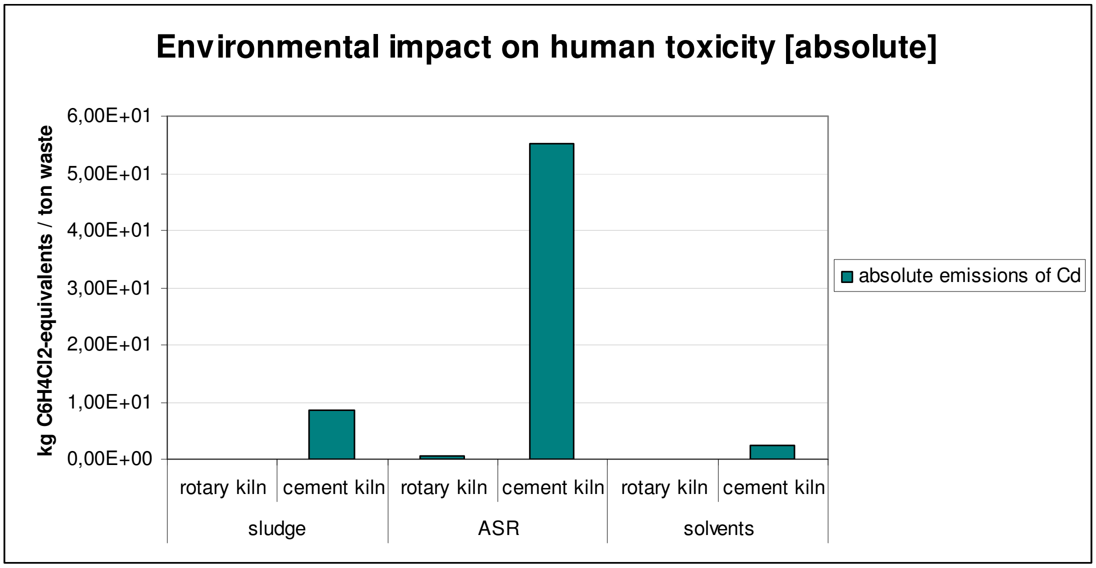
Human toxicity → Cd

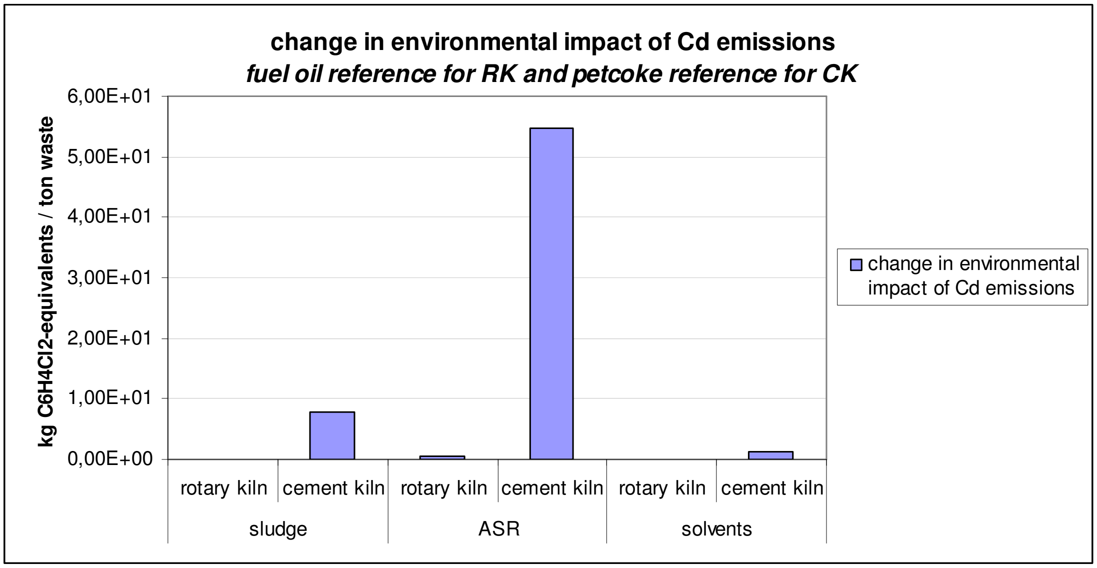
furnace type	transfer coefficient	Cd/Cd		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0001	1		14,7	0,026	0,131
cement kiln	0,0106	1		21	0	0

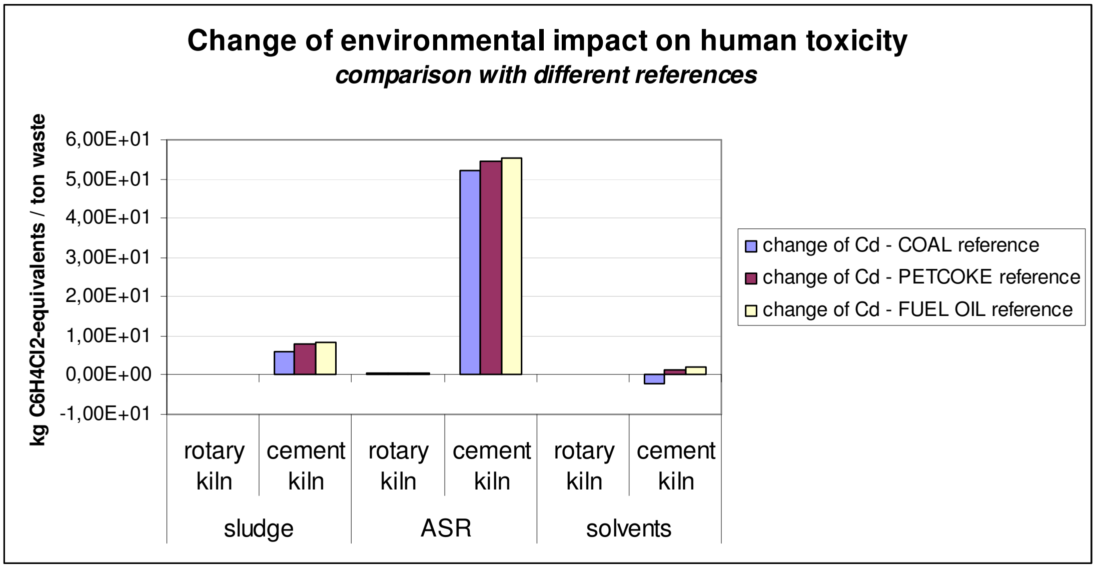
fuel type	energetic value [MJ/kg]	cadmium content [kg/ton]
coal	29,55	3,40E-03
fuel oil	40,4	2,50E-04
petcoke	33,7	0,00093

waste type	energetic value [MJ/kg]	cadmium content [kg/ton]		functional unit [ton]
sludge	13,95	0,0053		1
ASR	16,5	0,0348		1
solvents	25,8	0,0015		1

electricity production avoided emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cd


change in environmental impact of Cd emissions
fuel oil reference for RK and petcoke reference for CK
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cd emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
-1,00E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cd - COAL reference
change of Cd - PETCOKE reference
change of Cd - FUEL OIL reference

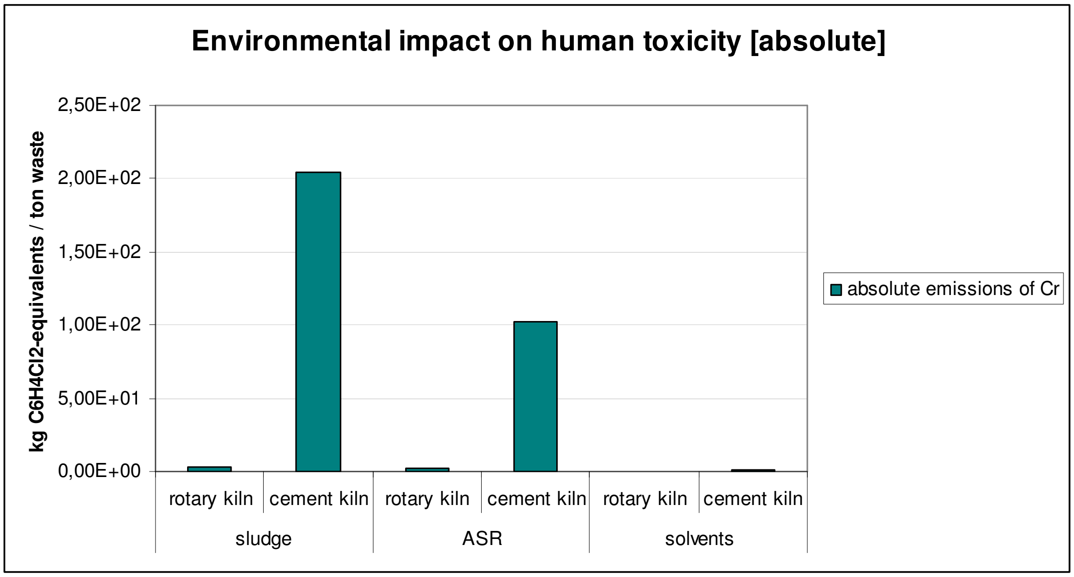
Human toxicity → Cr

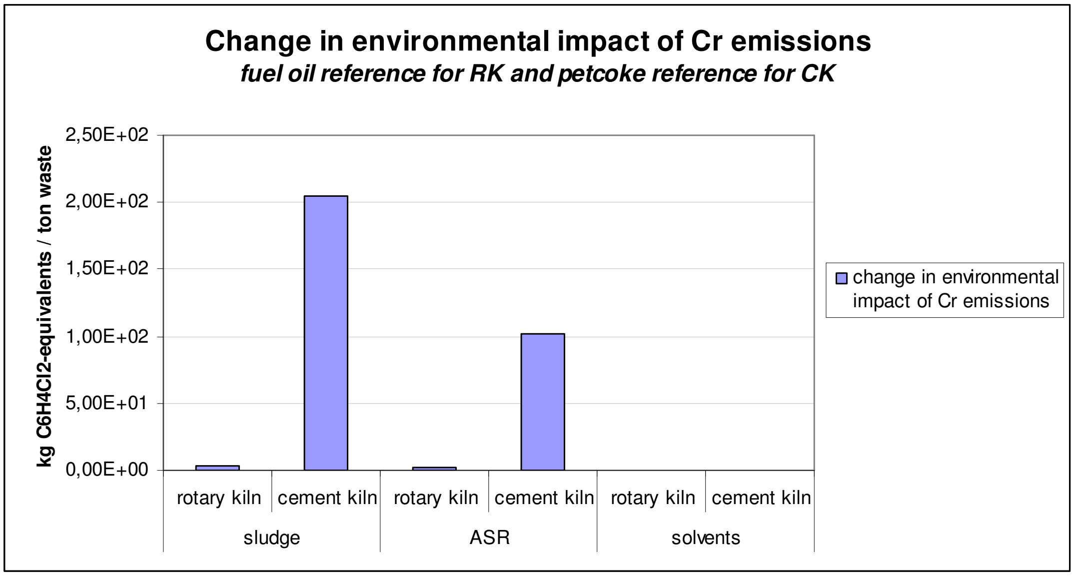
furnace type	transfer coefficient	Cr/Cr		minimal energy demand	electrical yield	steam yield
rotary kiln	5,00E-05	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

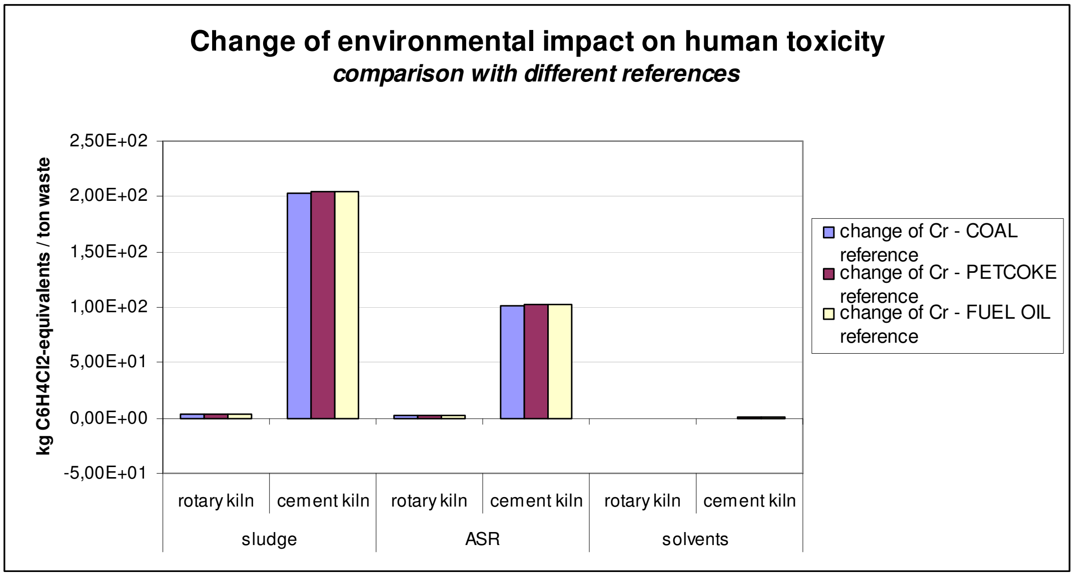
fuel type	energetic value [MJ/kg]	chromium content [kg/ton]
coal	29,55	2,52E-02
fuel oil	40,4	1,60E-03
petcoke	33,7	0,0045

waste type	energetic value [MJ/kg]	chromium content [kg/ton]		functional unit [ton]
sludge	13,95	2,406		1
ASR	16,5	1,204		1
solvents	25,8	0,0093		1

electricity production avoided emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on human toxicity [absolute]


Change in environmental impact of Cr emissions
fuel oil reference for RK and petcoke reference for CK


Change of environmental impact on human toxicity
comparison with different references

Human toxicity → Hg

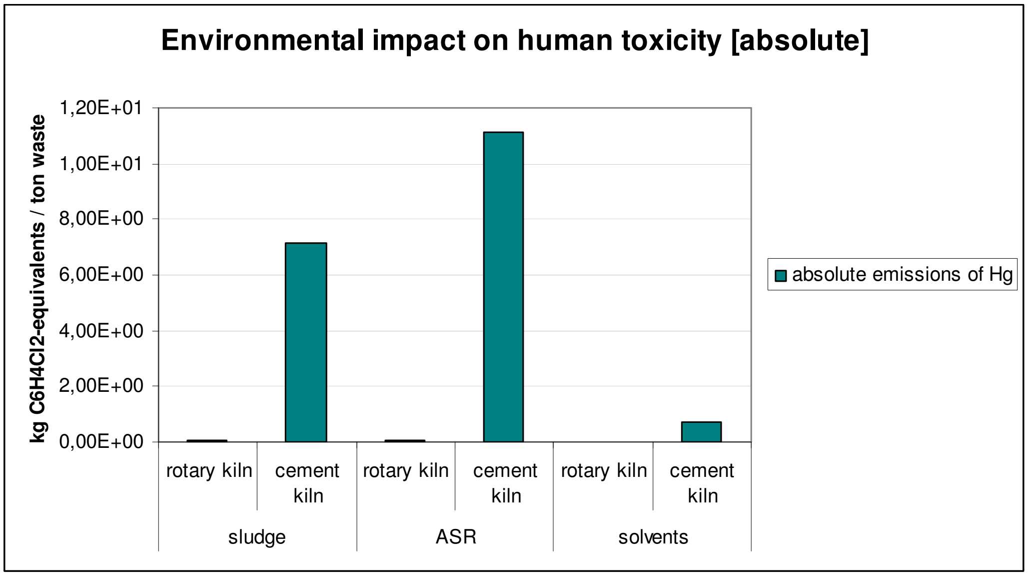
furnace type	transfer coefficient	Hg/Hg		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0022	1		14,7	0,026	0,131
cement kiln	0,3958	1		21	0	0

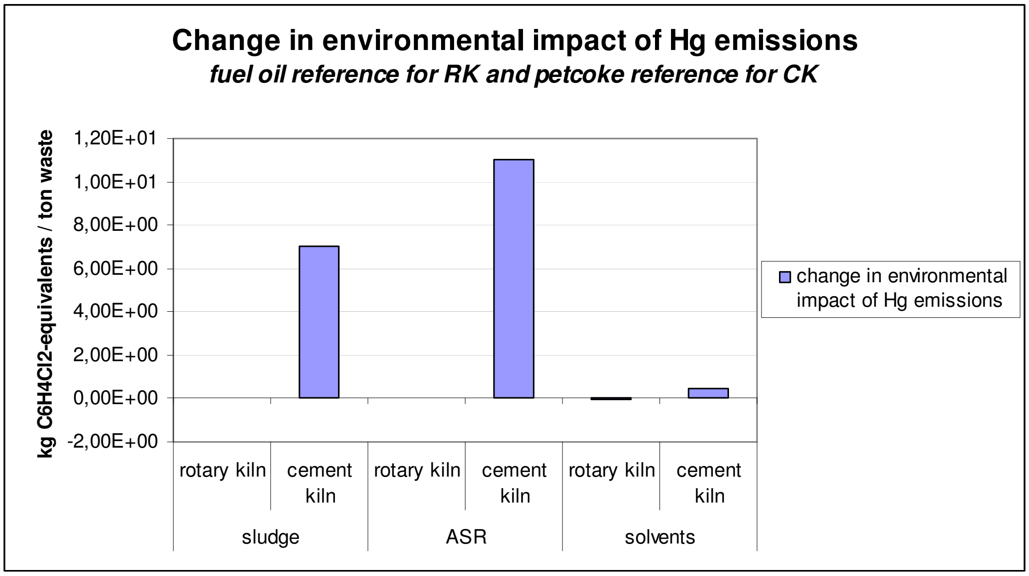
fuel type	energetic value [MJ/kg]	mercury content [kg/ton]
coal	29,55	3,60E-04
fuel oil	40,4	2,00E-03
petcoke	33,7	0,00013

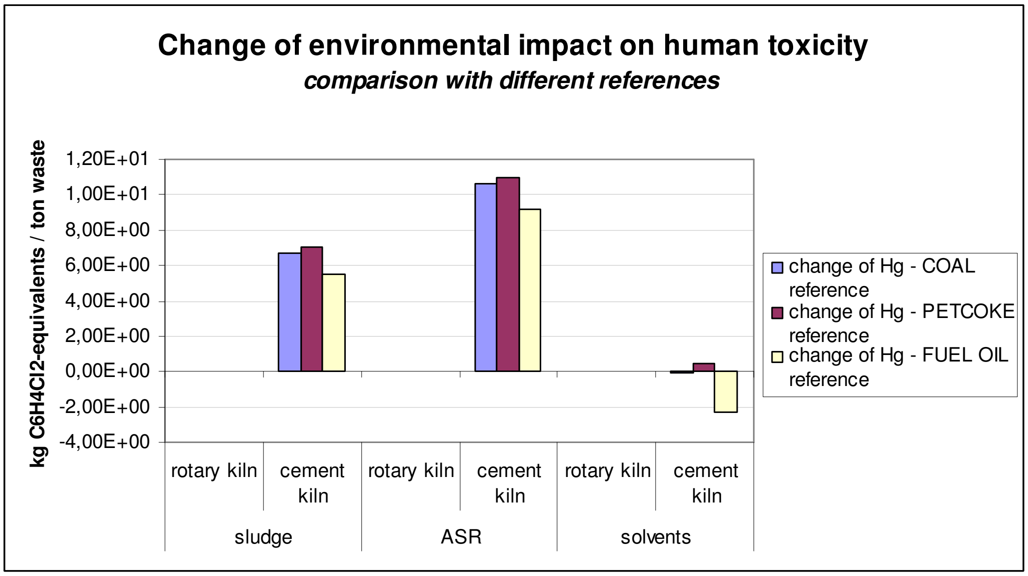
waste type	energetic value [MJ/kg]	mercury content [kg/ton]		functional unit [ton]
sludge	13,95	0,003		1
ASR	16,5	0,00469		1
solvents	25,8	0,0003		1

electricity production avoided emissions	average emissions Hg [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	average emissions Hg [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,20E+01
1,00E+01
8,00E+00
6,00E+00
4,00E+00
2,00E+00
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Hg


Change in environmental impact of Hg emissions
fuel oil reference for RK and petcoke reference for CK
kg C6H4Cl2-equivalents / ton waste
1,20E+01
1,00E+01
8,00E+00
6,00E+00
4,00E+00
2,00E+00
0,00E+00
-2,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Hg emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,20E+01
1,00E+01
8,00E+00
6,00E+00
4,00E+00
2,00E+00
0,00E+00
-2,00E+00
-4,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Hg - COAL reference
change of Hg - PETCOKE reference
change of Hg - FUEL OIL reference

Human toxicity → Pb

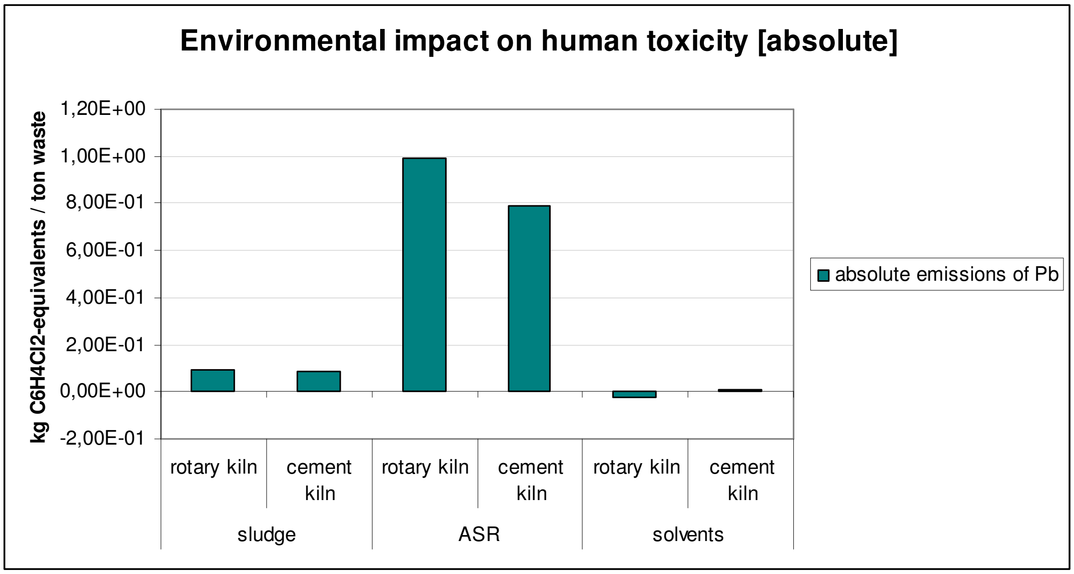
furnace type	**transfer coefficient**	**Pb/Pb**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0009	1		14,7	0,026	0,131
cement kiln	0,0007	1		21	0	0

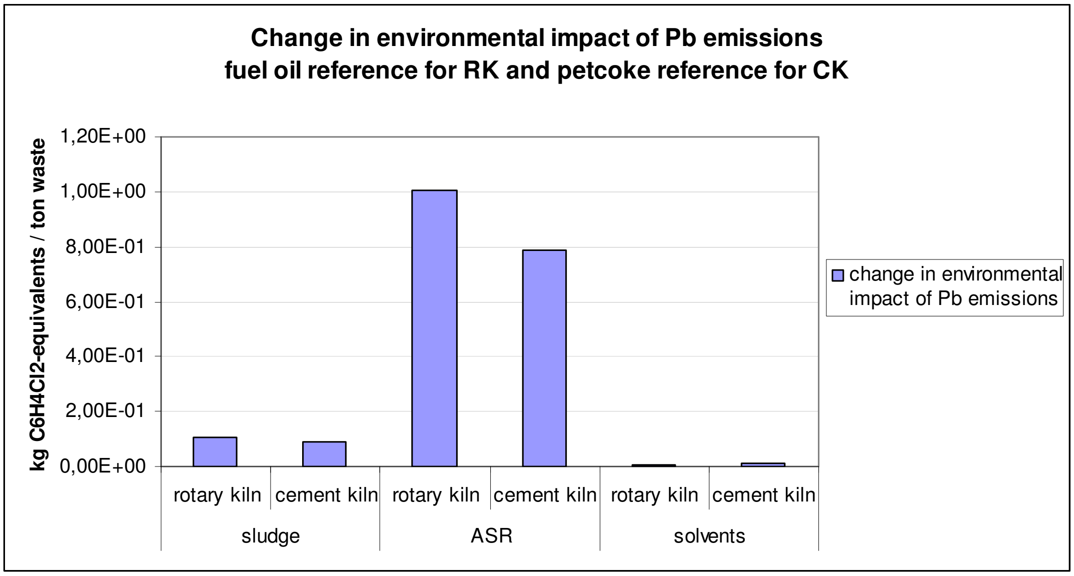
fuel type	**energetic value [MJ/kg]**	**lead content [kg/ton]**
coal	29,55	3,71E-02
fuel oil	40,4	3,80E-02

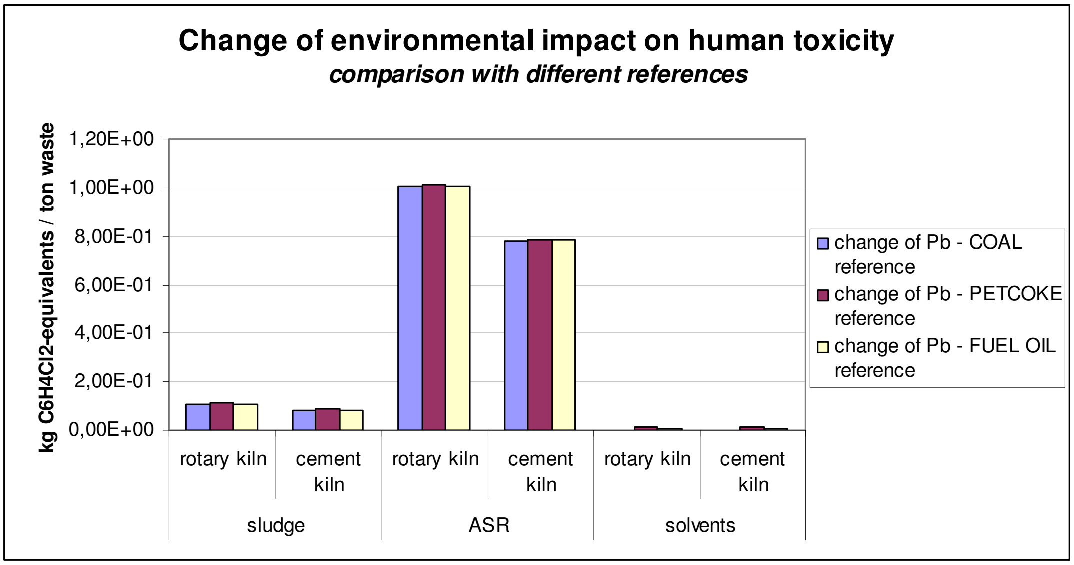
petcoke	33,7	0,0012

waste type	**energetic value [MJ/kg]**	**lead content [kg/ton]**		**functional unit [ton]**
sludge	13,95	0,27		1
ASR	16,5	2,394		1
solvents	25,8	0,0339		1

electricity production avoided emissions	**average emissions Pb** [kg/GJ]
gas	0
coal	5,35E-05
energetic mixture [BE]	**1,03E-05**
steam production avioded emissions	**average emissions Pb** [kg/GJ]
gas	0
coal	0,0000214
energetic mixture [BE]	4,11094E-06


Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
-2,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Pb


Change in environmental impact of Pb emissions
fuel oil reference for RK and petcoke reference for CK
kg C6H4Cl2-equivalents / ton waste
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Pb emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Pb - COAL reference
change of Pb - PETCOKE reference
change of Pb - FUEL OIL reference

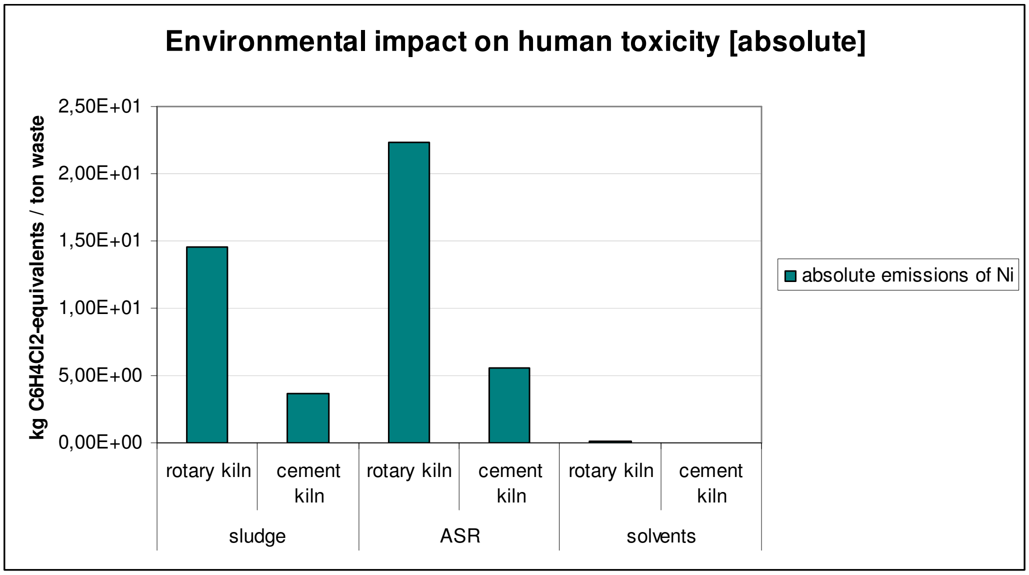
Human toxicity → Ni

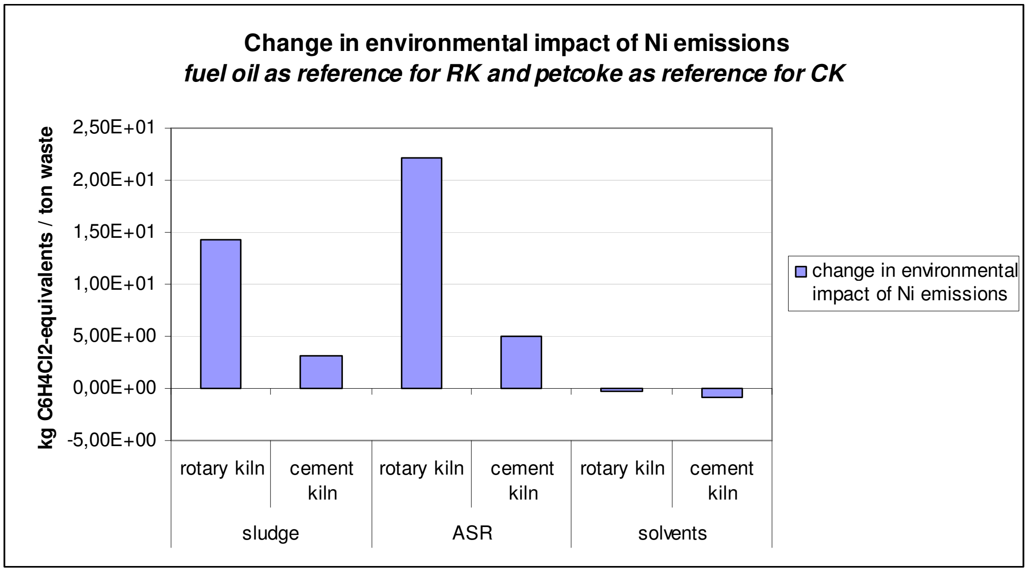
furnace type	transfer coefficient	Ni/Ni		minimal energy demand	electrical yield	steam yield
rotary kiln	8,00E-04	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

