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The Extension of the RAINS Model to Greenhouse Gases

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Abstract

Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements for both traditional air pollution problems as well as climate change. A methodology has been developed to extend the RAINS integrated assessment model to explore synergies and trade-offs between the control of greenhouse gases and air pollution. With this extension, the RAINS model allows now the assessment of emission control costs for the six greenhouse gases covered under the Kyoto Protocol (CO_2, CH_4, N_2O and the three F-gases) together with the emissions of air pollutants SO_2, NO_x, VOC, NH_3 and PM.

In the first phase of the study, emissions, costs and control potentials for the six greenhouse gases covered in the Kyoto Protocol have been estimated and implemented in the RAINS model. Emission estimates are based on methodologies and emission factors proposed by the IPCC emission reporting guidelines. The large number of control options for greenhouse gases have been grouped into approximately 150 packages of measures and implemented in the RAINS model for the European countries. These control options span a wide range of cost-effectiveness. There are certain advanced technical measures that will involve very high costs, there is a variety of measures with moderate costs, and certain measures exist for which the economic assessment suggests even negative costs, if major side impacts (cost savings) are calculated.

The extended RAINS model framework will offer a tool to systematically investigate such economic and environmental synergies between greenhouse gas mitigation and air pollution control while avoiding negative side impacts.

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Table of contents

1 Introduction

1.1 *Interactions between air pollution control and greenhouse gas mitigation*

Recent scientific insights open new fields for an integrated assessment that could potentially lead to a more systematic and cost-effective approach for managing these traditional pollutants simultaneously with greenhouse gases:

- Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements for both traditional air pollution problems as well as climate change. Climate change measures that aim at reduced fossil fuel combustion will have ancillary benefits for regional air pollutants (see, e.g., Syri *et al.*, 2001). In contrast, some ammonia abatement measures can lead to increases of N_2O emissions, while structural measures in agriculture could reduce both regional air pollution and climate change. Methane is both an ozone precursor and a greenhouse gas; hence its abatement will have synergistic effects and some cheap abatement measures may be highly cost effective.

- Some air pollutants (e.g., tropospheric ozone and aerosols) are also important greenhouse gases and exert radiative forcing. Changes in tropospheric ozone were found to have the third-largest positive radiative forcing after CO_2 and CH_4 (IPCC: Houghton *et al.*, 2001), while sulphate aerosols exert negative forcing. Understanding is growing on the role of carbonaceous aerosols, suggesting warming effects for black carbon and cooling for organic carbon.

- Other air pollutants such as ozone, NO_x, CO and VOC act as indirect greenhouse gases influencing, e.g., via their impact on OH radicals, the lifetime of direct greenhouse gases (e.g., methane and HFC). Global circulation models have only begun to incorporate atmospheric chemistry and to take full account of the important roles of conventional air pollutants.

- It is also clear that interactions between air pollutants and radiative forcing can be multiple and can act in opposite directions. For instance, increases in NO_x emissions decrease (via OH radicals) the lifetime of methane in the atmosphere and thereby cause reduced radiative forcing. At the same time, NO_x emissions produce tropospheric ozone and thus increase radiative forcing. A further pathway leads to increased nitrogen deposition that may cause, via the fertilisation effect, enhanced growth of vegetation, which, in turn, offers an increased sink for carbon. The net effect cannot yet be fully quantified.

- Time is an important factor in this context. While the impacts from some climate change policies on air pollution may yield short-term (secondary) benefits, the lifetime of air pollutants with radiative forcing is generally shorter than that of greenhouse gases. Hence, any climate change benefits from reduced air pollution will come earlier than those of greenhouse gas abatement. While the climate change benefits (such as temperature decreases) take effect on the long-term, reduced air pollution will yield benefits in the short and medium term.

1.2 The RAINS extension to include greenhouse gases

The Regional Air Pollution Information and Simulation (RAINS) model has been developed by the International Institute for Applied Systems Analysis (IIASA) as a tool for the integrated assessment of emission control strategies for reducing the impacts of air pollution. The present version of RAINS addresses health impacts of fine particulate matter and ozone, vegetation damage from ground-level ozone as well as acidification and eutrophication. In order to meet environmental targets for these effects in the most cost-effective way, RAINS considers emission controls for sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), ammonia (NH_3) and fine particulate matter (PM).

Considering the new insights into the linkages between air pollution and greenhouse gases, work has begun to extend the multi-pollutant/multi-effect approach that RAINS presently uses for the analysis of air pollution to include emissions of greenhouse gases. This could potentially offer a practical tool for designing national and regional strategies that respond to global and long-term climate objectives (expressed in terms of greenhouse gas emissions) while maximizing the local and short- to medium-term environmental benefits of air pollution. The emphasis of the envisaged tool is on identifying synergistic effects between the control of air pollution and the emissions of greenhouse gases. It is not proposed at this stage to extend the RAINS model towards modelling the climate system.

1.3 Objective of this report

The objective of this report is to describe the progress made in extending the RAINS model with the emissions and costs of controlling greenhouse gases.

1.4 Structure of the report

The report has the following structure: Chapter 2 describes the methodology to extend the RAINS air pollution model to include emissions of greenhouse gases. Chapter 3 reviews sources of CO_2 emissions and options for controlling them. Chapter 4 does the same for methane, Chapter 5 for nitrous oxides and Chapter 6 for HFC, PFC and SF_6. Chapter 7 presents initial results of the extended model.

2 Methodology

2.1 Introduction

A methodology has been developed to assess, for any exogenously supplied projection of future economic activities, the resulting emissions of greenhouse gases and conventional air pollutants, the technical potential for emission controls and the costs of such measures, as well as the interactions between the emission controls of various pollutants. This new methodology revises the existing mathematical formulation of the RAINS optimisation problem to take account of the interactions between emission control options of multiple pollutants and their effects on multiple environmental endpoints.

This chapter first describes the existing RAINS methodology. Subsequently, the method to calculate future emissions is explained. Then the costing methodology is described and the new formulation of the optimisation method is summarised.

2.2 The RAINS methodology for air pollution

The Regional Air Pollution Information and Simulation (RAINS) model developed by the International Institute for Applied Systems Analysis (IIASA) combines information on economic and energy development, emission control potentials and costs, atmospheric dispersion characteristics and environmental sensitivities towards air pollution (Schöpp *et al.*, 1999). The model addresses threats to human health posed by fine particulates and ground-level ozone as well as risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated ambient levels of ozone. These air pollution related problems are considered in a multi-pollutant context (Figure 2.1) quantifying the contributions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of fine (PM2.5) and coarse (PM10-PM2.5) particles. A detailed description of the RAINS model, on-line access to certain model parts as well as all input data to the model can be found on the Internet (http://www.iiasa.ac.at/rains).

The RAINS model framework makes it possible to estimate, for a given energy- and agricultural scenario, the costs and environmental effects of user-specified emission control policies. Furthermore, a non-linear optimisation mode has been developed to identify the cost-minimal combination of emission controls meeting user-supplied air quality targets, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. The optimisation capability of RAINS enables the development of multi-pollutant, multi-effect pollution control strategies. In particular, the optimisation can be used to search for cost-minimal balances of controls of the six pollutants (SO_2, NO_x, VOC, NH_3, primary $PM_{2,5}$, primary $PM_{10-2.5}$ (= PM coarse)) over the various economic sectors in all European countries that simultaneously achieve user-specified targets for human health impacts (e.g., expressed in terms of reduced life expectancy), ecosystems protection (e.g., expressed in terms of excess acid and nitrogen deposition), and maximum allowed violations of WHO guideline values for ground-level ozone.

