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Environmental performance of industrial companies, sites, installations and production processes

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Abstract

A set of 10 environmental impact indicators is proposed for the evaluation the environmental impact of industrial installations and processes or industrial companies and sites: global warming, destruction of the ozone layer (ozone depletion), acidification, photochemical ozone creation, human toxicity, ecotoxicity, eutrophication, resource consumption (abiotic depletion), water consumption and waste production. These are »weighed« indicators: the individual emissions or discharges of components contributing to a certain theme are multiplied with a weighing factor and aggregated. Eco-efficiency indicators are calculated by dividing the »weighed« indicators by a value related to production. These relative indicators make it possible to quantify the evolution of the environmental performance for a process, company or industrial site and to evaluate which component(s) contribute(s) most to a given theme, thus allowing to set priorities for lowering the environmental impact. Examples illustrate the proposed method. Attention is also given to the emission of persistent organic pollutants (POPs) during the incineration of waste, trying to answer the question: are waste incinerators sinks or sources of POPs? It is shown that for non-carcinogenic effects of POPs, according to the incineration scenario, the weighed input/output ranges from 0.3 to 20,500 when considering the POPs in flue gases and solid residues.

Abbreviations:

ADP	– abiotic depletion potential;
AP	– acidification potential;
ASR	– automotive shredder residue;
CKC	– chlorine fluorine carbon;
DP	– desication potential;
EPI	– environmental performance indicator;
ETP	– ecotoxicity potential;
GWP	– global warming potential;
MSW	– municipal solid waste;
NP	– nutrient potential;
PAH	– polyaromatic hydrocarbon;
PCCDD/F	– polychlorinated biphenyls and furans;
PEC	– predicted environmental concentration;
PNCP	– predicted no-effect concentration;
POCP	– photochemical ozone creation potential
POP	– persistent organic pollutant;
VNCI	– Vereniging Nederlandse Chemische Industrie;
WEEE	– waste of electrical and electronic equipment

INTRODUCTION

The impact assessment concept of Life Cycle Assessment can be used to assess the environmental impact of industrial companies, sites, installations and production processes relative to environmental themes such as global warming, destruction of the ozone layer, acidification, photochemical ozone creation, human toxicity, ecotoxicity, eutrophication, resource consumption, water consumption and production of waste. For each theme in this approach an *Environmental Performance Indicator* (EPI) *(1, 2, 3, 4)* or *Environmental impact indicator* can be obtained, by multiplying the emissions with appropriate weighing factors and aggregating them.

The absolute indicators calculated in this way are however no proper estimators for environmental performance of industrial companies and sites, installations and production processes, because e.g. closing-down and starting-up of installations, decreasing or increasing production would influence the »environmental performance« *(5, 6)*. It is therefore preferable to divide the absolute impact by a value related to production, in order to obtain a relative indicator or eco-efficiency indicator. In this paper a set of 10 eco-efficiency indicators is proposed. These *eco-efficiency indicators* reflect trends in environmental performance and allow to evaluate progress made in eco-efficiency.

Resource consumption by a production process is usually considered a negative element. In this respect waste incineration is to be considered a special type of process: the »main raw material« is in fact waste and the incinerator may produce »secondary raw materials«. Moreover an incinerator incinerates the POPs (persistent organic pollutants) present in the waste. If they would not be incinerated they would spread into the environment. On the other hand new POPs are unintentionally formed during (or after) the incineration process. Therefore it is important if the environmental impact of waste incineration is considered, to include the question if an incinerator is a net sink or source of POPs. The second part of this paper deals with a methodology to compare the toxicity weighed amount of POPs in the input with the one in the output, in order to decide if an incinerator is a net sink or source of POPs.

METHOD

Eco-efficiency indicator

A process is characterised by inputs, such as resources and energy, and by outputs: the product(s), emissions to air, discharges to surface water, waste and by-products (Figure 1).

The environmental impact, is calculated by multiplying the individual emissions or discharges of each chemical component E_i (kg/year), contributing to an environmental theme, with a weighing factor (WF_i) and aggregating the products. The total environmental impact for one theme is thus the sum of individual contributions to that theme; it is an absolute value. This method was developed by GRI *(1)* and VNCI *(4)*.

