LCA Discussions: A New Calculation Model for Interpreting the Results of an LCA Revised*

The 'Virtual Pollution Prevention Costs '99'

A Single LCA-Based Indicator for Emissions

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Preamble

In literature, many models (qualitatively as well as quantitatively) can be found to cope with the problem of communicating results of LCA analyses with decision takers. Most models translate data on emissions in a single indicator, using a classification and characterisation step. More than 30 of these models have been looked at, 14 of which have been studied in detail. From these analyses, it was concluded that there is still a need for further development.

A new model for a single indicator has been designed on the basis of the following main criteria:

i. The model must be easily explainable to non-specialists (i.e. the model must relate to 'normal life')
ii. The model must be 'transparent' for a specialist:
   - Since the choice of the region influences all these kind of calculations, specialists must be able to adapt the data for the calculation to cope with the choice of a specific region (the data in this publication is for the Dutch and West European region).
   - Since the character of these calculations is that some arbitrary decisions cannot be avoided, the model must have a structure that enables an easy assessment of the effect of these decisions, so that the experts can adapt the model to their own judgements.

Based on the analyses of the aforementioned existing models, it was concluded that a model based on the **marginal prevention costs** seems to give the best fit with the two criteria mentioned above.

These marginal prevention costs are assessed for seven emission effect classes on the basis of prevention measures which are based on readily available technologies. The costs of the measures are based on current West European price levels.

Essential to the model is that it must be judged whether the set of measures is sufficient to reach a sustainable level of emissions.

Given a certain region one can calculate the effect of the set of measures (provided that enough data on that region is available) for the current situation. These calculations , based on West European current price levels, have been made for The Netherlands as a region for the following classes of emissions:

- acidification, eutrophication, summer smog, winter smog and heavy metals, based on the previous work of IVM, Amsterdam
- global warming by CO_2 emissions based on the previous work of ECN, Petten

Furthermore, it has been checked how the assumptions are related to the current emission targets of the Dutch government, and it has been discussed how this data may relate to other regions in the world.

The following data set is proposed to be applied as marginal prevention costs:

- 6.40 Euro/kg SO_x equivalent for acidification
- 3.05 Euro/kg PO_4 equivalent for eutrophication
- 50.00 Euro/kg VOC equivalent for summer smog
- 12.30 Euro/kg fine dust for winter smog
- 680 Euro/kg Zn equivalent for heavy metals
- 12.30 Euro/kg PAH equivalent for carcinogenics
- 114 Euro/1000 kg CO_2 equivalent for global warming

The 'virtual pollution prevention costs '99' is proposed as a single indicator for emissions, being the sum of the marginal prevention costs of all aforementioned classes of pollution.

Keywords: Acidification; characterisation; classification; communicating; Dutch; emissions; eutrophication; global warming; heavy metals; LCA; marginal prevention costs; region; single indicator; summer smog; sustainable; virtual pollution costs '99; West European; winter smog

1 Introduction: The Need for a Single Indicator

LCAs are often made to compare alternative solutions (for products, services, functions, etc.). But how to compare the results of two different LCAs? Only environmental experts are able to interpret the results, but their complex decisions are not easy to communicate to managers, designers, politicians and governments. One of the important issues here is the comparison of the several types ('classes') of emissions.

Given the fact that the Life Cycle Analyses, as a tool for the assessment of products and services, has been nearly fully developed (only some details in de ISO definitions are still under discussion), the question now arises as to what to do with the results.

There are two major issues in this area:

1. How to communicate the results of an LCA to other people than the environmental specialists
2. How to compare two (or more) alternatives for a product, service or function (i.e. how to compare two or more Life Cycle Inventories)

These issues get gradually more important when we, in our society, want to *do* something in the field of sustainability.

* Due to the discussion comments received so far, the article has been revised.

Then the results of LCAs have to be communicated to the three stakeholders: Governments, companies and consumers/ citizens, in order to make clear to them which decisions are in the right direction in terms of sustainability. In the case of emissions, these issues are of extra importance, since the impact of emissions will not show up directly, but only in the Long Term (when it is too late to do something about it).

To enable these stakeholders to make the right decisions that will support a sustainable society, one yardstick is required for emissions.

2 The Problem of Weighing Several Types of Emissions

A generally accepted route towards a single indicator is an approach which is based on splitting the problem into two levels (ISO, 14040):

a. Combining emissions with the same nature of effect: the so called 'classification' in groups; followed by weighing of the importance of an emission within each class: The so called 'characterisation' within the group. For each group, this leads to an 'equivalent weight of the lead pollutant in the class'.
b. Finding a weighing principle to add up the different classes.

For most of the major pollutants, the classification and the characterisation factors (i.e. the weighing factors within classes) can be assessed from the chemical, physical or biological effect they have:

– Acidification: characterised by simple formulas from chemistry
– Eutrophication: characterised by simple formulas from chemistry
– Summer smog: characterised by relatively simple chemical reactions which form ozone
– Winter smog: characterised by the 'just detectable effect at long term exposure', norms given by the World Health Organisation in the Air Quality Guidelines for Europe
– Heavy metals: characterised by the 'just detectable effect at long term exposure', norms given by the World Health Organisation in the Air Quality Guidelines for Europe and Water Quality Guidelines for Europe
– Carcinogenics: derived from the rate of development of cancer (number of patients in a population of 1 billion people), given in the Air Quality Guidelines
– Global warming: rather complex calculations on the reflection of light and its thermal consequences (note that only the relative effects of the several gases have to be known for the weighing; the impact in absolute terms is a problem which hasn't be resolved yet)

The characterisation factors resulting from the above criteria, which are used in the model for pollution prevention costs '99, are given in **Table 1** (→ *Appendix*).

Note that all these weighing principles are based on the concentration levels in air or in water. If the rate of decay (or absorption) was known for all these emissions, it would have been possible to determine the sustainable emission norms because these norms could have been calculated for the 'steady state of a closed region' (i.e. the total sustainable emission in that region is set equal to the decay or absorption rate of that matter at the maximum allowable air or water concentration).