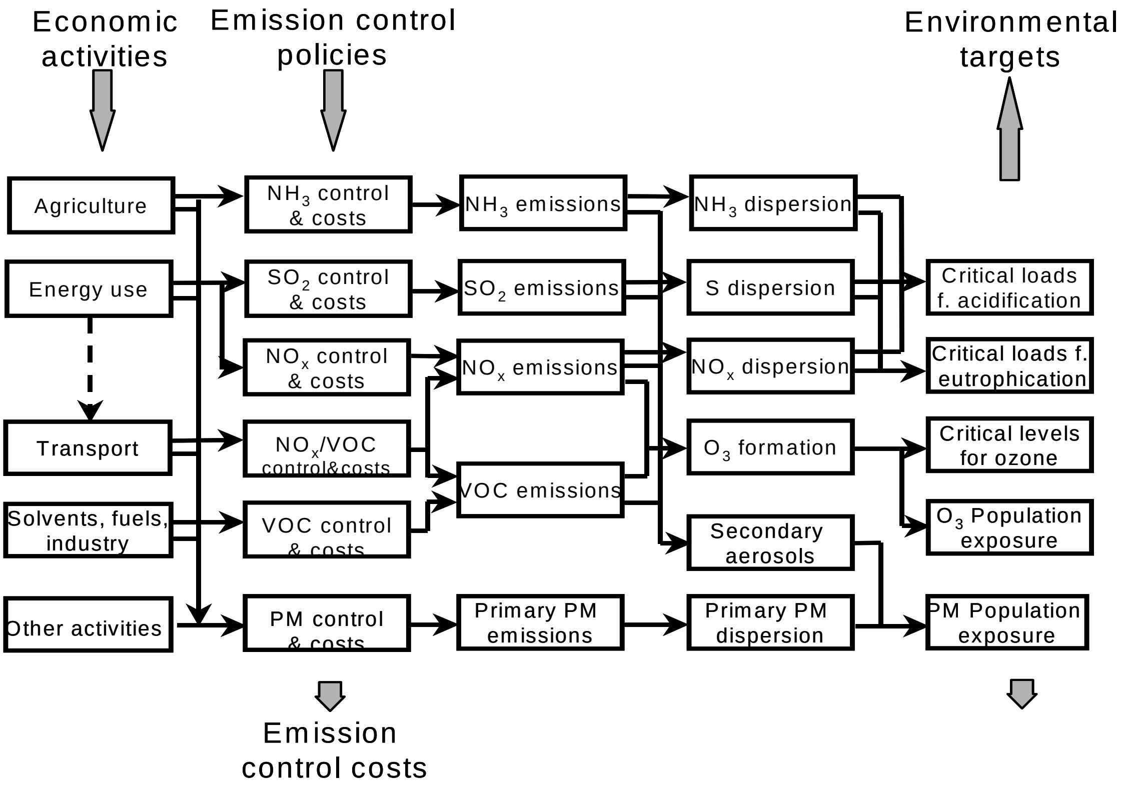

Figure 2.1: Flow of information in the RAINS model

2.3 Emission calculation

The methodology adopted for the estimation of current and future greenhouse gas emissions and the available potential for emission controls follows the standard RAINS methodology. Emissions of each pollutant *p* are calculated as the product of the activity levels, the "uncontrolled" emission factor in absence of any emission control measures, the efficiency of emission control measures and the application rate of such measures:

$$E_{i,p} = \sum_{j,k,f} E_{i,j,f,t} = \sum_{j,k,m} A_{i,j,k} ef_{i,j,t} (1 - eff_{t}) X_{i,j,f,t} \qquad \text{Equation 2.1}$$

where

i,j,t,f	Country, sector, abatement technology, fuel,
$E_{i,p}$	Emissions of the specific pollutant *p* in country *i*,
A	Activity in a given sector,
Ef	"Uncontrolled" emission factor,
$Eff_{k,p}$	Reduction efficiency of the abatement option *k*, and
X	Actual implementation rate of the considered abatement.

If no emission controls are applied, the abatement efficiency equals zero ($eff_{k,p} = 0$) and the application rate is one ($X = 1$). In that case, the emission calculation is reduced to simple multiplication of activity rate by the “uncontrolled” emission factor.

2.4 Cost calculation

2.4.1 General approach

The cost evaluation in the RAINS model attempts to quantify the values to society of the resources diverted in order to reduce emissions in Europe (Klimont *et al.*, 2002). In practice, these values are approximated by estimating costs at the production level rather than at the level of consumer prices. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Any taxes added to production costs are similarly ignored as transfers, as are subsidies.

A central assumption in the RAINS cost calculation is the existence of a free market for (abatement) equipment throughout Europe that is accessible to all countries at the same conditions. Thus, the capital investments for a certain technology can be specified as being independent of the country. Simultaneously, the calculation routine takes into account several country-specific parameters that characterise the situation in a given region. For instance, these parameters include average boiler sizes, capacity/vehicles utilization rates and emission factors.

The expenditures for emission controls are differentiated into

- investments,
- fixed operating costs, and
- variable operating costs.

From these three components RAINS calculates annual costs per unit of activity level. Subsequently, these costs are expressed per ton of pollutant abated.

Some of the parameters are considered common to all countries. These include technology-specific data, such as removal efficiencies, unit investment costs, fixed operating and maintenance costs, as well as parameters used for calculating variable cost components such as the extra demand for labour, energy, and materials.

Country-specific parameters characterise the type of capacity operated in a given country and its operation regime. These parameters include the average size of installations in a given sector, operating hours, annual fuel consumption and mileage for vehicles. In addition, the prices for labour, electricity, fuel and other materials as well as cost of waste disposal also belong to that category.

Although based on the same principles, the methodologies for calculating costs for individual sectors need to reflect the relevant differences, e.g., in terms of capital investments. Thus, separate formulas are developed for stationary combustion sources, stationary industrial processes and mobile sources (vehicles). All costs in RAINS are expressed in constant € (in prices of the year 2000).

2.4.2 Stationary combustion sources

2.4.2.1 Investments

Investments cover the expenditure accumulated until the start-up of an abatement technology. These costs include, e.g., delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement and capital. The RAINS model uses investment functions where these cost components are aggregated into one function. For stationary combustion sources the investment costs for individual control installations may depend on the boiler size *bs*. The form of the function is described by its coefficients ci^f and ci^v. Coefficients *ci* are valid for hard coal fired boilers. Thus, coefficient *v* is used to account for the different flue gas volume to be handled when other fuel is used. Additional investments, in the case of retrofitting existing boilers/furnaces, are taken into account by the retrofitting cost factor *r*. Specific investments are described as a function of the size of the installation, the flue gas volume and the retrofit factor:

$$I = (ci^f + \frac{ci^v}{bs}) * v * (1 + r) \quad \text{Equation 2.2}$$

For all pollutants, investments are annualised over the technical lifetime of the plant *lt* by using the real interest rate *q* (as %/100):

$$I^{an} = I * \frac{(1 + q)^{lt} * q}{(1 + q)^{lt} - 1} \quad \text{Equation 2.3}$$

2.4.2.2 Operating costs

The annual **fixed expenditures** OM^{fix} cover the costs of repairs, maintenance and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for annual fixed expenditures, a standard percentage *f* of the total investments is used:

$$OM^{fix} = I * f \quad \text{Equation 2.4}$$

The **variable operating costs** OM^{var} are related to the actual operation of the plant and may take into account elements such as

- additional demand for labour,

- increased or decreased energy demand for operating the device (e.g., for fans and pumps), and
- waste disposal.

These cost items are calculated with the specific demand λ^x of a certain control technology and its (country-specific) price c^x:

$$OM^{var} = \lambda^l c^l + \lambda^e c^e + ef * \eta * \lambda^d c^d \qquad \text{Equation 2.5}$$

where

η	emission removal efficiency,
λ^l	labour demand,
λ^e	additional energy demand
λ^d	demand for waste disposal (per unit of emission reduced),
c^l	labour cost,
c^e	energy price,
c^d	waste disposal cost,
ef	unabated emission factor.