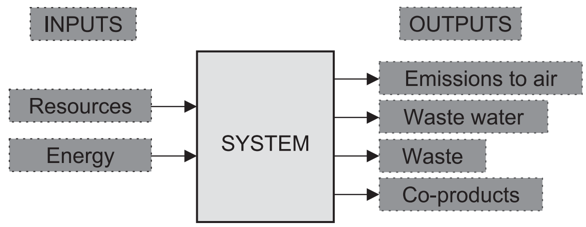

Figure 1. *Inputs and outputs of a process.*

As argued in the introduction, it is preferable to divide these absolute figures by a value related to production (P) to obtain *relative indicators* or *eco-efficiency indicators* (equation 1). The value related to production can be the monetary value of the product, the turnover or added value for a company… When the monetary value of the product(ion) fluctuates as a function of time, it may e.g. be preferable to replace it by the amount (mass) of product. In this aspect our method differs from the methods of GRI and VNCI that use absolute indicators.

$$\text{Eco-efficiency indicator} = \frac{\sum_i E_i \times WF_i}{P} \qquad (1)$$

Equation (1) is used to calculate the contribution to »global warming«, »ozone depletion«, »acidification«, »photochemical ozone creation«, »human toxicity«, »ecotoxicity«, and »eutrophication«. Emissions to the atmosphere contribute to all seven themes, water discharges contribute to the latter three. The weighing factors for these themes are found in literature (see 2.2.) Also for »abiotic depletion« weighing factors were developed (see 2.2). For «water consumption« and «waste production« no valuable weighing factors exist, some are in development.

The system boundaries correspond to the boundaries of the considered geographical site; this means that only the inputs and outputs of the site are considered; emissions of suppliers are not. When considering the evolution of the environmental impact of the site, is has to make sure that no outsourcing to suppliers has occurred, which would only apparently reduce the environmental impact.

Weighing factors

The following weighing factors were used:

Global Warming Potential (GWP), based on atmosphere-chemical models; it gives the potential of a gas to contribute to the warming of the earth relative to the reference component CO_2 *(7, 8)*.

Ozone Depletion Potential (ODP), based on atmospheric models and laboratory simulations, expresses the potential of a gas to destroy ozone. CFC11 is used as reference component *(9)*.

• *Acidification Potential* (AP), based on the RAINS-model; the reference component is SO_2 *(10)*.

• *Photochemical Ozone Creation Potential* (POCP), based on the Photochemical Trajectory model that simulates the chemistry of the polluted air above West-Europe; the reference component is ethylene *(11, 12)*.

Human Toxicity Potential, based on the USES 2.0 model, taking into account toxicity characteristics, persistency, bioaccumulation…of components *(13)*. Doses, transport and transformation in the environment, and expose routes are also considered. The human toxicity potential gives the impact on human health of components emitted to the atmosphere or discharged in surface water. The USES 2.0 model uses Risk Characterisation Ratios (RCR):

$$RCR_{i,e} = \frac{PEC_{i,e}}{PNEC_i} \tag{2}$$

with $PEC_{i,e}$ = Predicted Environmental Concentration (of component in air or water)

$PNEC_i$ = Predicted No-effect Concentration (NOAL = No-Observed-Adverse-Effect-Level). 1,4-dichlorobenzene is used as reference component *(10)*.

• *Ecotoxicity Potential* (ETP), also based on the USES 2.0 model *(13)*. Ecotoxicity gives the impact of components, emitted to the atmosphere or discharged into surface water, on the ecosystem (flora and fauna). 1,4-dichlorobenzene is used as reference component *(10)*.

• *Nutrient Potential* (NP), expressed as the amount of oxygen consumed by Redfield Algae due to the uptake of nitrate and phosphate. Eutrophication is the excess of algae bloom as a consequence of the release of nitrate and phosphate. Phosphate is the reference component *(14)*.