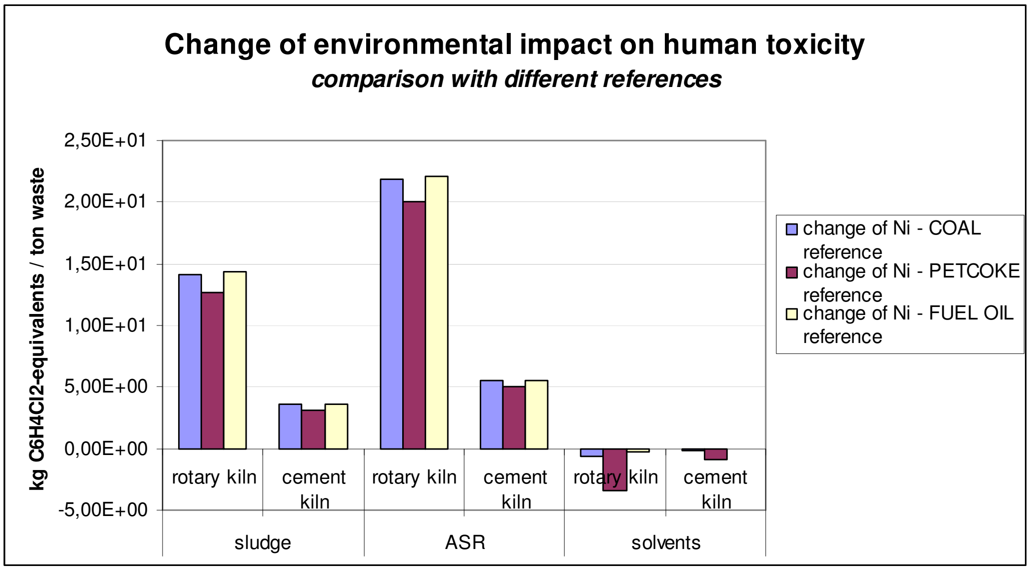
fuel type	energetic value [MJ/kg]	Nickel content [kg/ton]
coal	29,55	3,32E-02
fuel oil	40,4	2,10E-02
petcoke	33,7	0,167

waste type	energetic value [MJ/kg]	Nickel content [kg/ton]		functional unit [ton]
sludge	13,95	0,52		1
ASR	16,5	0,7994		1
solvents	25,8	0,0043		1

electricity production avoided emissions	average emissions Ni [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
2,50E+01
2,00E+01
1,50E+01
1,00E+01
5,00E+00
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Ni


Change in environmental impact of Ni emissions
fuel oil as reference for RK and petcoke as reference for CK
kg C6H4Cl2-equivalents / ton waste
2,50E+01
2,00E+01
1,50E+01
1,00E+01
5,00E+00
0,00E+00
-5,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Ni emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
2,50E+01
2,00E+01
1,50E+01
1,00E+01
5,00E+00
0,00E+00
-5,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Ni - COAL reference
change of Ni - PETCOKE reference
change of Ni - FUEL OIL reference

Human toxicity → Cu

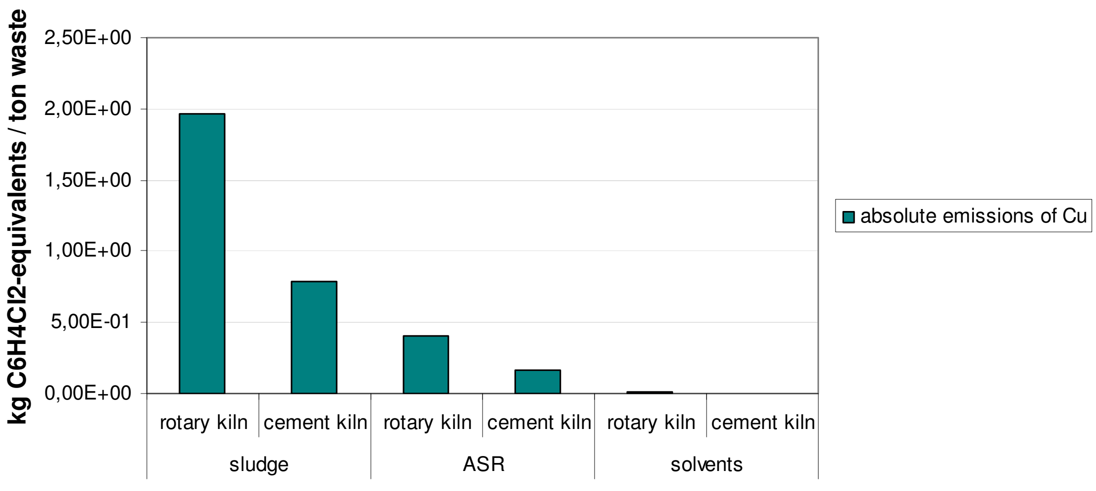
furnace type	transfer coefficient	Cu/Cu		minimal energy demand	electrical yield	steam yield
rotary kiln	5,00E-04	1		14,7	0,026	0,131
cement kiln	2,00E-04	1		21	0	0

fuel type	energetic value [MJ/kg]	cupper content [kg/ton]
coal	29,55	2,00E-02
fuel oil	40,4	4,77E-03
petcoke	33,7	7,41E-02

waste type	energetic value [MJ/kg]	cupper content [kg/ton]		functional unit [ton]
sludge	13,95	0,913		1
ASR	16,5	0,1855		1
solvents	25,8	5,48E-03		1

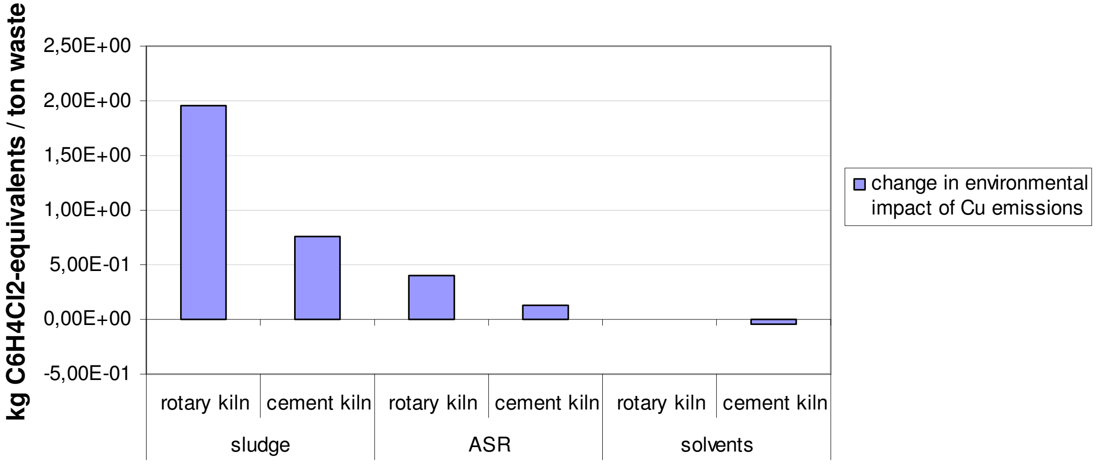
electricity production avioded emissions	average emissions Cu [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

Environmental impact on human toxicity [absolute]



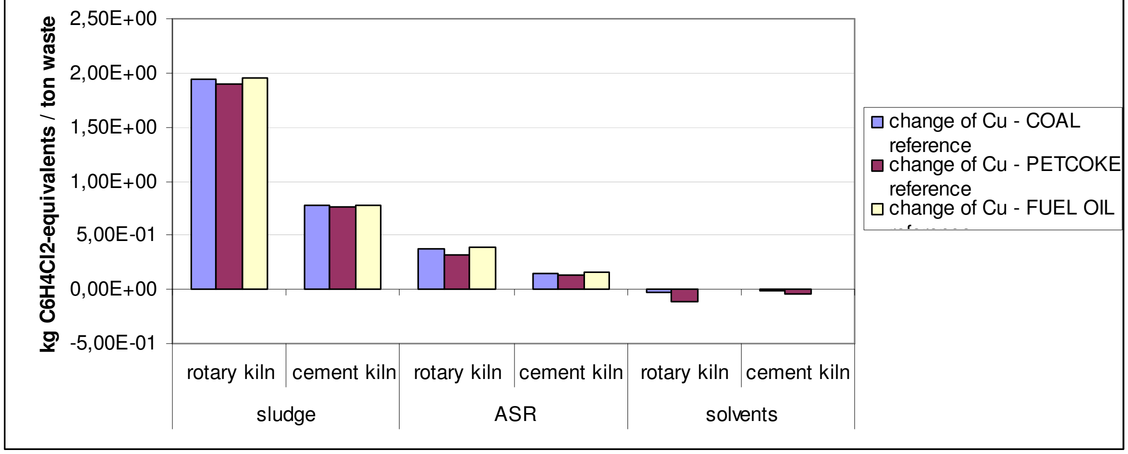
Change in environmental impact of Cu emissions

fuel oil as reference for RK and petcoke as reference for CK



Change of environmental impact on human toxicity

comparison with different references



Human toxicity → Zn

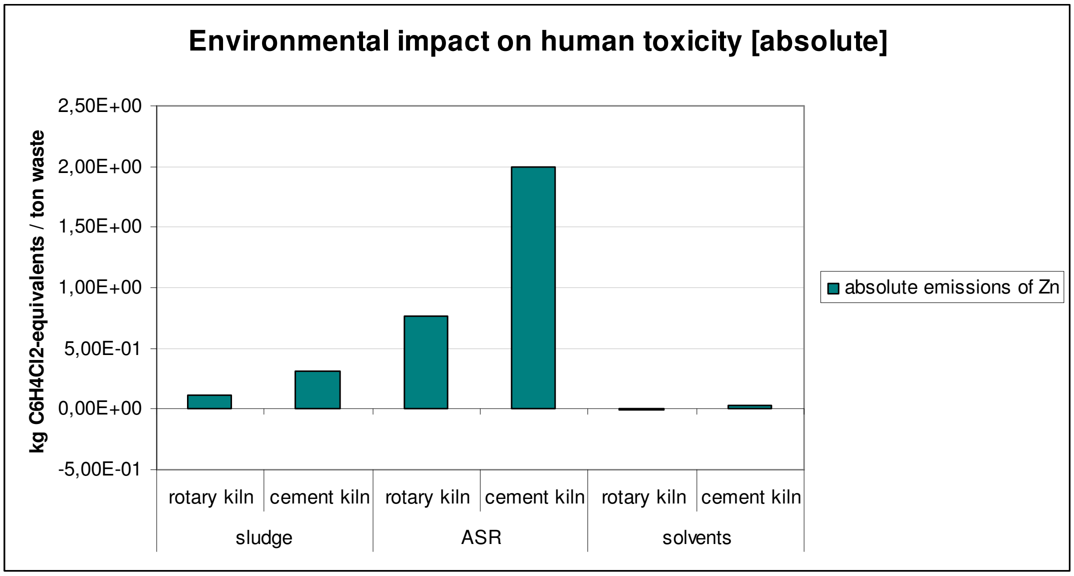
furnace type	transfer coefficient	Zn/Zn		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0007	1		14,7	0,026	0,131
cement kiln	0,0017	1		21	0	0

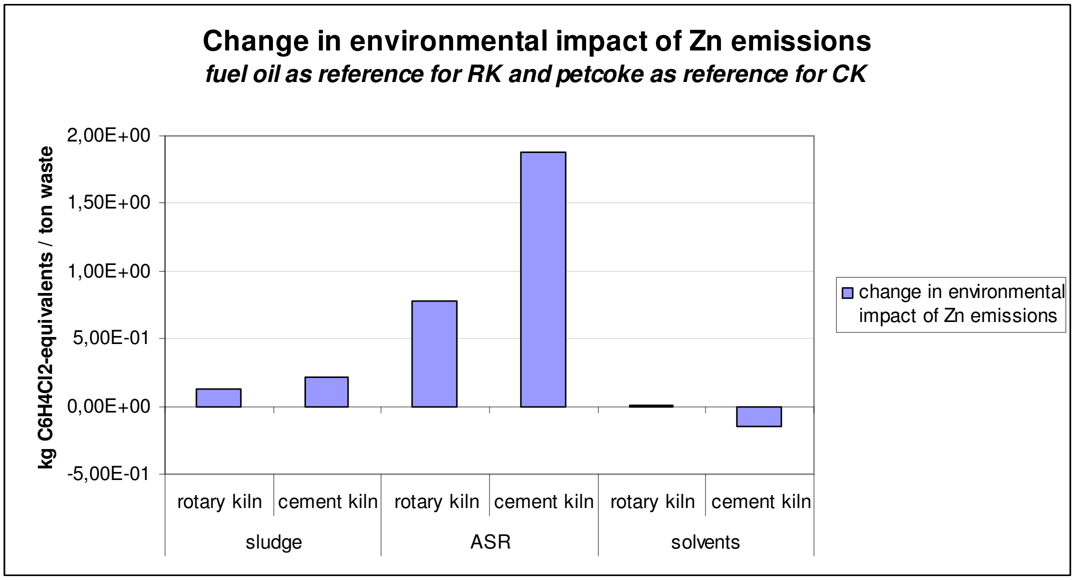
fuel type	energetic value [MJ/kg]	Zinck content [kg/ton]
coal	29,55	6,18E-02
fuel oil	40,4	7,73E-03

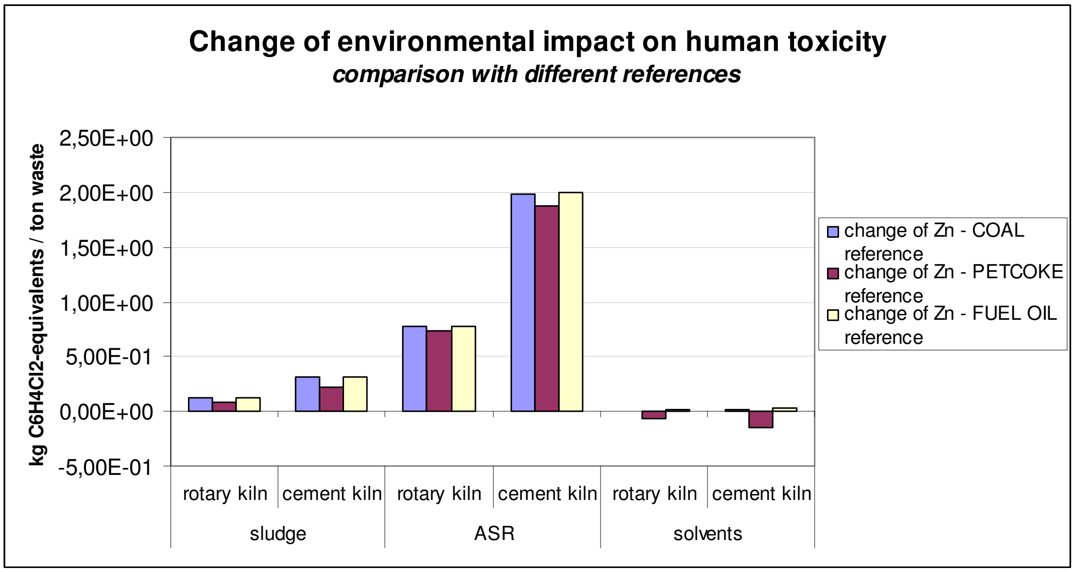
petcoke	33,7	1,31E+00

waste type	energetic value [MJ/kg]	Zinck content [kg/ton]		functional unit [ton]
sludge	13,95	1,758		1
ASR	16,5	11,09		1
solvents	25,8	1,57E-01		1

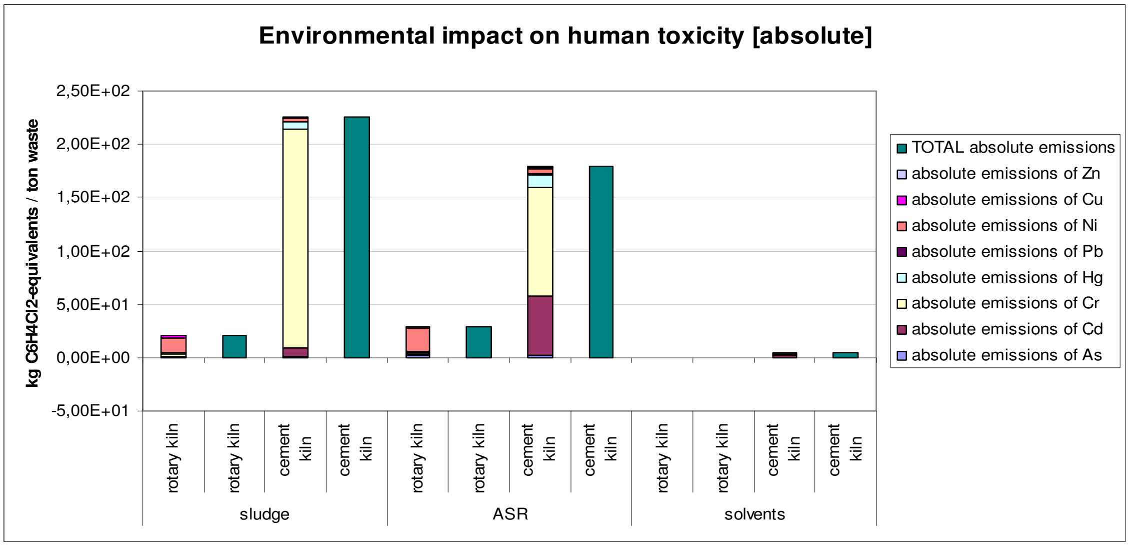
electricity production avoided emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	1,35E-04
energetic mixture [BE]	**2,59335E-05**
steam production avioded emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	0,000054
energetic mixture [BE]	1,03734E-05

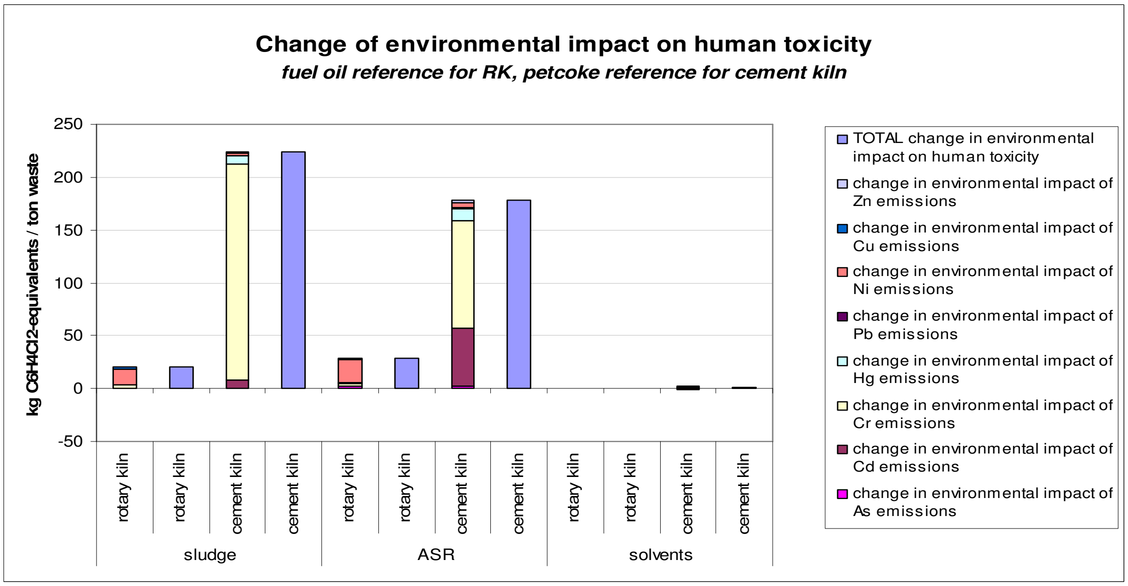

Environmental impact on human toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
2,50E+00
2,00E+00
1,50E+00
1,00E+00
5,00E-01
0,00E+00
-5,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Zn

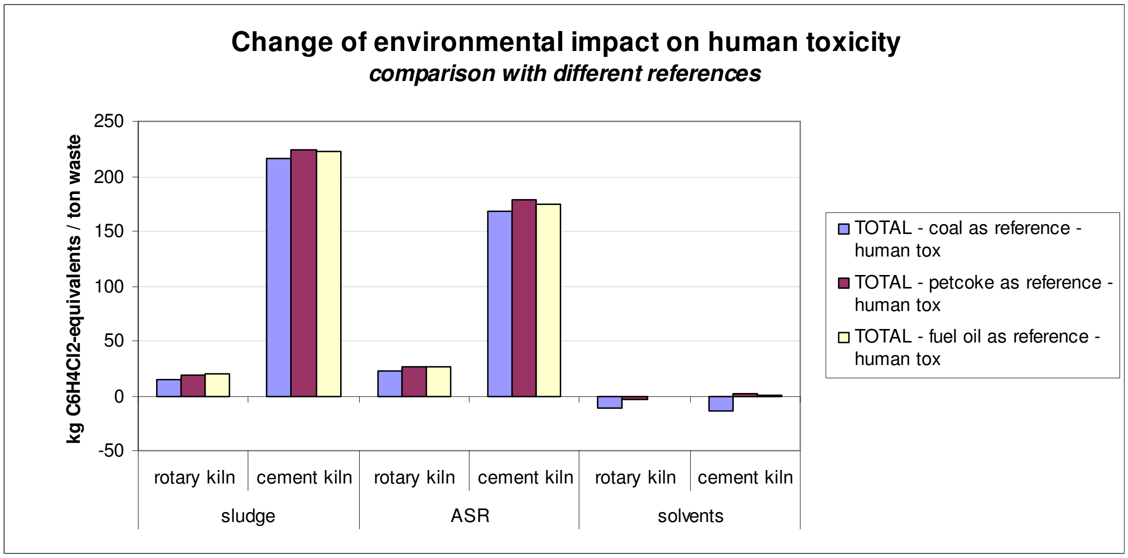

Change in environmental impact of Zn emissions
fuel oil as reference for RK and petcoke as reference for CK
kg C6H4Cl2-equivalents / ton waste
2,00E+00
1,50E+00
1,00E+00
5,00E-01
0,00E+00
-5,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Zn emissions


Change of environmental impact on human toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
2,50E+00
2,00E+00
1,50E+00
1,00E+00
5,00E-01
0,00E+00
-5,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Zn - COAL reference
change of Zn - PETCOKE reference
change of Zn - FUEL OIL reference

Human toxicity → TOTAL







Fresh water toxicity →As

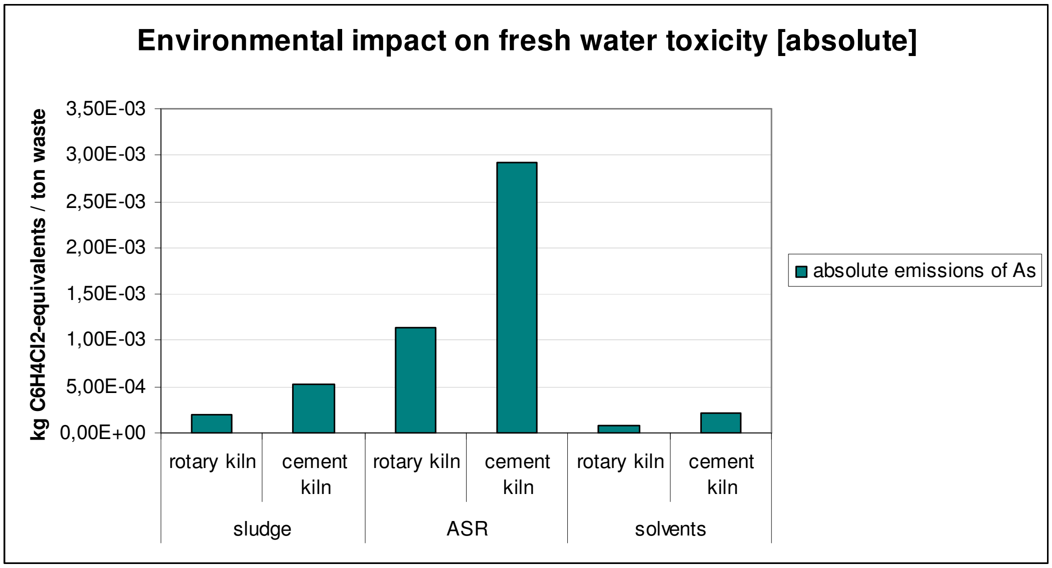
furnace type	transfer coefficient	As/As		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0002	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

fuel type	energetic value [MJ/kg]	arsenic content [kg/ton]
coal	29,55	1,62E-01
fuel oil	40,4	3,00E-04
petcoke	33,7	0,0009

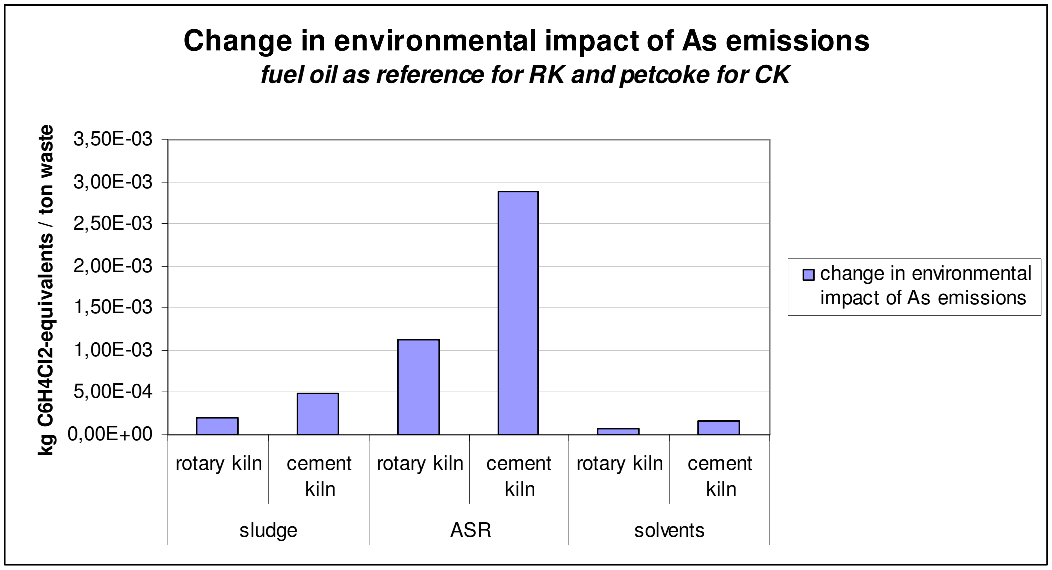
waste type	energetic value [MJ/kg]	arsenic content [kg/ton]		functional unit [ton]
sludge	13,95	0,0058		1
ASR	16,5	0,0325		1
solvents	25,8	0,00245		1

electricity production avoided emissions	average emissions As [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	average emissions As [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

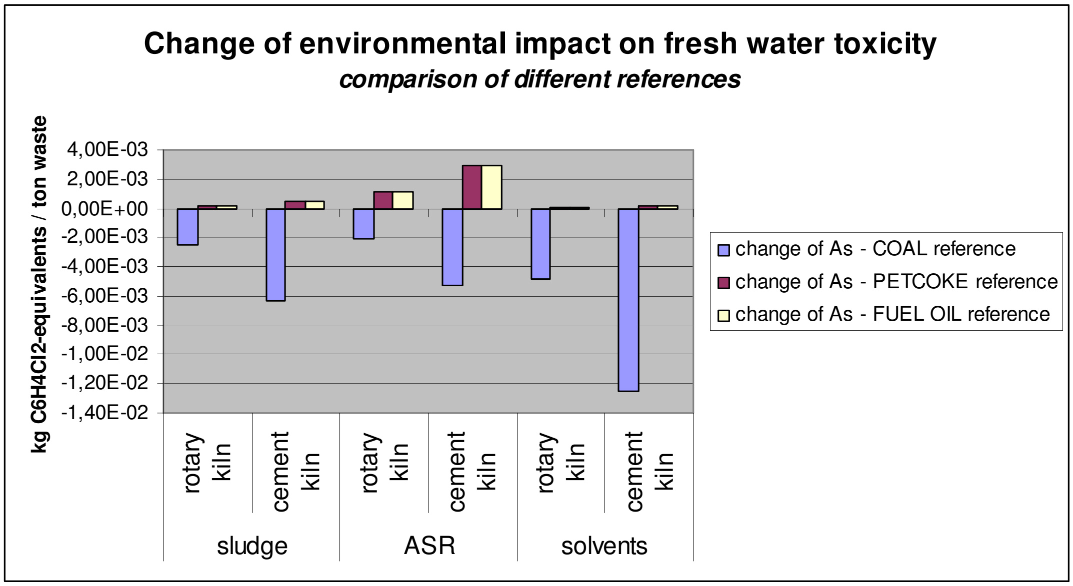


Environmental impact on fresh water toxicity [absolute]