Unfortunately, there is no consensus about decay and/or absorption rates (e.g. part of the debate on global warming concentrates on the absorption rate of the earth of CO_2).

This is also the reason that pesticides cannot be dealt with in the aforementioned classification-characterisation system: They differ enormously in decay rates. Pesticides with ultra short decay rates (a few days) are basically harmless and pesticides with decay rates of many years should be banned.

The problem of how to find weighing factors for the different effect classes is dealt with in the next chapter.

3 Weighing Principles for the Different Classes

Since the chemical, physical and biological characteristics of the several classes differ, other weighing criteria must be applied to weigh the classes.

In general, there are three ways to weigh several different types of *potential* damage:

1. Weigh the *negative value* of the damage (the '*impact*')
2. Weigh the required effort to *prevent* the damage
3. Weigh the required effort to '*repair*' the damage

It is generally accepted that the third option is in general not the desired option for sustainability problems, since a 'repair' of emissions is either not possible or much more expensive than prevention. (Examples of 'repair' are the attempts to restore regional biodiversity in town and country planning)

So we can weigh the classes either according to type 1 (impact) or type 2 (prevention).

In general, it is possible to weigh both impact or prevention by:

a. 'Points'
b. 'Money'

The four resulting possibilities for weighing are depicted in **Fig. 1**.

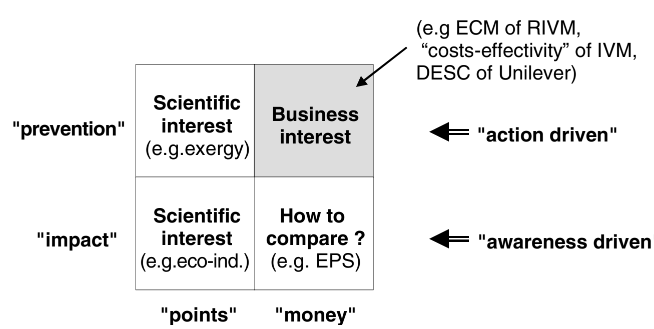

Fig 1: Portfolio of models for a single indicator
(General literature on description of tools: Braunschweig et al., 1996; Lehni, 1998; Keffer et al., 1999; Tulenheimo et al., 1996; Graedel, 1998; Hoogendoorn, 1998; Nijland et al., 1998; Haas, 1997; Beetstra, 1998; Müller et al., 1997); (Web sites of European projects on tools: Chainet, Deeds, ExterneE, WBCSD)

The vast majority of the models for a single indicator are based on the combination of 'impact' and 'points', perhaps a result of the fact that environmentalist often use LCAs to make other people aware of the gloomy problem (the potential damage or impact).

The Swedish EPS model is based on a 'willingness to pay' which is determined by assessing the negative value of the damage (impact), so this system is a combination of 'impact' and 'money'.

In the exergy models which are currently developed, calculations are made on the prevention of emissions, so these calculations are a combination of 'prevention' and 'points'.

There are two macro-economic models which are not LCA based but which are basically a combination of 'prevention' and 'money': The 'Milieu Kosten Model' (Environmental Costs Model) of RIVM, Bilthoven, and 'kosteneffectiviteit' (cost effectivity) of IVM, Amsterdam. The DESC model of Unilever is designed for micro-economic decisions (choices on products and processes) and also belongs in this category.

Models for weighing based on damage (impact) have two fundamental problems:

- Weighing of the impact is a very subjective and arbitrary matter: How to compare a fatal illness with dying trees and/or extinguishing species?
- Knowing that prevention is the required route towards a sustainable society, why weigh on the basis of impact? (Shouldn't we prevent rather than accept the damage?)

Models for weighing based on prevention suffer all from the problem of setting the sustainable norms for emissions; basically there are three types of norms:

I. The absolute norms for maximum emissions at the sustainable level
II. The norms based on the economic optimum of prevention: The emission level where the costs of prevention equal the costs of damage (impact), see **Fig. 2**
III. The current practice of prevention, being the 'revealed preference' (Huppes et al., 1997); note that this 'revealed preference' is not used here for target setting, but only for weighing the relative importance of each of the classes

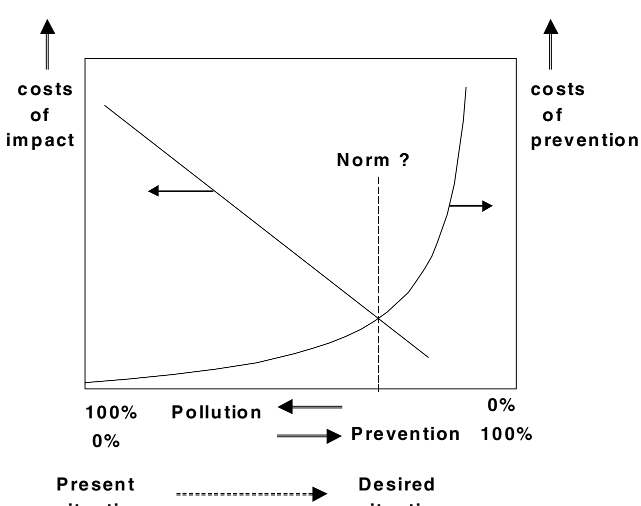

Fig. 2: The economic optimum as a norm for emission prevention?

The **first method** (I) suffers from the fact that, from a scientific point of view, it is not possible to predict these 'absolute' norms (is the complex calculation method 100% correct? How can one cope with all future developments and risks?).

The **second method** (II) suffers basically from the same problem as the damage based methods: How to quantify the value of the damage caused by the emissions.

> **Note:** In a qualitative form, however, this method in some specific cases plays a role in decision taking. An example is the ban on CFCs within the EC: It was obvious that prevention costs of using other gases were much lower than the damage costs of the damage to the ozone layer. Another example is an attempt of the 'ExterneE' project of the EC on energy (http://Externe.jrc.es/).

The **third method** (III) is still under discussion at CML, Leiden. The key question here is whether this economic principle, valid for 'free and transparent markets', can be applied for marginal costs of prevention of emissions as well.

