Cost-effective pollution-abatement in an input-output model

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Abstract
Production activities exert a negative impact on the environment through emissions of pollutants. Environmental policies aim at the implementation of abatement technologies to reduce these emissions. Cost-effectiveness analysis is often applied as a tool to find abatement strategies that yield a certain emission reduction at minimum direct abatement cost to the producer concerned. The strength of this tool is the possibility to compare various abatement technologies at a rather detailed level. However, in a cost-effectiveness analysis the influence of the abatement costs on the rest of the economy is neglected. The eventual effect of the increase in production cost on the price of intermediates and final demand is not taken into account.
In this paper we present the first steps towards an input-output model that will give in to these objections. A standard environmental input-output model is extended in such a way that it is possible to evaluate the cost and emission reduction of various abatement strategies. The model is formulated as an optimization model, minimizing total (economy-wide) production cost.
The model results in a list of specific end-of-pipe abatement technologies that have to be applied in various sectors in order to achieve the national or sector-specific emission reduction targets for one or more pollutants at least cost for the economy as a whole. Moreover, under the assumption that the abatement costs can be passed on to the consumers (and neglecting the possible consequences for competitiveness on the international market), the model will show the price change of final demand commodities. This will help policymakers to evaluate the eventual distribution of the abatement costs over society.

Introduction
The Input–Output framework has been developed for the quantitative description of system interdependencies. The framework can be used to model interdependencies in both the money economy and in the physical world. It therefore proofed to be useful for the description of interdependencies between the economic system and the ecological system. Examples of early applications for environmental modelling are the works of Cumberland (1966), Daly (1968), Ayres and Kneese (1969), Leontief (1970) and Victor (1972). The Input-Output framework has been used in many studies to analyse the environmental impact of technological changes and changes in final demand since these early studies.
To analyse the impact of prices, levies or for cost-efficiency studies the Input-Output frameworks proofed to be less suitable. If the impact of price-changes (caused by taxes or levies) is limited to a change in final demand volume or composition everything is still fine (Symons *et al.*, 1994; Cornwell and Creedy, 1996). But if the impact also includes changes in producers behaviour the Input-Output

system runs into problems. There is only a limited amount of studies on the interdependency between technological choices and prices within the Input-Output literature; the study by Duchin and Lange (1992) is one of them. Moreover, the extended input-output framework seems hardly fit to study the impact of emission taxes on the reduction of emissions (Idenburg and Steenge, 1991).

Many environmental-economic models have been constructed for the purpose of evaluating the economic impacts of environmental policies. On the one hand there are top-down models, that evaluate the system from aggregate economic variables. On the other hand there are bottom-up models, that consider technological options or project-specific policies (Markandya *et al.*, 2001). Top-down models assess macro-economic impacts of environmental policies, but disregard the specific abatement technologies that have to be implemented. Bottom-up models focus on specific abatement options, but cannot deal with the indirect economic effects induced (Dellink, 2003). For environmental policymakers rather detailed information on abatement options is important. Therefore, bottom-up models often are used in the process of environmental policymaking.

An example of a bottom-up model that played an important role in the negotiations in Europe that led to emission reduction targets for air pollution is the RAINS model (Alcamo *et al.*, 1990; Amann *et al.*, 1999). This model includes detailed data on the cost and effect of abatement options for emissions of air pollutants from various activities. The model allows to evaluate what abatement options have to be implemented in order to achieve specific targets with respect to air pollution at least cost. Brink (2003) and Klaassen et al. (2004) present extensions of this modelling approach to include both air pollutants and greenhouse gases. These models can provide detailed data on the direct cost of abatement, but they do not allow to analyse the impact of abatement on the economy and to evaluate the consequences of abatement for the prices of commodities. Therefore, in this paper we propose a way to integrate the bottom-up, cost-minimizing approach and the environmental Input-Output framework. The proposed model allows to link a rather detailed descriptions of an economic system by an Input-Output model, to rather detailed information on abatement options.

In the paper we first present an evaluation of the use of the environmental Input-Output framework and various shortcomings for environmental policy analysis, particularly with respect to air pollution issues. Then a description and the equations are presented of an extension of the standard environmental Input-Output framework, that makes it more suitable for environmental policy evaluation. Finally, we present some results of a numerical application of the proposed model for the Dutch economy, evaluating abatement of CO_2 and NO_x emissions from the production sectors.

Environmental policy in IO models

Since Leontief's (1970) well known extension of input-output analysis to include environmental issues, an increasing amount of literature has occurred on environmental input-output models. These models are based on a standard input-output model augmented by (i) *pollution*, generated by industries as a by-product to their normal economic production, and (ii) *pollution-abatement*, i.e. activities by purification sectors, eliminating the pollution produced by the conventional industries (e.g. Lowe, 1979; Idenburg and Steenge, 1991; Lager, 1998; Luptacik and Böhm, 1999; Nakamura and Kondo, 2002).

Following the reformulation of the Leontief environmental input-output (EIO) model as suggested by various authors (e.g. Lowe, 1979; Idenburg and Steenge, 1991; Luptacik and Böhm, 1999), the model can be written as:

$$\begin{pmatrix} I - A_{11} & -A_{12} \\ -\alpha A_{12} & I - \alpha A_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} y \\ 0 \end{pmatrix} \tag{1}$$

where

A_{11} is the square matrix of conventional input-output coefficients;
A_{12} is the coefficient matrix of economic inputs per unit level of abatement activities;
A_{21} is the matrix showing environmental pollution per unit of production by the conventional sectors;
A_{22} the matrix showing pollution generated as a by-product of abatement activities;
x_1 is the vector of production levels of the conventional sectors;
x_2 shows the levels of abatement activities;
y is the vector of final demand for conventional goods;
α is a diagonal matrix with the percentage of the pollution which has to be eliminated.