Change in environmental impact of As emissions

fuel oil as reference for RK and petcoke for CK



Change of environmental impact on fresh water toxicity

comparison of different references

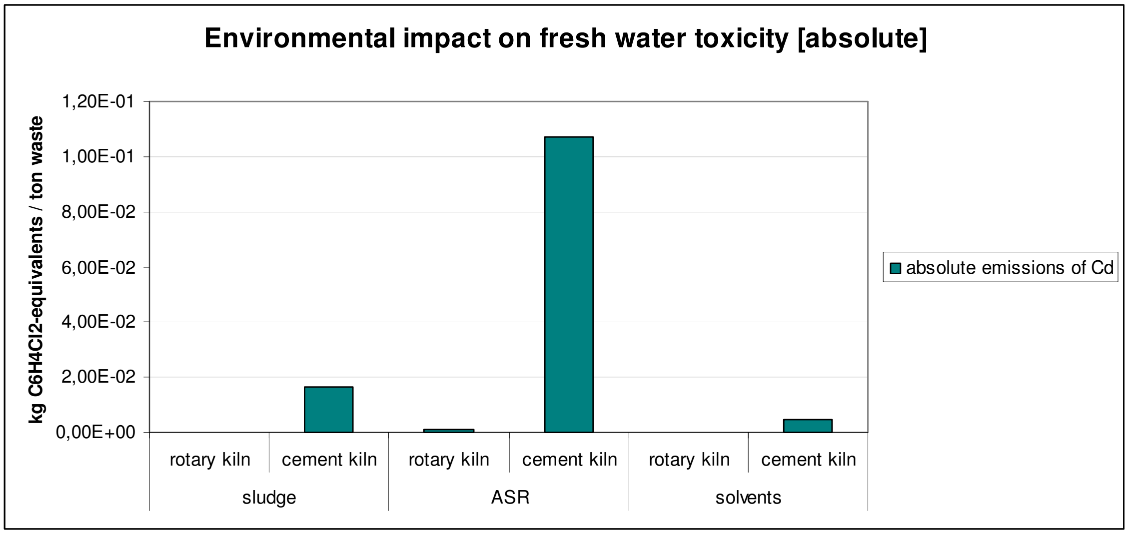
Fresh water toxicity → Cd

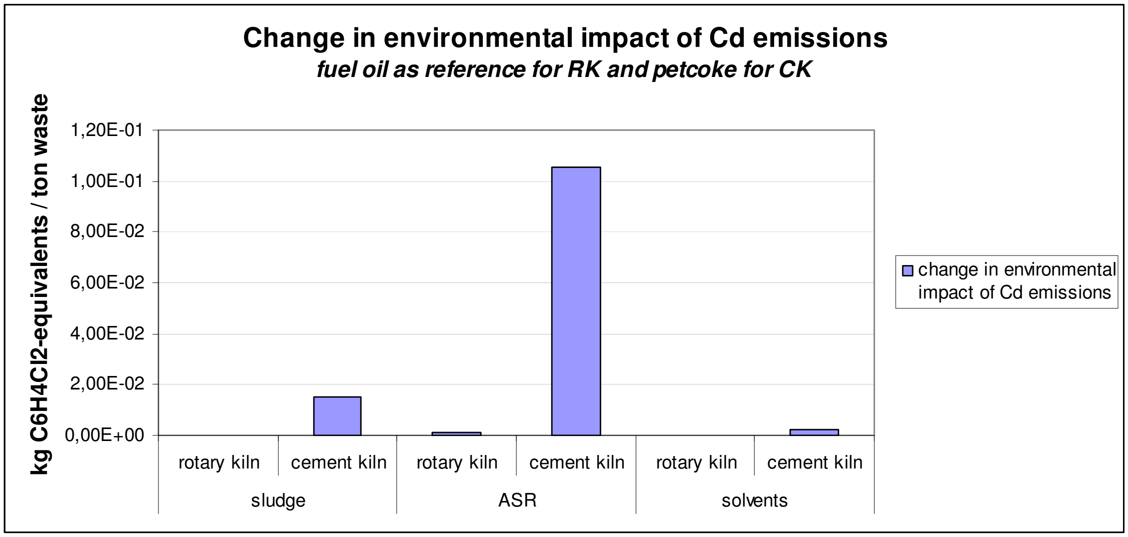
furnace type	**transfer coefficient**	**Cd/Cd**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0001	1		14,7	0,026	0,131
cement kiln	0,0106	1		21	0	0

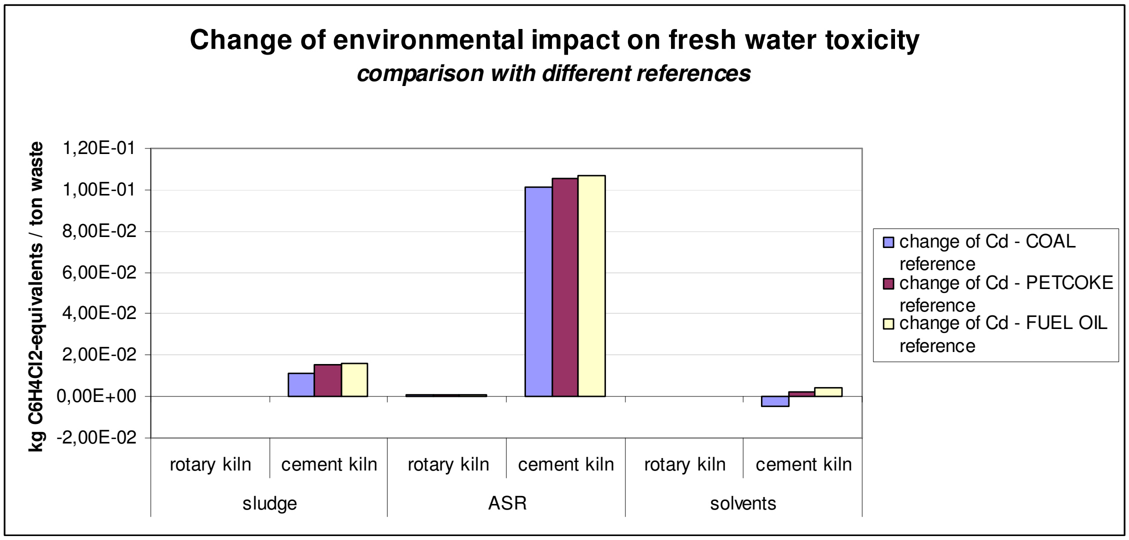
fuel type	**energetic value** **[MJ/kg]**	**cadmium content** **[kg/ton]**
coal	29,55	3,40E-03
fuel oil	40,4	2,50E-04
petcoke	33,7	0,00093

waste type	**energetic value** **[MJ/kg]**	**cadmium content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,0053		1
ASR	16,5	0,0348		1
solvents	25,8	0,0015		1

electricity production avoided emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on fresh water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,20E-01
1,00E-01
8,00E-02
6,00E-02
4,00E-02
2,00E-02
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cd


Change in environmental impact of Cd emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,20E-01
1,00E-01
8,00E-02
6,00E-02
4,00E-02
2,00E-02
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cd emissions


Change of environmental impact on fresh water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,20E-01
1,00E-01
8,00E-02
6,00E-02
4,00E-02
2,00E-02
0,00E+00
-2,00E-02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cd - COAL reference
change of Cd - PETCOKE reference
change of Cd - FUEL OIL reference

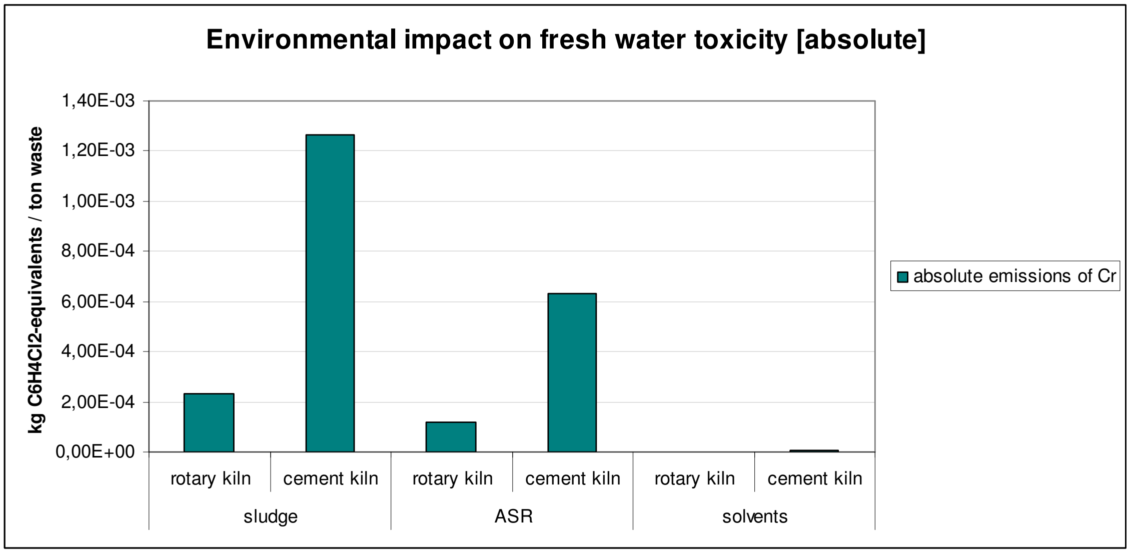
Fresh water toxicity → Cr

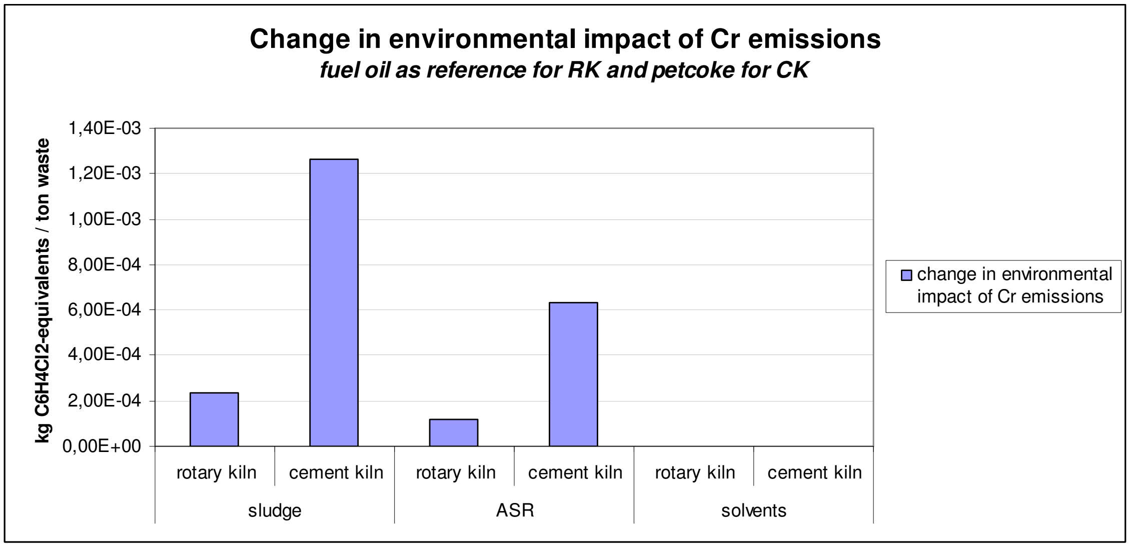
furnace type	**transfer coefficient**	**Cr/Cr**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	5,00E-05	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

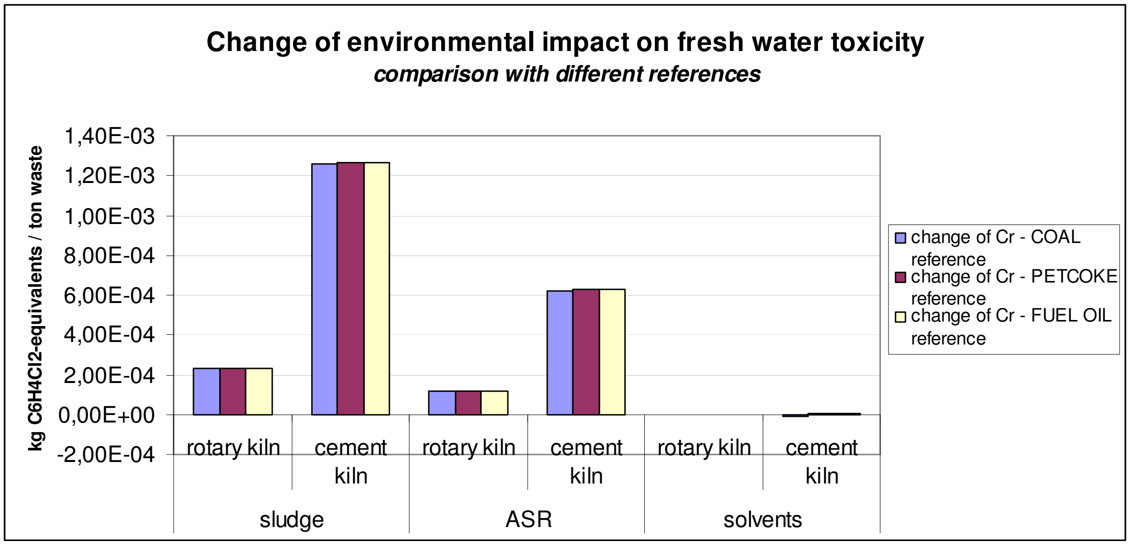
fuel type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**
coal	29,55	2,52E-02
fuel oil	40,4	1,60E-03
petcoke	33,7	0,0045

waste type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	2,406		1
ASR	16,5	1,204		1
solvents	25,8	0,0093		1

electricity production avoided emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on fresh water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,40E-03
1,20E-03
1,00E-03
8,00E-04
6,00E-04
4,00E-04
2,00E-04
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cr


Change in environmental impact of Cr emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,40E-03
1,20E-03
1,00E-03
8,00E-04
6,00E-04
4,00E-04
2,00E-04
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cr emissions


Change of environmental impact on fresh water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,40E-03
1,20E-03
1,00E-03
8,00E-04
6,00E-04
4,00E-04
2,00E-04
0,00E+00
-2,00E-04
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cr - COAL reference
change of Cr - PETCOKE reference
change of Cr - FUEL OIL reference

Fresh water toxicity → Hg

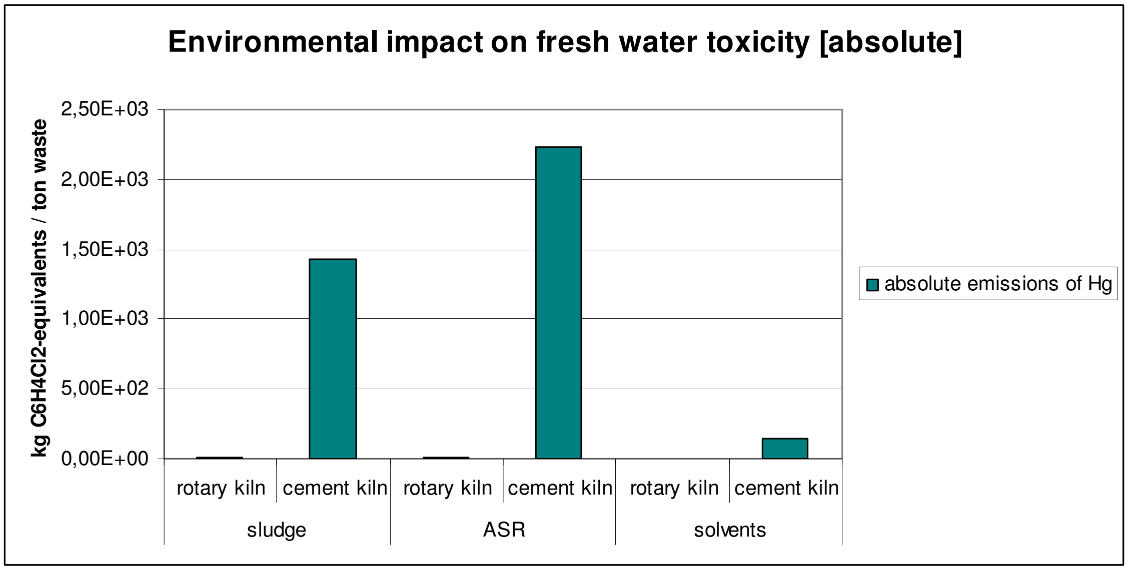
furnace type	**transfer coefficient**	**Hg/Hg**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0022	1		14,7	0,026	0,131
cement kiln	0,3958	1		21	0	0

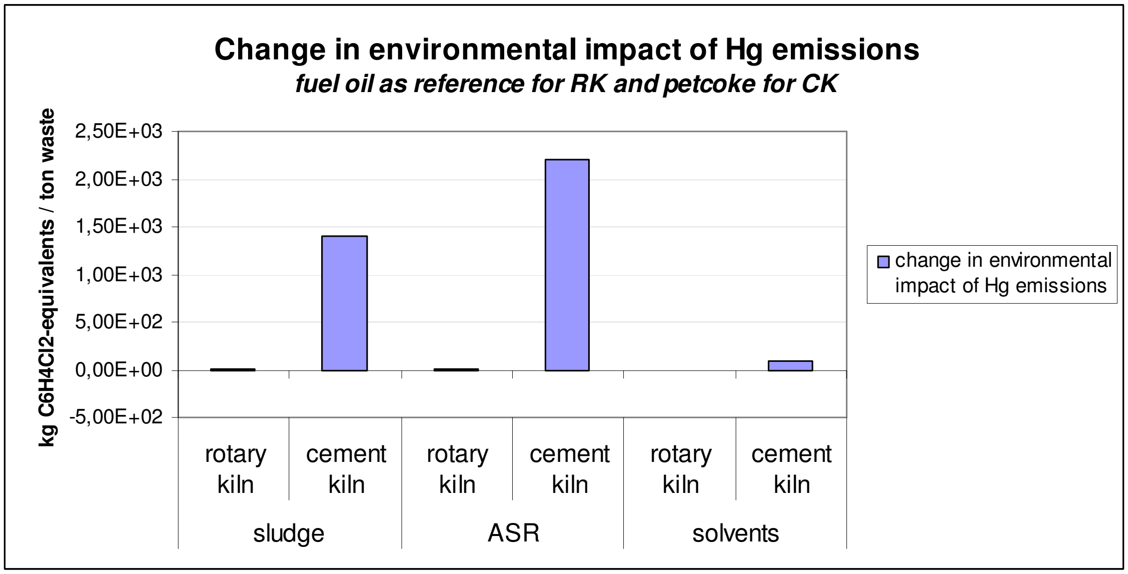
fuel type	**energetic value** **[MJ/kg]**	**mercury content** **[kg/ton]**
coal	29,55	3,60E-04
fuel oil	40,4	2,00E-03
petcoke	33,7	0,00013

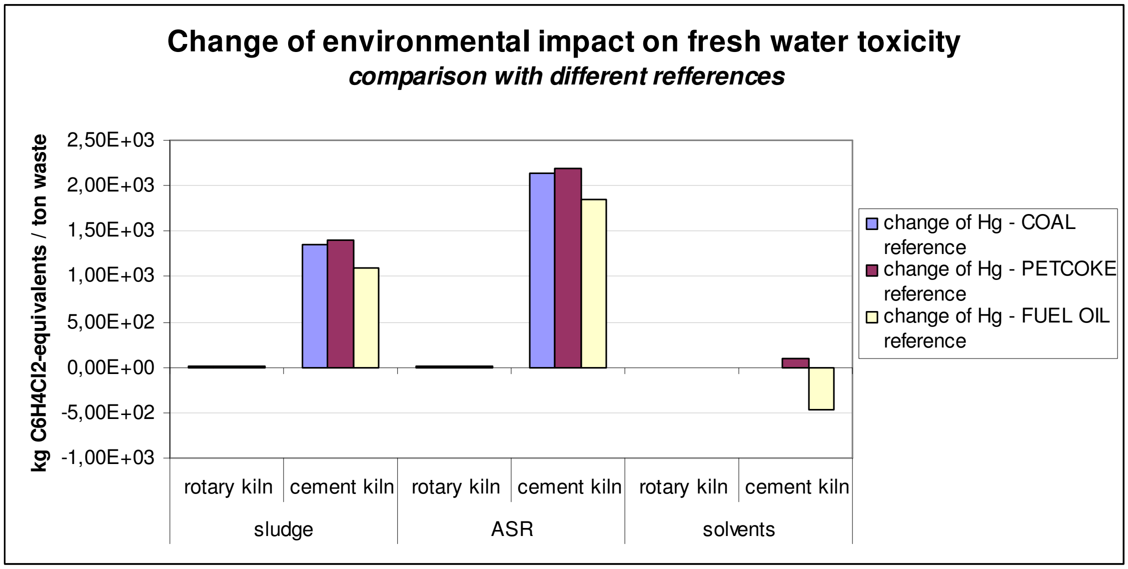
waste type	**energetic value** **[MJ/kg]**	**mercury content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,003		1
ASR	16,5	0,00469		1
solvents	25,8	0,0003		1

electricity production avoided emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on fresh water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Hg


Change in environmental impact of Hg emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
-5,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Hg emissions


Change of environmental impact on fresh water toxicity
comparison with different refferences
kg C6H4Cl2-equivalents / ton waste
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
-5,00E+02
-1,00E+03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Hg - COAL reference
change of Hg - PETCOKE reference
change of Hg - FUEL OIL reference

Fresh water toxicity → Pb

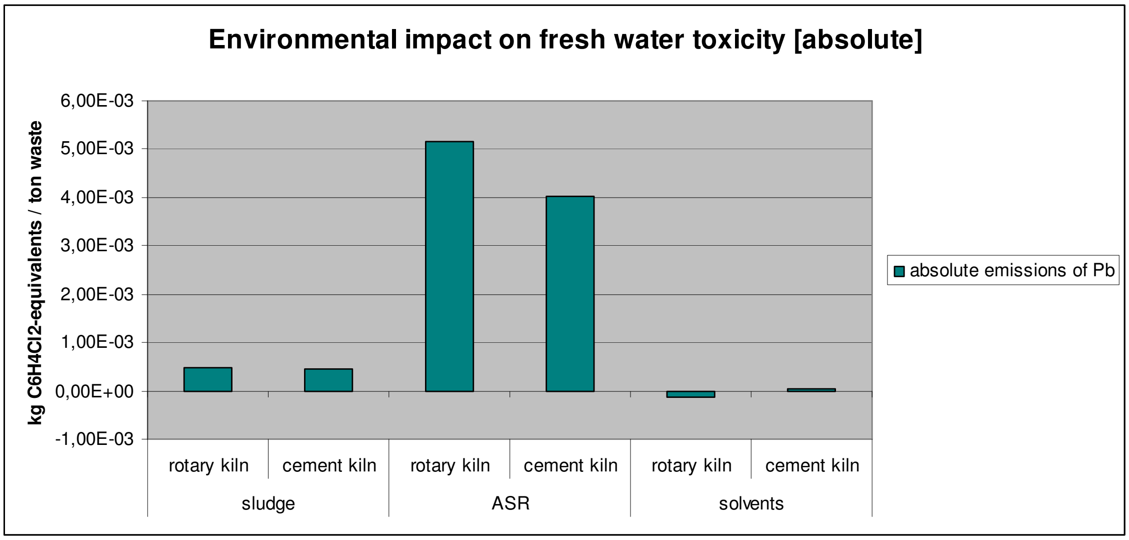
furnace type	**transfer coefficient**	**Pb/Pb**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0009	1		14,7	0,026	0,131
cement kiln	0,0007	1		21	0	0

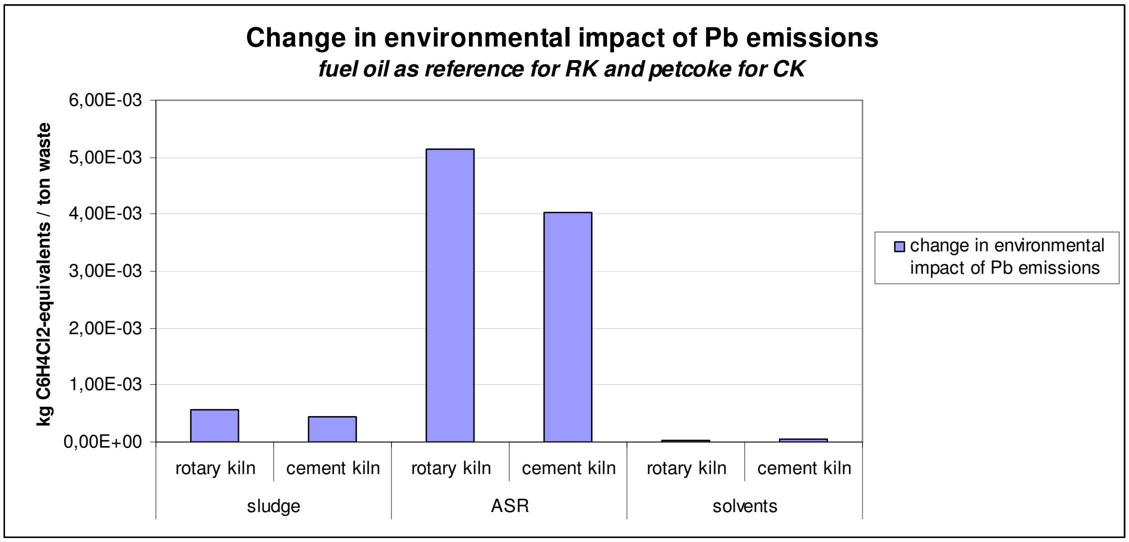
fuel type	**energetic value [MJ/kg]**	**lead content [kg/ton]**
coal	29,55	3,71E-02
fuel oil	40,4	3,80E-02
petcoke	33,7	0,0012

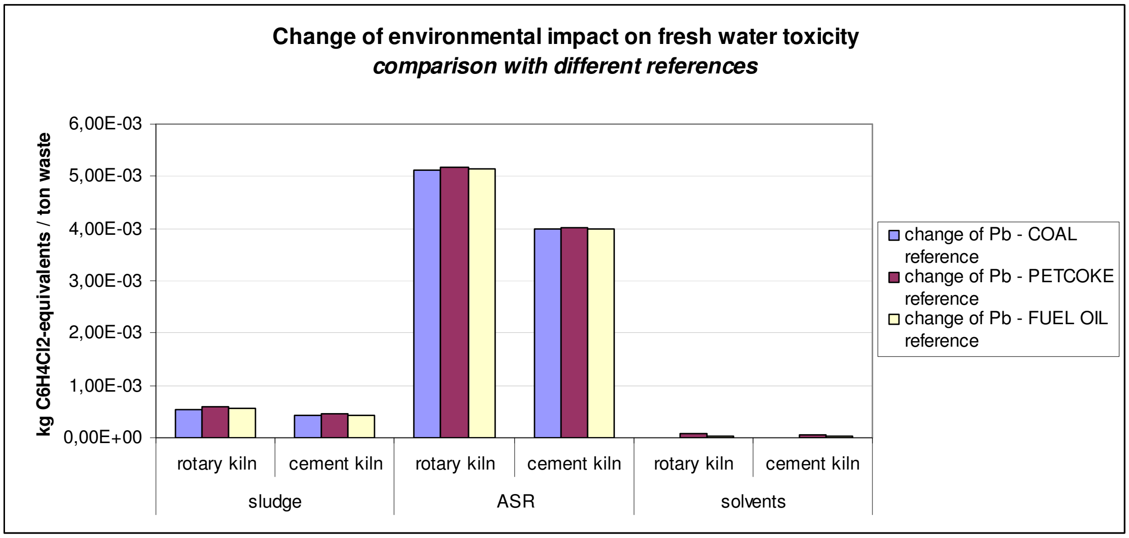
waste type	**energetic value [MJ/kg]**	**lead content [kg/ton]**		**functional unit [ton]**
sludge	13,95	0,27		1
ASR	16,5	2,394		1
solvents	25,8	0,0339		1

electricity production avoided emissions	**average emissions Pb** [kg/GJ]
gas	0
coal	5,35E-05
energetic mixture [BE]	**1,03E-05**

steam production avioded emissions	**average emissions Pb** [kg/GJ]
gas	0
coal	0,0000214
energetic mixture [BE]	4,11094E-06


Environmental impact on fresh water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
6,00E-03
5,00E-03
4,00E-03
3,00E-03
2,00E-03
1,00E-03
0,00E+00
-1,00E-03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Pb


Change in environmental impact of Pb emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
6,00E-03
5,00E-03
4,00E-03
3,00E-03
2,00E-03
1,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Pb emissions


Change of environmental impact on fresh water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
6,00E-03
5,00E-03
4,00E-03
3,00E-03
2,00E-03
1,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Pb - COAL reference
change of Pb - PETCOKE reference
change of Pb - FUEL OIL reference

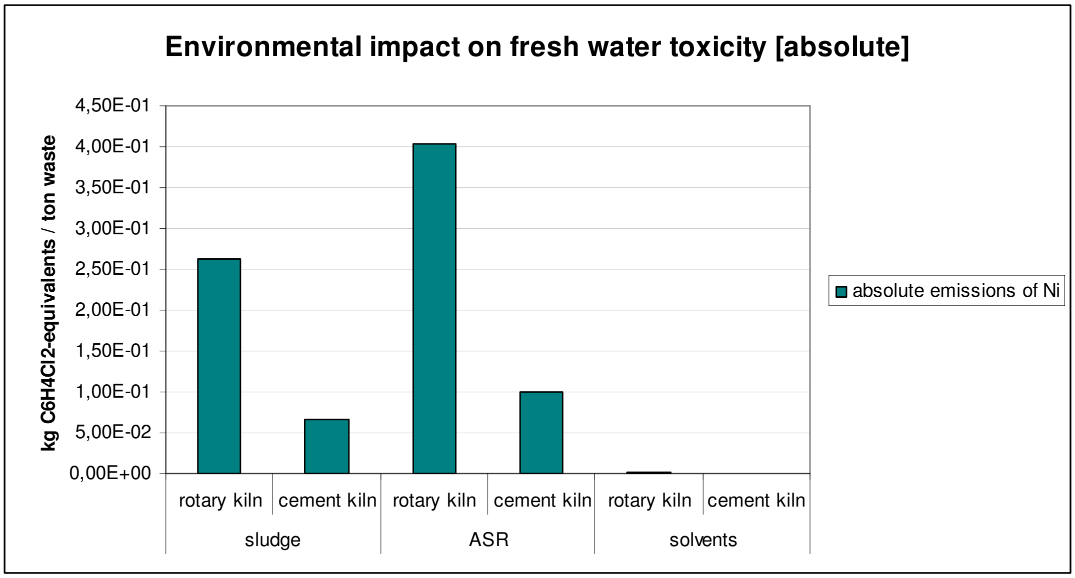
Fresh water toxicity → Ni

furnace type	**transfer coefficient**	**Ni/Ni**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	8,00E-04	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