• *Abiotic Depletion Potential* (ADP), used for the consumption of fossil fuels and mineral raw materials, is based on the world reserves of raw materials and their exploitation rate. World reserves can be defined as geological reserves (total amount on earth), ultimately extractable reserves (exploitable with new technologies) and economic reserves (exploitable with current technologies). As no data are available for ultimately extractable reserves, and as extracting companies are in general reluctant to give information about known (economic) reserves, data on geological reserves are used to calculate ADP's. The following equation is used *(15):*

$$ADP_i = \frac{ER_i}{(R_i)^2} \times \frac{(R_{ref})^2}{ER_{ref}} \tag{3}$$

with

ADP_i = abiotic depletion potential of component i;

R_i = geological reserve or ultimate reserve of component i (kg);

ER_i = exploitation rate of component i (kg/year);

R_{ref} = geological reserve of reference component (kg, antimony);

ER_{ref} = exploitation rate of reference component (kg antimony /year,).

• *Water consumption*. A difference must be made between surface water and ground water consumption. Surface water consumption is given in m^3. No weighing factor is used. Groundwater can be considered as a fund, a raw material regenerated on medium term. If the exploitation rate is higher than the regeneration rate, depletion or desiccation occurs. A lowering of the ground water level leads to changes in moisture content of the soil which in turn may lead to changes in oxygen content, acidity, availability of nutrients, resulting in a loss of plant species. Van Ek *et al. (16)* propose to establish a correlation between changes in groundwater use and the biodiversity of vegetation. This *Desication Potential* (DP) is still in development.

• *Waste Production* Potential (WP). Waste and co-products can be reused, recycled, landfilled, incinerated… As weighing factor, often »land use for landfilling« is used. »Environmental levies« could also be used; their values should in principle be based on the impact of the processing method on the environment. However, environmental levies might also be determined by other considerations. Therefore we prefer up to now to use produced waste quantities (ton), if possible subdivided in non-toxic and toxic waste.

APPLICATION OF THE METHOD

Obtained information

The set of 10 eco-efficiency indicators makes it possible to quantify trends in environmental performance and to evaluate which component(s) contribute(s) most to a given theme, so that priorities in lowering the environmental impact can be formulated. The contributions to the different themes can be combined into an *overall picture* allowing to evaluate the progress in eco-efficiency of industrial processes or installations and industrial companies or sites, compared to a reference situation.

Industrial site

The proposed method was applied to different processes. Some results are given in Figures 2, 3, 4, and 5.

Figure 2 gives the acidification potential (emissions of SO_2 and NO_x expressed as kg SO_2-equivalents) per ton of product for an industrial company for the period 1995–2005; acidification decreases in the considered period as a result of the decrease of the SO_2 emissions. Although SO_2 and NO_x emissions are comparable, SO_2 has a ca. 3 times higher contribution to acidification than NO_x.

For another industrial company, emissions into the atmosphere of naphthalene are comparable to these of PAH's, but 1.10^5–2.10^5 times higher than the PCDD/F emissions. Figure 3 shows the contribution to human

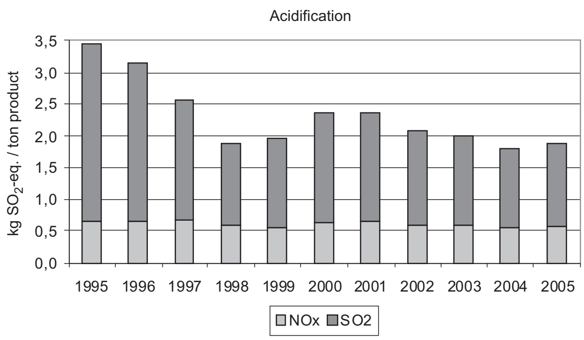

Figure 2. *Evolution to the contribution to acidification (SO_2 and NO_x emissions) per ton product.*

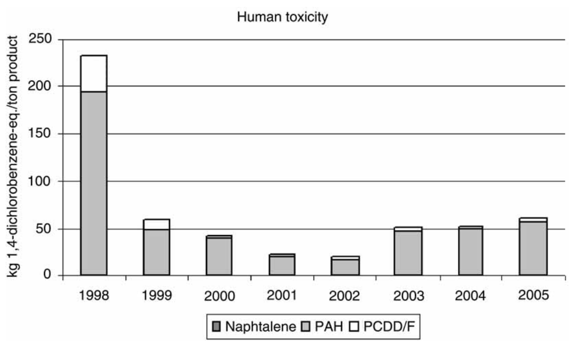

Figure 3. *Evolution to the contribution to human toxicity for napftalene, PAH's and PCDD/F per ton product (atmosphere).*