One example exists where this method has recently been applied (implicit): a 'convenant' (agreement) between the Dutch government and the Dutch chemical industry, where 'benchmarking of the world best practice' is used to agree on the measures to be taken to reduce the several emissions ('Benchmarking' is a modern management technique, used in many companies for medium term target setting. One might argue whether this technique generates targets which are 'stretched' enough for sustainability purposes. Note, however, that targets set by benchmarking are 'moving targets', since a 'best practice' is getting better and better over the years, a process caused by competition).

It is evident that a 'perfect' weighing principle does not exist. In the next chapter the possibilities of how to overcome this problem with a different approach is discussed.

4 The Development of a New Model

Since there is a need for a single indicator (as explained in the first chapter), and since there appeared to be no satisfactory existing, it has been decided to develop a new model, based on the following main criteria:

- The model must be easily explainable to non-experts (i.e. the model must relate to 'normal life')
- The model must be 'transparent' for specialists:
  - Since the choice of the region influences the calculations in the model, specialists must be able to adapt the data to cope with the choice of a specific region (the first calculations of the model have been made for the Dutch and/or West European region).
  - Since the character of these calculations is that some arbitrary decisions cannot be avoided, the model must have a structure that enables an easy assessment of the effect of these decisions, so that the experts can adapt the model to their own judgements.

Based on the analyses of Chapter 3, it was concluded that a model based on the **marginal prevention costs** seems to give the best fit with the two criteria mentioned above:

- The idea of prevention costs is easy to explain to non-experts (everybody is aware of the fact that measures to prevent emissions will cost extra money)
- The idea of marginal costs is easy to explain to non-experts (what matters is the most expensive measure our society is prepared to take; strategies of introduction are easy to explain and discuss as well; consequences for business strategies are easy to explain and discuss)
- The methodology of marginal cost calculations is 'transparent' as such for experts: experts can follow each step of the calculation and judge whether they agree on the data which is used, and they can assess the sensitivity for uncertainties of assumptions
- Experts can make calculations for different regions

The problem, of course, is how to deal with setting the sustainable norms for emissions (see Chapter 3 point I, II and III). The chosen strategy for this problem is: Keep the model as simple as possible (so it remains transparent). This is achieved by the following methodology:

Step 1: Estimate which set of measures (technical solutions, 'end of pipe' and/or process integrated) will meet the requirements for sustainability

Step 2: Relate these arbitrary norms to calculations of 'absolute' norms in literature and relate them to governmental (political) aims

Step 3: When the chosen norms of step 1 are not satisfactory in step 2, reset the norms in step 1 and repeat step 2; when the norms are OK, take the price of the most expensive measure

In this way, the complex calculation systems on 'absolute' norms (and the scientific discussions about them) are not integrated in the model, but are kept separate from the model on the marginal prevention costs. This separation of models is essential to keep the total system transparent (the complex situation with regard to greenhouse gases is a good example, see chapter 5.1).

5 The Norms in the Model and how they Relate to Other Norms and Aims

Applying the methodology of the previous chapter, the following norms are proposed:

- 6.40 Euro/kg SO_x equivalent for acidification
- 3.05 Euro/kg PO_4 equivalent for eutrophication
- 50.00 Euro/kg VOC equivalent for summer smog
- 12.30 Euro/kg fine dust for winter smog
- 680 Euro/kg Zn equivalent for heavy metals
- 12.30 Euro/kg PAH equivalent for carcinogenics
- 0.114 Euro/kg CO_2 equivalent for global warming

The relation with other norms for sustainability will be dealt with hereafter.

5.1 Global warming

The norm of 114 Euro/1000 kg CO_2 equivalent relates to the lists of prevention measures of **Table 2** (→ *Appendix*) for reduction of 'greenhouse gases' (end of pipe as well as process integrated measures). The list is a summary of measures that are technically feasible at current price levels used in the MARKAL and the MATTER models of ECN, Petten. The list applies to The Netherlands, but the list for Western Europe shows only minor differences (GIELEN, 1999 and 1998). The importance of such a list is, that it shows which measures are included and which are excluded at a certain price level. It provides the reader with a feeling for the economic feasibility of certain types of measures (for more details see *Table 2*):

- Biomass for production of electricity — 20 – 50 Euro/1000 kg CO_2 equivalent
- CO_2 storage at production of electricity — 50 – 80 Euro/1000 kg CO_2 equivalent
- Renewables (windmills, solar heating systems) — 80 – 114 Euro/1000 kg CO_2 equivalent

At this price level, some measures are excluded, like biofuel for cars and Photo Electric Cells.

Calculations with the MARKAL and MATTER models for The Netherlands (ECN, 1998; GIELEN, 1999) show that, starting a reduction programme in 1999, the Kyoto norm (- 6% in 2010 in relation to the level of 1990-1995) can just be reached at a norm of 80 Euro/1000 kg CO_2 equivalent.

Calculations with MATTER (GIELEN, 1999) show that a 114 Euro/1000 kg CO_2 equivalent can result in a reduction of 50% in 2020 (compared with the year 2000) for Western Europe as well as The Netherlands.

The aforementioned calculations show that the choice of 114 Euro/1000 kg CO_2 equivalent is somewhat arbitrary indeed:

- The Kyoto norm can be met with 80 Euro
- However, renewables (see above) come only in at a level of 80 - 114 Euro
- Is a reduction of 50% for Western Europe in 2020 enough (a factor of 4 can be reached at 500 Euro)?

Depending on the vision, the norm of 114 Euro can be too high or too low. It might be concluded, however, that the norm is not so 'way out', to 'begin with'. The norm reflects current best practices, and can be used to manage the transition towards a sustainable society. When better calculations become available in due time, one might 'tune' the norm.