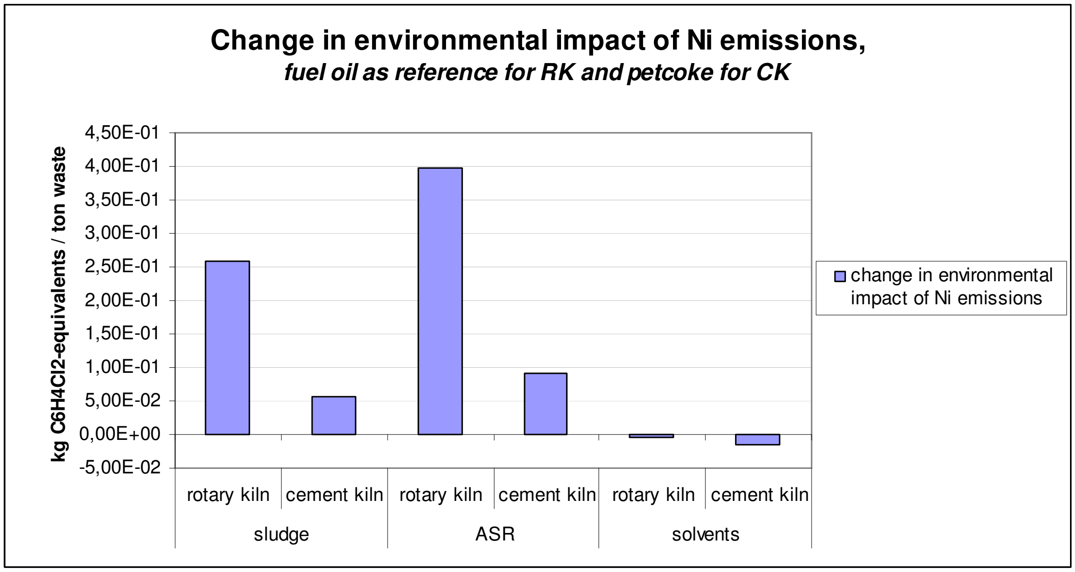
fuel type	**energetic value** **[MJ/kg]**	**Nickel content** **[kg/ton]**
coal	29,55	3,32E-02
fuel oil	40,4	2,10E-02
petcoke	33,7	0,167

waste type	**energetic value** **[MJ/kg]**	**Nickel content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,52		1
ASR	16,5	0,7994		1
solvents	25,8	0,0043		1

electricity production avoided emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

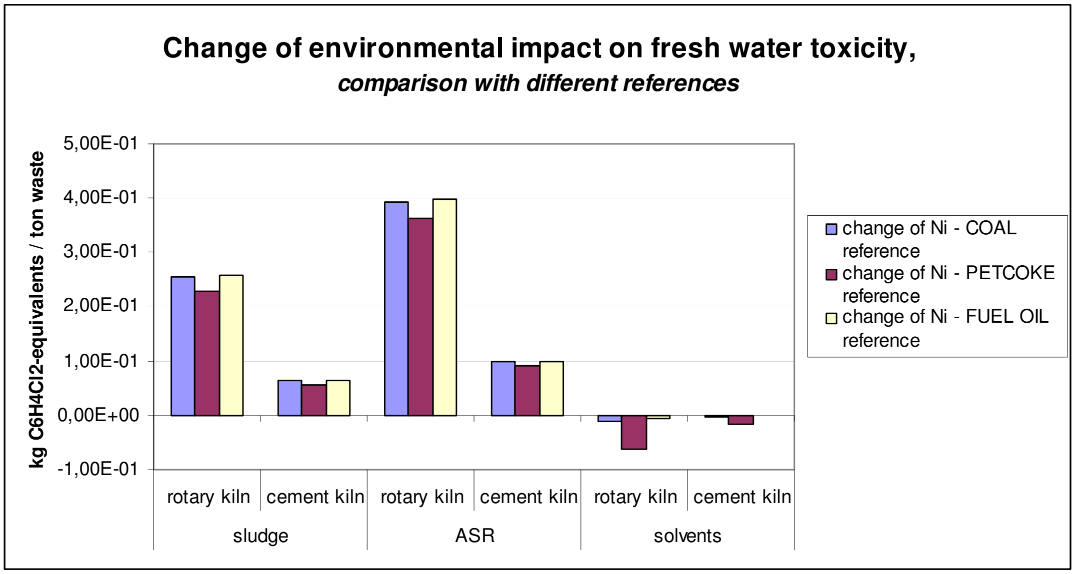


Environmental impact on fresh water toxicity [absolute]



Change in environmental impact of Ni emissions,

fuel oil as reference for RK and petcoke for CK



Change of environmental impact on fresh water toxicity,

comparison with different references

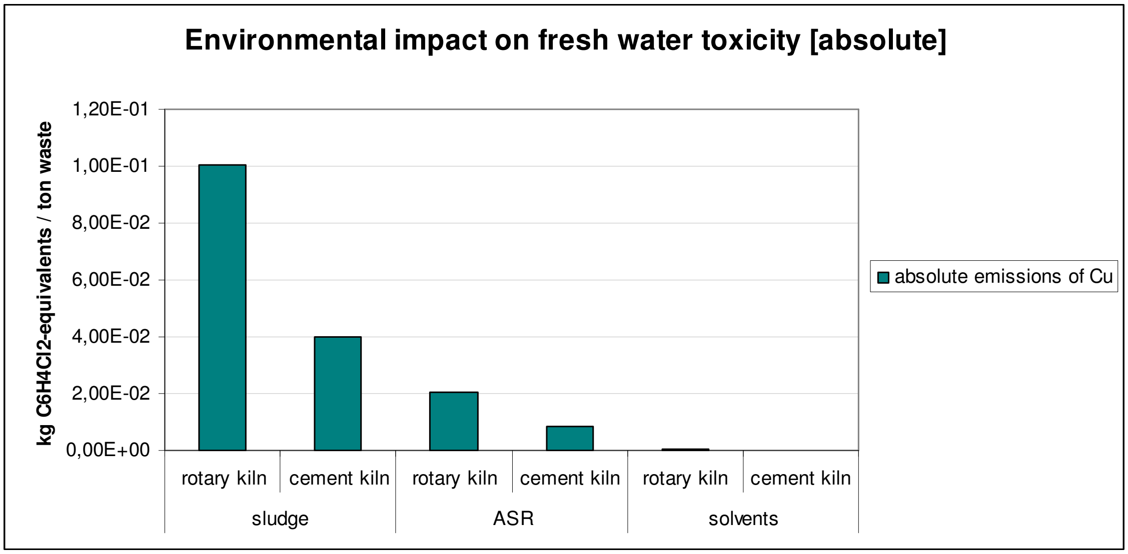
Fresh water toxicity → Cu

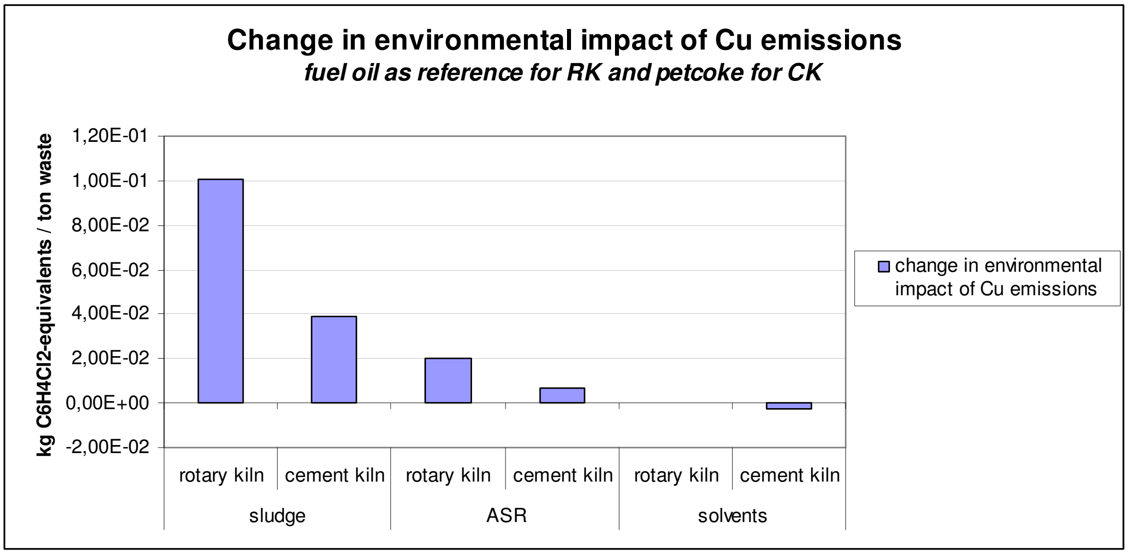
furnace type	transfer coefficient	Cu/Cu		minimal energy demand	electrical yield	steam yield
rotary kiln	5,00E-04	1		14,7	0,026	0,131
cement kiln	2,00E-04	1		21	0	0

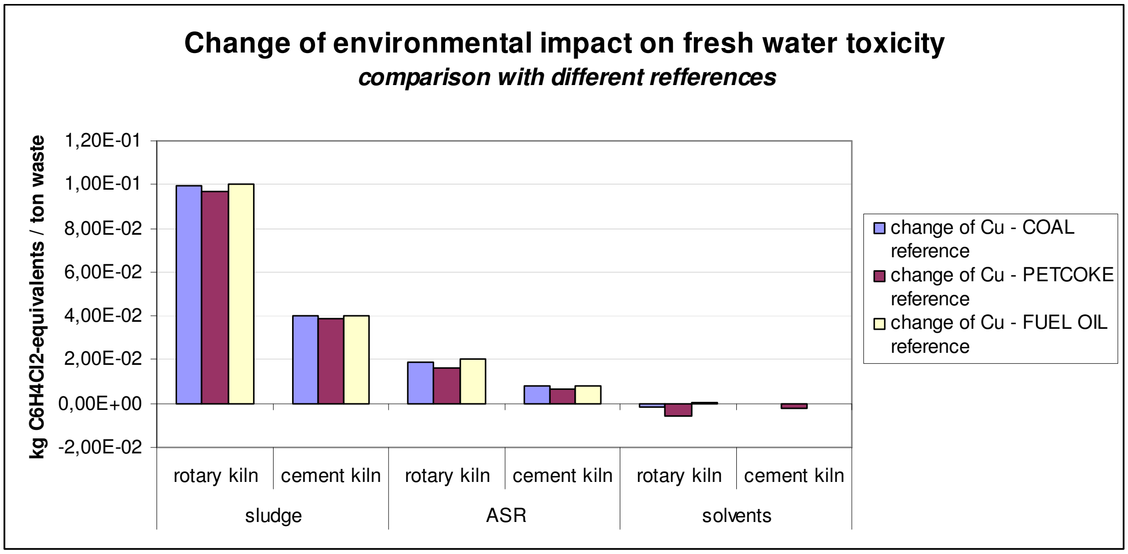
fuel type	energetic value [MJ/kg]	cupper content [kg/ton]
coal	29,55	2,00E-02
fuel oil	40,4	4,77E-03
petcoke	33,7	7,41E-02

waste type	energetic value [MJ/kg]	cupper content [kg/ton]		functional unit [ton]
sludge	13,95	0,913		1
ASR	16,5	0,1855		1
solvents	25,8	5,48E-03		1

electricity production avioded emissions	average emissions Cu [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on fresh water toxicity [absolute]


Change in environmental impact of Cu emissions
fuel oil as reference for RK and petcoke for CK


Change of environmental impact on fresh water toxicity
comparison with different refferences

Fresh water toxicity → Zn

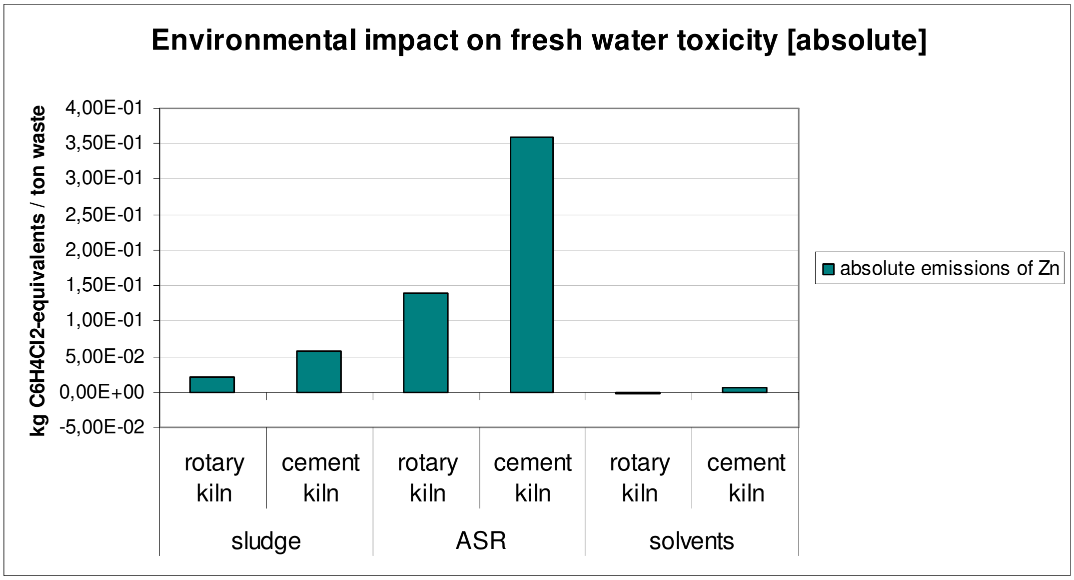
furnace type	**transfer coefficient**	**Zn/Zn**	☒	**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0007	1	☒	14,7	0,026	0,131
cement kiln	0,0017	1	☒	21	0	0

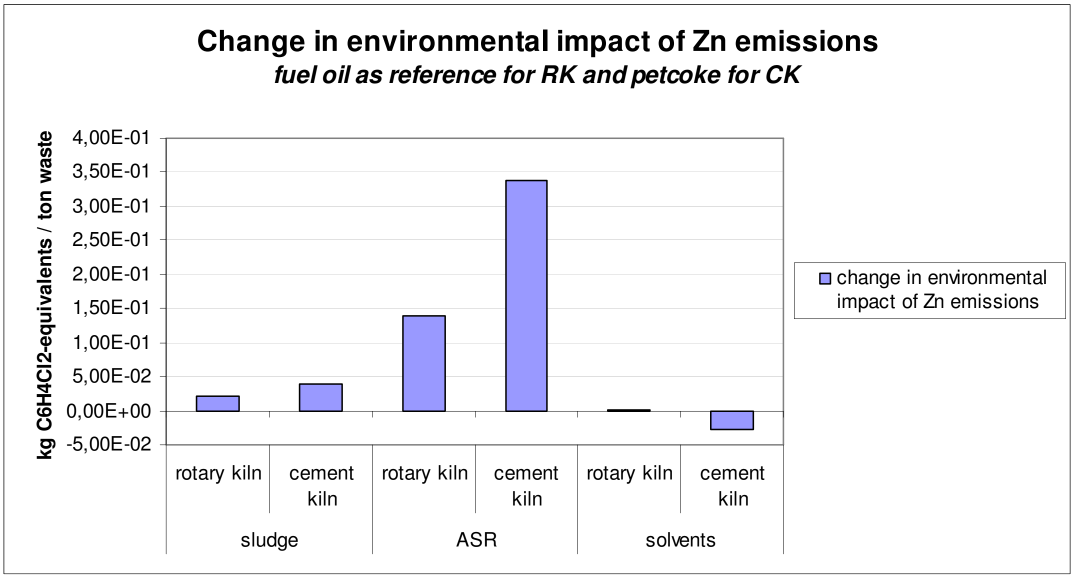
fuel type	**energetic value** **[MJ/kg]**	**Zinck content** **[kg/ton]**
coal	29,55	6,18E-02
fuel oil	40,4	7,73E-03
petcoke	33,7	1,31E+00

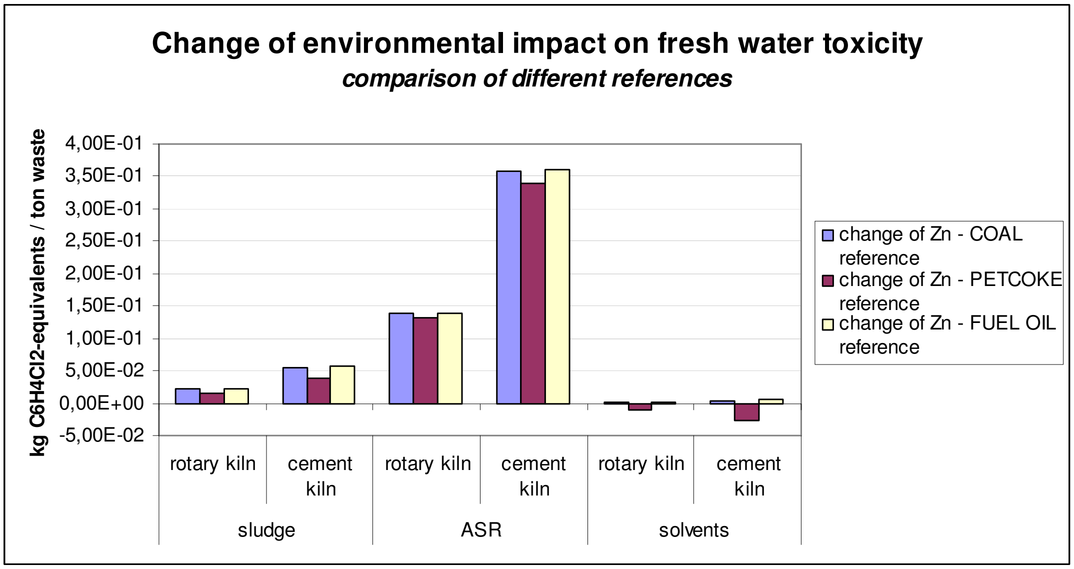
waste type	**energetic value** **[MJ/kg]**	**Zinck content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	1,758		1
ASR	16,5	11,09		1
solvents	25,8	1,57E-01		1

electricity production avoided emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	1,35E-04
energetic mixture [BE]	**2,59335E-05**

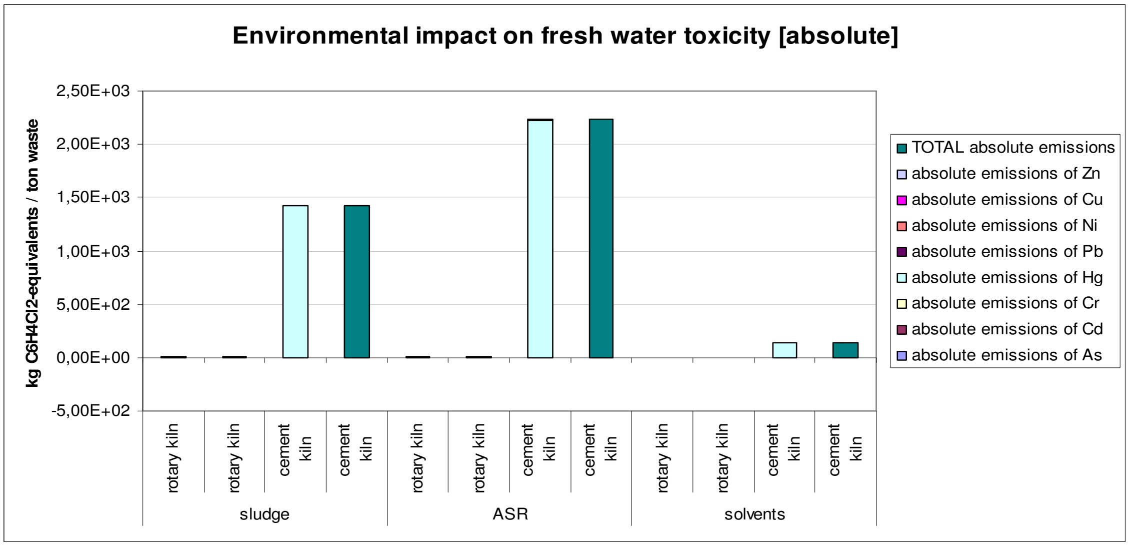
steam production avioded emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	0,000054
energetic mixture [BE]	1,03734E-05

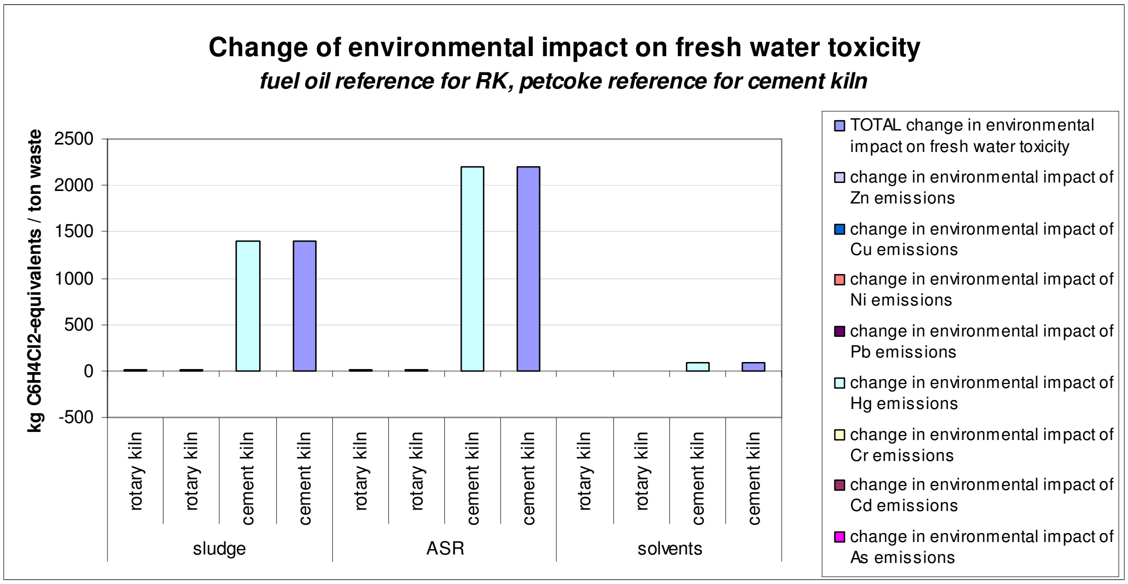

Environmental impact on fresh water toxicity [absolute]

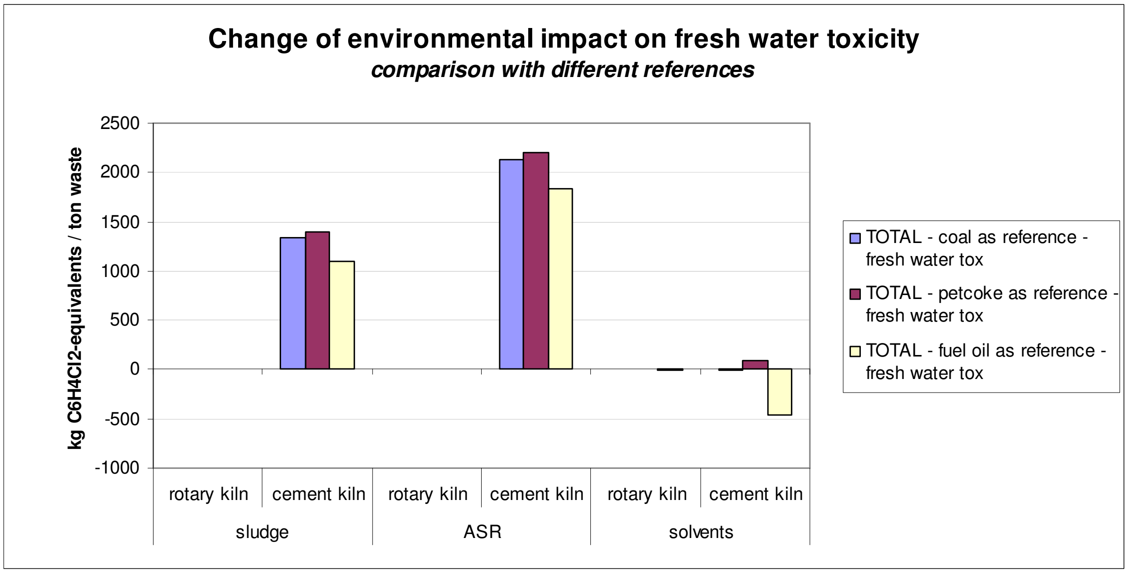

Change in environmental impact of Zn emissions
fuel oil as reference for RK and petcoke for CK


Change of environmental impact on fresh water toxicity
comparison of different references

Fresh water toxicity → TOTAL


Environmental impact on fresh water toxicity [absolute]


Change of environmental impact on fresh water toxicity
fuel oil reference for RK, petcoke reference for cement kiln


Change of environmental impact on fresh water toxicity
comparison with different references

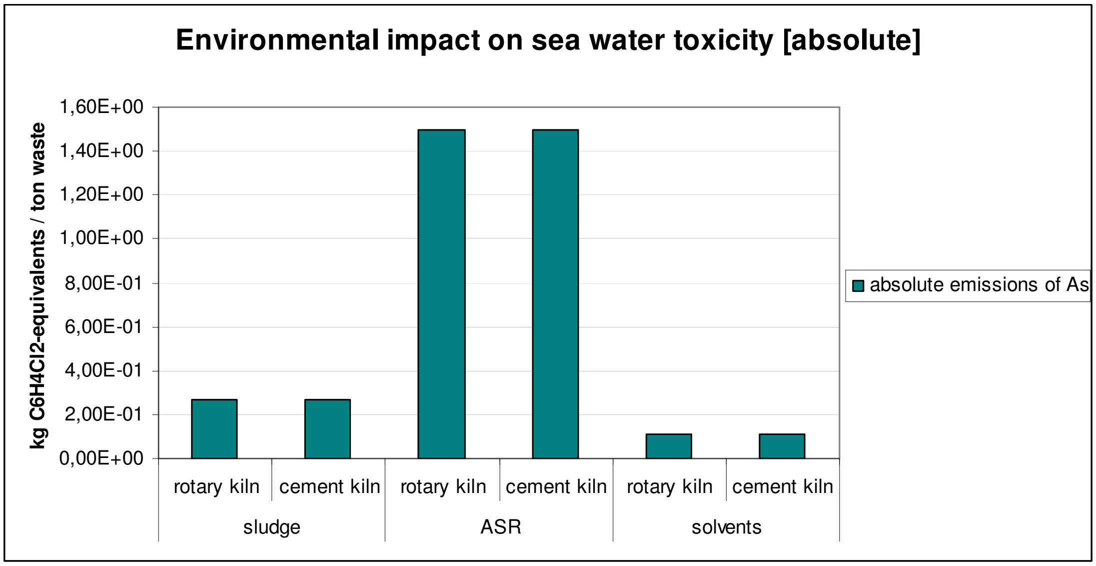
Sea water toxicity → As

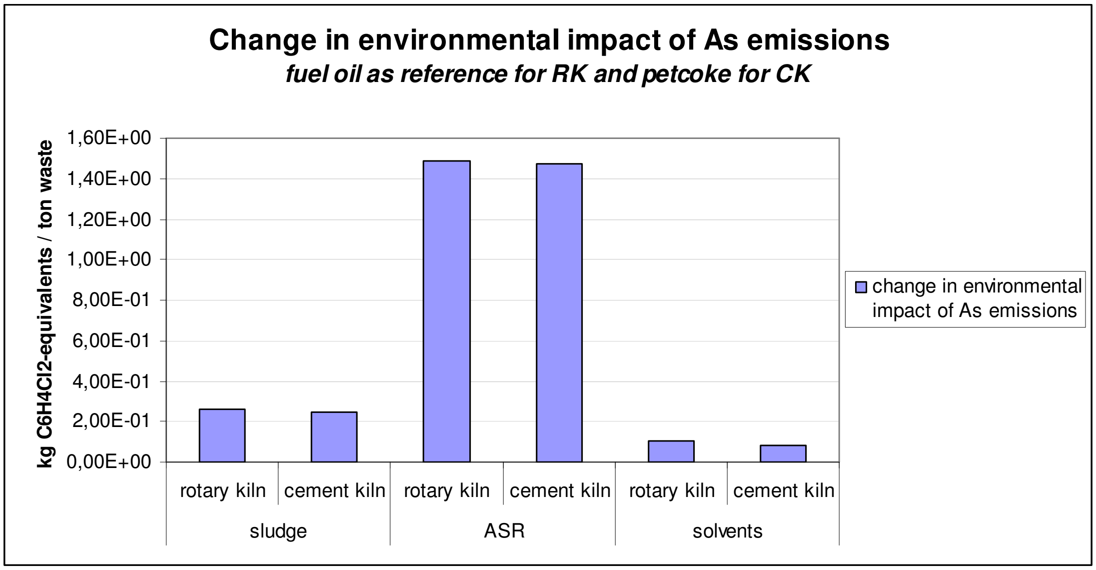
furnace type	**transfer coefficient**	**As/As**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0002	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