Leontief's extended system as represented by equation (1) has become an important framework for addressing economy-environment relationships. The approach is, however, characterized by a number of assumptions that cause some problems with the implementation of the model for environmental policy analysis. These have been pointed out and dealt with in several studies. In the following, we discuss three of them, that are relevant for the analysis of cost-efficient environmental policies with respect to air pollution.

First, pollution is supposed to be eliminated once it is released into the environment (surface water, atmosphere, etc.). Although this might be the case for certain types of pollution (like waste for example), for most gaseous substances (like greenhouse gases and air pollutants), once released into the atmosphere it is hardly possible to eliminate them (Lager, 1998). Instead, pollution has to be reduced at the source through the use of less polluting alternative production technologies. This can be achieved by substitution of the conventional production technology by less polluting production technologies or by applying add-on abatement technologies to the conventional production technologies. This has two important implications: (*i*) abatement activities (and their cost and effect) are directly related to the pollution at the various specific sources, and (*ii*) different substitution and add-on technologies will be available for each of the various sources, which implies that the cost of reduction and the reduction potentials are sector-specific.

This brings us to the second problem, viz. in the standard EIO model a choice among alternative production and abatement techniques is not allowed. It is assumed that there is exactly one production process for each good and exactly one abatement activity for each type of pollutant. However, in reality, several types of abatement methods will be available at different costs. Moreover, sometimes it is possible to apply multiple abatement methods together to a single pollutant and also to treat multiple pollutants simultaneously in a single abatement process. This gives problems with the traditional way input-output models are solved, because choice of technique implies that there are more processes than products and matrices will be rectangular. Lowe (1979) and Luptacik and Böhm (1999) give a reformulation of the Leontief environmental input-output system which allows for choice of technique, by formulating the input-output model as an optimization model. Nakamura and Kondo (2002) present a generalization of the Leontief environmental input-output model that "can deal with an arbitrary combination of treatment methods applied to an arbitrary combination of waste type provided that the combinations are technically feasible" (Nakamura and Kondo, 2002). In their model, the allocation of waste to the various treatment methods is exogenous to the model.

Finally, in the standard EIO model, it is assumed that the degree of abatement (i.e. the proportions of pollutants eliminated, represented by α in (1)) is exogenous to the model. Moreover, the proportional emission reduction is the same for each sector. With abatement taking place once pollutants are released into the environment this might be the right way to do, because the abatement cost for a unit of pollution are the same, regardless the source of pollution. The approach implies that the cost of abatement is spread over the sectors according to their relative contribution to total pollution. In the context of sector-specific abatement (at varying cost) this will not result in an efficient use of scarce resources to reduce environmental pollution. In fact, it reflects the instrument of environmental policy called command and control, prescribing the same abatement technology for each sector. Standard environmental economic theory shows that this will be suboptimal from a welfare maximizing perspective. With economic policy instruments, like tax and subsidy schemes and tradable permit systems, the sectoral degrees of abatement are determined by the market. This results in an efficient (i.e. minimizing the cost for the economy as a whole) way to reduce environmental pollution (see also Lager, 1998). Lager (1998) presents a model to find activity levels of processes and abatement techniques and a set of prices such that a given final demand for commodities can be met without violating the environmental constraints at minimum cost.

Environmental IO model for cost-effectiveness analysis

To be able to analyze cost-effective reduction of emissions of greenhouse gases and air pollutants we propose an extension of the EIO model that will meet the above mentioned problems. The various IO models including the environment (starting with Leontief (1970) and further developed by others (including Lowe, 1979; Luptacik and Böhm, 1999; Nakamura and Kondo, 2002)) serve as a starting point. Most important differences with the existing models are (*i*) the direct link between abatement options and the specific sector to which abatement options can be applied; (*ii*) endogenous determination of the abatement strategy (i.e. the various abatement options that will be applied in order to achieve the given emission targets; and (*iii*) inclusion of the price model to analyze the impact of abatement on prices of goods and services. The model is formulated as an optimization problem, minimizing the total cost of production (i.e. the gross national product (GNP) at factor cost) at which the society satisfies final demand and the environmental targets that may exist.

Base model

First a standard environmental IO model is described, which will be extended subsequently. In order to be able to include cost-effectiveness analysis (i.e. cost minimization) into the model, the model is formulated as an optimization model (see also Lowe, 1979; Luptacik and Böhm, 1999):

minimize

$$V(x^1) = v'^1 x^1 \qquad \text{(value added) (1)}$$

subject to

$$g \geq A^1 x^1 + \tilde{y} \qquad \text{(commodity constraints) (2)}$$

$$g = x^1 \qquad \text{(commodities vs. production) (3)}$$

$$p^1 \leq p^g A^1 + v^1 \qquad \text{(price model) (4)}$$

$$p^1 = p^g \qquad \text{(prices commodities vs. production) (5)}$$

$$e = E^1 x^1 \qquad \text{(pollution generation) (6)}$$

$$x^1 \geq 0; p^1 \geq 0$$

where

x^1 n-dimensional vector of industrial outputs

g m-dimensional vector of commodities

A^1 $(m \times n)$ matrix of input-output coefficients (i.e. inputs of commodity per unit of production x^1)

$\tilde{y}$ m-dimensional vector of final consumption demand for commodities (exogenous)

v^1 n-dimensional vector of primary input values per unit of industrial production x^1

p^1 n-dimensional vector of unit cost of production x_1 with respect to a unit of value-added

p^g m-dimensional vector of commodity prices with respect to a unit of value-added

e k-dimensional vector of pollution levels of k different pollutants

E^1 $(k \times n)$ matrix of emission coefficients (i.e. emission of pollutants per unit of production x^1)

In this model the number of commodities (m) is equal to the number of production processes (n). This implies that $g = x^1$ and $p^g = p^1$. Emissions are a by-product of industrial production.

Pollution is calculated as a by-product of industrial production, but does not influence the level of the decision variables x^1. As indicated above, abatement can be included in this model as an additional column for each pollutant.