2.4.2.3 Unit reduction costs

Unit costs per unit of activity

Based on the above-mentioned cost items, the unit costs for the removal of emissions can be calculated. All expenditures of a control technology are related to one activity unit, e.g., in case of stationary combustion to one unit of fuel input (in PJ). In case of stationary combustion, the investment-related costs are converted to fuel input by applying the capacity utilization factor *pf* (operating hours/year):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} \qquad \text{Equation 2.6}$$

The cost effectiveness of different control options can only be evaluated by relating the abatement costs to the amount of reduced emissions:

$$c_{PM_k} = c_{PJ} / (ef * \eta) \qquad \text{Equation 2.7}$$

2.4.3 Costs for industrial process emission sources

2.4.3.1 Investments

For industrial process sources investments are related to the activity unit of a given process. For the majority of processes these are annual tons produced. For refineries the investment function is related to one ton of raw oil input to the refinery. The investment function and annualised investments are given by the following two equations:

$$I = ci^{f} * (1 + r) \qquad \text{Equation 2.8}$$

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \qquad \text{Equation 2.9}$$

2.4.3.2 Operating costs

The operating costs are calculated with formulas similar to those used for stationary combustion. However, since the activity unit is different, the formulas have a slightly different form:

$$OM^{fix} = I * f \qquad \text{Equation 2.10}$$

$$OM^{var} = \lambda^{l} c^{l} + \lambda^{e} c^{e} + eff * \eta * \lambda^{d} c^{d} \qquad \text{Equation 2.11}$$

The coefficients λ^{l}, λ^{e}, and λ^{d} relate to one ton of product; *eff* is the emission factor for the specific pollutant.

2.4.3.3 Unit reduction costs

Unit costs per ton of product

This cost is calculated from the following formula:

$$c_{ton} = I^{an} + OM^{fix} + OM^{var} \qquad \text{Equation 2.12}$$

Unit costs per ton of pollutant removed

As for combustion sources, one can calculate costs per unit of emission removed:

$$c_{p_k} = c_{ton} / (eff * \eta) \qquad \text{Equation 2.13}$$

2.4.4 Mobile sources

2.4.4.1 Investments

The cost evaluation for mobile sources follows the same basic approach as for stationary sources. The most important difference is that the investment costs are given per vehicle, not per unit of production capacity. The following description uses the indices *i, j*, and *t* to indicate the nature of the parameters:

i	denotes the country,
j	the transport (sub)sector/vehicle category,
t	the control technology.

The costs of applying control devices to mobile sources include

- additional investment costs,
- increase in maintenance costs expressed as a percentage of total investments, and
- change in fuel cost resulting from the inclusion of emission control.

The investments $I_{i,j}$ are given in €/vehicle and are available separately for each technology and vehicle category. They are **annualised** according to

$$I_{i,j}^{an} = I_{j,t} \cdot \frac{(1+q)^{lt_{i,j,k}} \cdot q}{(1+q)^{lt_{i,j,k}} - 1} \qquad \text{Equation 2.14}$$

where

$lt_{i,j}$	lifetime of control equipment.

2.4.4.2 Operating costs

The increase in maintenance costs (**fixed costs**) is expressed as a percentage f of total investments:

$$OM_{i,j,t}^{fix} = I_{i,j,t} \cdot ft \qquad \text{Equation 2.15}$$

A change in fuel cost is caused by

- change in fuel quality required by a given stage of control, or
- change in fuel consumption after inclusion of controls.

It can be calculated as follows:

$$OM_{i,j,t}^{e}(t) = \Delta c_j^e + \lambda_{j,t}^e * (c_{i,j}^e + \Delta c_j^e) \qquad \text{Equation 2.16}$$

where

$\lambda^e_{j.t}$	percentage change in fuel consumption by vehicle type j caused by implementation of control measure t,
$c^e_{i,j}$	fuel price (net of taxes) in country i and sector j in the base year,
Δc^e_j	change in fuel cost caused by the change in fuel quality.

This change in fuel cost is related to one unit of fuel used by a given vehicle category.

2.4.4.3 Unit reduction costs

The unit costs of abatement ce_{PJ} (related to one unit of fuel input) are time dependent and add up to:

$$ce_{PJ,i,j} = \frac{I_{i,j}^{an} + OM_{i,j}^{fix}}{fuel_{i,j}(t)} + OM_{i,j}^{e}(t) \qquad \text{Equation 2.17}$$

These costs can be related to the emission reductions achieved. The costs per unit of abated are then:

$$cn_{i,j} = \frac{ce_{i,j}(t)}{ef_{i,j} * \eta}$$

Equation 2.18

The most important factors leading to differences among countries in unit abatement costs are: different annual energy consumption per vehicle and country-specific unabated emission factors.

2.5 The optimisation including greenhouse gases

2.5.1 Objective

Traditionally, the RAINS model employs ‘national cost curves’ for emission controls for each pollutant and country, which rank the available emission control measures according to their cost-effectiveness. While such cost curves are computationally efficient and facilitate understanding and review by national experts, they cannot directly capture interactions between the emission control options of different pollutants. In the earlier analyses of air pollution strategies, only few of such interactions were of practical relevance (e.g., three way catalysts simultaneously controlling NO_x and VOC emissions), and tailored solutions were developed to handle these aspects. Now, with the new focus on greenhouse gases, such interactions become more relevant, and a new concept needed to be developed.

Instead of national (pollutant-specific) emission reduction levels curtailed by the national cost curves, the new methodology uses the application of individual emission control options as decision variables. All economic and emission-relevant features are directly connected to these variables. This allows to fully capturing all interactions between pollutants for each individual emission control measure. In such a way, the traditional ‘cost curve’ approach of the RAINS model is replaced by a ‘technology-driven’ problem formulation. The major disadvantage of this approach is that it puts significantly higher demands on computing power. The larger dimensions of the optimisation problem will also limit the practical possibility for analysing non-linear relationships (e.g., in the formation of ground-level ozone). It needs to be examined to what extent such a constraint will limit the accuracy of results, or alternatively whether a tailored mathematical algorithm can be developed that enables treatment of the most important non-linearities.

The new formulation of the RAINS model allows simulation of a variety of flexible mechanisms for controlling GHG and air pollution emissions. This includes, *inter alia*, the possibility of simulating carbon taxes for all greenhouse gases, emission taxes for conventional air pollutants, trading of carbon and other greenhouse gases within selected countries in Europe (e.g., the EU), and the clean development mechanism of the Kyoto protocol where emission permits could be acquired from Non-Annex 1 countries. In doing so the analysis of European medium-term emission control strategies can be embedded in the context of global long-term development, which might determine, *inter alia*, carbon prices for the world market under alternative regimes of flexible mechanisms.

2.5.2 General specification

A new formulation of a mathematical programming problem describing the interactions of emission control options for different pollutants has been developed, focusing on the country-specific costs functions that simultaneously address several pollutants.

The following variables are defined:

- Index *i* corresponds to a region or country. The number of elements is about 50.
- Index *j* corresponds to a receptor or grid cell. The number of elements is around 500.
- Index *p* corresponds to a directly emitted pollutant. The number of pollutants is about 11 (SO_2, NO_X, VOC, NH_3, PM, CO_2, CH_4, N20, HFC, PFC, SF_6).
- Index *d* corresponds to derived types of pollutants (or pollutant species). This is currently only the case for PM for which RAINS distinguishes PM fine, PM coarse and PM rest.
- Index *s* corresponds to a sector (the number of elements is about 30).
- Index *f* corresponds to a specific fuel-type activity (e.g. brown coal or industrial production type).
- Index *a* corresponds to an “economic” activity (a combination of a sector and fuel type activity for example gasoline use in transport). The number of elements is around 300 for each region.
- Index *t* corresponds to a technology. Such technologies may consist of two types:
    - No control (e.g. brown coal use in power generation)
    - Control options (e.g. combustion modification of brown coal fired power plant)

The **decision variables**, i.e., the variables to be changed in order to satisfy the objective function, are the activity rates x_{iat}, reflecting the levels at which a technology *t* is used for activity *a* in region *i*. For example, such a decision variable would describe the extent to which combustion modification is used for new hard coal fired plants in Poland.

The **objective function** consists then of the minimisation of total pollution control costs for all relevant pollutants over all relevant regions subject to constraints on regional emissions. The objective function is to minimise total costs over all countries:

$$Total\ costs = \sum_{i \in I} \cos t_i \qquad i \in I \qquad \text{Equation 2.19}$$

The costs for each country consist of the sum of the costs for all technologies over all relevant activities:

$$Costs_i = \sum_{a \in Ai} \sum_{t \in Ta} C_{iat} X_{iat} \qquad i \in I,\ \ a \in A, t \in T_a \qquad \text{Equation 2.20}$$

where C_{iat} are the unit costs of emission control measure t applied to activity a. X_{iat} are the activity rates related to these control measures t and T_a is the set of all emission control measures of activity a. Ai is the set of activities.