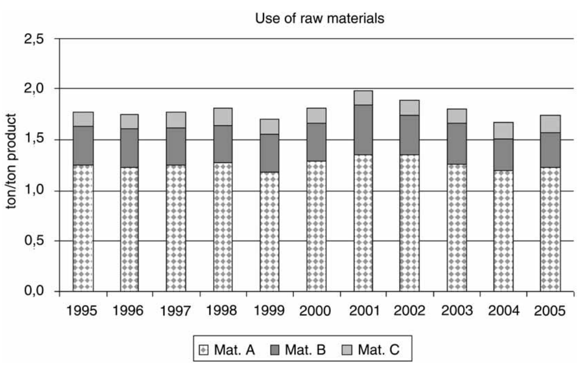

Figure 4. *Consumption of raw materials (ton/ton product).*

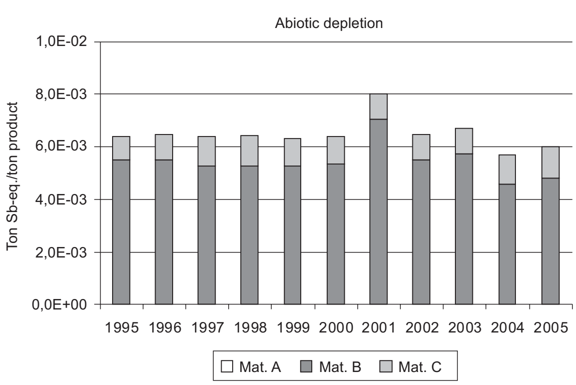

Figure 5. *Evolution of the contribution of the consumption of raw materials to abiotic depletion per ton product.*

toxicity (HT) of naphthalene, PAHs and PCDD/Fs, expressed as kg 1,4-dichlorobenzene-equivalents per ton product. Due to its low toxicity, the contribution of naphthalene is negligible, that of PCDD/F is non-negligible but small and that of PAHs is most important. The PCDD/F emissions decreased from 1998 to 2005 as a consequence of the combination of end-of-pipe techniques and process integrated measures. The increase from 2003–2005 of PAH's, is due to the increase of dust emissions on which PAH's are adsorbed.

Figure 4 gives the consumption (per ton of product) of three raw materials by a process. The consumption of material A is clearly more important than the one of B and C; its contribution to the theme »abiotic depletion«, expressed as ton Sb-equivalents per ton product, is however negligible, due to its high geological reserve (Figure 5).

Overall picture

The contributions of a company to the different environmental themes for 2005, are combined in Figure 6 and compared to the reference year 1995 (index 100). The considered company improved its eco-efficiency in the categories human toxicity and eco-toxicity, acidification and ozone depletion with minimum 40% in 2005 compared to 1995. Also the performance with respect to water consumption, waste production and the contribution to eutrophication and photochemical ozone creation were considerably lower in 2005 compared to 1995. The contribution to abiotic depletion and global warming were only slightly lower in 2005 than in 1995.

WASTE INCINERATION: SINK OR SOURCE OF PERSISTENT ORGANIC POLLUTANTS (POPS)?

Processes where waste is thermally treated (mainly incinerated), occupy a special position from the point of view of human toxicity (and ecotoxicity) which is not covered by the approach mentioned. Such installations are usually considered as a source of persistent organic components (POPs). Indeed, in waste incinerators, persistent organic components, such as PCDD/Fs and PCBs are unintentionally formed and are found in the output of the incinerator. On the other hand the incinerated waste also contains a range of POPs, which are destroyed during combustion. The approach mentioned in 2.1. takes into account the emissions of these compounds into air and water, mainly through the human toxicity potential and the ecotoxicity potential. However, it is completely neglected that some POPs present in the waste products (input of incinerator), would probably spread through the environment if they were not destroyed. In addition, POPs are not only emitted into air and water but are also found in the incinerator residues (bottom ash, fly ash, flue gas cleaning residues).