Extended model

The model described above is extended by including q abatement technologies that can be applied to reduce emissions of the emissions of the k pollutants. Abatement technologies are included as separate production processes that can be added to the (conventional) production processes producing the commodities. In fact, these abatement technologies yield the commodity 'emission reduction' that can be used as an input in the production process of the sector that applies the technology. Each technology can be applied in only one sector, whereas a sector has choice of several technologies and can also apply several abatement technologies together. The potential emission reduction of each abatement technology is limited to a given level. The total reduction in emissions is the sum of the reduction by the separate technologies. Although an abatement technology is primarily intended to reduce emissions of one pollutant, there may also be side-effects on emissions of other pollutants.

The model applies a marketable permit scheme. This implies that a sector is allowed to produce emissions of a certain pollutant only to the quantity of emission permits it can buy. A control authority (government) decides on the total quantity of emission permits issued. Moreover, it is possible to restrict the quantity of permits for a specific sector (i.e. sector-specific emission reduction targets) or a group of sectors. Within these restrictions emission permits can be freely traded between firms at whichever price is agreed for that trade.

A sector that causes emissions of pollutants is faced with a choice between buying emission permits for these pollutants, applying abatement technologies or a combination of these. Sectors are assumed to minimize total cost of production, so the choice will depend on the cost of abatement and the price of emission permits. Firms will invest in abatement if the cost of an additional unit of emission reduction (i.e. marginal abatement cost) is less than the price of a permit. At the 'optimum' level of pollution the marginal abatement cost will be equal to the permit price.

The cost of abatement depends on the technologies available and their cost. These are different for the various sectors in the model. The cost of abatement is made up of the amount of inputs from other sectors and the primary inputs (e.g. labor) required for using the abatement technologies. These requirements are given by the (fixed) technical and primary input coefficients for each abatement technology.

Trading of emission permits will lead to an equilibrium market price equal to the shadow price of pollution at the optimum level (i.e. no sector is able to further reduce its emissions at lower marginal cost). The price of emission permits depends on the quantity of permits available and the abatement cost of the various trading partners. If only the total quantity of permits is restricted, there will be one permit price for the economy as a whole. If there are sector specific restrictions on the quantity of permits, the permit price may differ between sectors because the additional restriction may lead to different shadow prices of pollution in different sectors. If there is no restriction on the quantity of permits or if the restriction is not binding, the price of permits will be zero.

Pollution is a by-product of production and hence can be seen as an input that is required for the production of the commodity concerned. If a production process causes emissions of pollutants, abatement and/or emission permits are a necessary input for this production process. The sum of abatement and permits for a specific pollutant must be equal to the amount of emissions of that pollutant. In fact, the cost of the input 'pollution' in a production process is made up of the cost of abatement that is applied and the cost of permits that have to be obtained by the sector concerned.

The model is formulated as an optimization problem minimizing total cost of production (i.e. the sum of the cost of the primary inputs in the various sectors) given restrictions on final demand and quantities of emission permits. Decision variables are the production level in the various sectors, the level of abatement by the various abatement technologies and the amount of permits obtained by each sector. The model is formulated as follows:

minimize

$$v^1 x^1 + v^2 x^2 \qquad \text{(value added) (7)}$$

subject to

$$x^1 \geq A^1 x^1 + A^2 x^2 + \tilde{y} \qquad \text{(commodity constraints) (8)}$$

$$H_Z x^2 \geq \hat{x}^1 e_z^1 + \sum_{s=1}^{k} H_s \hat{x}^2 e_z^2 - tp_z \quad \forall\, z = 1 \ldots k \qquad \text{(level of abatement) (9)}$$

$$tp_z \leq \tilde{e}_z \quad \forall\, z = 1 \ldots k \qquad \text{(restriction on quantity of permits for sector) (10)}$$

$$i' tp_z \leq t\tilde{e}_z \quad \forall\, z = 1 \ldots k \qquad \text{(restriction on total quantity of permits) (11)}$$

$$x^2 \leq r \qquad \text{(maximum reduction) (12)}$$

$$x^1 \geq 0; x^2 \geq 0; tp_z \geq 0$$

where

- x^1 *n*-dimensional vector of industrial outputs produced by the initial production technologies
- x^2 *q*-dimensional vector of reductions in emissions (primary pollutant) by abatement technologies
- A^1 $(m \times n)$ matrix of input-output coefficients (i.e. inputs of commodity per unit of production x^1)
- A^2 $(m \times q)$ matrix of input-output coefficients (i.e. inputs of commodity per unit of abatement x^2)
- $\tilde{y}$ *m*-dimensional vector of final consumption demand for commodities (exogenous)
- v^1 *n*-dimensional vector of primary input values per unit of industrial production x^1
- v^2 *q*-dimensional vector of primary input values per unit of abatement x^2
- e_z^1 *n*-dimensional vector of emission coefficients for pollutant *z* from production x^1 (i.e. emission of pollutant *z* per unit of production x^1)
- e_z^2 *q*-dimensional vector of side-effects of abatement x^2 on emission of pollutant *z* (i.e. emission of pollutant *z* per unit of abatement x^2; a negative value indicates an emission reduction)
- H_z $(n \times q)$ matrix linking abatement technology *j* for the reduction of pollutant *z* to production process *i*; with elements $h_{ij} = 1$ if abatement technology *j* can be applied to production process *i* and $h_{ij} = 0$ otherwise
- tp_z *n*-dimensional vector of quantity of tradable permits for pollutant *z* obtained by production sectors

$\tilde{e}_z$ n-dimensional vector of sector-specific restriction on quantity of permits for pollutant z

$t\tilde{e}_z$ restriction on total quantity of permits for pollutant z

r q-dimensional vector of maximum reduction in emissions by abatement technologies of the pollutant it is primarily aimed at (relative to total emissions of the appropriate sector)

Moreover, a circumflex (^) indicates matrix diagonalization of vector and i' is the unity row (i.e. a row containing all 1's).