The emissions of pollutant p of activity a is the sum of the emissions related to activity rates x_{at} is defined as

$$Em_{ipa} = \sum_{t \in Ta} E_{ipat} X_{iat} \qquad ,i \in I,\ \ p \in P, a \in A \qquad \text{Equation 2.21}$$

with E_{ipat} as the unit emissions of pollutant p by technology t per activity (the emission factor). For instance, the emissions of NO_x from brown coal fired power plants are calculated as the sum of the emissions from the amount of brown coal fired without NO_x control, with combustion modification and with selective catalytic reduction. The total emissions of pollutant p in a region are calculated as the sum of the emissions from all activities (brown coal, hard coal, natural gas etc) and are defined by

$$Tot\ Em_{ip} = \sum_{t \in Ai} Em_{ipat} \qquad i \in I,\ \ p \in P \qquad \text{Equation 2.22}$$

Finally, **constraints** can be formulated for the problem. The activity rates themselves can be bounded, e.g., because certain technologies can only be applied to new installations:

$$X_{iat\min} \le X_{iat} \le X_{iat\max} \qquad i \in I,\ \ t \in T, a \in A \qquad \text{Equation 2.23}$$

In addition, emissions for each activity can be bounded, e.g., because of legislation. total emissions levels of a region can be specified for each pollutant:

$$TotEm_{ip} \le TotEM_{ip\max} \qquad i \in I,\ \ p \in P \qquad \text{Equation 2.24}$$

When specifying the maximum emission levels, the corresponding total costs (as well as the marginal costs) can be calculated for reaching that level. The specification of alternative emission levels can then be used to generate individual points of the cost function for a pollutant. The minimum value that the total emissions can take then reflects the full application of best available technologies.

More complex constraints can also be added. First, the total (exogenous) demand for an activity can be specified to be at least as high as that in the baseline. E.g., when reducing carbon dioxide emissions in the power sector, the amount of electricity generated has to be at least as high as in the baseline. Secondly, constraints might result from legislation requiring the application of technologies that are not worse (in terms of emissions per unit) than a certain reference technology. E.g., new coal-fired plants have to use at least combustion modification, but may use more efficient measures such as selective catalytic reduction. Third, it is straightforward to extend the optimisation by adding constraints on the deposition or concentrations of certain pollutants for one or several receptor points. This feature already exists in the present RAINS module. Finally, in particular for the control of greenhouse gas emissions, a constraint can be specified for the sum of the emissions of the basket of greenhouse gas (using, e.g., their greenhouse warming potential as weights), either for each region separately or jointly for several regions.

The simulation of joint implementation (JI) or carbon trading (ET) is another extension. Once can distinguish two cases. If JI or ET is only considered between the regions distinguished in the model, the constraint on total emissions (Equation 2.23) is modified to include emissions of all regions:

$$Tot\ Em_{ip} = \sum_{i \in I} \sum_{t \in Ai} Em_{ipa} \qquad i \in I\ ,\quad p \in P \qquad \text{Equation 2.25}$$

while the objective function (Equation 2.18) remains unchanged. If not all regions participate in the trades, the number of trading regions can be limited to a subset of regions.

Trading or JI with regions outside the model domain is modelled through a modification of the objective function. This will still minimise pollution control costs subject to the usual constraints (in particular Equations 2.19 to 2.25) but consider, in addition to the costs of controlling emissions within the model domain (i.e., of all countries part of the set *I*), also the (net) costs of buying emissions from elsewhere. These net costs of buying emissions elsewhere equal the (permit) price per unit of pollutant (T_p) times the (net) quantity bought (Qi_p) by each region/country. The price can be set exogenously, e.g., using the results of other global models. Thereby, the objective function now is to minimise:

$$Total\ costs = \sum_{i \in I} \cos t_i + \sum_{i \in I} Tp \times Qip \qquad \text{Equation 2.26}$$

The volume of emission reductions that can be bought for a given price can be restricted by adding a constraint on the quantity than can be bought for that particular price.

2.6 Sector disaggregation

2.6.1 Aggregation of emission sources

Greenhouse gas emissions are released from a large variety of sources with significant technical and economic differences. Conventional emission inventory systems, such as the inventory of the United Nations Framework Convention on Climate Change (UNFCCC), distinguish more than hundreds of different processes causing various types of emissions.

In the ideal case, the assessment of the potential and costs for reducing emissions should be carried out at the very detailed process level. In reality, however, the necessity to assess abatement costs for all countries in Europe, as well as the focus on emission levels in 10 to 20 years from now restricts the level of detail which can be maintained. While technical details can be best reflected for individual (reference) processes, the accuracy of estimates on an aggregated national level for future years will be seriously hampered by a general lack of reliable projections of many of these process-related parameters (such as future activity rates, autonomous technological progress, etc.). For an integrated assessment model focusing on the pan-European scale it is therefore imperative to aim at a reasonable balance between the level of technical detail and the availability of meaningful data describing future development, and to restrict the system to a manageable number of source categories and abatement options.

2.6.2 Criteria for aggregation

For the RAINS greenhouse gas module, an attempt was made to aggregate the emission producing processes into a reasonable number of groups with similar technical and economic properties. Considering the intended purposes of integrated assessment, the major criteria for aggregation were:

- The importance of the emission source. It was decided to target source categories with a contribution of at least 0.5 percent to the total anthropogenic emissions in a particular country.
- The possibility of defining uniform activity rates and emission factors.
- The possibility of constructing plausible forecasts of future activity levels. Since the emphasis of the cost estimates in the RAINS model is on future years, it is crucial that reasonable projections of the activity rates can be constructed or derived.
- The availability and applicability of “similar” control technologies.
- The availability of relevant data. Successful implementation of the module will only be possible if the required data are available.

It is important to carefully define appropriate activity units. They must be detailed enough to provide meaningful surrogate indicators for the actual operation of a variety of different technical processes, and aggregated enough to allow a meaningful projection of their future development with a reasonable set of general assumptions.

2.6.3 Generic activity data

The RAINS model database includes activity data for historical years, i.e., 1990, 1995 and 2000, and projections up to 2030. In fact, the model allows for several projections (activity pathways) that can be stored and used to assess alternative scenarios.

Historical data and projections of future activities like population, fuel consumption, number of animals, etc., were taken from the existing RAINS database, which has been compiled from UN, EUROSTAT and IEA statistics. For the six greenhouse gases, the following sources have been used in addition to the RAINS database.

Table 2.1: Data sources used for estimating greenhouse gas emissions in RAINS

Sector	CO_2	CH_4	N_2O	F-gases
Fuel combustion: stationary	RAINS, IEA	RAINS	RAINS	
Transport	RAINS	RAINS	RAINS	RAINS, AEAT(2003), O&L (2001)
Fuel production		RAINS, PRIMES		
Industrial process emissions	RAINS		RAINS, UNFCCC (2004)	RAINS, UNFCCC (2004) H&H (200) AEAT (2003), S&L (1999)
Fugitive emissions	UNFCCC (2004)			
Domestic sector				UNFCCC (2004). O&S (2001), P (2001)
Agriculture (livestock & rice cultivation)		RAINS, Houghton *et al.*, 1997	RAINS, EUROSTAT	
Waste (population)		UN (2000), World Bank (2001)	RAINS	

H&H (2000): Harnisch and Hendriks (2000); O&L (2001): Oinonen and Soimakallio (2001); P: Poulsen (2001); S&L (Schwarz and Leisewitz, 1999).

3 Carbon dioxide

3.1 *Introduction*

Carbon dioxide, at a concentration near 0.04 percent, is the compound that exerts the strongest climate forcing of all trace gases in the atmosphere. Among the trace gases, the contribution of carbon dioxide to the greenhouse effect is estimated at 60 percent, which is about 70 percent of the gases covered by the Kyoto protocol (not considered in the Kyoto basket are ozone, a secondary compound, and CFC, being phased out already according to the Montreal protocol). Atmospheric concentrations have increased by about a third over the last 200 years (Houghton *et al.*, 2001).