In order to quantitatively compare the toxicity of POPs going into the waste incinerators to that of POPs coming out of waste incinerators, a »toxicity factor« must be used, by which each POP mass is multiplied before

TABLE 1

Toxicity weighed input/output for POPs for3 scenarios of waste incineration in Flanders.

Scenario	POPs toxicity input/output for flue gases and solid residue	POPs toxicity input/output for flue gases
BAT compliant rotary kiln for hazardous waste	19,500–20,500	> 6.10^6
BAT compliant MSW grate furnace	0.3–2.0	170–1100
BAT compliant MSW grate furnace co-combusting plastics of WEEE and ASR	2.2–14.6	2,500–6,700

the masses are added to give the toxicity weighed POP mass. For non-carcinogenic effects of chronic oral exposure, the input and output masses can be divided by the 'minimal risk dose' (MRD) *(17, 18, 19)*. As an example this method was applied for non-carcinogenic POPs to three different scenarios of waste incineration: a BAT compliant rotary kiln, a BAT compliant grate furnace for the incineration of MSW (municipal solid waste) and a BAT compliant MSW grate furnace co-combusting plastics of WEEE (waste of electric and electronic equipment) and ASR (automotive shredder residue). Their toxicity weighed input/output ratio is given in table 1. A distinction is made between the total output of the incinerator (flue gases + solid residue) and the output in the flue gases only. Indeed, only a very small amount of POPs are directly emitted in the flue gases; the largest fraction of POPs (75–98 %) is concentrated in a small volume of solid residues specially treated (solidification + landfilling). From the figures in table 1 can be concluded that hazardous waste incineration in a rotary kiln is clearly a sink of POPs. Also co-combusting of MSW with WEEE and ASR in a grate furnace, destroys more POPs than are formed. For a grate furnace combusting only MSW the conclusion is not clear. If only POPs in flue gases are considered, toxicity weighed input/output ratios from 170–1,100 to > 6.10^6 are obtained for the three scenarios.

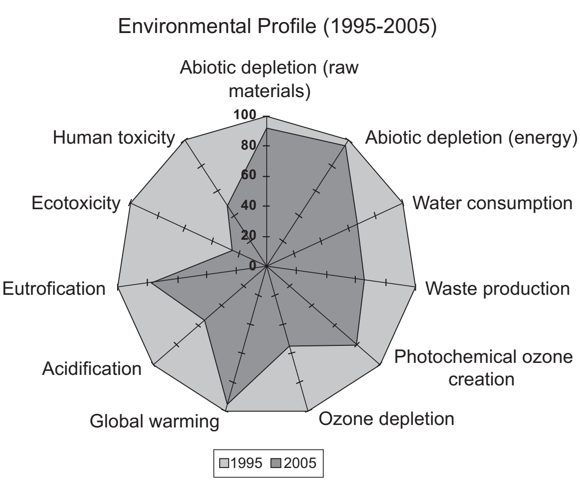

Figure 6. *Evolution of environmental profile of a company (1995–2005).*

CONCLUSION

A set of 10 eco-efficiency indicators, based on environmental themes, are proposed. The indicators are calculated by multiplying the individual emissions or discharges of a chemical component contributing to an environmental theme, with a weighing factor, aggregating the products and dividing the obtained value by a value related to production. These relative indicators were used to obtain trends in environmental performance and to give evaluations in progress made in improving the eco-efficiency for processes and industrial companies. Moreover, from their calculation it could be derived which component(s) contribute(s) most to a given theme.

Installations for waste incineration are often considered as a source of POPs. It is however neglected that some POPs are present in the waste products. In order to quantitatively compare the toxicity of POPs going into the waste incinerator to that of POPs coming out, toxicity weighed POP mass should be used. This method was applied for non-carcinogenic effects of POPs, to three different waste incineration scenarios. Weighed input/output ratios for POPs ranged from 0.3 to 20,500 when considering the POPs in flue gases and solid residus and from 170– > 6.10^6 considering only the POPs in flue gases.

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