In the current formulation of the model, abatement technologies have to be attributed to one pollutant at which reduction it is primarily aimed. Effects on other pollutants are considered as a side-effect, although they are entirely integrated in the optimization. Whereas x^1 indicates the value of commodities produced, x^2 indicates the quantity of emission reduction of the pollutant of primary concern. The amount of inputs required for abatement and side-effects on emissions of other pollutants are linearly related to x^2 via A^2 and e_z^2.

The reduction of the primary pollutant is restricted to a maximum reduction relative to the total amount of emissions from the appropriate sector r. Moreover, the sum of reductions by several abatement technologies for the same pollutant within one sector is restricted to the maximum reduction of the most effective technology.

The price model is given by:

maximize

$$p^1\tilde{y} - \sum_z p_z^{tp} tp_z \qquad \text{(value added) (13)}$$

subject to

$$p^1 \leq p^1 A^1 + \sum_z p_z^e e_z^1 + v^1 \qquad \text{(price of commodities) (14)}$$

$$p^2 \leq p^1 A^2 + \sum_z p_z^e H_z^2 e_z^2 + v^2 \qquad \text{(price of abatement) (15)}$$

$$p_z^e = \frac{H_z \hat{x}^2 p^2 + p_z^{tp} tp_z}{H_z \hat{x}^2 + tp_z} \quad \forall z = 1 \ldots k \qquad \text{(average price of pollution) (16)}$$

$$p^1 \geq 0; p^2 \geq 0; p_z^e \geq 0; p_z^{tp} \geq 0 \qquad (17)$$

p^1 n-dimensional vector of unit cost of production x^1 with respect to a unit of value-added

p^2 q-dimensional vector of unit cost of production x^2 with respect to a unit of value-added

p_z^e n-dimensional vector of prices of pollution z from sectors with respect to a unit of value-added

p_z^{tp} n-dimensional vector of prices of emission permits for pollution z from sectors

The price of emission permits for a specific pollutant paid by a sector cannot be lower than the marginal cost of reduction of that pollutant in the same sector. If this would be the case, it would be cheaper for the sector to implement less abatement and instead buy more emission permits. If there is not a sector-specific restriction on the quantity of emission permits, but only a national restriction, the permit price will be the same for each sector. If a sector-specific restriction is introduced, prices may be different for different sectors.

The price of commodities p^g is affected by environmental policy through the price of emissions p_z^e which depends on the permit price p_z^{tp} and the cost of abatement reflected in p^2. This implies that with more stringent restrictions on the quantity of emission permits, resulting in a higher permit prices and marginal abatement cost, the cost of polluting production increases and hence the price of the associated commodities.

Results of a numerical application of the model

This section presents the results of a numerical application of the model. We used a highly aggregated input-output table of the Dutch economy, with five production sectors causing emissions of two pollutants (Table 1). Emissions can be abated by a number of abatement technologies with different abatement potential and different cost (Table 2). 43 abatement options were included in the analysis. The data for the abatement options were taken from an inventory of CO_2 and NO_x abatement options for the Netherlands (Daniels and Farla, 2006). Daniels and Farla (2006) report for each abatement option the potential abatement of the primary pollutant, possible side effects on other pollutants, and the cost of the abatement options per unit emission reduction of the pollutant. The abatement costs consist of various elements, including investments in machines and buildings, and energy and labor inputs. Although the share of these factors in the total cost is different for each abatement option. For the time being, however, it was assumed that for each abatement option 50% of the cost concerns inputs from the industry, 20% is input from the energy sector, 10% concerns deliveries by the services sector and 20% is labor cost. This assumption will be reconsidered in a follow-up of this analysis. Obviously, technologies will substantially differ with respect to the different inputs required. Moreover, in particular in the case of CO_2 abatement technologies, including energy saving, technologies will also yield benefits, i.e. a decrease in inputs required from the energy sector. This requires, however, the interpretation of the more detailed data behind the total cost figures that were presented by Daniels and Farla (2006). For the purpose of the current model analysis, i.e. to illustrate the working of the proposed model, it was not considered necessary to improve the data in this way.

Table 1 Input-output table of the Dutch economy (2000; financial flows in mln €)

	Agriculture	Industry	Energy	Services	Transport	Final demand	**Totals**
Agriculture	2450	8275	38	637	55	10146	**21601**
Industry	3322	35410	771	27696	2494	141222	**210915**
Energy	987	4413	8670	3574	275	12621	**30540**
Services	2787	32073	2060	188697	7089	302703	**535409**
Transport	77	456	223	9831	3511	23670	**37768**
Value added	11978	130288	18778	304974	24344		**490362**
Totals	**21601**	**210915**	**30540**	**535409**	**37768**	**490362**	
Pollution							
CO_2 emissions (Mton)	10.2	46.6	51.0	22.5	27.2		157.5
NO_x emissions (kton)	44.4	56.0	54.0	76.9	317.1		548.4

Table 2 Abatement of CO_2 and NO_x emissions in the various sectors[a]

	Potential abatement	**Range of cost-effectiveness**	**Number of abatement options**
CO_2 abatement	Mton CO_2	€/ton CO_2	
Services	3.4	19 - 2471	5
Energy	18.9	25 - 259	8
Industry	9.6	11 - 1042	8
Agriculture	3.0	21 - 2111	3
Transport	3.8	143 - 868	5
NO_x abatement	kton NO_x	€/kg NO_x	
Services	0.8	3 - 28	3
Energy	18.7	6 - 6	1
Industry	12.5	3 - 10	3
Agriculture	2.5	5 - 33	3
Transport	21.0	1 - 3	4

[a] Data taken from Daniels and Farla (2006); further details are presented in the appendix