The atmosphere acts as just one reservoir in the global carbon cycle. Other compartments are dissolved CO_2 in seawater, especially in the deep ocean, biomass of terrestrial or marine organisms and in soils, fossilised biomass as peat, fossil gas, oil, and coal, and carbonated minerals (e.g., lime). While vegetation is both emitting and absorbing CO_2, it is primarily combustion of fossil fuels which cause an unbalanced concentration increase. The oxidation of carbon stored in the fuels to CO_2 is the process that releases energy, so energy production and CO_2 emissions are intrinsically linked processes. Significant differences in CO_2 emissions per energy released occur between natural gas, having also considerable content of chemically bound hydrogen to oxidise into water, and coal that contains only little hydrogen and thus has highest emissions. Any change in the natural equilibrium of carbon between atmosphere and biosphere (e.g., land use change, deforestation) also impacts atmospheric CO_2 concentrations, as do processes, which tackle carbonated minerals (cement production, but also volcanoes)

This chapter first describes the emission source categories for CO_2 considered in RAINS and then the emission factors and the method to calculate emissions. Subsequently, the options and costs for the main fuel combustion sectors (power plants and district heating, transport, the domestic sector) are discussed before some initial results are shown.

3.2 *Emission source categories*

The UNFCCC distinguishes the following sources of emissions: biomass burning, international bunkers, fugitive emissions from fuels, fuel combustion (sector approach), industrial processes, solvent and other product use, agriculture, land-use change, forestry and waste (UNFCCC, 2004; http://ghg.unfccc.int). In the UNFCC inventory, the category "National Total" does not include emissions resulting from fuel sold to ships or aircraft engaged in international transport (international bunker fuel emissions). Furthermore, in the case of CO_2, the "National Total" does not include emissions from biomass burning or emissions or removals from the land-use change and the forestry sector. Instead emissions from biomass, burning, land-use change and forestry as well as international bunkers are reported separately.

For the Annex I countries, 95 percent of the national total CO_2 emissions in 1990 (14615 Mt CO_2) originated from fuel combustion. Industrial processes contributed roughly five percent. Fugitive emissions caused around one percent of the emissions. Solvent and other product use and agricultural waste contributed around 0.15 percent of the Annex I emissions. In the non-Annex I countries total national emissions were 1560 Mt CO_2. In these countries, fossil fuel combustion was responsible for around 94 percent and industrial processes for the remaining six percent. Other source categories were negligible in 1990.

For Annex I countries, international bunkers, if added to the national totals, would increase the 1990 emissions by some two percent, and biomass burning would add another three percent. Land-use and forestry changes resulted in a net decrease of emissions by roughly 13 percent in the Annex I countries. In non-Annex I countries, national bunkers are as large as six percent of the total national emissions reported. Biomass burning would increase national totals by 16 percent of the emissions. Land-use change and forestry are five percent of the national total of the Annex I countries for 1990.

3.3 Emission factors

In the interest of a comprehensive economic assessment of the full range of options for the control of greenhouse gases, RAINS attempts to capture all anthropogenic sources of CO_2 emissions. In view of the relevance of the sources, the current version of RAINS focuses on fuel combustion, industrial processes and fugitive emissions. Thus, the current assessment does not include CO_2 emissions from solvent use, other products, from agricultural waste and fugitive emissions. While international bunkers for national and international air transport are included in RAINS, international bunkers for shipping are not included at the current stage. Also, for the current assessment, the analysis does not include emissions from biomass burning for non-energy purposes, land-use changes and forestry. Including these sources would provide an interesting extension of the approach in the future.

3.3.1 Energy use

CO_2 emissions from fuel consumption primarily depend on the carbon content of the fuel. Data on the supply of commercial fuels, combined with typical carbon content figures, provide then a sound starting point for the estimation on CO_2 inventories (Houghton *et al.*, 1997b; p. 1.1.) The RAINS model uses energy balances on energy content basis (PJ) that can be combined with the IPCC reference values for the carbon emission factors. Since fuel qualities and emission factors may differ substantially between countries, the IPCC recommends the use of local energy factors and emission factors when preparing national inventories. The RAINS model already includes information on country- and sector-specific heat values but currently does not include information on country-specific carbon emission factors. For the time being the reference approach is used to calculate the national CO_2 emissions from the energy use of fossil fuels.

In addition, fossil fuels are also used for non-energy purposes (non-energy use of fuels), e.g., the production of ammonia from natural gas or asphalt from oil. Some of these applications result in the storage of carbon. Part of the carbon stored might oxidise quickly such as the carbon from fertiliser production, lubricants, detergents and volatile organic solvents (Houghton *et al*., 1997b; p. 1.25 to 1.28). Table 3.1 provides the CO_2 emission factors that are presently used by RAINS.

3.3.2 Industrial processes

A range of (non-energy related) industrial activities leads to CO_2 emissions. Industrial processes that, potentially, lead to CO_2 emissions include production and handling of mineral products (cement production, limestone production, limestone use and soda-ash production), chemical industry (ammonia, carbides), metal production (iron, steel and ferroalloys, aluminium, magnesium and other metals) as well as other sources (Houghton *et al.*, 1997b; p. 2.3). The IPCC emission inventory guidelines specify methodologies based on reference emission factors for cement production, lime production, limestone use, soda-ash production, ammonia production, calcium carbide production, iron and steel, ferroalloy as well as primary aluminium production.

Table 3.1 summarises the emission factors used in this study for energy and the most important non-energy sources by type of fuel. Emission coefficients are based on IPCC (Houghton *et al.*, 1997b).

Table 3.1: Reference emission factors for CO_2

RAINS fuel category	Energy [kg CO_2/GJ]	Non-energy use of fuel [kg CO_2/GJ]	Industrial processes [kg CO_2/ton]
Brown coal	99.5	25.8	
Hard coal	94.3	23.9	
Derived coal	100.0	25.5	
Other solids 1 (Biomass)	0.0	0.0	
Other solids 2 (Other waste)	55.0	0.0	
Heavy fuel oil	76.7	19.5	
Middle distillates	73.4	36.9	
Gasoline	68.6	18.0	
LPG	68.6	18.0	
Methanol	68.6	18.0	
Natural gas	55.8	37.8	
Cement production (ton cement)			500
Lime production (ton lime)			785-913

3.3.3 Fugitive emissions from energy

Fugitive emissions from energy are releases of gases from human activities. These emissions may in particular arise from the production, processing, transportation, storage and use of fuels. Although the most significant GHG here is methane, CO_2 emissions may result from burning of coal in coal deposits and waste piles (Houghton *et al*., 1997b;. p. 1.112) and from SO_2 scrubbing. National inventories sometimes include estimates for these fugitive emissions (see www.unfccc.org). Reported total fugitive emissions in Europe amount to about 0.5 percent of the total CO_2 emissions. For the time being RAINS excludes this category, but future extension could include them in a simplified way by relying on the national estimates.

3.4 Emission control options and costs

While there are a limited number of options under development to capture carbon dioxide at its sources, the more important potential for reducing carbon dioxide emissions results from lower consumption of carbon intensive fuels. Such reductions can be achieved through lower final demand for energy, through increased fuel conversion efficiency to satisfy a given final demand with less primary energy input, and through fuel substitution where carbon intensive fuels are replaced by fuels with less carbon content.

Compared to the 'add-on' emission control options as they are included in the air pollution related parts of RAINS, modelling of such structural changes requires a fundamentally different concept. In contrast to the 'add-on' options, the structural composition of energy consumption and the consumption volumes of individual fuels cannot be considered as fixed exogenous inputs for the modelling exercise, but evolve as the central means for controlling the level of CO_2 emissions. Thus, the most important relationships that safeguard internal consistency (e.g., between demand and supply) and constraints that limit the application potentials to realistic rates need to be reflected in the modelling approach.

Traditionally, the options and the potentials for modifications in energy systems are studied with specialised energy models, which attempt to outline potential changes in energy systems based on empirically observed behavioural and economic principles while maintaining physical consistency in the energy and material flows. Although there is wide variety of modelling concepts, it is common to such specialised energy models that realism in their analysis evolves through the level of detail that is considered. Consequently, models that assess concrete options for changes, e.g., in national energy systems, exhibit a good deal of complexity with significant technical and structural detail.