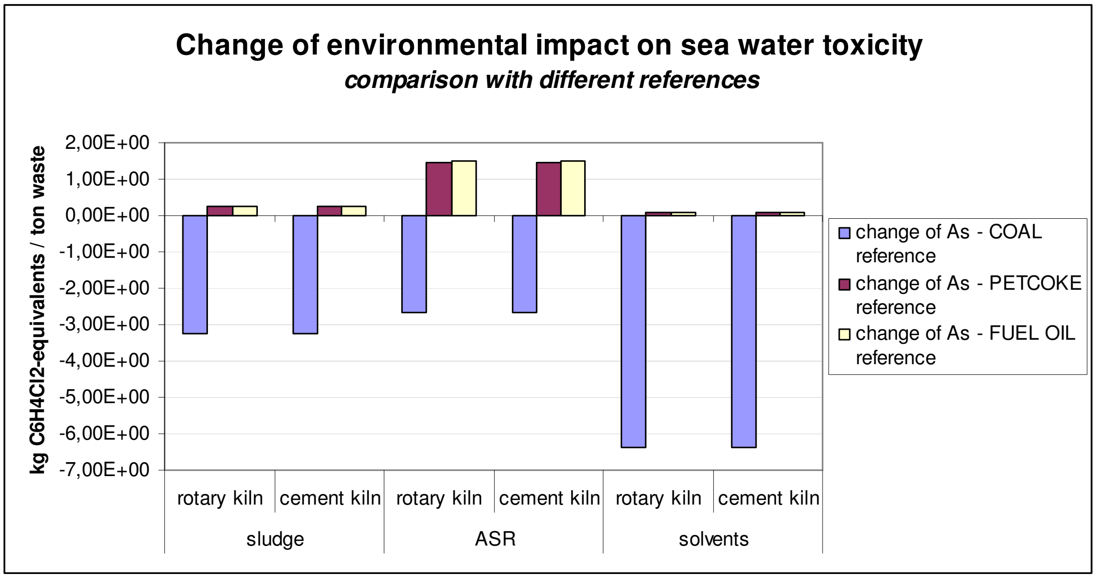
fuel type	**energetic value** **[MJ/kg]**	**arsenic content** **[kg/ton]**
coal	29,55	1,62E-01
fuel oil	40,4	3,00E-04
petcoke	33,7	0,0009

waste type	**energetic value** **[MJ/kg]**	**arsenic content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,0058		1
ASR	16,5	0,0325		1
solvents	25,8	0,00245		1

electricity production avoided emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on sea water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of As


Change in environmental impact of As emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of As emissions


Change of environmental impact on sea water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
2,00E+00
1,00E+00
0,00E+00
-1,00E+00
-2,00E+00
-3,00E+00
-4,00E+00
-5,00E+00
-6,00E+00
-7,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of As - COAL reference
change of As - PETCOKE reference
change of As - FUEL OIL reference

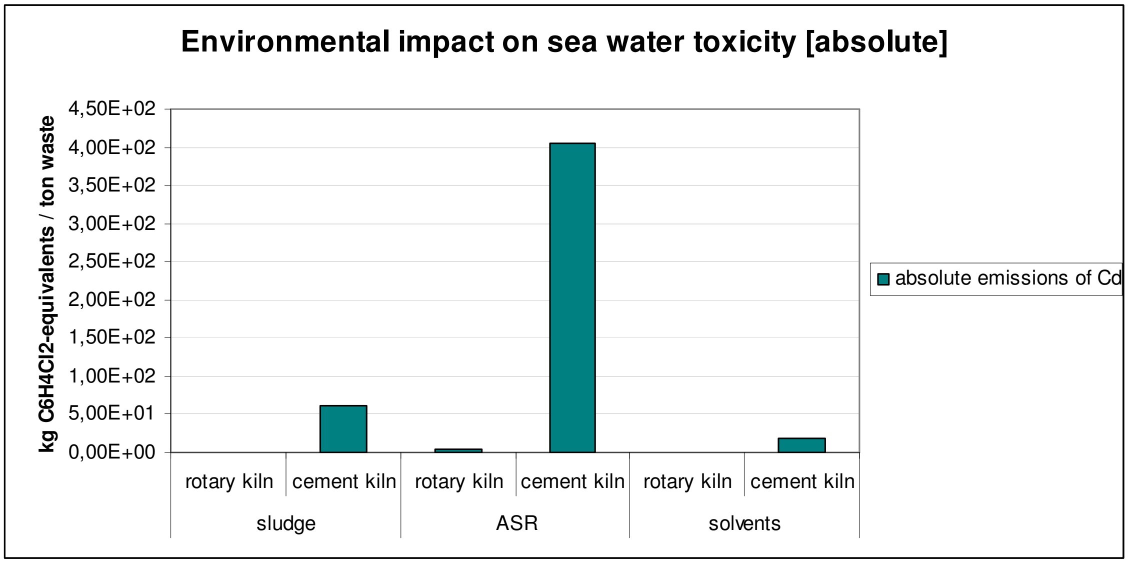
Sea water toxicity → Cd

furnace type	transfer coefficient	Cd/Cd		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0001	1		14,7	0,026	0,131
cement kiln	0,0106	1		21	0	0

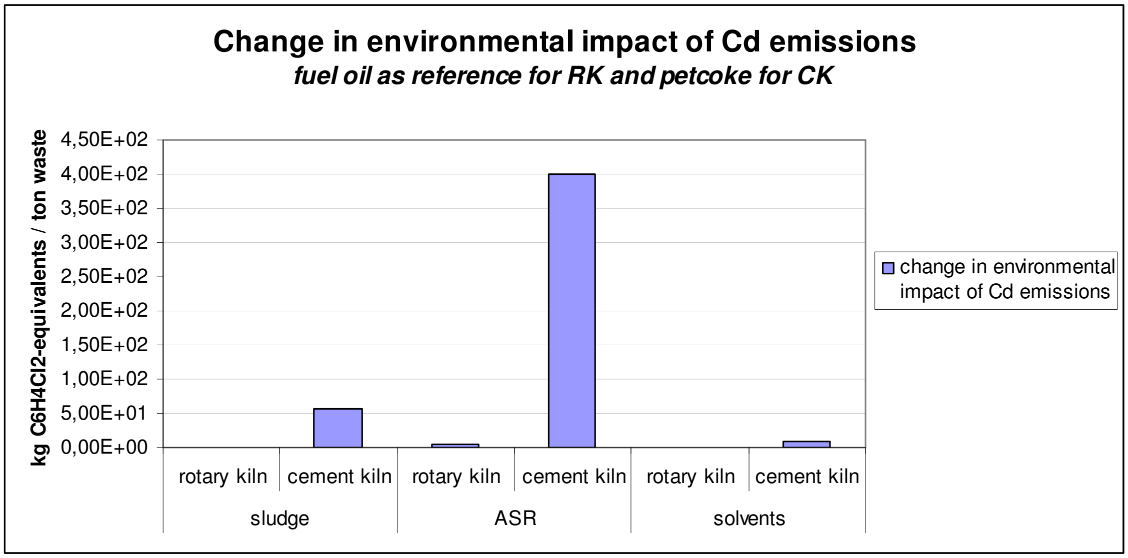
fuel type	energetic value [MJ/kg]	cadmium content [kg/ton]
coal	29,55	3,40E-03
fuel oil	40,4	2,50E-04
petcoke	33,7	0,00093

waste type	energetic value [MJ/kg]	cadmium content [kg/ton]		functional unit [ton]
sludge	13,95	0,0053		1
ASR	16,5	0,0348		1
solvents	25,8	0,0015		1

electricity production avoided emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

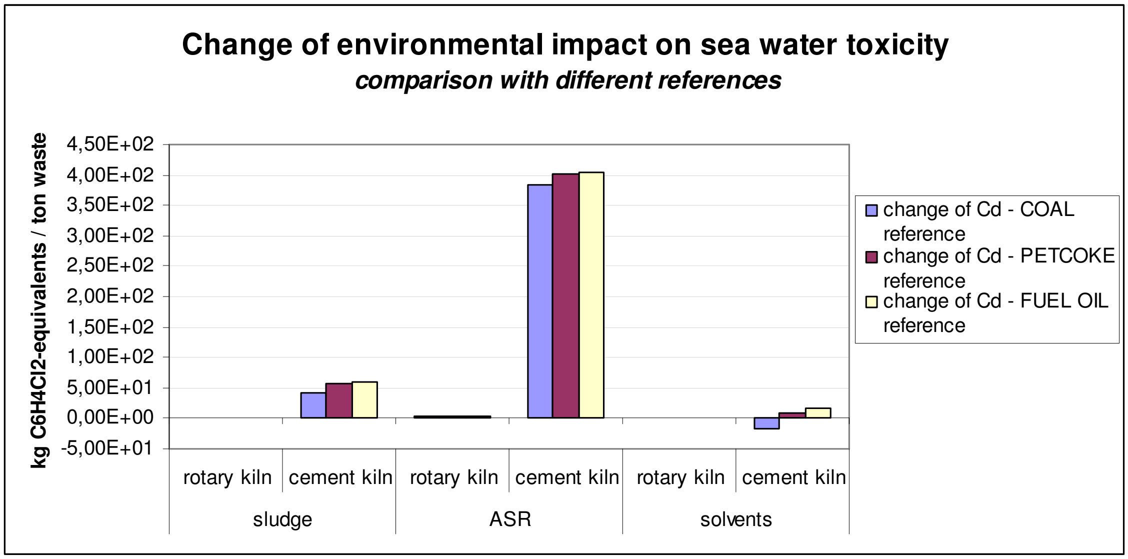


Environmental impact on sea water toxicity [absolute]



Change in environmental impact of Cd emissions

fuel oil as reference for RK and petcoke for CK



Change of environmental impact on sea water toxicity

comparison with different references

Sea water toxicity → Cr

furnace type	**transfer coefficient**	**Cr/Cr**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	5,00E-05	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

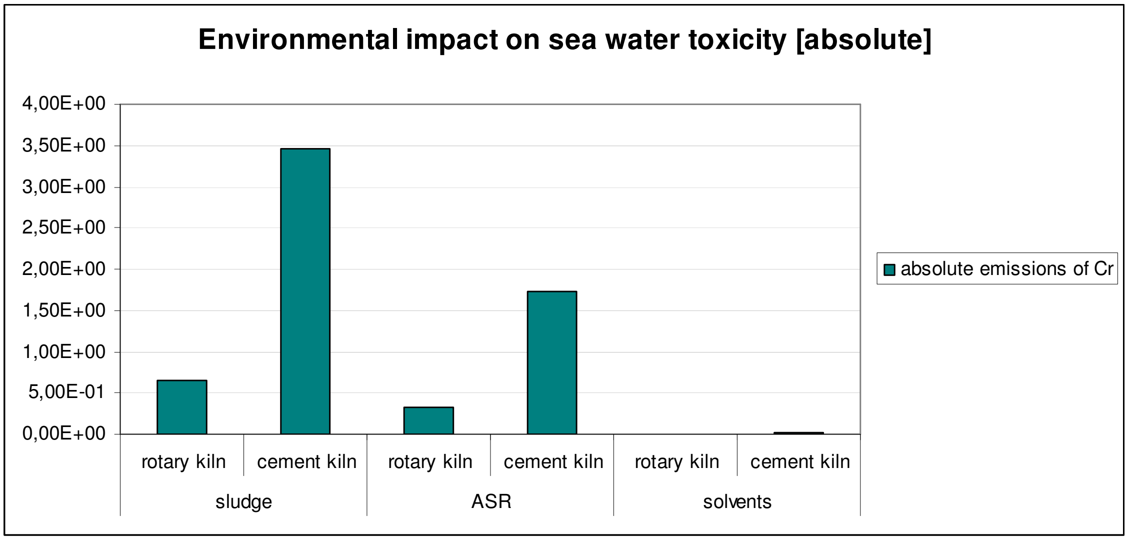
fuel type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**
coal	29,55	2,52E-02
fuel oil	40,4	1,60E-03

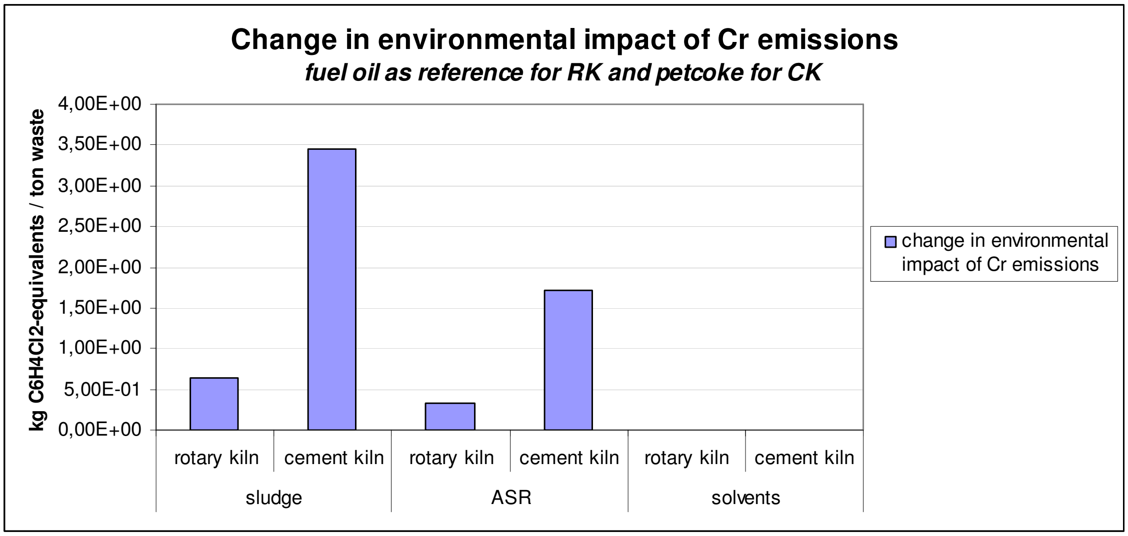
petcoke	33,7	0,0045

waste type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	2,406		1
ASR	16,5	1,204		1
solvents	25,8	0,0093		1

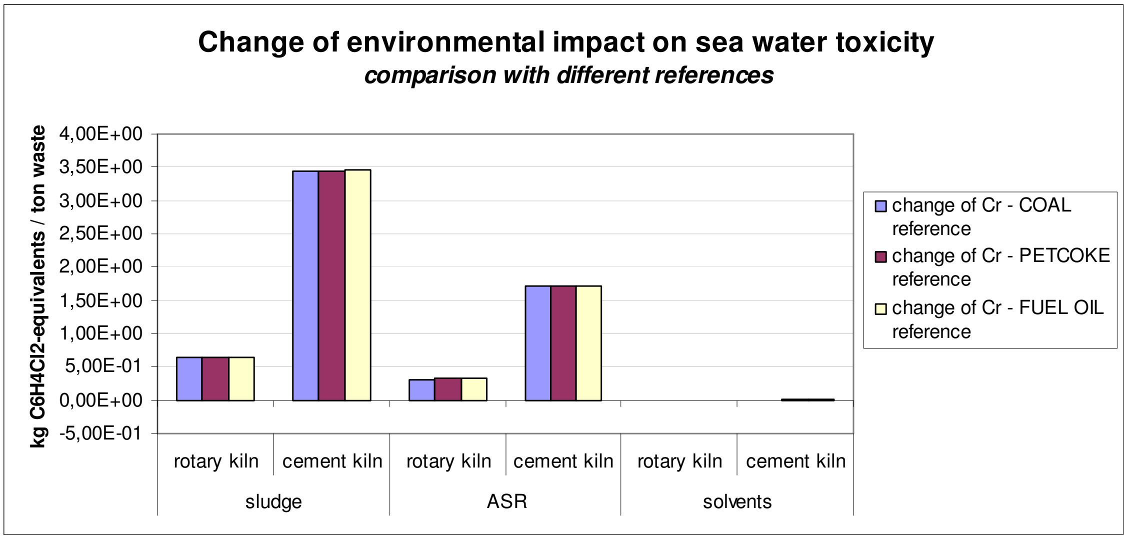
electricity production avoided emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on sea water toxicity [absolute]


Change in environmental impact of Cr emissions

fuel oil as reference for RK and petcoke for CK


Change of environmental impact on sea water toxicity

comparison with different references

Sea water toxicity → Hg

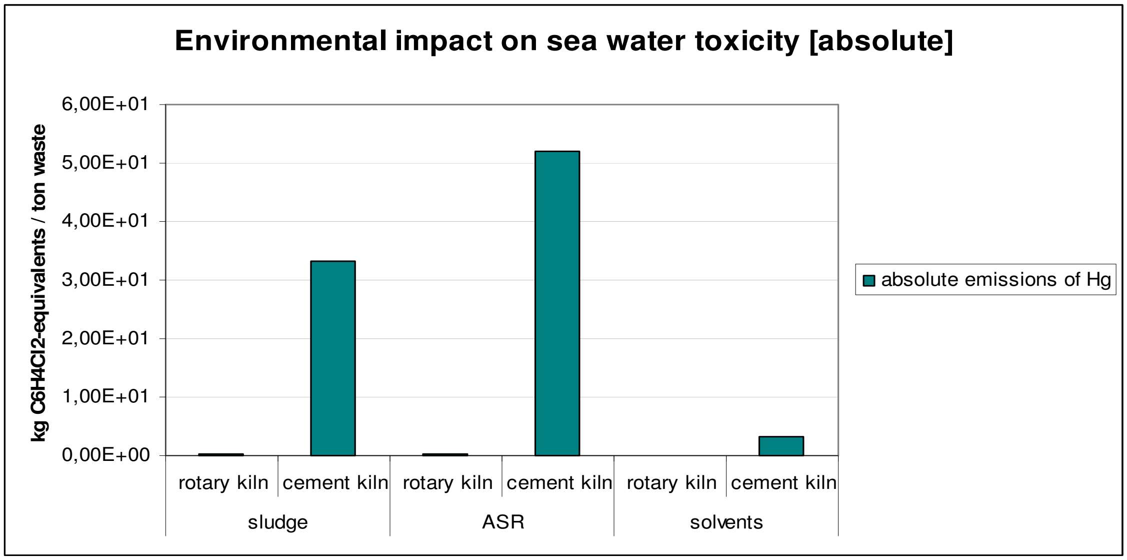
furnace type	**transfer coefficient**	**Hg/Hg**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0022	1		14,7	0,026	0,131
cement kiln	0,3958	1		21	0	0

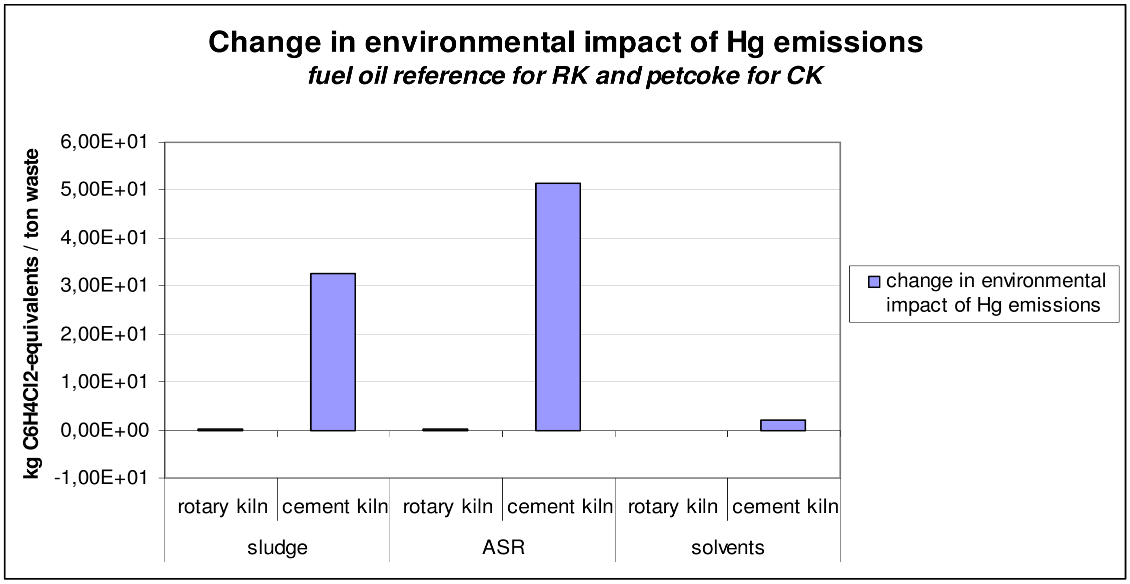
fuel type	**energetic value** **[MJ/kg]**	**mercury content** **[kg/ton]**
coal	29,55	3,60E-04
fuel oil	40,4	2,00E-03
petcoke	33,7	0,00013

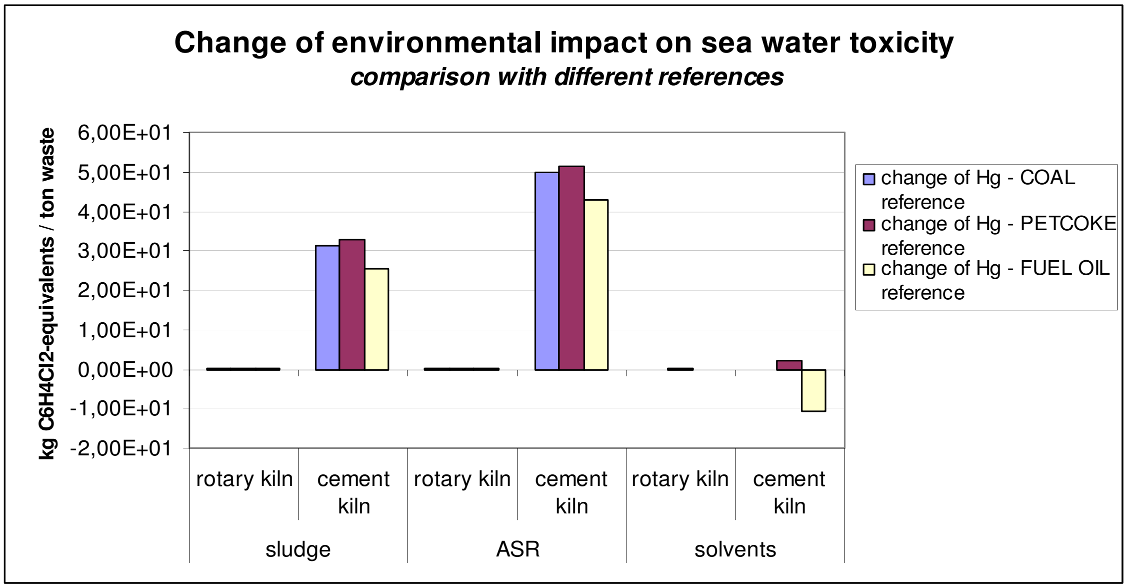
waste type	**energetic value** **[MJ/kg]**	**mercury content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,003		1
ASR	16,5	0,00469		1
solvents	25,8	0,0003		1

electricity production avoided emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on sea water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Hg


Change in environmental impact of Hg emissions
fuel oil reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
-1,00E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Hg emissions


Change of environmental impact on sea water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
6,00E+01
5,00E+01
4,00E+01
3,00E+01
2,00E+01
1,00E+01
0,00E+00
-1,00E+01
-2,00E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Hg - COAL reference
change of Hg - PETCOKE reference
change of Hg - FUEL OIL reference

Sea water toxicity → Pb

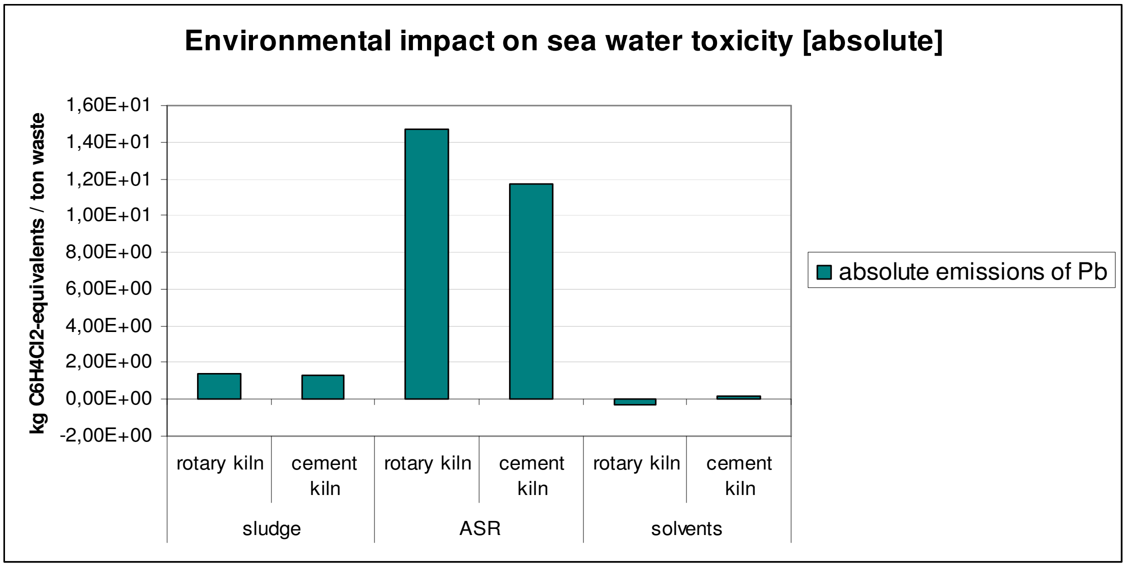
furnace type	transfer coefficient	Pb/Pb		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0009	1		14,7	0,026	0,131
cement kiln	0,0007	1		21	0	0

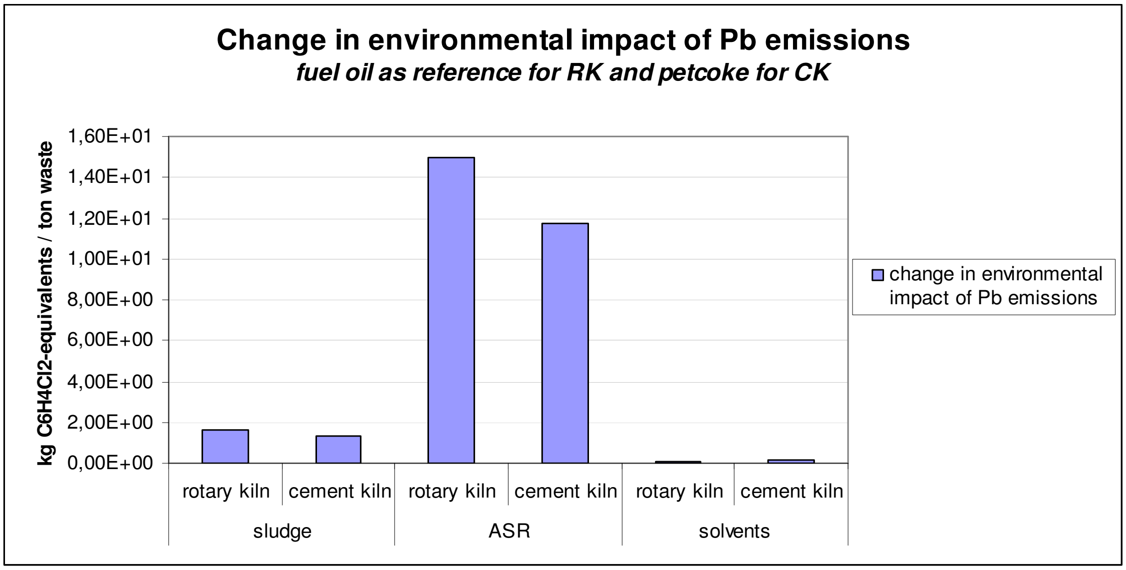
fuel type	energetic value [MJ/kg]	lead content [kg/ton]
coal	29,55	3,71E-02
fuel oil	40,4	3,80E-02

petcoke	33,7	0,0012

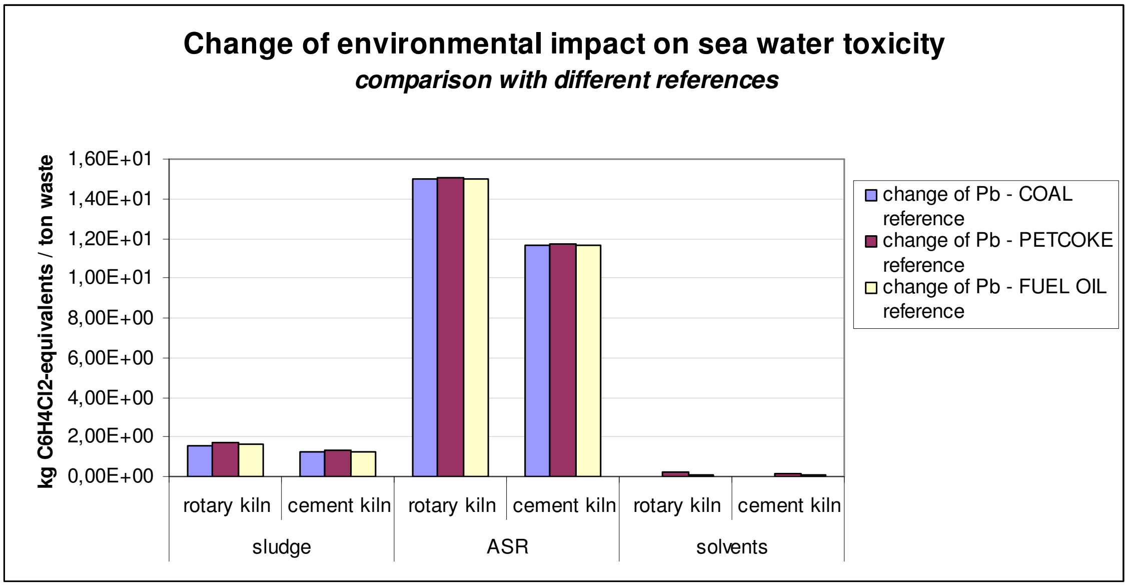
waste type	energetic value [MJ/kg]	lead content [kg/ton]		functional unit [ton]
sludge	13,95	0,27		1
ASR	16,5	2,394		1
solvents	25,8	0,0339		1

electricity production avoided emissions	average emissions Pb [kg/GJ]
gas	0
coal	5,35E-05
energetic mixture [BE]	**1,03E-05**
steam production avioded emissions	**average emissions Pb** [kg/GJ]
gas	0
coal	0,0000214
energetic mixture [BE]	4,11094E-06


Environmental impact on sea water toxicity [absolute]