5.2 Acidification

The norm of 6.40 Euro/kg SO_x equivalent for acidification relates to a list of 141 measures of RIVM, Bilthoven. This list of measures comprises all sectors of society (industry, agriculture, buildings and houses, transport, etc.). Economically feasible at the norm are 121 measures of this list, all based on commercially available technologies. Included are (among others):

- Measures related up to the 'EURO 3-mid' norms for cars, trucks, busses and tractors
- A vast list of measures for low NO_x emissions in power plants
- 'Low emission stables' and 'equilibrium nutrification' practises for fertilisation of land

IVM, Amsterdam, used the RIVM database to make a calculation for the Dutch situation based on the year 1992 (DELLINK et al., 1997) (→ *Fig. 3*). Applying the norm for the marginal prevention costs of 6.40 Euro/kg SO_x equivalent to the curve of **Fig. 3** results in an emission reduction of 750 million kg of SO_x equivalent per annum.

Calculations of IVM (DELLINK et al., 1997) suggest an emission reduction of 635 million kg SO_x equivalent per annum (the calculation ranges from 485 to 775 million kg SO_x equivalent per annum).

To reach the emission norm of the Dutch government of 240 million kg SO_x equivalent per annum for 2010, the emission reduction must be 720 million SO_x equivalent per annum.

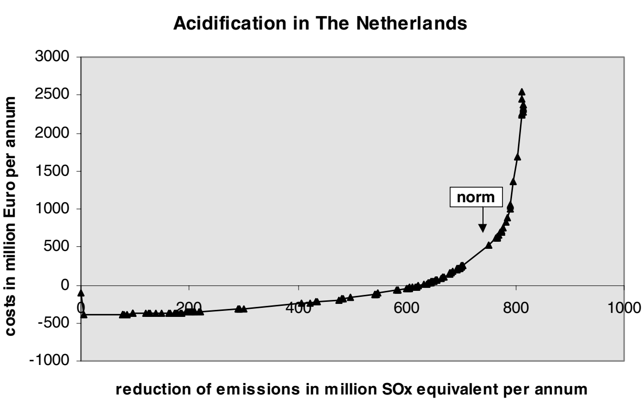

Fig. 3: The emission reduction curve for acidification in The Netherlands. Source: IVM, Amsterdam (DELLINK et al., 1997)

Note 1: The negative costs at the left end of the curve result from max. speed restrictions for cars (90 km/hr) and trucks (80 km/hr), resulting in reduced fuel consumption (calculated as savings).

Note 2: The lists of 141 measures does not comprise 'high tech' solutions like the introduction of 'green cars', low-emission chicken farms, manure conversion techniques, etc. These measures tend to be slightly more expensive than the norm. An introduction of such techniques, however, will result in a lower slope of the tail-end of the curve.

5.3 Eutrophication

Calculations for eutrophication of land for The Netherlands are complex:

- The pollution within The Netherlands is of the same magnitude of what is imported and exported by the rivers
- The residence time in soil and water is several years, so the 'steady state' is complex to assess

As a result of these factors, calculations and discussions about the subject are rather blurred.

For eutrophication of land, a norm has been chosen of 3.05 Euro/kg PO_4 equivalent, being the price of sustainable manure processing.

Using the RIVM database for eutrophication, IVM calculated the situation for The Netherlands based on the year 1992 (→ *Fig. 4*). The quantum leap from 15 to 340 kg PO_4 equivalent per annum is the result of sustainable manure processing.

However, 340 kg PO_4 equivalent is approx. 50% of the estimated current emission level.

The aim of the Dutch government is a reduction of a factor 4 for the year 2010. This seems to be feasible only when the total production of meat in Holland is reduced drastically, which has already been a political discussion in Holland for many years, but which will come now to conclusions under the pressure of EC regulations.

The conclusion is that only a combination of measures (technical process improvements in combination with a reduction of production) can lead to a sustainable situation.

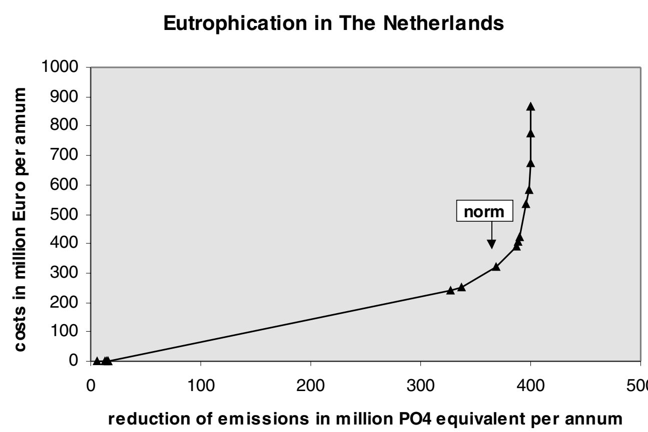

Fig. 4: The emission reduction curve for eutrophication of land in The Netherlands. Source: IVM, Amsterdam (DELLINK et al., 1997)

5.4 Summer smog

The norm of 50.00 Euro/kg VOC equivalent for summer smog relates to a list of 31 measurements of RIVM, Bilthoven. This list of measures comprises mainly measures for cars, trucks and busses.

The last measure which determines the marginal costs is the '2001 – stringent' emission classification for cars. (note that this classification also includes a very low emission level for NO_x).

IVM, Amsterdam, used the RIVM database to make a calculation for the Dutch situation based on the year 1992 (→ *Fig. 5*). Applying the norm for the marginal prevention costs 50.00 Euro/kg VOC equivalent to the curve of **Fig. 5**, results in an emission reduction of approx. 180 million kg VOC equivalent per annum.

Calculations of IVM suggest an emission reduction of 162 million kg VOC equivalent per annum (the calculation ranges form 112 to 212 million kg VOC equivalent per annum).

Since measures against acidification and global warming effect summer smog as well, the Dutch government has no special aim and policy for this class of emissions.