Without additional abatement, total emissions of CO_2 and NO_x by the production sectors in the Netherlands are 157.5 megaton and 548.4 kiloton respectively. These emission levels are well above the emission targets set by the Dutch government. The model is used to analyze the effects of a limit on emissions. As described above, in the model this is modeled in such a way that firms are required to buy emission permits for each unit of CO_2 and NO_x that are emitted during the production process. For each pollutant, the total amount of permits is limited to the maximum emission level that is allowed. If the restriction on permits is binding (i.e. is the emission level is higher than the amount of permits available) permits will get a price on the market and somewhere in the economy abatement will have to take place in order to limit total emissions. If a sector faces a price for emission permits that is higher than the price of abatement by a certain abatement option in that sector, the sector will implement this abatement option. The price of the permits will at least be as high as the price of abatement by the most expensive abatement option that is implemented in the economy. Since there is free trade of permits among sectors, permits will be allocated over sectors such that the total abatement cost over all sectors is minimized. As a consequence of the system of tradable emission permits, emissions will have a price in (like other inputs to the production process) that adds to the total production cost. The external cost of pollution will be internalized in the prices of the commodities.

Restrictions on emissions of CO_2 only

Results of calculations with the model show that a cost-efficient overall reduction of CO_2 emissions by up to 5% can be realized at relatively low cost by abatement in the agriculture and industry. A further reduction in emissions (up to 20%) requires substantial abatement costs, in particular for abatement options in the energy sector (Figure 1). Total abatement cost in the energy sector increase to more than 7% of value added. In addition to the cost of abatement options, production sectors also have to pay for the remaining emissions, for which emission permits are required. With increasing emission reduction targets the permits become more scarce and hence the permit price increases. The expenditures on CO_2 emission permits increase to about € 30 billion with a CO_2 emission reduction of 20% (Figure 2), which is about 6% of GNP. The expenditures are relatively high in the most CO_2 intensive sectors, viz. the energy sector (> 40% of value added) and the transport sector (25% of value added). As a result of the abatement cost and the cost of the emission permits, production costs increase, and as a consequence the prices of the various commodities increase (Figure 3).