Change in environmental impact of Pb emissions

fuel oil as reference for RK and petcoke for CK


Change of environmental impact on sea water toxicity

comparison with different references

Sea water toxicity → Ni

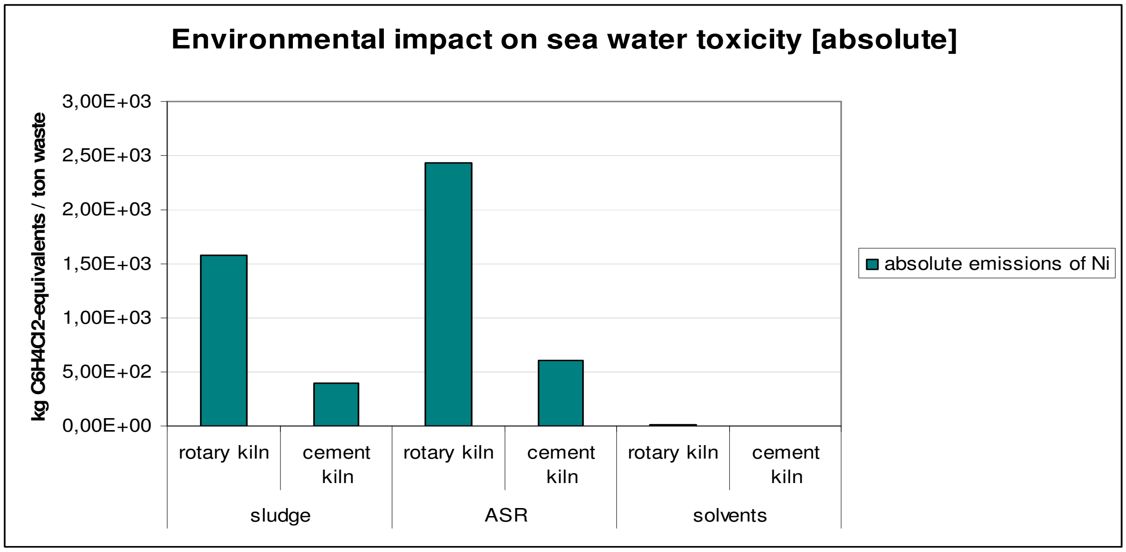
furnace type	transfer coefficient	Ni/Ni		minimal energy demand	electrical yield	steam yield
rotary kiln	8,00E-04	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

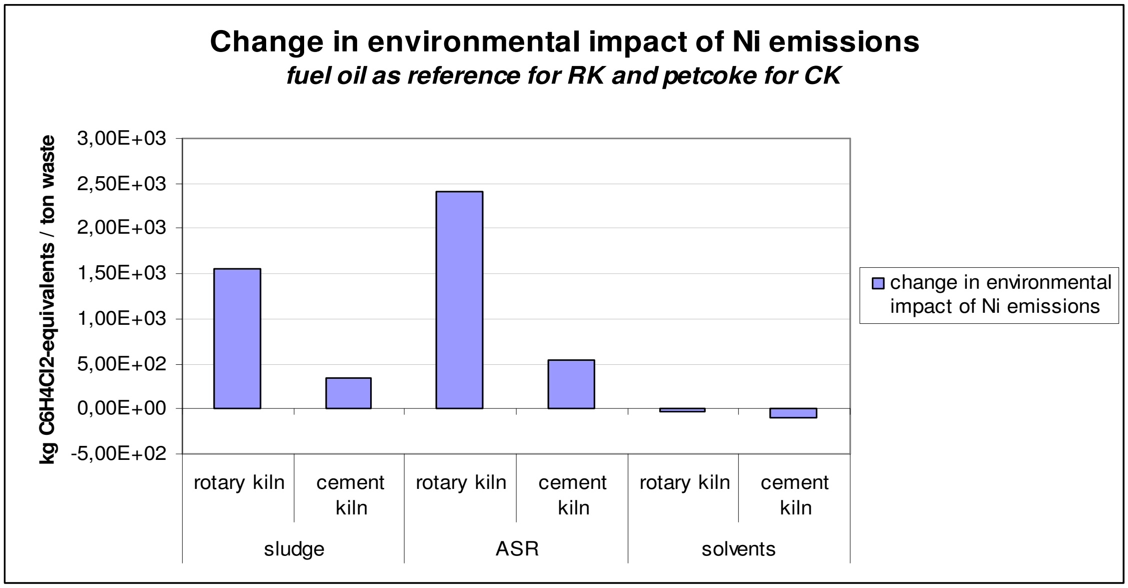
fuel type	energetic value [MJ/kg]	Nickel content [kg/ton]
coal	29,55	3,32E-02
fuel oil	40,4	2,10E-02
petcoke	33,7	0,167

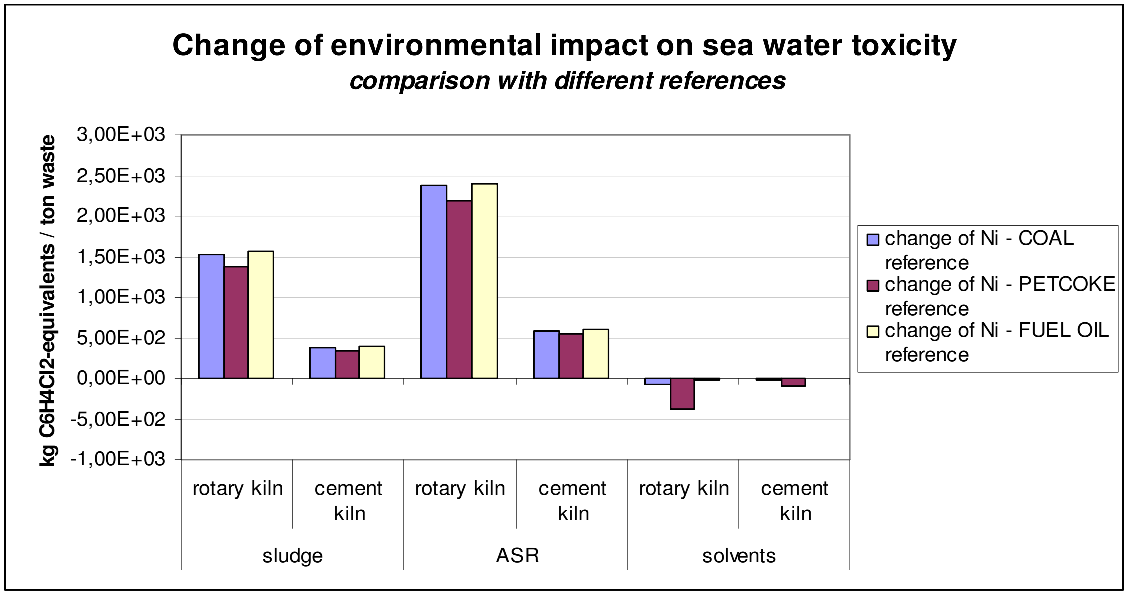
waste type	energetic value [MJ/kg]	Nickel content [kg/ton]		functional unit [ton]
sludge	13,95	0,52		1
ASR	16,5	0,7994		1
solvents	25,8	0,0043		1

electricity production avoided emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on sea water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
3,00E+03
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Ni


Change in environmental impact of Ni emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
3,00E+03
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
-5,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Ni emissions


Change of environmental impact on sea water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
3,00E+03
2,50E+03
2,00E+03
1,50E+03
1,00E+03
5,00E+02
0,00E+00
-5,00E+02
-1,00E+03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Ni - COAL reference
change of Ni - PETCOKE reference
change of Ni - FUEL OIL reference

Sea water toxicity → Cu

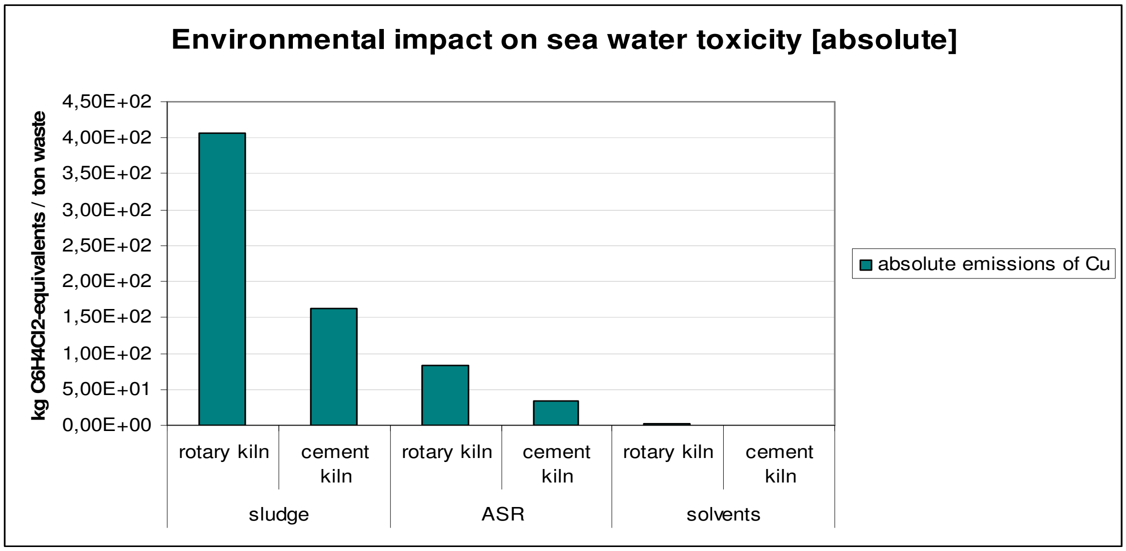
furnace type	transfer coefficient	Cu/Cu		minimal energy demand	electrical yield	steam yield
rotary kiln	5,00E-04	1		14,7	0,026	0,131
cement kiln	2,00E-04	1		21	0	0

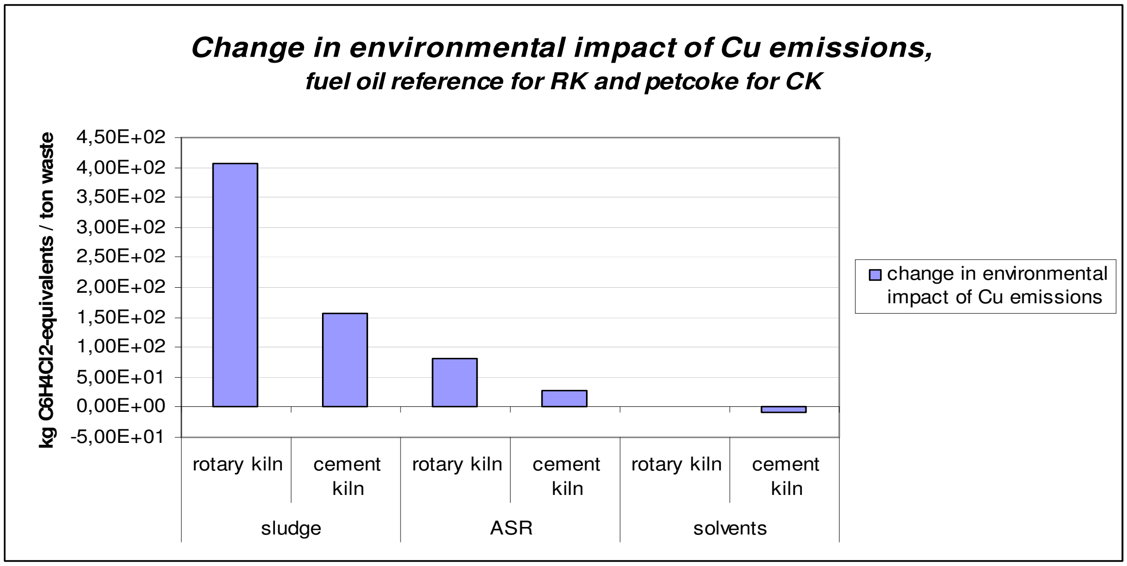
fuel type	energetic value [MJ/kg]	cupper content [kg/ton]
coal	29,55	2,00E-02
fuel oil	40,4	4,77E-03
petcoke	33,7	7,41E-02

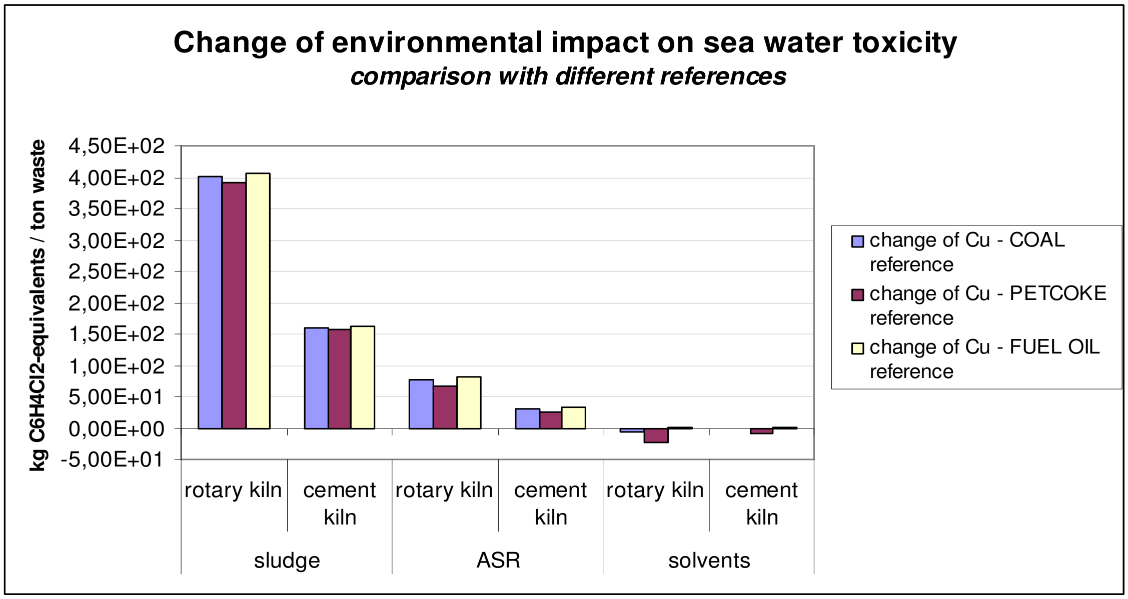
waste type	energetic value [MJ/kg]	cupper content [kg/ton]		functional unit [ton]
sludge	13,95	0,913		1
ASR	16,5	0,1855		1
solvents	25,8	5,48E-03		1

electricity production avioded emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on sea water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
4,50E+02
4,00E+02
3,50E+02
3,00E+02
2,50E+02
2,00E+02
1,50E+02
1,00E+02
5,00E+01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cu


Change in environmental impact of Cu emissions,
fuel oil reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
4,50E+02
4,00E+02
3,50E+02
3,00E+02
2,50E+02
2,00E+02
1,50E+02
1,00E+02
5,00E+01
0,00E+00
-5,00E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cu emissions


Change of environmental impact on sea water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
4,50E+02
4,00E+02
3,50E+02
3,00E+02
2,50E+02
2,00E+02
1,50E+02
1,00E+02
5,00E+01
0,00E+00
-5,00E+01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cu - COAL reference
change of Cu - PETCOKE reference
change of Cu - FUEL OIL reference

Sea water toxicity → Zn

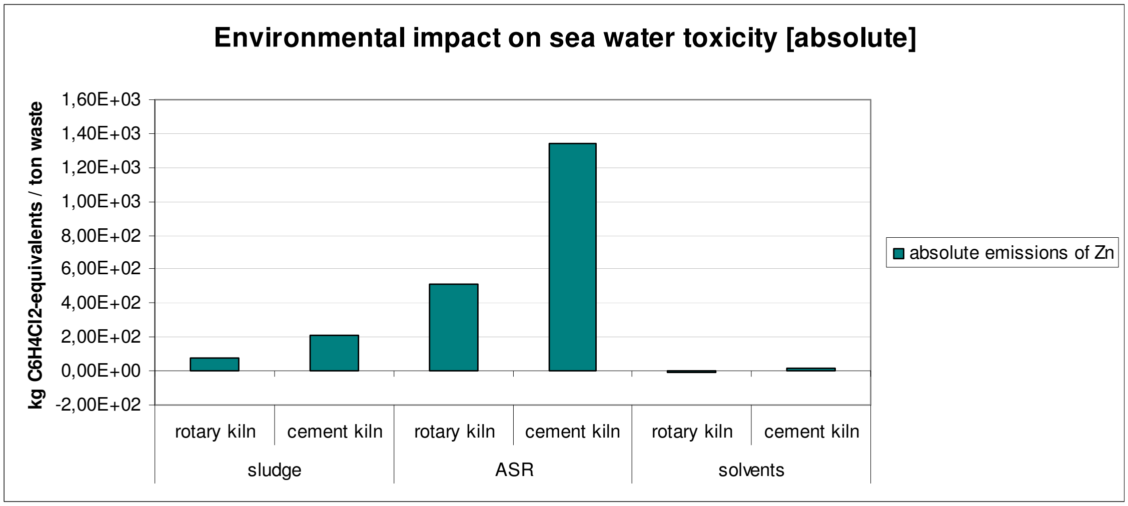
furnace type	transfer coefficient	Zn/Zn		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0007	1		14,7	0,026	0,131
cement kiln	0,0017	1		21	0	0

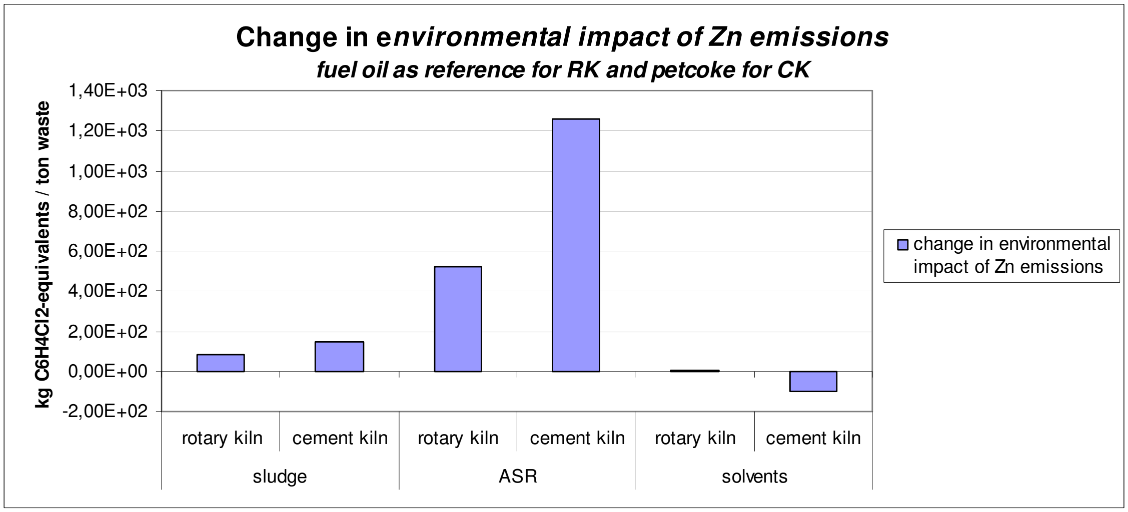
fuel type	energetic value [MJ/kg]	Zinck content [kg/ton]
coal	29,55	6,18E-02
fuel oil	40,4	7,73E-03

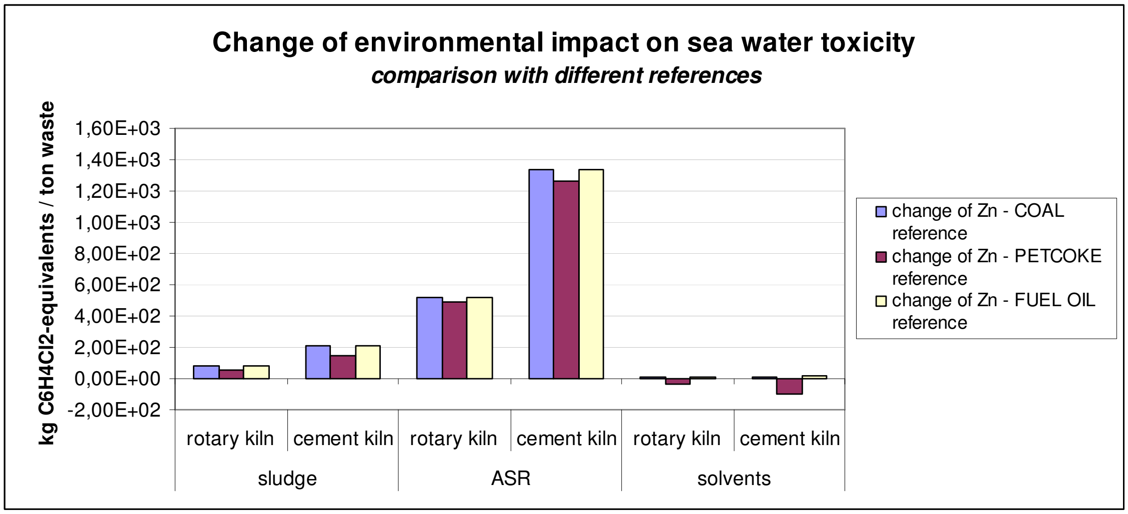
petcoke	33,7	1,31E+00

waste type	energetic value [MJ/kg]	Zinck content [kg/ton]		functional unit [ton]
sludge	13,95	1,758		1
ASR	16,5	11,09		1
solvents	25,8	1,57E-01		1

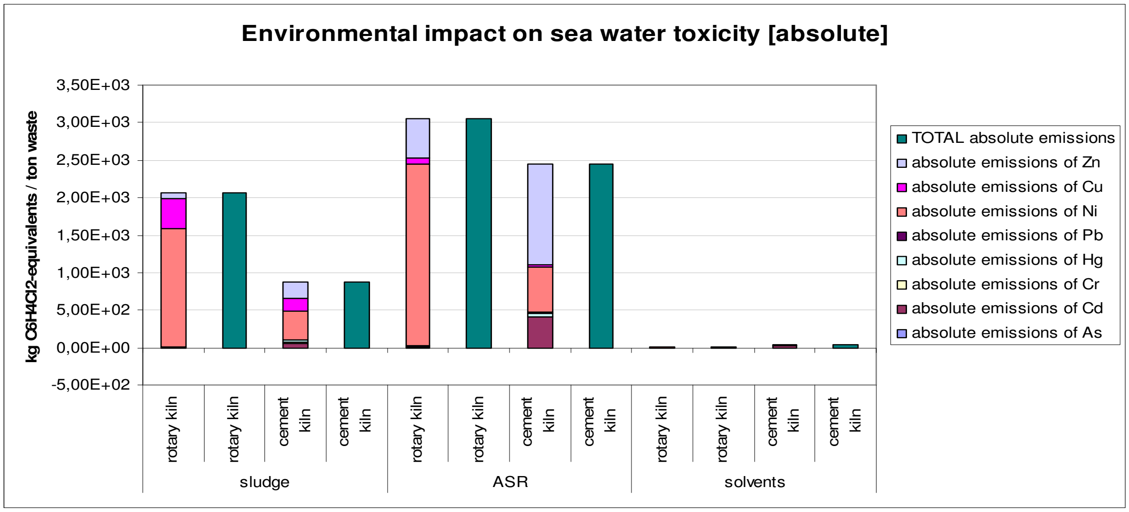
electricity production avioded emissions	average emissions Zn [kg/GJ]
gas	0
coal	1,35E-04
energetic mixture [BE]	**2,59335E-05**
steam production avioded emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	0,000054
energetic mixture [BE]	1,03734E-05

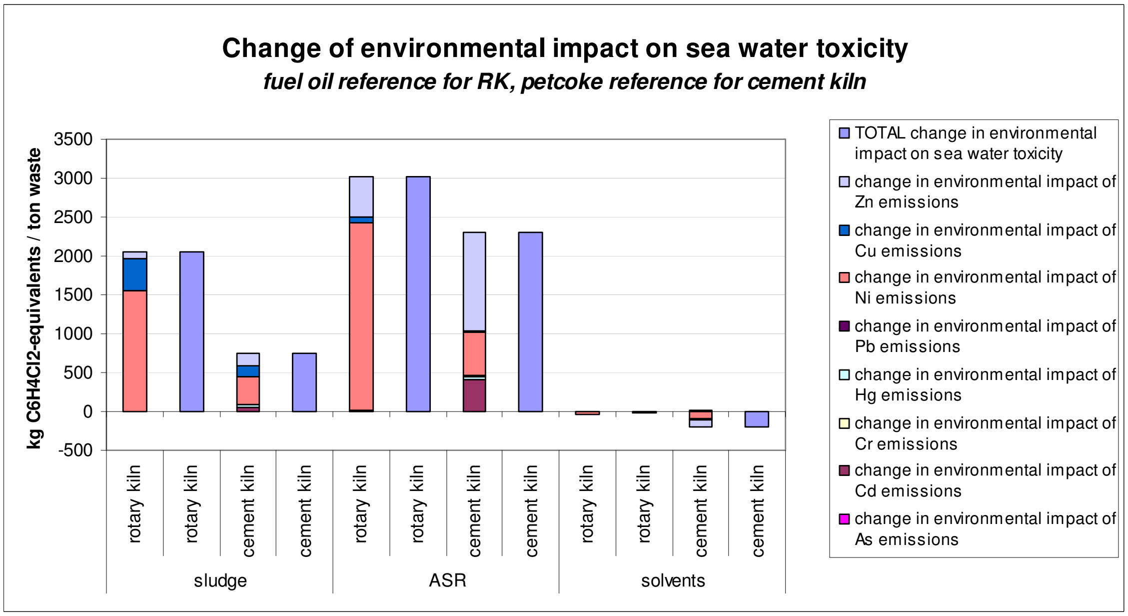

Environmental impact on sea water toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,60E+03
1,40E+03
1,20E+03
1,00E+03
8,00E+02
6,00E+02
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Zn

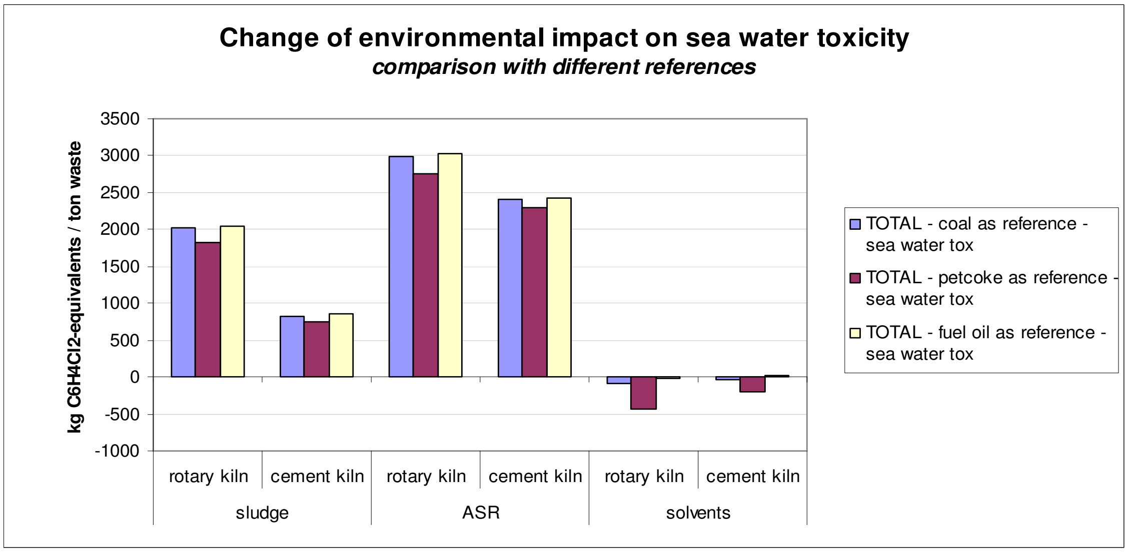

Change in environmental impact of Zn emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,40E+03
1,20E+03
1,00E+03
8,00E+02
6,00E+02
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Zn emissions


Change of environmental impact on sea water toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,60E+03
1,40E+03
1,20E+03
1,00E+03
8,00E+02
6,00E+02
4,00E+02
2,00E+02
0,00E+00
-2,00E+02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Zn - COAL reference
change of Zn - PETCOKE reference
change of Zn - FUEL OIL reference

Sea water toxicity → TOTAL







Terrestrial toxicity → As

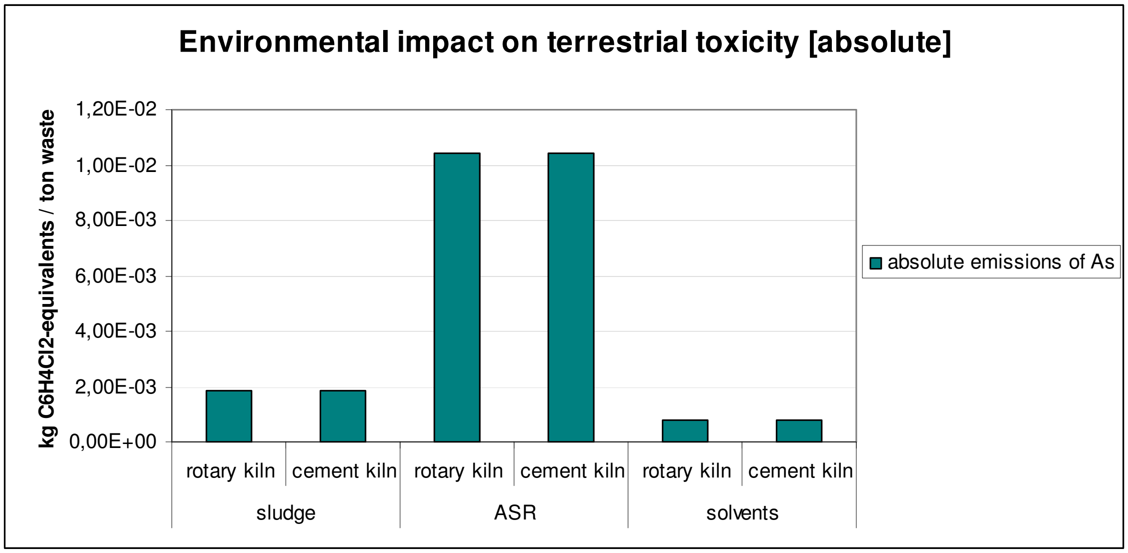
furnace type	transfer coefficient	As/As		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0002	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