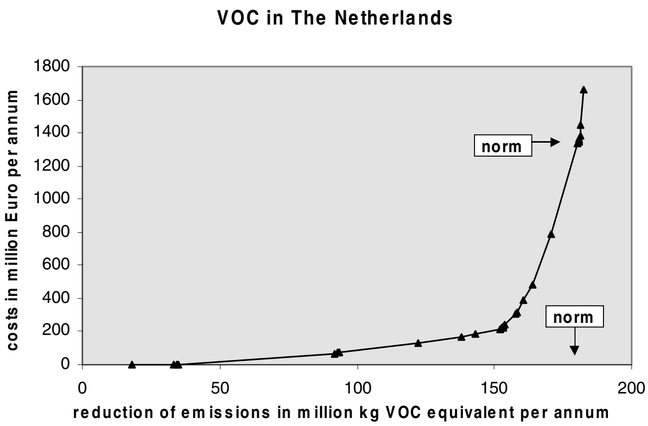

Fig. 5: The emission reduction curve for VOC (to reduce summer smog) in The Netherlands. Source: IVM, Amsterdam (Dellink et al., 1997)

5.5 Winter smog

The norm of 12.30 Euro/kg fine dust for winter smog relates to a list of 38 measures for reduction of fine dust of RIVM, Bilthoven. This list of measures comprises mainly measures for cars, trucks and busses.

The last measure which determines the marginal costs of 12.30 Euro/kg fine dust is the 'EURO 2' emission classification for diesel (note that this classification is also included in the measures for acidification).

IVM, Amsterdam, used this RIVM database to make a calculation for the Dutch situation based on the year 1992 (→ *Fig. 6*). Applying the norm for the marginal prevention costs 12.30 Euro/kg fine dust to the curve of **Fig. 6**, results in an emission reduction of approx. 35 million kg fine dust per annum.

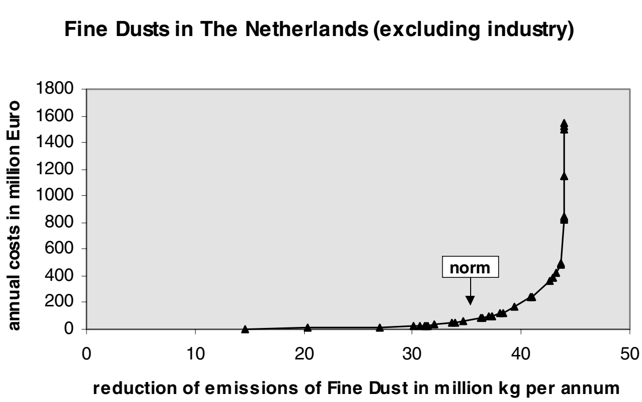

Fig. 6: The emission reduction curve for fine dust (to reduce summer smog) in The Netherlands. Source IVM, Amsterdam (Dellink et al., 1997)

Calculations of IVM suggest an emission reduction of 30 million kg fine dust per annum (excluding industry). The calculation ranges from 25 to 35 million kg fine dust per annum.

Note: These figures are excluding industry. Industry emissions are 40% of the total emissions and it is assumed that these emissions can be reduced at a same factor for even a lower price.

Since measures against acidification and global warming effect fine dust as well, the Dutch government has no special aim and policy for this class of emissions.

5.6 Heavy metals

The norm of of 680 Euro/kg for heavy metals relates to a list of 14 measures for reduction of zinc of RIVM, Bilthoven. This list of measures comprises mainly measures for construction materials.

Zinc has been selected to be the norm for heavy metals since the emissions of zinc account for about 60% (weight) of the total heavy-metal emissions.

The last measure which determines the marginal costs of 680 Euro/kg zinc is replacement of zinc by coatings at construction materials (replacement of galvanised steel)

IVM, Amsterdam, used this RIVM database to make a calculation for the Dutch situation based on the year 1992 (→ *Fig. 7*). Applying the norm for the marginal prevention costs of 680 Euro/kg zinc to the curve of **Fig. 7**, results in an emission reduction to water of approx. 250,000 kg zinc per annum.

Calculations of IVM suggest a emission reduction of 250,000 kg zinc per annum is required. This caclulation is rather inaccurate and ranges from from 107,000 to 407,000 kg zinc per annum.

The emission norms of heavy metals to be set by the Dutch government are currently still under discussion.

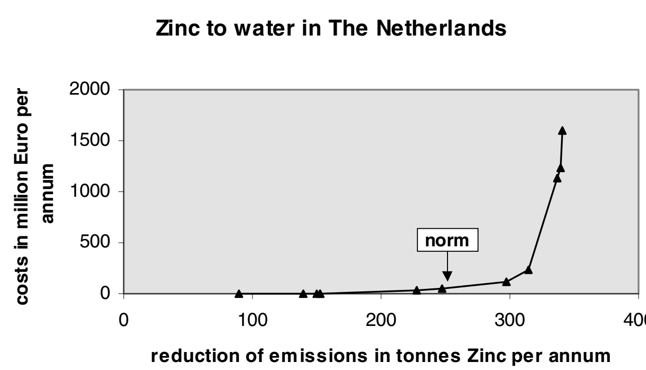

Fig. 7: The emission reduction curve for zinc in The Netherlands. Source IVM, Amsterdam (Dellink et al., 1997)

5.7 Carcinogenics

No calculation of the prevention costs is available for carcinogenics.

As a norm, 12.30 Euro/kg PAH equivalent for carcinogenics has been taken.

This is the same norm as for fine dust, since an important part of the cause for cancer is caused by fine dust (solid and/or liquid).

6 Example: The Pollution Prevention Costs '99 of Paper

As an example, a calculation of the pollution prevention costs '99 of the production of paper (wood-based, chlorine-free, bleached white printing paper) is given in **Table 3** (→ *Appendix*). Data are from BUWAL (Oekobilanz von Packstoffen, 1990), Bern.

Note 1: The LCA of paper can vary considerably with the actual production chain (differences in production plants of pulp and of paper, and differences in transport chains). Typical chains can deviate by a factor of 2 or more from the average. Thus, the LCA methodology as well as the method of pollution prevention costs '99 can only be used in the *benchmarking* of production chains (comparing two or more cases). Data like the data in **Table 3** can never be considered as 'the absolute truth'.