It is difficult to maintain the level of detail that is obviously required for any realistic quantitative assessment of the options for structural changes in national energy systems in one pan-European modelling exercise, as envisaged for the RAINS model. However, the difficulty to fully capture all necessary detail of a specific aspect of pollution is not new to RAINS: similar situations apply to the modelling of atmospheric transport or to the simulation of environmental impacts, which are traditionally described with complex models that incorporate a great deal of detailed and site-specific data. In these cases, 'reduced-form' representations of the complex disciplinary models have been successfully developed for RAINS that describe, in terms of selected output indicators, the relevant response of the full system towards well-defined changes in input variables in mathematically efficient form.

To model the potential of structural changes that can lead to reductions in CO_2 emissions, RAINS follows the same concept. RAINS implements the most important relationships that safeguard physical consistency (e.g., to balance demand and supply for the individual fuels), and applies constraints to the substitution potentials that are derived from specialised energy models, which capture the full detail of national energy systems. In such a way, the RAINS greenhouse gas model needs to be operated in conjunction with national energy models that provide for each country the substitution potentials under a range of assumptions. While the energy model will provide a baseline projection and the potentials for and costs of deviations from this baseline, the RAINS model will then balance such measures against controls of other air pollutants and greenhouse gases in such a way that the environmental targets will be achieved in a (cost-) optimal way.

In order to maintain the model system manageable, the options for structural changes that are considered in the model should be restricted to the most relevant alternatives. Obviously, the choice of options to be considered depends on the sector. The following sections describe the measures in the power sector, for transport and part of the options in the residential and commercial sectors. The modelling of industrial energy combustion is still under development.

3.4.1 Emission control options in the power generation sector

3.4.1.1 Fuel substitution

Options for fuel substitution

As one of the main practical options for reducing CO_2 emissions from power generation RAINS considers the substitution of carbon-intensive fuels by carbon-free fuels or fuels with less carbon content. Thus, in the present implementation, RAINS provides for the possibility to replace

- hard coal,
- brown coal,
- fuel oil, and
- natural gas,

by

- natural gas,
- nuclear energy,
- hydropower,
- biomass combustion,

- on-shore wind turbines,
- off-shore wind turbines,
- solar photovoltaic, and
- other forms of renewable energy such as geothermal, wave and solar thermal.

Each potential replacement option (i.e., from each original power generation mode to each low carbon mode) is modelled as an individual measure, with country-specific costs and country-specific application potentials. In total, RAINS considers in principle 31 explicit options for fuel substitution (Table 3.2). Furthermore, RAINS distinguishes between new-built capacities and existing plants, in order to reflect limitations in replacement potentials for existing infrastructure imposed by practical considerations, increased costs of retrofit measures and the shorter remaining lifetime of investments for already existing plants. In principle, the same options as shown in Table 3.2 apply for existing power plants. The main difference is that for shifting from brown coal, hard coal or heavy fuel oil to natural gas only the difference in fuel costs matters, since it is assumed that (part of the) boilers can be substituted without additional investments in the boiler. In case of shifting from existing fossil fuel plants (be it brown coal, hard coal, heavy fuel oil) to (new) nuclear or renewable plants, the sunk costs are considered.

Table 3.2: Options for fuel substitution considered in RAINS

Original fuel	Gas	Nuclear	Hydro-power	Biomass	Wind onshore	Wind offshore	Solar photo-voltaic	Other renewables
Brown coal	x	x	x	x	x	x	x	x
Hard coal	x	x	x	x	x	x	x	x
Heavy fuel oil	x	x	x	x	x	x	x	x
Natural gas		x	x	x	x	x	x	x

RAINS considers the differences in power generation efficiencies between these options and calculates the resulting changes in primary energy input in order to maintain the original volume of electricity output. To give an example, 1 PJ of hard coal can be burned in an existing hard coal fired power plant with a (net) efficiency of 35 percent, thus generating 1*0.35 = 0.35 PJ of electricity. To generate the same amount of electricity using natural gas (with an assumed efficiency of 50 percent) 0.35/0.5 = 0.7 PJ of gas input is needed. Technology-specific average fuel efficiencies for the various energy technologies are derived from the literature (Table 3.3).

Table 3.3: Net electricity production efficiencies assumed for fuel substitution

	Net electricity production efficiency [%]
Brown coal	33
Hard coal	35
Heavy fuel oil	35
Gas	50
Nuclear	100
Hydropower	100
Biomass (wood)	33
Wind, on-shore	100
Wind, off-shore	100
Solar photovoltaic	100
Other renewables (wave, geothermal energy)	15

Potential for fuel substitution

As discussed before, the RAINS model starts from an exogenously supplied baseline scenario of energy consumption. Such projections of energy use are supposedly internally consistent in terms of physical energy and material flow balances and consistent with a wide range of assumptions, including the rate of economic growth, the evolution of the economic wealth of consumers, consumer preferences, the development of global energy prices, technological progress, import and export flows of energy, energy policy and carbon prices. Any such projection, however, is only one possible picture of the future development, and alternative assumptions on relevant driving factors will lead to alternative developments. It is important, however, to determine the physical, technical and economic limitations within which fuel substitution can take place, as they will serve as constraints to the calculations of the RAINS model.

There are important physical limitations, in particular to the availability of fuels. While the availability of globally traded fuels, such as coal, oil and gas, is usually not of prime relevance for possible deviations from medium-term national energy projections, the availability of renewable energy sources is a crucial element in national fuel substitution strategies. For this report, country-specific data was compiled from several studies on the potential supply of electricity from the major renewable energy sources in the power sector. Table 3.4 provides illustrative estimates of the potential supply of renewable energy in Europe. These potentials are based on a variety of studies and include results of the PRIMES model for the “with climate policies” scenario developed for the needs of the CAFE program (http://europa.eu.int/com/environment/air/cafe/activities/basescenario.htm).

It is important to note that these estimates have been derived from scenario studies, where the indicated volumes of renewable energy have been considered as economically attractive under certain (climate) objectives, i.e., for a given carbon price and with assumptions on the prices of other energy forms and the pace of diffusion of the renewable technologies. The full technical potential for renewable energy might be larger, though only available at higher costs. It is also important to mention that these estimates relate to different points in time (2010 and 2020), and were conducted at different times. The more recent estimates (e.g., for PRIMES) show in general higher potentials than the earlier studies (CEC, 1994; ESD, 1997; Hendriks *et al.*, 2001). Information on hydropower, biomass and wind energy in 2000 and, to a certain degree 2010, is also available for Bulgaria, Norway, Romania, Switzerland, Turkey, Cyprus and Malta. Further work with specialised energy models will be necessary to refine these estimates, to clarify their time-dependencies and to determine their economic aspects, so that these features can be included in the RAINS calculations.

Country-specific estimates are also available the potential contribution of solar photovoltaic, geothermal energy and solar thermal energy (ESD, 1997; Hendriks *et al.*, 2001) as well as for tidal energy, especially tidal barriers. The currently available output from the PRIMES model does not contain information of the potential for solar PV and tidal energy. Further analysis is needed to arrive at robust estimates. Compared to hydropower, biomass and wind, the potential of these other renewables in Europe is relatively small, at least up to 2020.

Table 3.4: Estimates of the potential availability of hydropower, biomass and wind energy for electricity production in Europe. (Sources: CEC, 1994; ESD, 1994; Hendriks *et al.*, 2001; PRIMES, EUROSTAT, 2003; IEA, 2003b). Fuel input (PJ) for hydropower 100 percent efficiency is assumed.