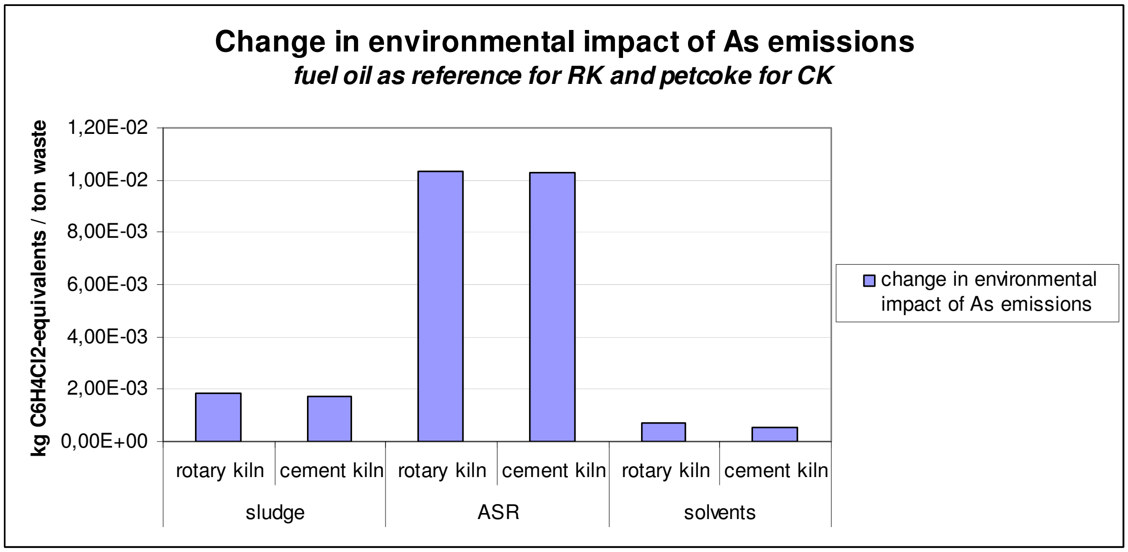
fuel type	energetic value [MJ/kg]	arsenic content [kg/ton]
coal	29,55	1,62E-01
fuel oil	40,4	3,00E-04

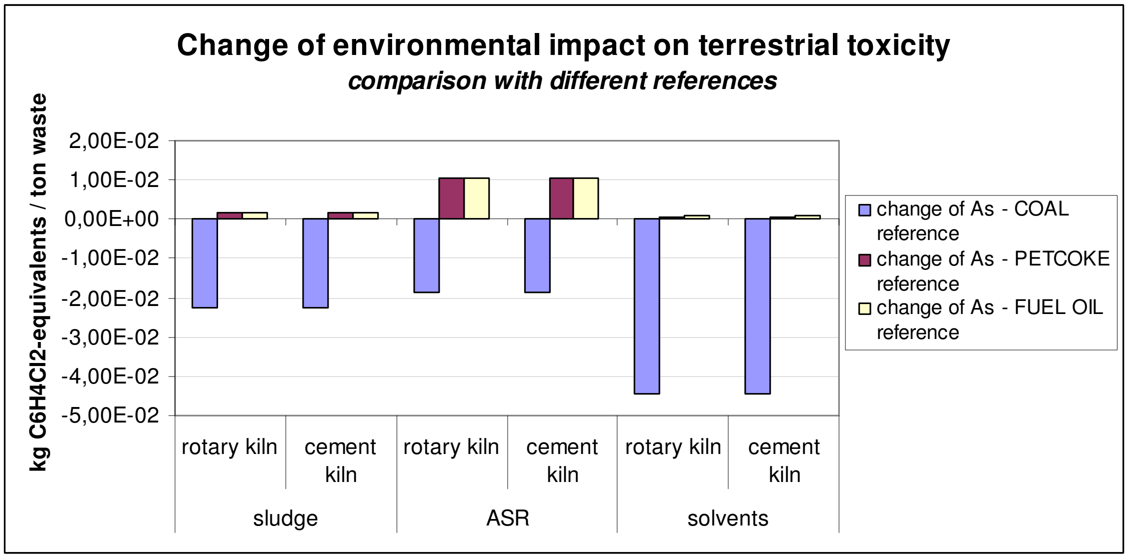
petcoke	33,7	0,0009

waste type	energetic value [MJ/kg]	arsenic content [kg/ton]		functional unit [ton]
sludge	13,95	0,0058		1
ASR	16,5	0,0325		1
solvents	25,8	0,00245		1

electricity production avoided emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions As** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on terrestrial toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,20E-02
1,00E-02
8,00E-03
6,00E-03
4,00E-03
2,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of As


Change in environmental impact of As emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,20E-02
1,00E-02
8,00E-03
6,00E-03
4,00E-03
2,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of As emissions


Change of environmental impact on terrestrial toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
2,00E-02
1,00E-02
0,00E+00
-1,00E-02
-2,00E-02
-3,00E-02
-4,00E-02
-5,00E-02
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of As - COAL reference
change of As - PETCOKE reference
change of As - FUEL OIL reference

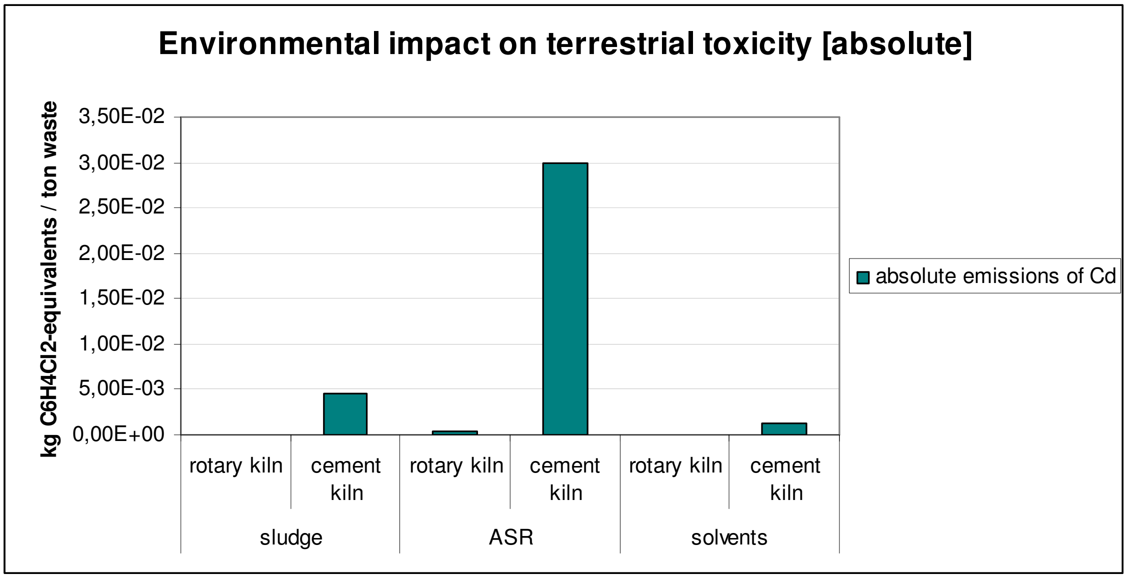
Terrestrial toxicity → Cd

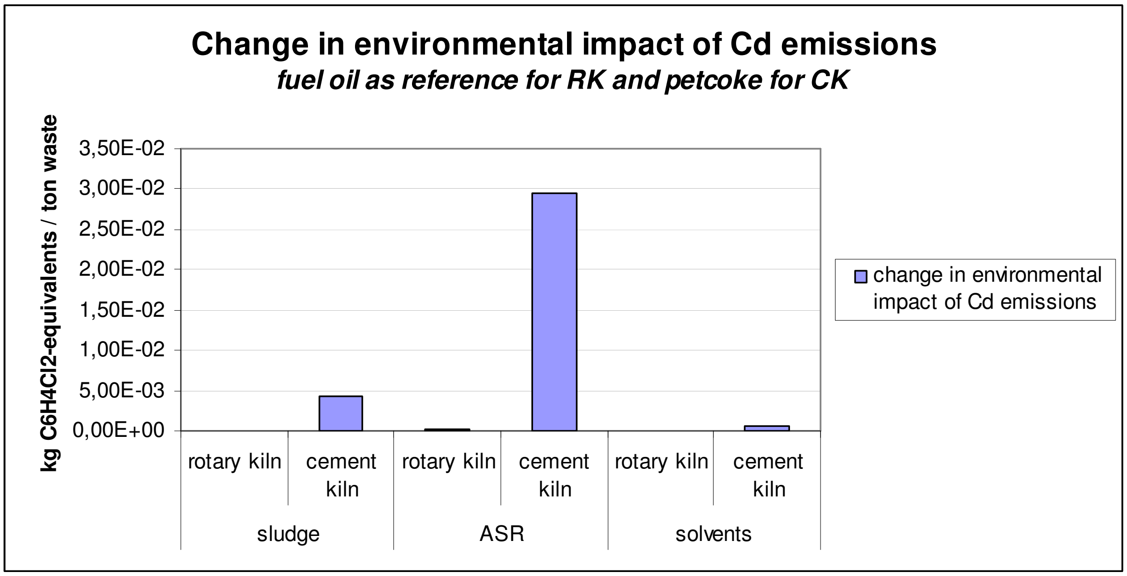
furnace type	**transfer coefficient**	**Cd/Cd**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0001	1		14,7	0,026	0,131
cement kiln	0,0106	1		21	0	0

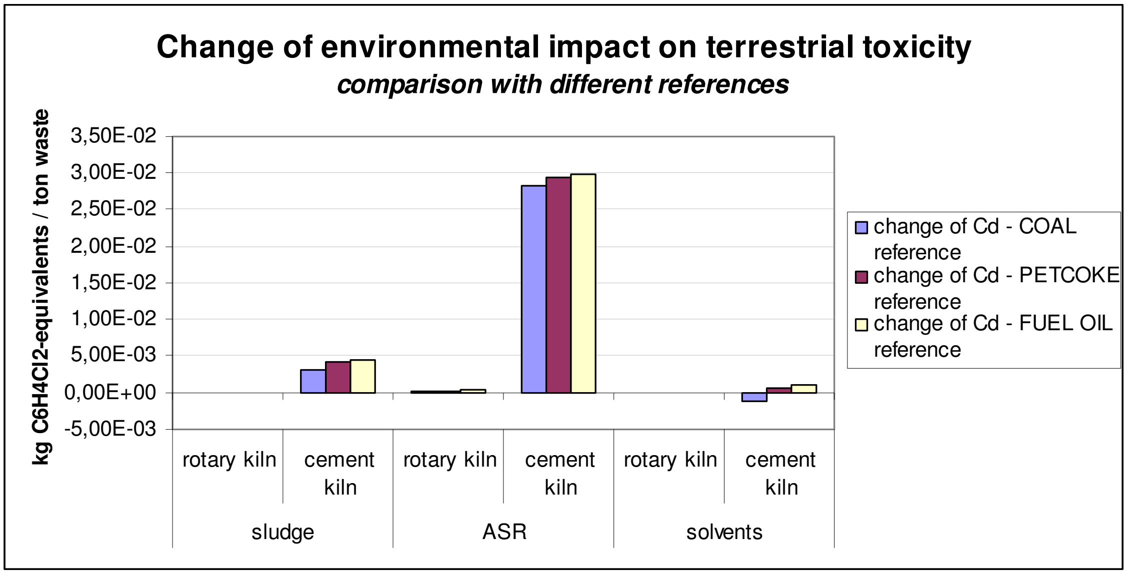
fuel type	**energetic value** **[MJ/kg]**	**cadmium content** **[kg/ton]**
coal	29,55	3,40E-03
fuel oil	40,4	2,50E-04
petcoke	33,7	0,00093

waste type	**energetic value** **[MJ/kg]**	**cadmium content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,0053		1
ASR	16,5	0,0348		1
solvents	25,8	0,0015		1

electricity production avoided emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production aviοded emissions	**average emissions Cd** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on terrestrial toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
3,50E-02
3,00E-02
2,50E-02
2,00E-02
1,50E-02
1,00E-02
5,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cd


Change in environmental impact of Cd emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
3,50E-02
3,00E-02
2,50E-02
2,00E-02
1,50E-02
1,00E-02
5,00E-03
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cd emissions


Change of environmental impact on terrestrial toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
3,50E-02
3,00E-02
2,50E-02
2,00E-02
1,50E-02
1,00E-02
5,00E-03
0,00E+00
-5,00E-03
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cd - COAL reference
change of Cd - PETCOKE reference
change of Cd - FUEL OIL reference

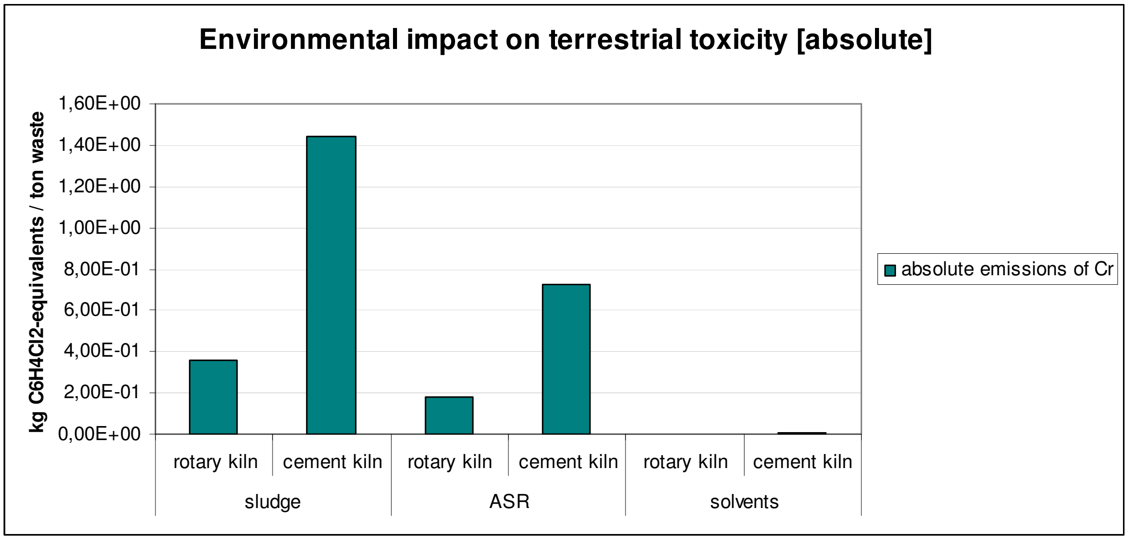
Terrestrial toxicity → Cr

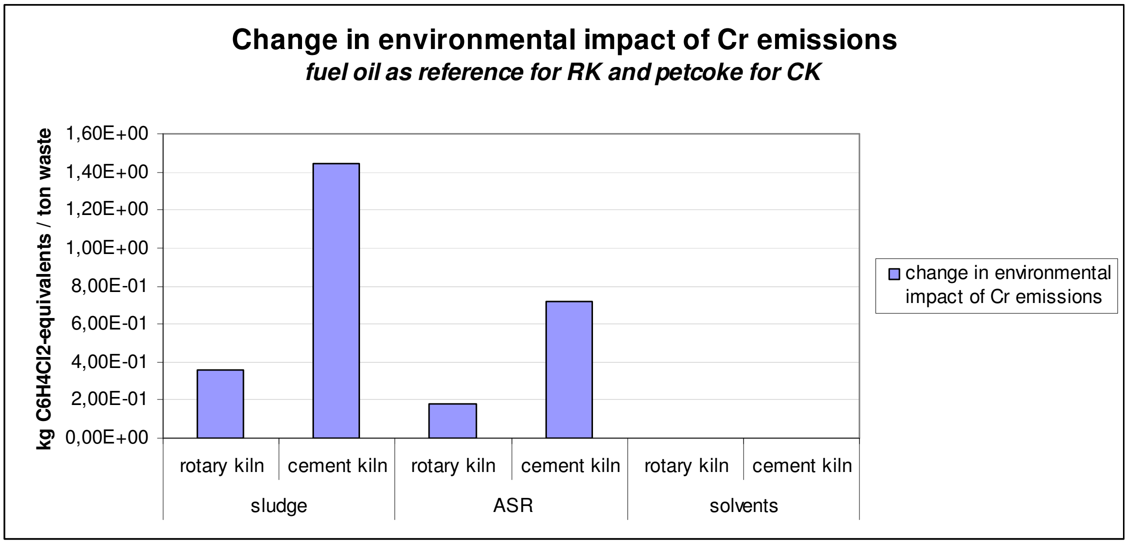
furnace type	**transfer coefficient**	**Cr/Cr**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	5,00E-05	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

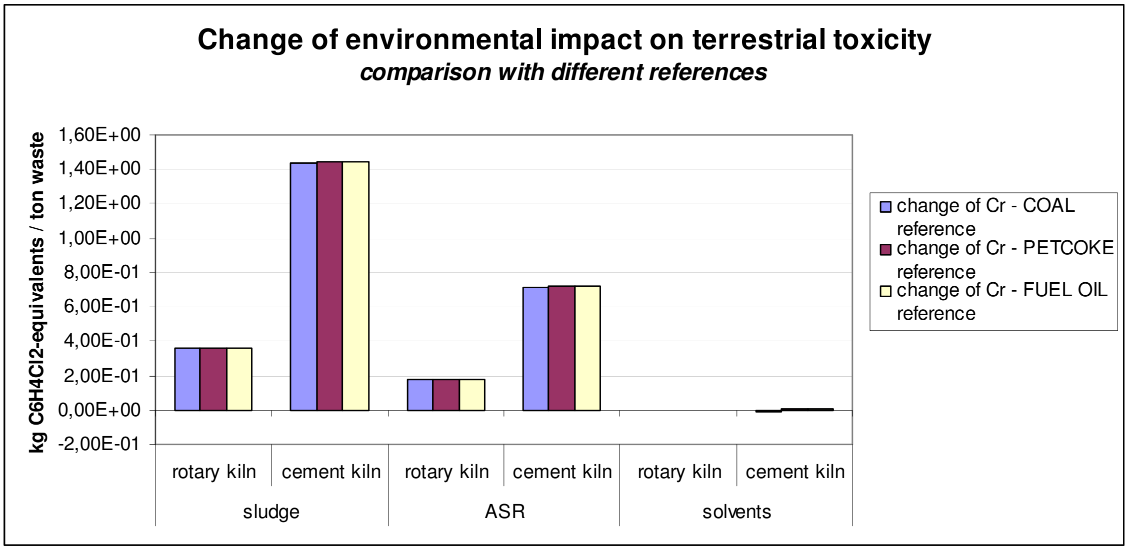
fuel type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**
coal	29,55	2,52E-02
fuel oil	40,4	1,60E-03
petcoke	33,7	0,0045

waste type	**energetic value** **[MJ/kg]**	**chromium content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	2,406		1
ASR	16,5	1,204		1
solvents	25,8	0,0093		1

electricity production avoided emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**
steam production avioded emissions	**average emissions Cr** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on terrestrial toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cr


Change in environmental impact of Cr emissions
fuel oil as reference for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cr emissions


Change of environmental impact on terrestrial toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
-2,00E-01
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cr - COAL reference
change of Cr - PETCOKE reference
change of Cr - FUEL OIL reference

Terrestrial toxicity → Hg

furnace type	**transfer coefficient**	**Hg/Hg**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	0,0022	1		14,7	0,026	0,131
cement kiln	0,3958	1		21	0	0

fuel type	**energetic value [MJ/kg]**	**mercury content [kg/ton]**
coal	29,55	3,60E-04
fuel oil	40,4	2,00E-03
petcoke	33,7	0,00013

waste type	**energetic value [MJ/kg]**	**mercury content [kg/ton]**		**functional unit [ton]**
sludge	13,95	0,003		1
ASR	16,5	0,00469		1
solvents	25,8	0,0003		1

electricity production avoided emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Hg** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

Characterisation factor of mercury on terrestrial toxicity is 0.

Terrestrial toxicity → Pb

furnace type	transfer coefficient	Pb/Pb		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0009	1		14,7	0,026	0,131
cement kiln	0,0007	1		21	0	0

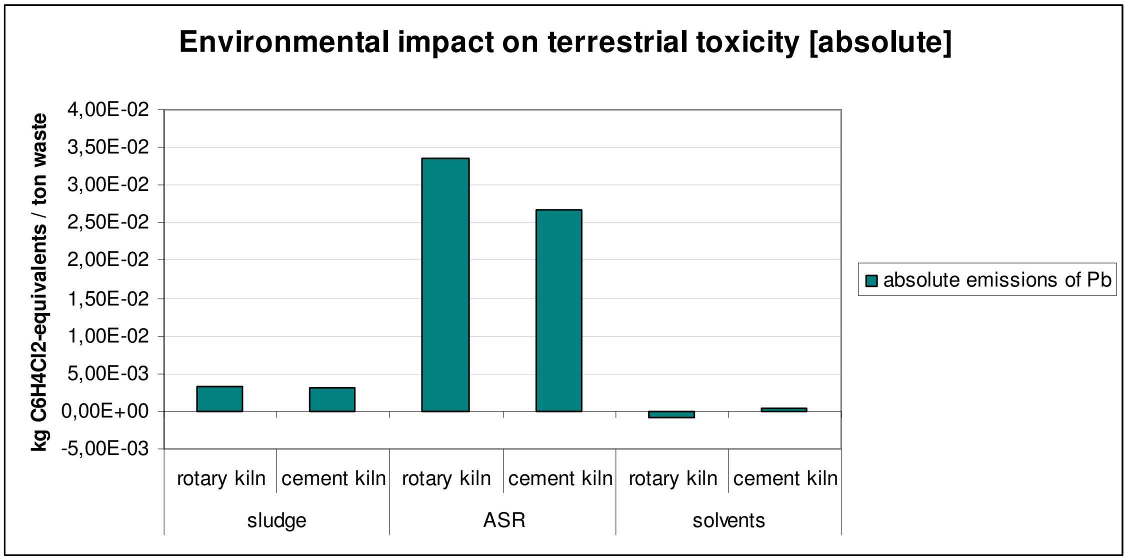
fuel type	energetic value [MJ/kg]	lead content [kg/ton]
coal	29,55	3,71E-02
fuel oil	40,4	3,80E-02

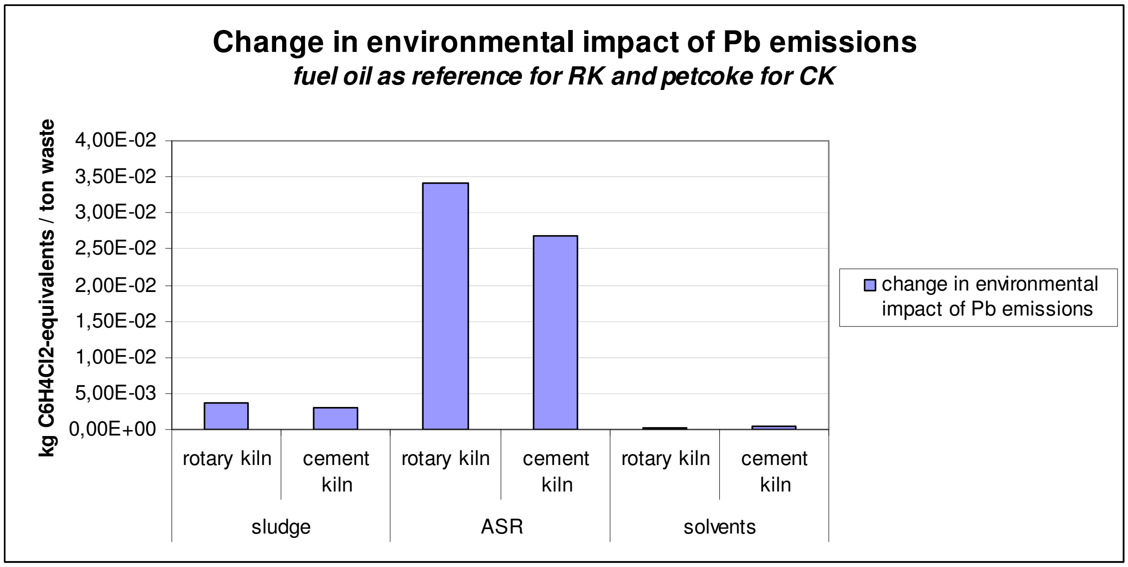
petcoke	33,7	0,0012

waste type	energetic value [MJ/kg]	lead content [kg/ton]		functional unit [ton]
sludge	13,95	0,27		1
ASR	16,5	2,394		1
solvents	25,8	0,0339		1

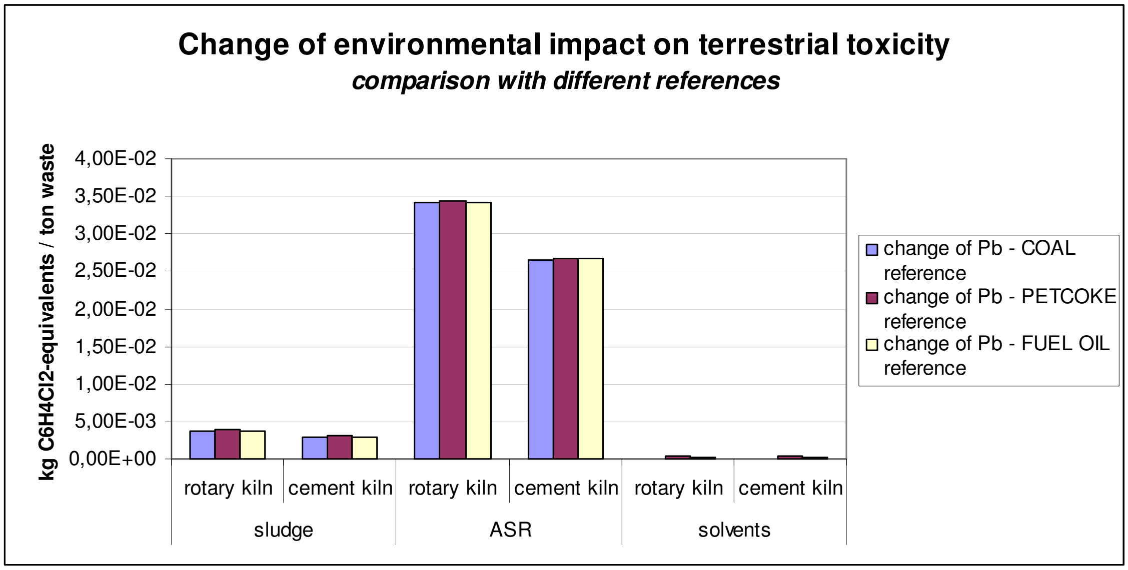
electricity production avoided emissions	average emissions Pb [kg/GJ]
gas	0
coal	5,35E-05
energetic mixture [BE]	**1,03E-05**

steam production avioded emissions	average emissions Pb [kg/GJ]
gas	0
coal	0,0000214
energetic mixture [BE]	4,11094E-06


Environmental impact on terrestrial toxicity [absolute]


Change in environmental impact of Pb emissions

fuel oil as reference for RK and petcoke for CK


Change of environmental impact on terrestrial toxicity

comparison with different references

Terrestrial toxicity → Ni

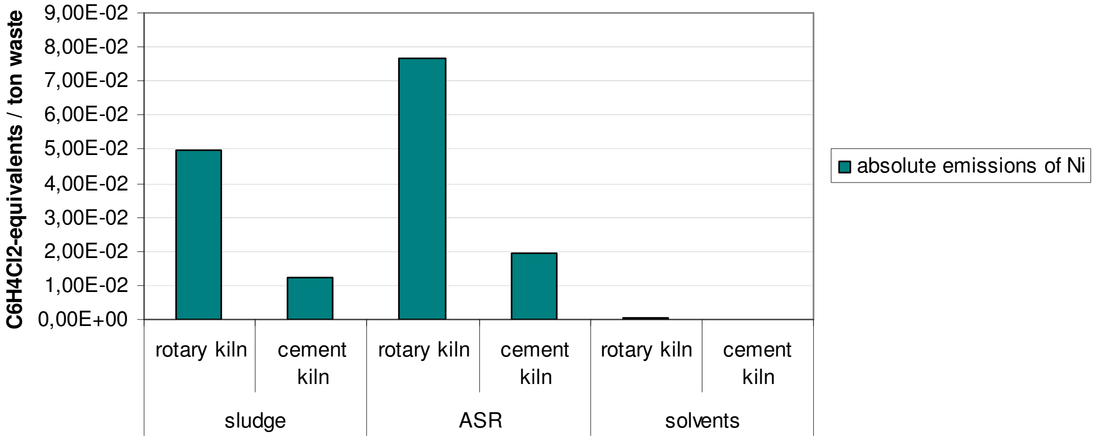
furnace type	transfer coefficient	Ni/Ni		minimal energy demand	electrical yield	steam yield
rotary kiln	8,00E-04	1		14,7	0,026	0,131
cement kiln	0,0002	1		21	0	0

fuel type	energetic value [MJ/kg]	Nickel content [kg/ton]
coal	29,55	3,32E-02
fuel oil	40,4	2,10E-02
petcoke	33,7	0,167

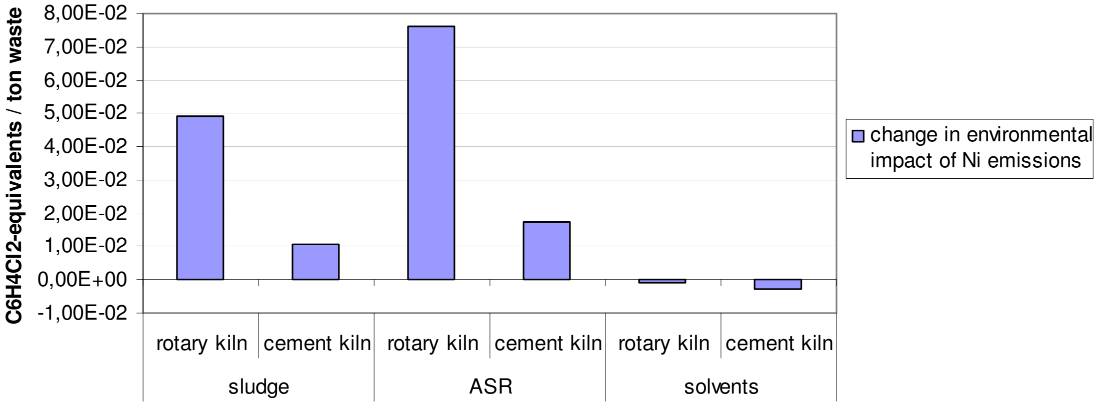
waste type	energetic value [MJ/kg]	Nickel content [kg/ton]		functional unit [ton]
sludge	13,95	0,52		1
ASR	16,5	0,7994		1
solvents	25,8	0,0043		1

electricity production avoided emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production avioded emissions	**average emissions Ni** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0