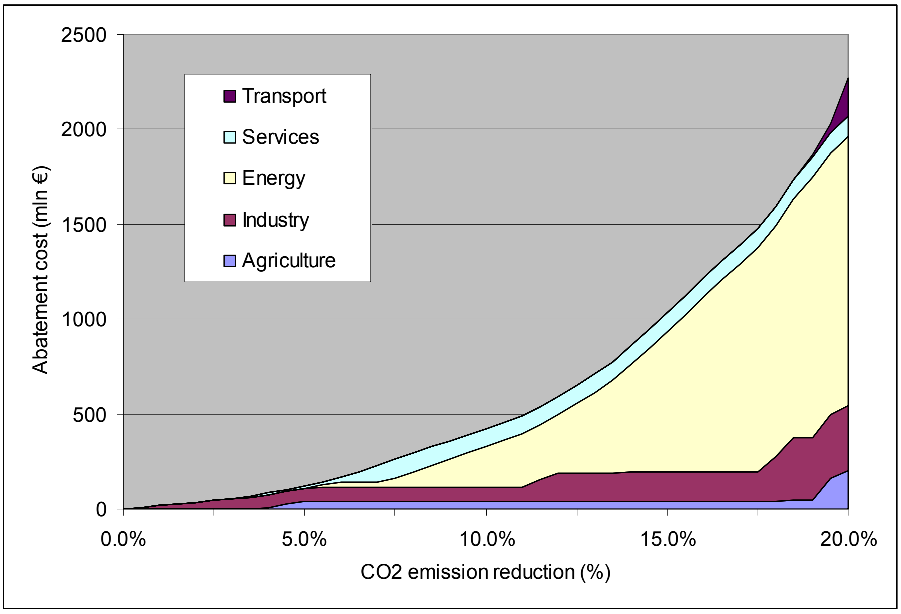

Figure 1 Cost of CO_2 abatement

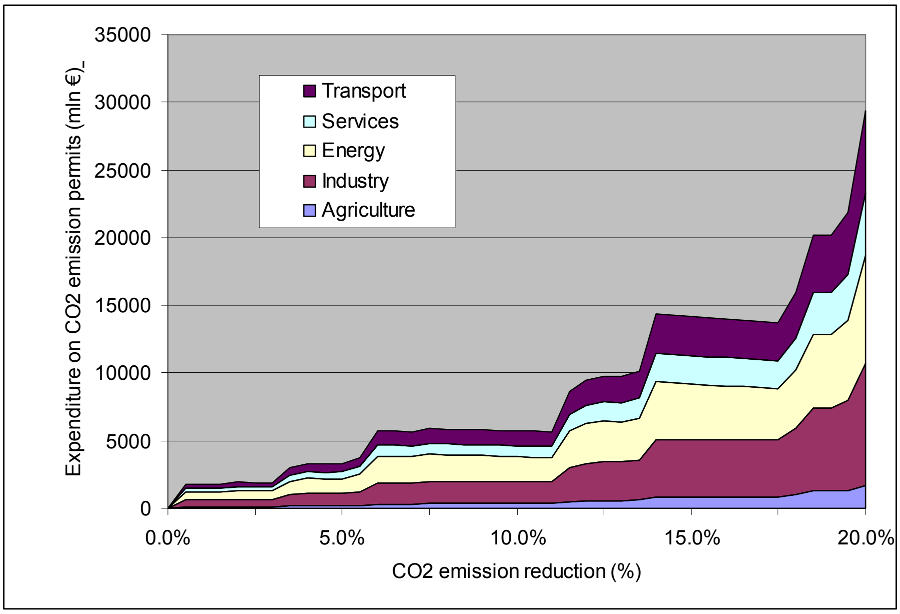

Figure 2 Expenditure on CO_2 emission permits

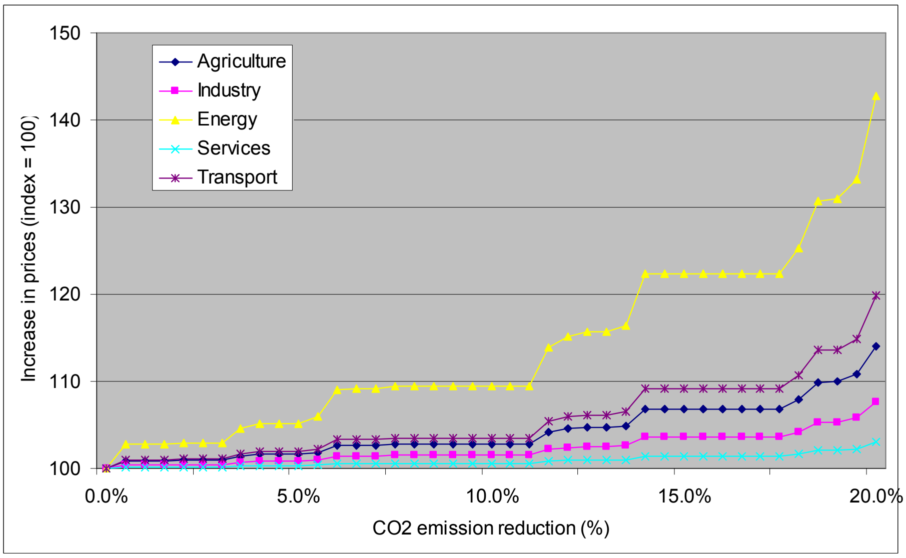

Figure 3 Increase in prices of commodities as a result of increasing CO_2 emission reduction

Restrictions on emissions of NO_x only

A cost-efficient overall reduction of NO_x emissions by up to 3% can be realized at relatively low cost by abatement in the transport sector. A further reduction in emissions (up to 10%) requires substantial abatement costs, in subsequently the energy sector, industry and agriculture (Figure 4). Total abatement costs as % of value added are limited in each sector. The expenditures on NO_x emission permits increase to about € 5 billion with a NO_x emission reduction of 10% (Figure 5), which is about 1% of GNP. The expenditures are relatively high (>10% of value added) in the transport sector, which is the most NO_x intensive sector. As a result of the abatement cost and the cost of the emission permits the prices of the various commodities increase (Figure 6).