	Hydropower			Biomass			Wind		
	Literature		PRIMES	Literature		PRIMES	Literature		PRIMES
	2000	2010	2020	2000	2010	2020	2000	2010	2020
Austria	151	156	171	23	14	30	0	7	189
Belgium	2	1	2	13	1	22	0	14	13
Bulgaria	10	15	15	0		27		2	
Cyprus						3			
Czech Rep.	6	12	15	11	0	18	0	2	10
Denmark	0	0	0	44	10	77	15	49	47
Estonia	0	0	0	2	0	6	0	0	1
Finland	53	69	50	12	23	33	0	25	11
France	241	258	261	30	41	52	0	32	88
Germany	78	66	102	20	31	184	34	94	316.
Greece	13	32	23	0	13	10	2	14	16
Hungary	1	10	1	0	0	1	0	0	10
Ireland	3	3	3	0	2	9	1	20	11
Italy	159	169	161	15	17	128	2	51	71
Latvia	10	0	16	7	0	9	0	0	5
Lithuania	1	0	2	1	0	8	0	0	5
Luxembourg	0	0	1	1	0	1	0	0	1
Malta	0	98	0	0		1		5	
Netherlands	1	1	1	30	4	60	3	40	27
Norway	510		518	0	.	2	0	0	
Poland	8	26	19	2	0	27	0	6	47
Portugal	41	41	58	11	5	42	1	19	11
Romania	53	83	88	1		39		3	
Slovakia	17	12	20	0	0	11	0	2	7
Slovenia	14	0	20	0	0	7	0	0	1
Spain	102	120	163	24	19	254	17	32	124
Sweden	284	332	246	18	23	32	2	34	30
Switzerland	133		145	4		11	0	0	
Turkey	111		281	3		31	0	0	
UK	18	22	18	45	38	167	3	43	145
Total	2019	1526	2398	318	241	1301	80	493	1015

Table 3.5: Estimates of the potential availability of solar photovoltaic, geothermal and wave/tidal energy in Europe (EU-23) (PJ_{el})

	Solar photovoltaic			Geothermal			Tidal		
	Literature		PRIMES	Literature		PRIMES	Literature		PRIMES
	2000	2010	2020	2000	2010	2020	2000	2010	2020
Austria	0	0	.	0	0	1	0	0	.
Belgium	0	0	.	0	0	0	0	0	.
Bulgaria	.	1	.	.	.	.	.	.	
Czech Rep.	0	0	.	0	0	0	0	0	.
Cyprus	.	.	.	.	.	.	.	.	
Denmark	0	0	.	0	0	0	0	0	.
Estonia	0	0	.	0	0	0	0	0	.
Finland	0	0	.	0	0	0	0	0	.
France	0	1	.	0	0	0	2	4	.
Germany	2	1	.	0	0	0	0	0	.
Greece	0	1	.	0	0	0	0	0	.
Hungary	0	0	.	0	0	0	0	0	.
Ireland	0	0	.	0	0	0	0	0	.
Italy	1	2	.	17	22	24	0	0	.
Latvia	0	0	.	0	0	0	0	0	.
Lithuania	0	0	.	0	0	0	0	0	.
Luxembourg	0	0	.	0	0	0	0	0	.
Malta	.	.	.	.	.	.	.	.	
Netherlands	0	0	.	0	0	0	0	0	.
Norway									
Poland	0	2	.	0	0	0	0	0	.
Portugal	0	1	.	0	0	0	0	0	.
Romania		1							
Slovakia	0	0	.	0	0	0	0	0	.
Slovenia	0	0	.	0	0	0	0	0	.
Spain	1	3	.	0	0	1	0	0	.
Sweden	0	0	.	0	0	0	0	0	.
Switzerland									
Turkey									
UK	0	0	.	0	0	0	0	14	.
Total	4	13	.	17	24	26	2	18	.

For comparison, Hendriks *et al.* (2001) estimate for 2010 for the EU-15 potentials of 7.3 PJ_{el} for solar PV, 34 PJ_{el} for geothermal, 2 PJ_{el} for wave energy and 378 PJ_{el} for tidal energy.

Additional assumptions need to be made on the potential for the expansion of natural gas and nuclear energy in the electricity sector. Since these potentials depend largely on national peculiarities (e.g., political preferences, structural features of the gas infrastructure, etc.), RAINS derives constraints for the increased use of natural gas and nuclear energy from specific scenarios developed with national energy models that address these questions on a solid basis. Thus, these substitution potentials have to be seen as a scenario dependent input to RAINS, and no absolute limits are considered in the RAINS databases.

The RAINS analysis distinguishes cases where existing plants continue to operate with lower carbon fuels (natural gas, biomass) without major retrofit investments, and fuel substitution options, which require complete construction of new generating capacity (wind, solar, hydropower, etc.).

Costs of fuel substitution

For fuel substitution, costs are determined as the difference between the electricity generation costs of the existing (new) power plants (included in the baseline) and the power plants that will substitute them. For each power generation option, costs are calculated following the standard approach in RAINS, i.e., considering investments as well as fixed and variable operating costs including the costs of fuel. Investments are distributed over the technical lifetime of the equipment, using a standard discount rate of four percent. Investments (I) are annualised over the technical lifetime of the plant t by using the real interest rate q (as %/100) and expressed per kW electric capacity:

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \qquad \text{Equation 3.1}$$

Investments include all costs accrued until the start-up of an installation (construction, engineering, land use, licensing fees, etc.). Fixed operating costs include costs that are related to the existing capacity but independent of its actual operation, such as routine maintenance, insurance, etc., while variable operating costs cover labour costs, fuel costs, and costs for other production means such as cooling water or waste disposal. It is important to mention that air pollution control costs, e.g., for flue gas desulphurisation, $DeNO_x$ equipment and dust filters are not included in these cost data, since they are calculated separately in the RAINS model. For new generation capacities the technical lifetimes assumed are technology-specific and vary between 15 and 30 years (see Table 3.7).

The annual **fixed expenditures** OM^{fix} (per kW_{el}) cover the costs of repairs, maintenance and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for annual fixed expenditures, a standard percentage f of the total investments is used:

$$OM^{fix} = I * f \qquad \text{Equation 3.2}$$

In turn, the **variable operating costs** OM^{var} per kW_{el} are related to the actual operation of the plant and take into account fuel use (fuel input), efficiency and operating hours. In case of co-generation revenues from heat generation can also be reflected.

$$OM^{var} = c^{f} * (3.6/1000) * pf * 100 / \eta^{e} \qquad \text{Equation 3.3}$$

where

c^f fuel price (cost per unit; €/GJ),

pf plant factor (annual operating hours at full load),

η^e electricity generation efficiency (%).

The total costs per kWh electricity produced can than be expressed as:

$$Ce = (I^{an} + OM^{fix} + OM^{var}) / pf \qquad \text{Equation 3.4}$$

Alternatively, these costs can be expressed per PJ electricity produced by converting kWh into PJ_{el}. In this case the additional costs of substituting a fossil-fuel fired (reference *r*) plant by an alternative fuel *a* related to on PJ of electricity produced are:

$$\Delta Ce_{ra} = Ce_a - Ce_r \qquad \text{Equation 3.5}$$

The additional cost can then be expressed in PJ of input of the reference fuel (e.g., per PJ of hard coal) by multiplying the additional costs (per PJ_{el}) by the generation efficiency of the reference fuel:

$$\Delta Cf_{ra} = \Delta Ce_{ra} * \eta_r{}^e / 100 \qquad \text{Equation 3.6}$$

The costs per ton CO_2 abated can be calculated by subtracting the emissions of the alternative fuel (per unit of reference fuel replaced) from the emissions (per PJ of the reference fuel) of the reference fuel

$$\Delta E_{r \to a} = \Delta Cf_{ra} / ((e_{ffr} - e_{ffa}) * \eta_r / \eta_a) \qquad \text{Equation 3.7}$$

Country-specific costs of electricity generation are calculated based on technology-specific and fuel-specific combustion efficiencies as well as country-specific capacity utilisation rates and fuel prices for each individual country. Relevant data are already contained in the RAINS databases (see http://www.iiasa.ac.at/web-apps/tap/RainsWeb/MainPageEmco.htm).

Default data for alternative means of electricity production are provided in Table 3.6. Fuel prices (net of VAT and fuel taxes) vary from country to country. They are reported on a regular basis by the International Energy Agency (e.g., IEA, 2003a). The values given in Table 3.6 represent typical values for the year 2000 over all countries for which data are reported. The price for brown coal (on an energy content basis) is assumed equal to the hard coal price in a country. Fuel costs for biomass were based on Hendriks *et al.* (2001) and time series data on biomass prices charged for industrial and electricity generation (Lindmark, 2003). Biomass prices are generally considered region- and country-specific. While they have been relatively stable in the past, for scenario calculations both capacity utilisation rates and fuel prices need to be provided as an integral part of the energy projection.