Note 2: As the calculations of the Simapro computer model are based on a similar set of characterisation data, as mentioned in chapter 2 and provided in **Table 2**, the Simapro output on the level of characterisation data (the 'equivalent weight') may be used as input for the last step of the calculation of the pollution prevention costs. However, one must be careful here: A comparison of the two sets of data for classification and characterisation show that Simapro counts some pollutants in two classes (e.g. CH_4, NO, NO_x, ammonia) whereas these pollutants count only in one class in the pollution prevention costs model. The reason behind this is simple: These pollutants create *damage* in more than one impact class, but they only have to be dealt with once in terms of pollution *prevention*.

7 Discussion

7.1 'Virtual' costs

It is important to mention that the curves of Fig. 3 through 7 are related to the present and *not* to the future. These curves describe the present state in virtual terms ('what if we already had taken the measures now'). **Table 2** is also in current prices, the ECN calculations which are referred to in chapter 5.1, however, make extrapolations in future years (applying economic growth scenarios).

All measures are readily available technologies at current price levels. It is important to realise that the tail ends of the curves will get flatter (bend to the right) in future because of two effects:

- 'Technological learning curves' and 'economies of scale' when a technology gets widely applied in the market
- Innovation of the technologies of measures and invention of new measures when big potential markets are expected to develop in the foreseeable future (because of the acceptance of a marginal cost level)

Case studies (Jantzen, 1995) on the history of prices for waste-water treatment systems (for phosphor) and exhaust gas systems (desulfurisation of exhausts of power plants, exhaust systems for cars) suggest that the 'technical learning effect' (price reduction) is 4% - 10% every year over the period of the first ten years in which these systems were introduced in full scale. The history of low NO_x burners show that innovation resulted in a price reduction of 15% - 30% every year over a period of 6 to 10 years.

The conclusion is that one should avoid calculations which go too far into the future, since technologies and prices for measures have not yet been developed.

7.2 Why 'marginal prevention costs' instead of 'total prevention costs'?

An important aspect of the model is that 'marginal prevention costs' have been chosen as a norm, where these marginal prevention costs are defined as the maximum costs of a list of selected measures which are assumed to be sufficient to create a sustainable situation ('if we had taken these measures now, we would expectedly have a sustainable situation').

Fig. 3 through **7** suggest that it is also possible to take the 'total prevention costs' as a norm. However, in doing so, the character of the model will change: the 'total prevention costs' are very sensitive for the choice of the region (with certain characteristics of density of population, regional industrial activity, etc.) at the moment in time (on the road to sustainability, these total costs will change constantly, whereas the marginal costs stay constant when the other parameters do not change).

In the marginal costs model, the calculations on the total prevention effects (**Fig. 3** through **7**) are *only for validation* of the norms: if similar calculations for the areas of Tokyo or Los Angeles show that the marginal cost norms have to be more stringent, the 'virtual pollution costs' have to be adapted accordingly.

The idea of 'the prevention costs of the most expensive measure of the list' relates to the idea of applying the 'best practice' (in terms of technical feasibility and economic optimum) for sustainability. The 'best practice' approach requires that the best practice will be applied in a total region, regardless of the fact that parts of that region could cope with less than the best practice (Example: In The Netherlands there is only a serious summer smog problem in the Rotterdam area, however national emission norms are applied to the whole country to prevent the 'export' of environmental problems to relatively clean sub-regions). It is a political decision (the political will) to which area (the World, the Western World, the European Community or to one country) the norm will be applied. Only when norms are set for the whole World, can problems like 'export of environmental problems' and 'levelling the commercial playing field' be resolved definitely.

Note 1: The 'best practice' approach is already accepted within some big multinational companies. (Unilever has an environmental policy that *current* best practice technologies which are applied in e.g. Holland, also have to be implemented in production facilities in other parts of the world. Shell is trying to implement this way of thinking in terms of their 'norms and values' as well)

Note 2: It is not allowed to add-up the total costs of prevention of **Fig. 3** through **7** to calculate the 'grand total costs of prevention' for the region. The reason is that some measures do have an impact in more than one Figure, resulting in 'counting double for one measure'. Note that this effect doesn't influence the marginal prevention cost model.

7.3 How to deal with other prevention costs than those in these 7 classes?

There has been a recent tendency to take many more classes into account. See **Table 4** (→ *Appendix*) for some leading models. The model of the 'virtual eco-costs' (where a depletion of materials and fossil fuels is also taken into account) is an example of that (Vogtländer, 1999)

We think, however, that the following three issues should be dealt with separately:

a. The 'original' sustainability issues (pollution and depletion of the earth), which have a wider impact than just local and temporary effects
b. Local health and safety issues (including the local damage of noise and smell, emission levels inside manufacturing facilities, etc.)
c. Issues related with the conservation of nature (related with town and country planning, national parks, global master planning, etc.)

When these three issues are mixed up, the political discussions will get blurred. This, for instance, is the case in issue in The Netherlands – where to plan the future Amsterdam Schiphol Airport (to build an airport in the North Sea is a fair proposition from the point of view of health and safety, but not in the point of view of sustainability and/or conservation of nature).

The model which is presented in this article is a model for the first category only (point a.). It is not meant to deal with the other two categories (point b. and c.).

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ExterneE	http://Externe.jrc.es/
WBSCD	www.wbscd.ch/eurint/eeei.htm

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9 Appendix: Tables 1 - 4

Table 1: Characterisation factors, mass based (Goedkoop, 1995)