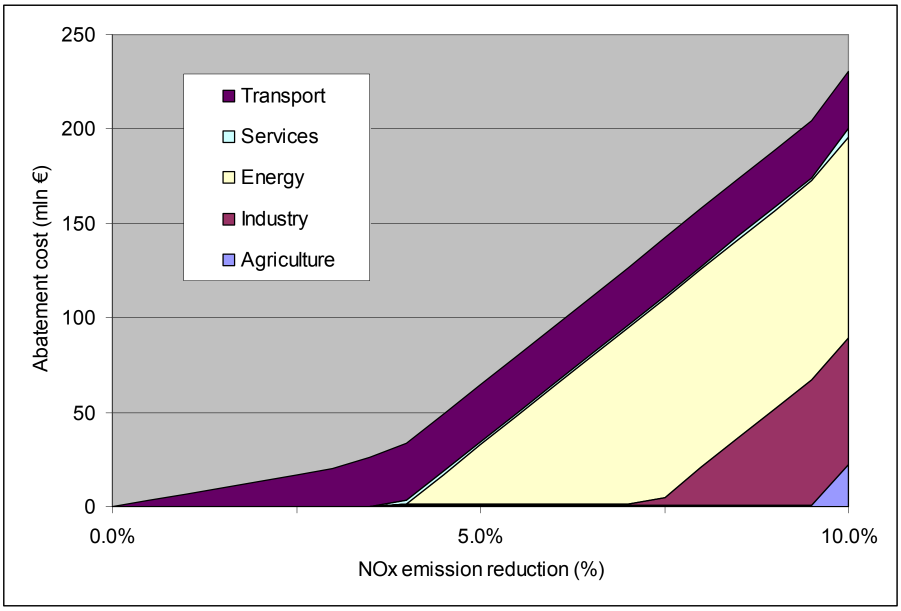

Figure 4 Cost of NO_x abatement

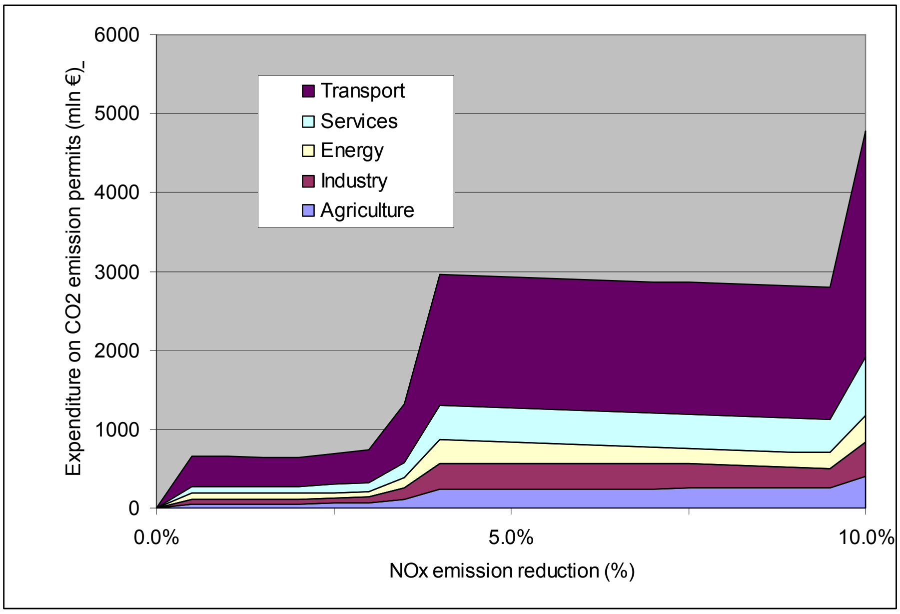

Figure 5 Expenditure on NO_x emission permits

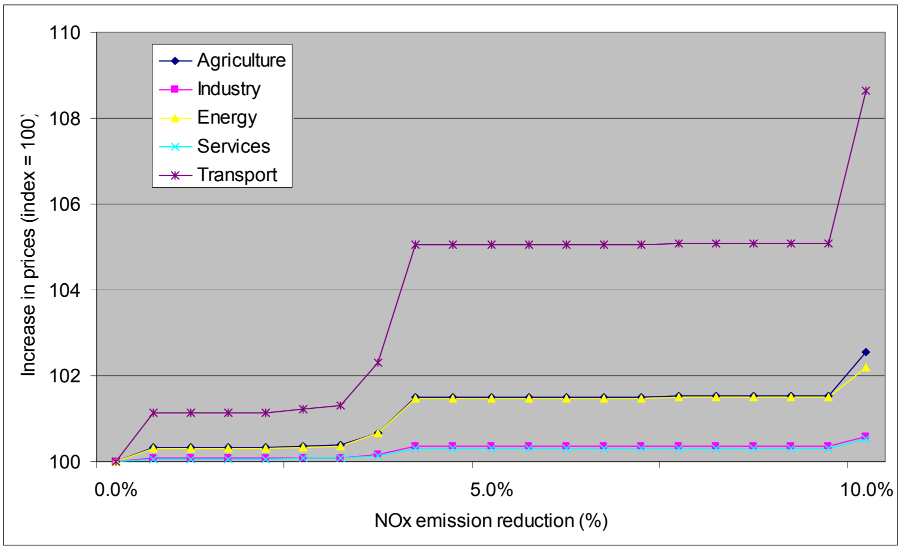

Figure 6 Increase in prices of commodities as a result of increasing NO_x emission reduction

Restrictions on emissions of CO_2 and NO_x simultaneously

In some cases, the abatement costs of a simultaneous reduction of CO_2 and NO_x emissions are less than the sum of the abatement cost required to achieve the same reductions for the pollutants individually. This is the result of synergy effects, i.e. abatement of one pollutant causes emissions of the other pollutant to decrease. In other cases, however, the cost of a simultaneous reduction of CO_2 and NO_x emissions is higher than the sum of reductions in each pollutant separately, as a result of abatement of one pollutant that causes an increase in the abatement of the other pollutant.

From the results (Figure 7 and Table 3) it follows that abatement cost increase substantially, in particular if the emission reduction targets for both pollutants are approaching the maximum feasible reduction (20% for CO_2, 10% for NO_x).

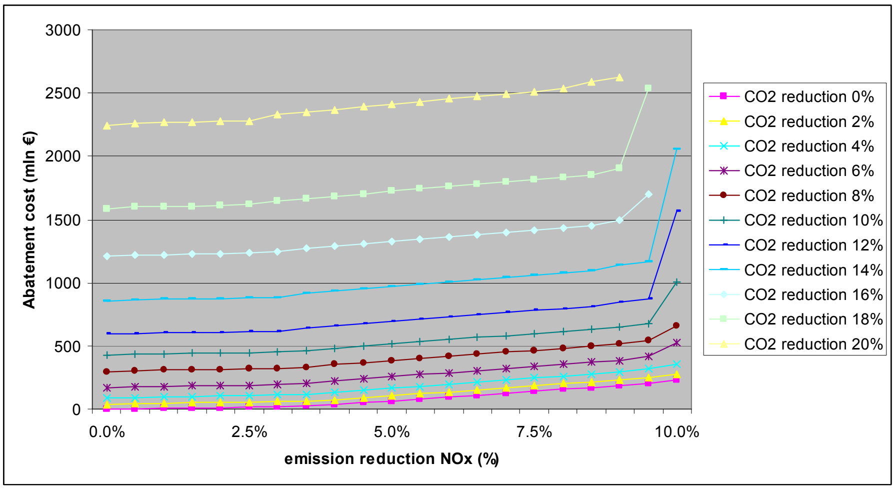

Figure 7 Abatement cost for different combinations of a simultaneous reduction of CO_2 and NO_x emissions

Table 3 Change in prices of commodities, payments for emission permits and abatement cost as a result of simultaneous reduction of CO_2 and NO_x emissions