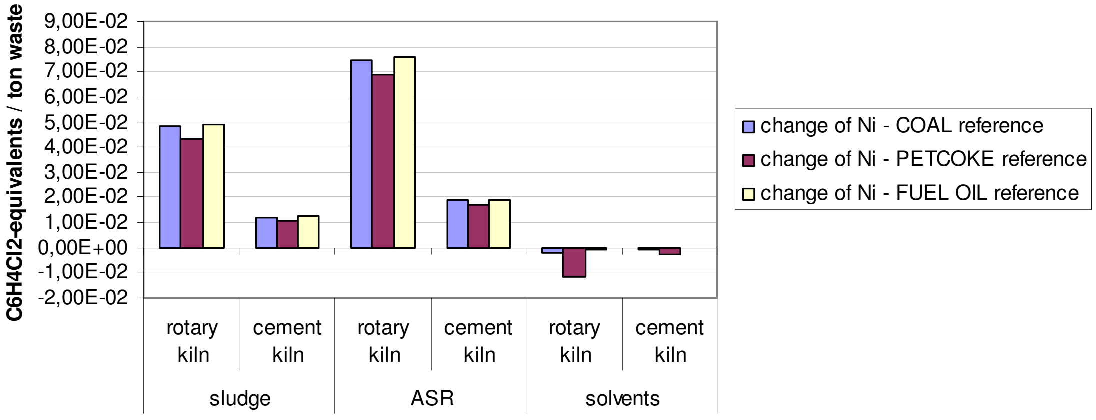


Environmental impact on terrestrial toxicity [absolute]



Change in environmental impact of Ni emissions

fuel oil as reference for RK and petcoke for CK



Change of environmental impact on terrestrial toxicity

comparison with different references

Terrestrial toxicity → Cu

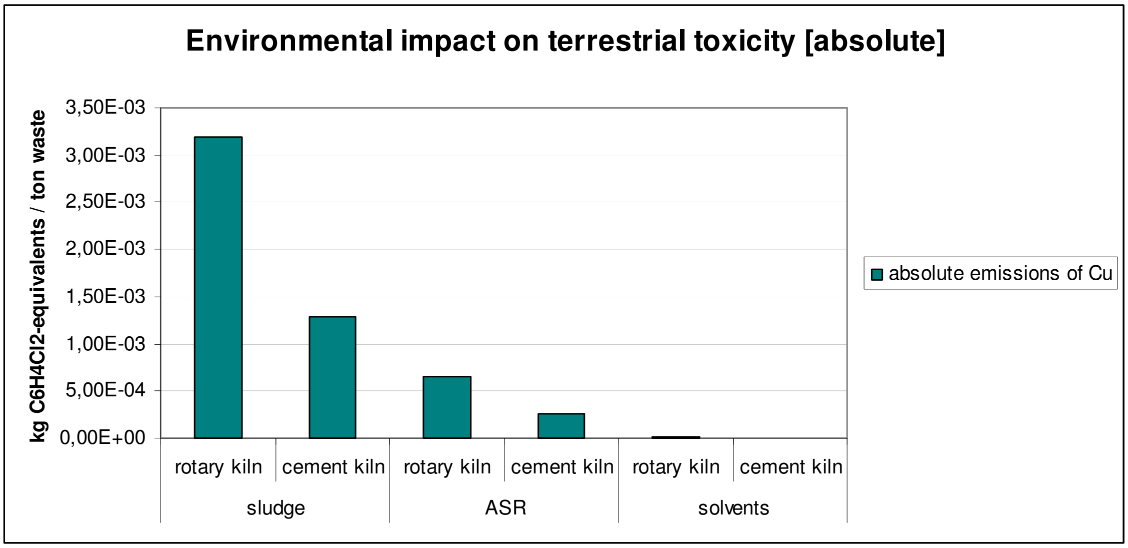
furnace type	**transfer coefficient**	**Cu/Cu**		**minimal energy demand**	**electrical yield**	**steam yield**
rotary kiln	5,00E-04	1		14,7	0,026	0,131
cement kiln	2,00E-04	1		21	0	0

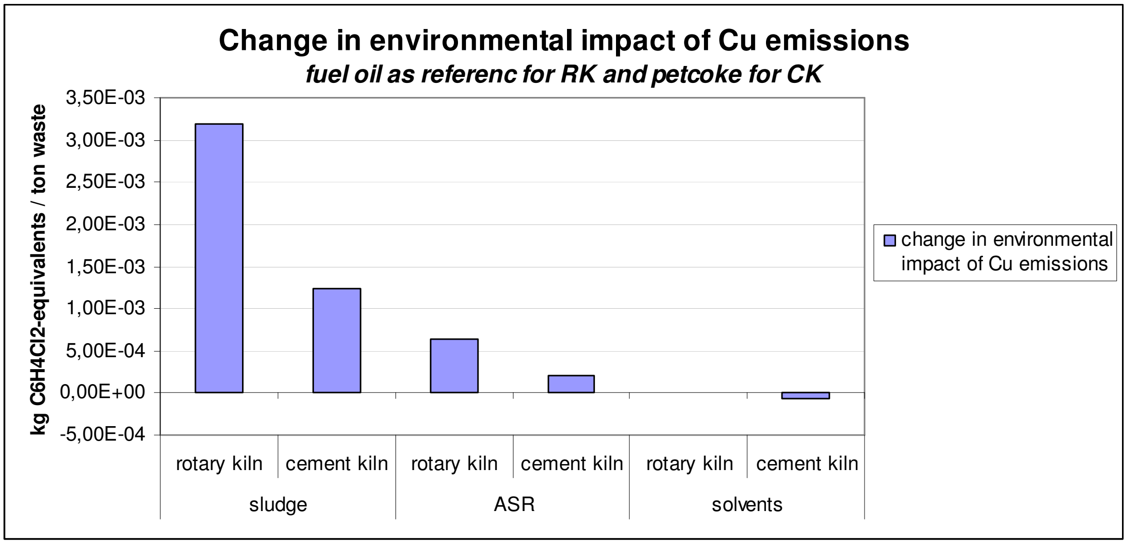
fuel type	**energetic value** **[MJ/kg]**	**cupper content** **[kg/ton]**
coal	29,55	2,00E-02
fuel oil	40,4	4,77E-03
petcoke	33,7	7,41E-02

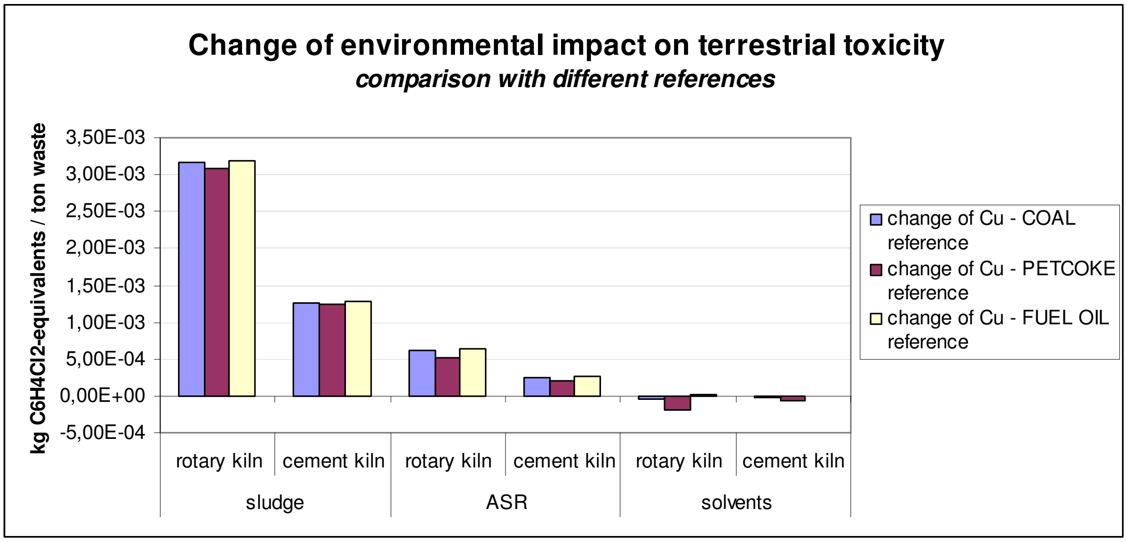
waste type	**energetic value** **[MJ/kg]**	**cupper content** **[kg/ton]**		**functional unit** **[ton]**
sludge	13,95	0,913		1
ASR	16,5	0,1855		1
solvents	25,8	5,48E-03		1

electricity production avoided emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	**0**

steam production aviooded emissions	**average emissions Cu** [kg/GJ]
gas	0
coal	0
energetic mixture [BE]	0


Environmental impact on terrestrial toxicity [absolute]
kg C6H4Cl2-equivalents / ton waste
3,50E-03
3,00E-03
2,50E-03
2,00E-03
1,50E-03
1,00E-03
5,00E-04
0,00E+00
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
absolute emissions of Cu


Change in environmental impact of Cu emissions
fuel oil as referenc for RK and petcoke for CK
kg C6H4Cl2-equivalents / ton waste
3,50E-03
3,00E-03
2,50E-03
2,00E-03
1,50E-03
1,00E-03
5,00E-04
0,00E+00
-5,00E-04
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change in environmental impact of Cu emissions


Change of environmental impact on terrestrial toxicity
comparison with different references
kg C6H4Cl2-equivalents / ton waste
3,50E-03
3,00E-03
2,50E-03
2,00E-03
1,50E-03
1,00E-03
5,00E-04
0,00E+00
-5,00E-04
rotary kiln
cement kiln
rotary kiln
cement kiln
rotary kiln
cement kiln
sludge
ASR
solvents
change of Cu - COAL reference
change of Cu - PETCOKE reference
change of Cu - FUEL OIL reference

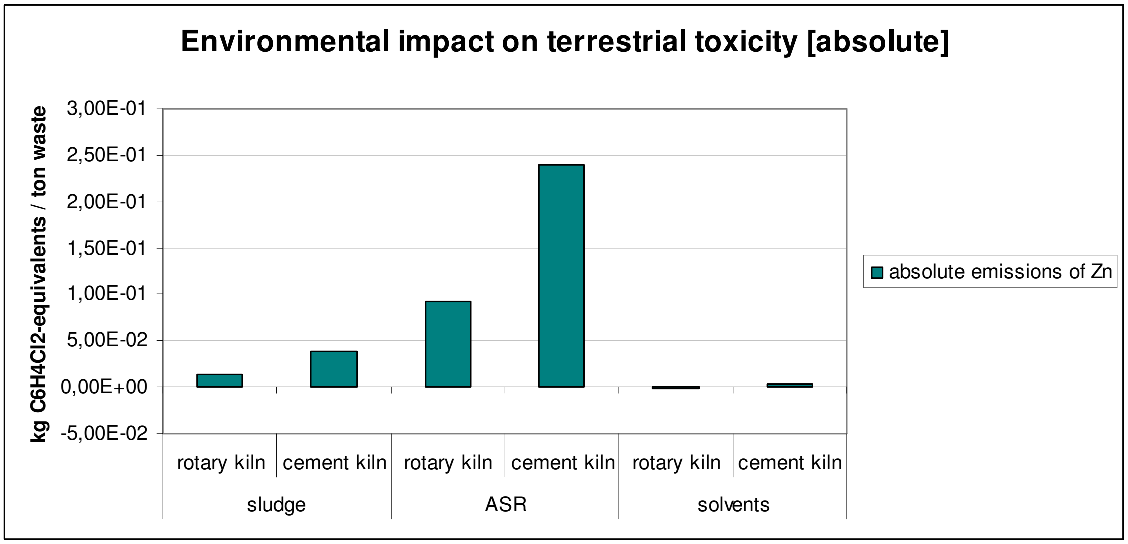
Terrestrial toxicity → Zn

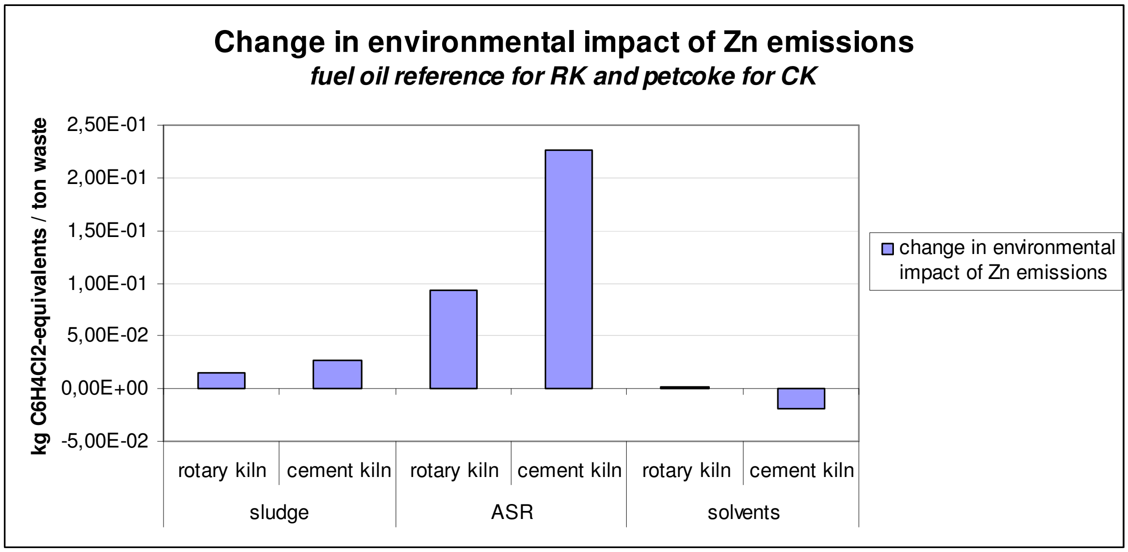
furnace type	transfer coefficient	Zn/Zn		minimal energy demand	electrical yield	steam yield
rotary kiln	0,0007	1		14,7	0,026	0,131
cement kiln	0,0017	1		21	0	0

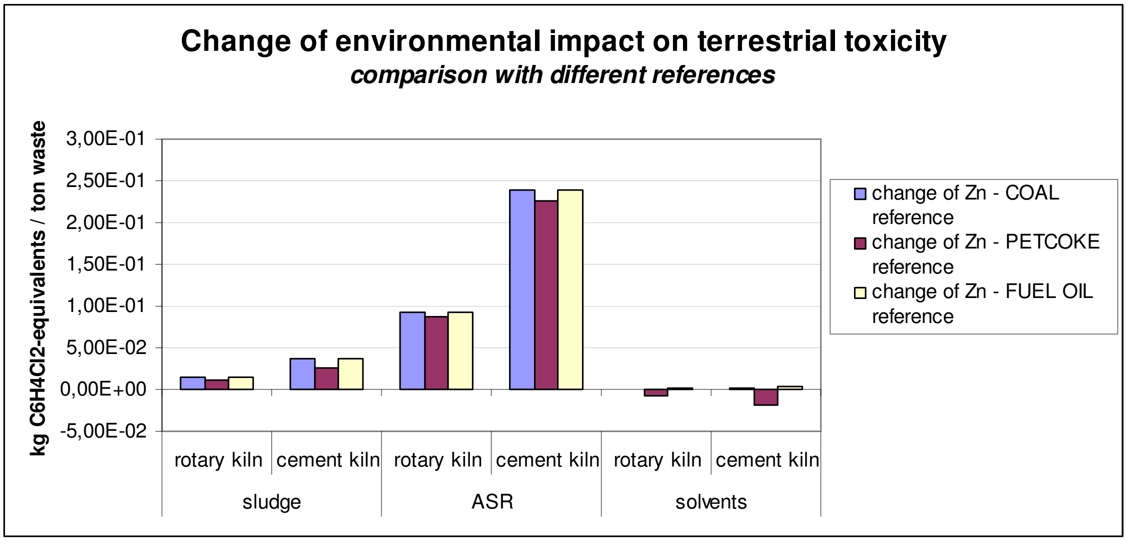
fuel type	energetic value [MJ/kg]	Zinck content [kg/ton]
coal	29,55	6,18E-02
fuel oil	40,4	7,73E-03
petcoke	33,7	1,31E+00

waste type	energetic value [MJ/kg]	Zinck content [kg/ton]		functional unit [ton]
sludge	13,95	1,758		1
ASR	16,5	11,09		1
solvents	25,8	1,57E-01		1

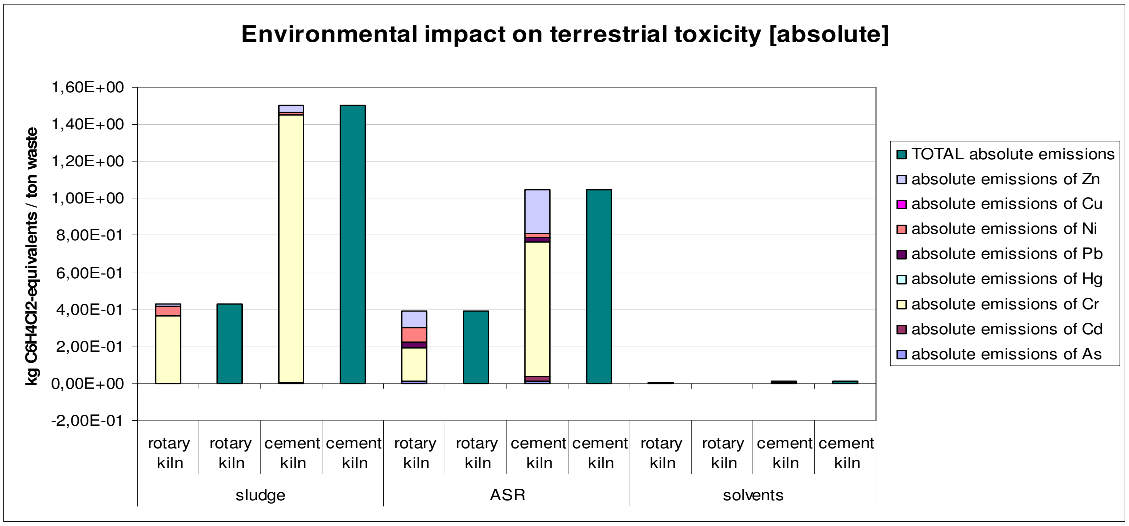
electricity production avoided emissions	average emissions Zn [kg/GJ]
gas	0
coal	1,35E-04
energetic mixture [BE]	**2,59335E-05**
steam production avioded emissions	**average emissions Zn** [kg/GJ]
gas	0
coal	0,000054
energetic mixture [BE]	1,03734E-05

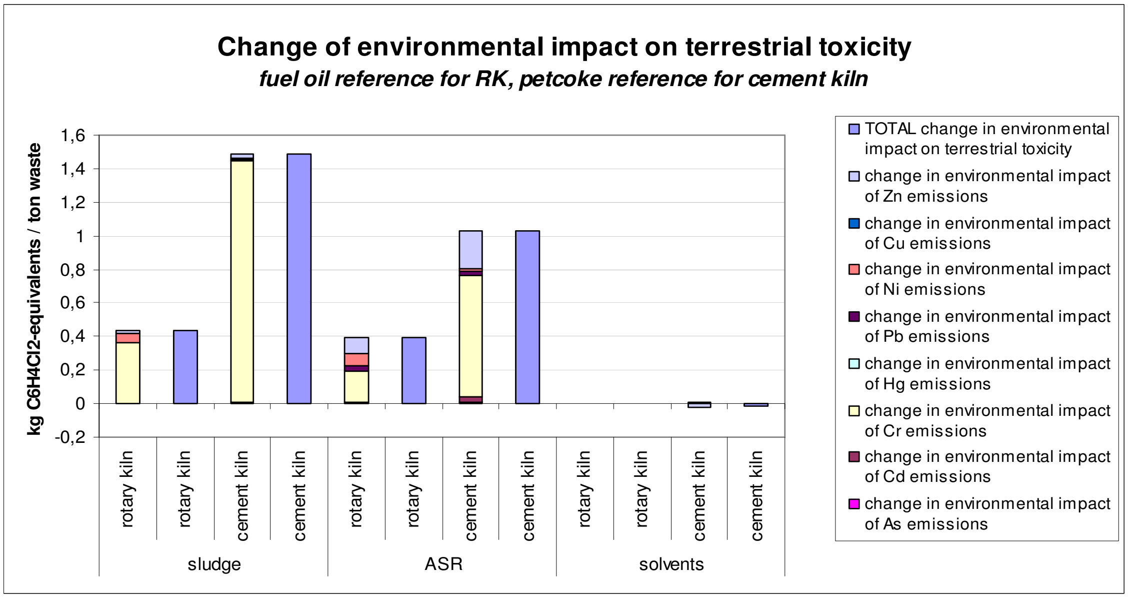

Environmental impact on terrestrial toxicity [absolute]

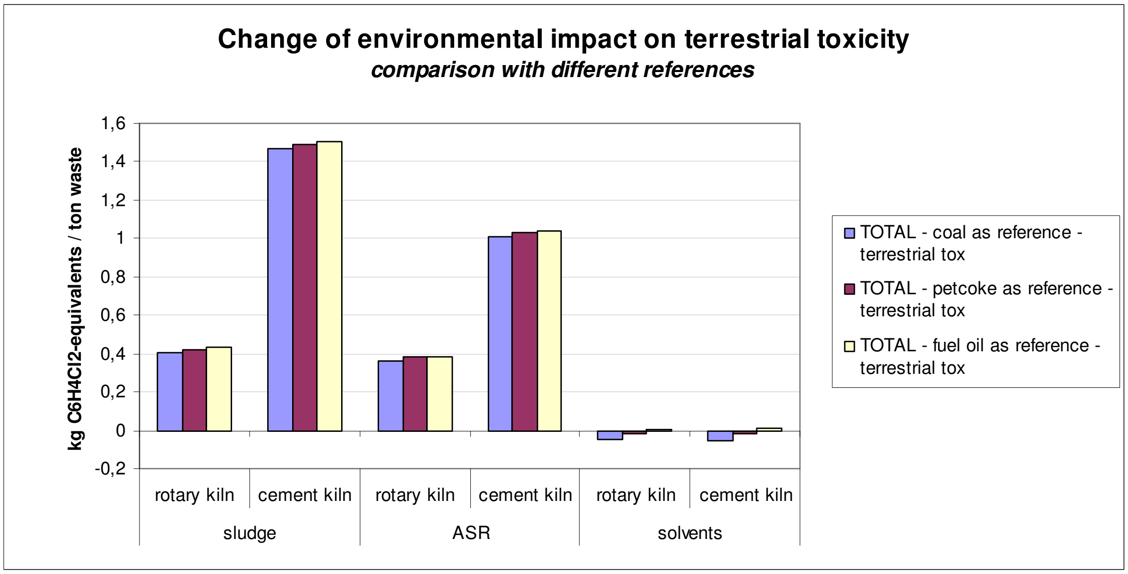

Change in environmental impact of Zn emissions
fuel oil reference for RK and petcoke for CK


Change of environmental impact on terrestrial toxicity
comparison with different references

Terrestrial toxicity → TOTAL







7.4 Annex IV: Comparison of the discharges into water and the airborne emissions at the Indaver site (rotary kiln)

First an inventory has been conducted about the total toxic load (year base) which is emitted into water and into air from the rotary kiln of Indaver, per ton of waste. This is followed by the determination of the environmental impact of both types of emissions.

WATER

			CHARACTERISATION FACTORS				
Parameter in wastewater	**load RK (ton)**	**load in kg per ton waste**	**HUMAN TOX.**	**FRESH WATER TOX.**	**TERRESTRIAL TOX.**	**SEAWATER TOX.**	**EUTROPHICATION**
dust	13,0	0,13419	0	0	0	0	0
BOD	11,0	0,11355	0	0	0	0	0
COD	102	1,05290	0	0	0	0	0
Zn	0,008	0,00008	5,80E-01	92	2,50E-21	1,40E+04	0
Cu	0,0006	0,00001	1,3	1200	4,10E-21	2,30E+05	0
Ni	0,04	0,00041	330	3200	1,00E-18	2,20E+06	0
Pb	0,0003	0,00000	12	9,6	4,80E-22	1100	0
As	0,003	0,00003	9,50E+02	2,10E+01	1,70E-20	1,20E+04	0
Cr(III)	< 0,00015	< 0,00000	2,1	6,9	2,30E-19	860	0
Hg	< 0,0003	< 0,00000	1400	1700	9,30E+02	2,10E+05	0
Mn	0,17	0,00175	0	0	0	0	0
Mo	0,39	0,00403	5500	480	2,30E-18	2,10E+06	0
Sb	0,08	0,00083	5,10E+03	2,00E+02	1,70E-17	1,20E+05	0
Cd	0,001	0,00001	230	1500	1,40E-20	2,20E+05	0
Co	< 0,0001	< 0,00000	97	1200	2,70E-18	4,40E+06	0
Total N	14,0	0,14452					4,20E-01
Total P	0,02	0,00015					3,06E+00

AIR					**CHARACTERISATION FACTORS**				
Parameter in air		**Load RK (ton)**		**load in kg per ton waste**	**HUMAN TOXICITY**	**FRESH WATER TOX**	**TERRESTERIAL TOX**	**SEAWATER TOX**	**EUTROPHICATION**
SO2		805		8,31					
NOx		**98959**		**1.022**					0,2
As	<	1,82	<	0,0188	3,50E+05	50	1600	2,30E+05	
Cd	<	1,12	<	0,0115	150000	290	81	1100000	
Co	<	1,24	<	0,0128	1,70E+04	640	1,10E+02	5,40E+06	
Cr	<	5,47	<	0,0565	650	1,9	3,00E+03	5,20E+03	
Cu	<	2,12	<	0,0219	4300	220	7,00E+00	890000	
Mn	<	2,15	<	0,0222	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
Ni	<	2,2	<	0,0227	35000	630	1,20E+02	3800000	
Pb	<	6,78	<	0,0700	470	2,4	1,60E+01	7,00E+03	
Sb	<	9,56	<	0,0986	6700	3,7	6,10E-01	33000	
Sn	<	2,15	<	0,0222	1,7	2,5	1,40E+01	7,50E+03	
Tl	<	2,15	<	0,0222	4,30E+05	1,60E+03	3,40E+02	2,60E+07	
V	<	2,15	<	0,0222	6200	1700	6,70E+02	1,20E+07	

IMPACT ASSESSMENT

Parameter in waste water	HUMAN TOX	FRESH WATER TOX	TERRESTERIAL TOX	SEA WATER TOX	EUTROPHICATION
dust	0	0	0	0	0
BOD	0	0	0	0	0
COD	0	0	0	0	0
Zn	5E-05	0,008	2,06E-25	1,1561	0
Cu	8E-06	0,007	2,54E-26	1,4245	0
Ni	0,136	1,321	4,13E-22	908,38	0
Pb	4E-05	3E-05	1,49E-27	0,0034	0
As	0,029	7E-04	5,26E-25	0,3716	0
Cr(III)	3E-06	1E-05	3,56E-25	0,0013	0
Hg	0,004	0,005	0,00288	0,6503	0
Mn	0	0	0	0	0
Mo	22,14	1,932	9,26E-21	8454,2	0
Sb	4,212	0,165	1,4E-20	99,096	0
Cd	0,002	0,015	1,45E-25	2,271	0
Co	5E-05	6E-04	1,39E-24	2,271	0
Total N	0	0	0	0	0,06
Total P	0	0	0	0	0

TOTAL	**26,53**	**3,456**	**0,00288**	**9469,8**	**0,06**

Parameter in air	HUMAN TOX	FRESH WATER TOX	TERRE-STRIAL TOX	SEA WATER TOX	EUTROPHICATION
SO2	0	0	0	0	0
NOx	0	0	0	0	204,3
As	6570	0,93	30,0378	4318	0
Cd	1729	3,34	0,933741	12680	0
Co	218,4	8,2	1,412962	69364	0
Cr	36,72	0,11	169,4567	293,7	0
Cu	94,18	4,8	0,153318	19493	0
Mn	0	0	0	0	0
Ni	795,4	14,3	2,727116	86359	0
Pb	32,89	0,17	1,11983	489,9	0
Sb	660,9	0,37	0,060173	3255	0
Sn	0,0378	0,06	0,311247	166,7	0
Tl	9559	35,6	7,558854	6E+05	0
V	137,8	37,8	14,89539	3E+05	0

TOTAL	**19836**	**105,7**	**228,7**	**1E+06**	**204,3**

EMISSIONS TO WATER/ AIR EMISSIONS	**HUMAN TOXICITY**	**FRESH WATER TOX**	**TERRESTRIAL TOX**	**SEAWATER TOX**	**EUTROPHICATION**
[%]	***0,134***	***3,27***	***0,001259***	***0,909***	***0,03***

It can be seen that only for fresh water toxicity the environmental impact of the toxic load in the waste water exceeds 1%, while the contribution to other impact categories remains well below 1%.

7.5 Annex V. Charactisation factors [CML-database]

Element	Global warming [kg CO_2-equivalents]	Acidification [kg SO_2-equivalants]	Photochemical smog [kg C_2H_4-equivalants]	Eutrophication [kg PO_4-equivalents]	Human toxicity [kg $C_6H_4Cl_2$-eqs.]	Fresh water toxicity [kg $C_6H_4Cl_2$-eqs.]	Sea water toxicity [kg $C_6H_4Cl_2$-eqs.]	Terrestrial toxicity [kg $C_6H_4Cl_2$-eqs.]
C as CO_2	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
S as SO_2	0,00	1,20	4,80 10^{-2}	0,00	0,096	0,00	0,00	0,00
N as NO_x	0,00	5,10 10^{-1}	4,27 10^{-1}	2,00 10^{-1}	0,00	0,00	0,00	0,00
As	0,00	0,00	0,00	0,00	3,50 10^{5}	5,00 10^{1}	2,30 10^{5}	1,60 10^{3}
Cd	0,00	0,00	0,00	0,00	1,50 10^{5}	2,90 10^{2}	1,10 10^{6}	8,10 10^{1}
Cr (III)	0,00	0,00	0,00	0,00	6,50 10^{2}	1,90	5,20 10^{3}	3,00 10^{3}
Cr (VI)	0,00	0,00	0,00	0,00	3,40 10^{6}	7,70	2,10 10^{4}	3,00 10^{3}
Hg	0,00	0,00	0,00	0,00	6,00 10^{3}	1,2 10^{3}	2,8 10^{4}	0,00
Ni	0,00	0,00	0,00	0,00	3,50 10^{4}	6,30 10^{2}	3,8 10^{6}	1,2 10^{2}
Pb	0,00	0,00	0,00	0,00	4,70 10^{2}	2,40	7,00 10^{3}	1,6 10^{1}
Cu	0,00	0,00	0,00	0,00	4,30 10^{3}	2,20 10^{2}	8,9 10^{5}	7,00
Zn	0,00	0,00	0,00	0,00	1,00 10^{2}	1,80 10^{1}	6,70 10^{4}	1,20 10^{1}