Substance		Weighing factor	Substance		Weighing factor
Global warming			**Carcinogenics**		
CO_2	Air	1	PAH	Air	In summer smog
N_2O	Air	270	Benzo[a]pyrene	Air	1
Dichloromethane	Air	15	As	Air	0.044
HFD-125	Air	3400	C_xH_y aromatic	Air	0.000011
HFC-134a	Air	1200	Benzene	Air	In summer smog
HFC-143a	Air	3800	Fluoranthene	Air	1
HFC-152a	Air	150	Ni	Air	0.44
Methane	Air	In summer smog	Cr (6+)	Air	0.44
Trichloromethane	Air	25	Tar	Air	0.000011
Acidification			ethylbenzene	Air	0.000011
NO_x	Air	0.7	**Summer Smog**		
SO_2	Air	1	C_xH_y	Air	0.398
HCL	Air	0.88	Phthalic acid anhydride	Air	0.761
HF	Air	1.6	Terpentine	Air	0.377
Ammonia	Air	1.88	Aldehydes	Air	0.443
NO	Air	1.07	PAH	Air	0.761
SO_x	Air	1	Methyl mercaptane	Air	0.377
NO_2	Air	0.7	Ethanol	Air	0.268
Eutrophication			Vinylacetate	Air	0.223
NO_x	Air	In acidification	Crude oil	Air	0.398
Ammonia	Air	In acidification	Ethylene glycol	Air	0.196
NO	Air	In acidification	Ethylene oxide	Air	0.377
NO_2	Air	In acidification	Caprolactam	Air	0.761
Nitrates	Air	0.42	Vinylchloride	Air	0.021
Phosphate	Air	1	Hydroxy compounds	Air	0.377
COD	Water	0.022	Ketones	Air	0.326
NH_3	Water	0.33	Diethyl ether	Air	0.398
Phosphate	Water	1	Tetrachloromethane	Air	0.021
NH_4+	Water	0.33	1,1,1-trichoroethane	Air	0.021
Ptot	Water	3.06	Dichloromethane	Air	0.01
Ntot	Water	0.42	Methane	Air	0.007
Heavy Metals			Hexaclorobiphenyl	Air	0.761
Hg	Air	1	Petrol	Air	0.398
Pb	Air	1	Alcohols	Air	0.196
Cd	Air	50	C_xH_y aliphatic	Air	0.398
Cadmium oxide	Air	50	C_xH_y chloro	Air	0.021
Heavy metals	Air	1	C_xH_y aromatic	Air	0.761
Mn	Air	1	Diphenyl	Air	0.761
Pb	Water	1	Isopropanol	Air	0.196
Hg	Water	10	Benzene	Air	0.189
Cd	Water	3	Ethene	Air	1
Sb	Water	2	Propane	Air	0.42
Cr	Water	0.2	Propene	Air	1.03
Cu	Water	0.005	Styrene	Air	0.761
Mo	Water	0.14	Toluene	Air	0.563
As	Water	1	Xylene	Air	0.85
Ba	Water	0.14	Phenl	Air	0.761
Ni	Water	0.5	VOC	Air	0.398
Mn	Water	0.02	Methyl ethyl ketone	Air	0.473
B	Water	0.03	Formaldehyde	Air	0.421
Winter Smog			Pentane	Air	0.408
Dust (SPM)	Air	1	Non methane VOC	Air	0.416
SO_2	Air	In acidification	Acetone	Air	0.178
Carbon black	Air	1	trichloroethene	Air	0.066
Soot	Air	1	Chlorophenols	Air	0.761
Iron dust	Air	1	Acetylene	Air	0.168
			Propionaldehyde, propanal	Air	0.603
			Naphtalene	Air	0.761
			1,2-dichloroethane	Air	0.021

Table 2: List of measures for reduction of greenhouse gases in order of rising prices (West European price level, 1998) (ECN, 1998)

	Costs (Euro / 1000 kg CO_2 equivalent)	Short description
1	0 (or negative)	1999 tax increase on petrol
2	0 (or negative)	2003 tax increase on petrol
3	0 (or negative)	Greening of taxes on cars (1)
4	0 (or negative)	Less fuel consumption cars 1999
5	0 (or negative)	Less fuel consumption cars 2003
6	0 (or negative)	Energy campaign on cars
7	0 (or negative)	Differentiating tax on new cars
8	0 (or negative)	Differentiating tax on existing cars
9	0 (or negative)	Increase of tire pressure
10	0 (or negative)	Stringent control on current speed max.
11	0 (or negative)	Energy savings of domestic appliances
12	0 (or negative)	Cruise control, etc. in cars
13	0 (or negative)	Max. speed trucks 80 km/hr , stringent control
14	0 (or negative)	Max. speed cars 100 km/hr , stringent control
15	0 (or negative)	Energy savings in domestic houses
16	0 (or negative)	Existing level of nuclear power
17	0 (or negative)	Energy savings in industry
18	0 (or negative)	Energy savings in farms
19	0 (or negative)	Commuting more by car sharing or by public transport
20	0 (or negative)	More public transport for short distances
21	0	PFCs reduction in the aluminium industry
22	0,2	HFC reduction by means of afterburners in industry
23	1,6	N_2O reduction in nitric acid production
24	4,1	Biochemical reduction of methane emissions at organic waste
25	4,5	Oxidation of methane at organic waste
26	9	Early closure of coal fired power plants
27	9	Replacing HFCs for coolants
28	11	Reduction methane emissions at gas fields
29	11	Replacing HFCs in hard foam
30	11	Replacing HFCs for aerosols
31	11	Recycling of HFCs for coolants
32	11	Reduction of HFC emissions in production of "closed" foam
33	11	Reduction SF6 emissions in chips industry
34	11	Reduction SF6 emissions from power switches
35	20	Bio mass for industrial heat and power plants
36	20	Carbon black for heat and power plants
37	20	CO_2 storage (underground) at refineries and ammonia production
38	25 - 110	Emission reduction in agriculture
39	22	Replacement of coal by gas in power plants
40	35	District heating near power plants
41	40	Reduction of HFC leakages
42	50	Reduction of methane emissions by manure processing
43	55	Gassification of biomass
44	57	CO_2 storage at new gas fired power plants
45	60	Energy savings by domestic heat pumps
46	65 - 155	Domestic solar heating (boiler) systems
47	65	Import of bio mass for industrial heat and power plants
48	70	Certificates for industry
49	70	NO_2 reductions from traffic
50	70	CO_2 storage at coal fired power plants
51	80	Nuclear power plants, new (this measure is skipped for obvious reasons)
52	90	CO_2 storage existing gas fired power plants
53	110	Energy savings in existing industrial buildings
54	40 - 130	Wind energy, on shore
55	140	Biofuels for cars
56	155	Expansion Dutch forests
57	180 -195	Domestic 'low energy' houses
58	100 - 230	Wind energy, off shore
59	145 - 245	'Low energy' buildings (new) in the industry
60	190 - 470	Further expansion Dutch forests
61	660	Photo Electric cells