Reduction (%)		**Price of commodities**					**Payments for CO2 and NOx emission permits (% of VA)**						**Total abatement cost (% of VA)**					
CO_2	NO_x	AGR	IND	ENE	SER	TRA	AGR	IND	ENE	SER	TRA	TOT	AGR	IND	ENE	SER	TRA	TOT
0%	0.0%	100.0	100.0	100.0	100.0	100.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0%	2.5%	100.3	100.1	100.3	100.1	101.2	0.5%	0.1%	0.4%	0.0%	1.6%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
0%	5.0%	101.5	100.4	101.5	100.3	105.1	2.1%	0.2%	1.5%	0.1%	6.8%	0.6%	0.0%	0.0%	0.2%	0.0%	0.1%	0.0%
0%	7.5%	101.5	100.4	101.5	100.3	105.1	2.1%	0.2%	1.1%	0.1%	6.9%	0.6%	0.0%	0.0%	0.6%	0.0%	0.1%	0.0%
0%	10.0%	102.6	100.6	102.2	100.5	108.6	3.4%	0.3%	1.8%	0.2%	11.8%	1.0%	0.2%	0.1%	0.6%	0.0%	0.1%	0.0%
5%	-0.4%	101.6	100.8	105.2	100.3	101.9	1.5%	0.7%	6.0%	0.2%	2.4%	0.7%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%
5%	2.5%	102.0	100.9	105.7	100.4	103.3	2.1%	0.8%	6.5%	0.2%	4.3%	0.8%	0.4%	0.1%	0.0%	0.0%	0.1%	0.0%
5%	5.0%	103.3	101.3	107.2	100.7	107.2	3.8%	1.0%	7.9%	0.3%	9.6%	1.3%	0.4%	0.1%	0.2%	0.0%	0.1%	0.0%
5%	7.5%	103.3	101.3	107.2	100.7	107.2	3.8%	1.0%	7.6%	0.3%	9.7%	1.3%	0.4%	0.1%	0.6%	0.0%	0.1%	0.1%
5%	10.0%	109.1	102.7	112.8	101.9	126.1	11.6%	1.9%	13.7%	0.9%	35.6%	3.6%	0.7%	0.1%	0.6%	0.0%	0.1%	0.1%
10%	-0.6%	102.8	101.5	109.5	100.6	103.5	2.8%	1.3%	9.7%	0.3%	4.5%	1.2%	0.3%	0.1%	1.1%	0.0%	0.0%	0.1%
10%	2.5%	103.2	101.6	109.9	100.7	104.8	3.3%	1.3%	10.2%	0.3%	6.2%	1.3%	0.4%	0.1%	1.1%	0.0%	0.1%	0.1%
10%	5.0%	104.4	101.9	111.1	100.9	108.7	5.0%	1.5%	11.0%	0.4%	11.6%	1.8%	0.4%	0.1%	1.6%	0.0%	0.1%	0.1%
10%	7.5%	104.4	101.9	111.1	100.9	108.7	5.0%	1.5%	10.7%	0.4%	11.6%	1.8%	0.4%	0.1%	2.0%	0.0%	0.1%	0.1%
10%	10.0%	143.5	111.0	145.4	109.1	239.4	59.3%	7.7%	46.8%	4.2%	191.6%	17.4%	0.8%	0.2%	3.0%	0.0%	0.1%	0.2%
15%	-0.2%	106.8	103.7	122.4	101.4	109.1	7.3%	3.2%	21.7%	0.7%	11.8%	2.9%	0.4%	0.1%	3.9%	0.0%	0.0%	0.2%
15%	2.5%	107.2	103.7	122.8	101.5	110.5	7.8%	3.3%	22.1%	0.7%	13.5%	3.0%	0.4%	0.1%	3.9%	0.0%	0.1%	0.2%
15%	5.0%	108.5	104.1	124.1	101.8	114.6	9.6%	3.5%	23.2%	0.8%	19.2%	3.5%	0.4%	0.1%	4.3%	0.0%	0.1%	0.2%
15%	7.5%	108.5	104.1	124.1	101.8	114.6	9.6%	3.5%	22.9%	0.8%	19.2%	3.5%	0.4%	0.1%	4.6%	0.0%	0.1%	0.3%
15%	10.0%	463.4	188.1	429.3	176.5	1301.4	503.4%	61.2%	339.1%	35.6%	1652.5%	145.6%	0.5%	1.0%	16.1%	-0.1%	2.0%	0.9%
20%	-0.6%	114.1	107.6	142.8	103.0	119.9	14.4%	6.9%	41.6%	1.5%	25.0%	6.0%	1.7%	0.3%	7.4%	0.0%	0.8%	0.5%
20%	2.5%	114.6	107.8	143.3	103.1	121.5	15.0%	7.0%	42.1%	1.5%	27.0%	6.1%	1.7%	0.3%	7.4%	0.0%	0.9%	0.5%
20%	5.0%	116.0	108.1	144.8	103.4	125.9	16.9%	7.2%	43.3%	1.7%	33.0%	6.7%	1.8%	0.3%	7.9%	0.0%	0.9%	0.5%
20%	7.5%	116.0	108.1	144.8	103.4	125.9	16.9%	7.2%	43.1%	1.7%	33.0%	6.7%	1.8%	0.3%	8.1%	0.0%	1.0%	0.5%

Discussion and Conclusions

This paper presented a model, based on the tradition of the environmental Input-Output framework, extended by a bottom-up framework for cost-efficiency analysis. The proposed model allows for the inclusion of rather detailed data on cost and effect of specific abatement options, which can be useful for policymakers. By combining this bottom-up approach with the Input-Output approach, the model can provide valuable information for the evaluation of environmental policies.

The model presented has several shortcomings and can be improved in several ways. The following caveats are most relevant and will be dealt with in further research:

- the model presented in this paper is a static model. In fact, this implies that the results represent a situation that might occur after a longer time period and without cost of adaptation. The model might be extended to include the dynamics of the economy by taking into account the timing of investments and also the timing of the constraints on the amount of emission permits.
- In the current analysis the only way to reduce emissions is by adding end-of-pipe technologies to the production processes, while in fact the production processes themselves remain unchanged. It might, however, in particular in a dynamic modelling context, be more efficient for firms to make structural changes to the production technologies that result in lower emissions of pollutants. In principle it is possible to include these structural changes in the analysis, because the specification of the model allows to include alternative production technologies to produce one commodity. Data on these kind of process-integrated technologies that can be included in an input-output model were, however, not available.
- Changes in the prices of commodities as a result of restrictions on emissions of pollutants will have an impact on the demand for these commodities. In a dynamic model this might result in sectors changing their production technologies in order to minimize the production cost. Moreover, final demand may change because of changes in relative prices. In a more extended modelling framework it may be possible to analyse these effects of environmental policy by modelling final demand endogenously. Currently, MNP is working on a way to estimate income and price-elasticities for the Netherlands on a rather detailed level. These might be used to extend the model in this way.
- In the presented model no attention is paid to international trade. This might, however, be relevant in the case of environmental policies. If a country introduces restrictions on emissions of pollutants while other countries do not have such restrictions, this might have consequences for the international competitiveness of the firms in the country. This may result in decreasing exports and increasing imports, because the commodities produced in other countries become relatively cheaper. Although the literature indicates that the effects of environmental policy on competitiveness is limited, it seems useful to spend further research on this subject.

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