Table 3: An example of the calculation of the pollution prevention costs '99. Wood-based, chlorine-free, bleached white printing paper, quantity 1 kg. (Data from BUWAL Oekobilanz von Packstoffen, 1990, Bern)

column 1	2	3	4	5	6	7	8
pollutant	**class**	**amount** (kg)	**characterisation factor**	3 x 4 **'kg equ.'**	**poll. prev. costs** (euro/kg)	5 x 6 **poll. prev. costs '99** (euro)	= sum of 7 **Total poll prev. costs '99** (euro)
ammonia	acidification	3,63E-06	1,88	6,82E-06			
HF	acidification	1,20E-08	1,6	1,92E-08			
NO_x	acidification	5,47E-03	0,7	3,83E-03			
SO_2	acidification	1,22E-02	1	1,22E-02			
			subtotal:	**1,60E-02**	6,4	1,03E-01	
ammonia	eutrophication	3,63E-06	in acidification				
NO_x	eutrophication	5,47E-03	in acidification				
COD	eutrophication	4,46E-02	0,022	9,81E-04			
NH_3	eutrophication	1,03E-06	0,33	3,40E-07			
			subtotal:	**9,82E-04**	3,05	2,99E-03	
CO_2	greenhouse ef.	1,61	1	1,61E+00			
N_2O	greenhouse ef.	3,59E-04	270	9,69E-02			
			subtotal:	**1,71E+00**	0,114	1,95E-01	
Hg in air	heavy metals	1,90E-08	1	1,90E-08			
Hg in water	heavy metals	100E-09	10	1,00E-08			
			subtotal:	**2,90E-08**	680	1,97E-05	
aldehydes	summer smog	1,02E-05	0,443/0,398 = 1,113	1,14E-05			
C_xH_y	summer smog	6,98E-03	0,398/0,398 = 1,0	6,98E-03			
methyl mercaptane	summer smog	1,85E-04	0,377/0,398 = 0,947	1,75E-04			
			subtotal:	**7,16E-03**	50	3,58E-01	
dust (SPM)	winter smog	4,57E-03	1	4,57E-03			
SO_2	winter smog	1,22E-02	in acidification				
			subtotal:	**4,57E-03**	12,3	5,62E-02	
			Total pollution prevention costs '99, 1 kg paper:				**7,14E-01**

Table 4: Classification in some models which are used in product design

Classes	**Eco-costs model Vogtländer**	**Eco-indicator '95**	**Eco-indicator '98**	**EPS [a]**	**SETAC**	**NOH**	**NSAEL**
Eutrofication	✓	✓	✓		✓	✓	✓
Acidification	✓	✓	✓		✓	✓	✓
Ozone layer		✓	✓		✓	✓	✓
Carcinogenics	✓	✓	✓				
Global warming	✓	✓	✓		✓	✓	✓
Heavy metals	✓	✓					
Winter smog	✓	✓				✓	
Summer smog	✓	✓			✓	✓	
Pesticides		✓					
Noise					✓	✓	
Smell					✓	✓	
Radiation					✓		
Health			✓	✓			
Human toxicity					✓	✓	✓
Respiration			✓				
Depletion materials	✓		✓	✓		✓	
Loss of agric. production				✓			
Damage ecosystems			✓				
Ecotoxicity			✓		✓	✓	
Biodiversity				✓			
Casualties					✓	✓	
Aesthetic values				✓			

[a] The EPS model deals directly with 'safeguard objects' without classification and charaterisation and determines the relative importance of the ecological burden by determining the 'willingness to pay' to avoid the damage.

Literature:
Eco-costs: (VOGTLÄNDER, 1999)
Eco-indicator '95: (GOEDKOOP, 1995)
Eco-indicator '98: (GOEDKOOP et al., 1998)
EPS: (STEEN, 1996)
SETAC: www.scientificjournals.com/lca/village/commWIA2.htm
NSEAL: (KORTMAN et al., 1994)

10 Call for Comments

1. We are very interested in similar calculations for other regions outside the Netherlands:

   a. Do you have similar calculations (referring to **Fig. 3 - 7**) for any of these classes or for other pollution classes?
   b. For CO_2 reduction: what are the costs for CO_2 reduction measures in your region and at what level of marginal prevention costs does your region comply with 'Kyoto', and at what level do you expect a 50% reduction?
   c. Do you have any examples of 'industrial best practices' and benchmarking, and what are the norms in these examples (emission levels, emission prevention levels, emission prevention costs)?

2. Do you have any suggestion to extend the classes in this article with another class, and how do you arrive then at the marginal prevention costs for that class (e.g. hindrance of noise)?

3. Especially for developing countries, it is possible to make a quick estimate of the pollution prevention costs (1. assess the regional environmental problems; 2. make a list of measures to be taken; 3. determine the marginal prevention costs for each class). This could result in a set of data for each different regions.
   Such a calculation model however makes sense only when the Life Cycle Inventory of emissions does take into account the region where the emission occurs, which adds quite some complications to the current LCA methodology.
   Do you feel there is a need for such an enhancement of the LCA methodology? Why and for which type of situations? Or do you feel that the LCA methodology should be kept simple?

4. The underlying idea of point 3 is that the developing countries cannot afford the prevention measures of the western world, and they don't need them (because their emission levels are low). However one may argue differently: in order to gain maximum environmental protection, best practices in the field of prevention measures should be applied world wide and 'export of environmental problems for economic reasons' should be suppressed. Such an approach would require world wide standards for prevention measures and/or prevention costs (in Euro or US $ per kg equivalent per class). In such a model regions with high emissions will have a high economic burden to prevent these emissions, regardless of there own sustainability norms and there economic situation. As a consequence the western world has to subsidise the developing countries where necessary.
   How should we arrive at such world wide norms? Do we expect then norms which will be totally different from the norms presented in this article, and if so why?

When you have comments on these questions and/or you have comments on any specific aspects of the calculation method which is presented in the article, please mailto:
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