Table 3.6: Default values for operating hours and fuel prices for electricity generation, used for RAINS calculations if no national data are available.

	Capacity utilisation [hours/year]		Fuel prices [€/GJ]
	Existing power plants	New power plants	
Brown coal	4425	4990	1.7
Hard coal	4000	4500	1.7
Biomass	4300	4700	3.2
Heavy fuel oil	3460	3850	4.0
Natural gas	2500	4700	3.5
Nuclear	5500	5500	2.0[a]
Wind turbines	2500	2500	-
Hydropower	3500	3500	-
Solar photovoltaic	1080	1080	-

[a] Includes the costs of uranium, enrichment as well as fabrication costs (recalculated per GJ fuel input assuming 100% efficiency (IEA/NEA, 1998).

Technology-related cost data were collected for all options considered in the RAINS model. Data were taken from the databases of IIASA's MESSAGE model (Nakicenovic *et al.*, 2000; Riahi and Roehrl, 2000; Riahi *et al.*, 2003; Strubegger and Reitgruber, 1995) and from a variety of other sources (Coenen, 1985; Hendriks *et al.*, 2001; IEA/NEA, 1998, Jankowski, 1997; IER, 2001; Marsh *et al.*, 2003).

Table 3.7 lists the major cost items for new power generating capacities and provides average unit costs for electricity production as calculated with the default values for capacity utilisation contained in the RAINS model and the energy prices listed in Table 3.6. In the RAINS model, the costs differ from country-to-country due to differences in operating hours and fuel prices. Costs of fuel substitution are calculated as the differences between the production costs of the new reference unit and the alternative with lower carbon emissions.

Table 3.7: Costs of new electricity generation options used for calculating costs of fuel substitution

	Investments [€/kW$_{el}$]	Fixed operating and maintenance costs [€/kW$_{el}$][%]	Typical unit costs [€cts/kWh]
Brown coal	1010	34.3 (4.3)	4.2
Hard coal	970	26.2 (2.7)	3.8
Heavy fuel oil	708	47.5 (6.7)	6.8
Natural gas	666	47.5 (6.7)	4.4
Nuclear energy	2010	90.0 (4.5)	4.4
Hydropower	3000	48.5 (1.6)	6.3
Biomass (wood)	1455	75.6 (5.2)	7.6
Wind turbines, onshore	1000	25.0 (2.5)	4.2
Wind turbines, offshore	1750	30.0 (1.7)	6.2
Solar photovoltaic	4000	92.2 (2.3)	29.9
Other renewables (i.e. geothermal, wave)	1420-3500	86-140.0 (6.1-4.0)	3.8-7.3

For existing power plants using coal and heavy fuel oil that can shift to natural gas (co-firing) or biomass without major additional investments, only the additional fuel-related costs are considered.

3.4.1.2 Fuel efficiency improvements

Options for fuel efficiency improvements

An important option for reducing carbon emissions is the improvement of fuel efficiency, which allows the production of the same amount of electricity with less fuel and hence less emissions. In most cases, energy models assume fuel efficiencies (for new electricity generation technologies) to improve autonomously over time, so that a gas turbine built in 2030 would be more efficient than a gas turbine built in 2010 due to autonomous technological progress. Also investment costs are often considered to decrease due to technical progress. Given the time horizon of RAINS up to 2030 and the uncertainties surrounding the efficiency improvements, the RAINS model considers combined heat and power generation (CHP) and (coal-based) integrated gasification combined cycle as two explicit options for efficiency improvements, but does not embark on assumptions on further autonomous efficiency improvements of conventional plants.

Cogeneration (or CHP) is a highly efficient technique to jointly produce thermal energy (heat) and electricity. In 1999, approximately 11 percent of total electricity generation in the EU-15 was generated by means of co-generation (CEC, 2002). The use of CHP depends critically on sufficient demand for heat close to the plant. Large combined cycle plants (100 to 250 MW$_{el}$) tend to be used in industries such as the chemical industry and the iron and steel industry. In non-ferrous metals, pulp and paper and food industry, smaller combined cycles are commonly used, although the food industry also tends to use gas turbines (Hendriks *et al.*, 2001). The commercial sector chiefly uses gas engines, and in the residential sector large combined cycles are common for district heating purposes.

Integrated Gasification Combined Cycle (IGCC) plants consist of a gasifier, a gas clean-up system and sulphur recovery plants, a gas turbine/generator, a heat recovery steam generator and the steam turbine generator. IGCC plants can be fired with different coals or oil derived feedstock such as heavy oil and tar. Biomass and waste can also be gasified. IGCC power plants combine with gasifiers and combined cycles two mature technologies. There is only limited experience in the commercial operation of integrated power plants (Rabitsch, 2000). Energy efficiencies of IGCC plants are higher than for conventional hard coal fired plants. In addition, SO_2 removal ranges from 90 to 99 percent. NO_x emissions are generally 70 to 80% lower than those from traditional coal-fired power plants (Schönhart, 1998). PM emissions are usually below the relevant emission limits for large combustion plants.

Potential for fuel efficiency improvements

Significant uncertainty exists on the potential fuel savings and penetration of renewable energy. The proposed Directive of the EU (CEC, 2002) therefore contains as a major element the obligation for EU member states to analyse the potential for (highly efficient) cogeneration facilities. Bearing this in mind, Hendriks *et al.* (2001) propose that CHP units might replace in industry non-CHP units to cover the growth in heat demand. In addition, existing steam boilers and steam turbines might be retrofitted by adding a separate gas turbine up-front. Existing steam boilers/steam turbines are assumed to produce 50 percent of industrial heat demand, of which around 80 percent might be covered by CHP. Increased availability of options to reduce energy demand might reduce the potential for CHP (Hendriks *et al.*, 2001). Thus, the potential reductions in emissions through CHP depend on the type of CHP applied and its efficiency. The type of CHP is mainly industry- and not necessarily country-specific.

According to Hendriks *et al*. (2001; p. 17), in the service and residential sectors only new dwellings and commercial sites are realistic markets for CHP. Thus, in Northern Europe 50 percent of the heat demand for new dwellings might be covered by CHP, in Central Europe 25 percent and in Southern Europe 10 percent. Without deeper insight into the PRIMES model it is difficult to examine to what extent the share of CHP increases in the various scenarios. Previous analysis with PRIMES indicated that, depending on the marginal carbon abatement costs, up to around 10 percent of the CO_2 emission reductions achieved in the EU might originate from an increased use of CHP. To arrive at country-specific details further analysis with energy models is needed.

In principle, IGCC plants can be used to replace conventional new hard coal fired plants, although at an extra costs. IEA estimates suggest that six to eight percent of total, global coal-fired capacity in 2010 could consist of IGCC plants.

Costs of fuel efficiency improvements

The literature provides a range of estimates of the costs and fuel efficiency improvements of different cogeneration technologies (Coenen, 1985; Jankowski, 1997; Hendriks *et al*., 2001), see Table 3.8.

Table 3.8: Costs and efficiencies of combined heat and power generation (CHP)

Fuel		Coal	Gas	Gas	Gas	Gas	Biomass
		CHP	Combined cycle, large plants	Combined cycle, district heating	Combined cycle, small plants	Gas turbine	
Size	MW_{el}	41	100-250	100-250	25-100	10-50	
Investment	€/kW_{el}	1400	500	680	750	800	1400
O&M fixed	€/kW_{el}	22	9	7	14	14	50
O&M variable	€/kWh	0.001	0.004	0.004	0.004	0.004	0
Efficiency:							
- Electricity	(%)	30	44	48	42	40	40
- Heat	(%)	34	34	36	32	39	39
Lifetime	Years	15	15	15	15	15	15

Estimates for the investment costs of a (coal-fired) IGCC plant amount at around 1550 €/kW_{el} (Rabitsch, 2000). Annual operating and maintenance costs are estimated at 78 €/kW_{el}. The electric efficiency is assumed to be 46 percent. Given the fuel costs for a coal-fired plant, electricity generation costs are around 5.5 cts/kWh compared to around 4 cts/kWh for a traditional single steam cycle coal-fired power plant. The SO_2 removal efficiency is typically 99 percent, and 80 percent of the NO_X emissions are removed.

3.4.1.3 Carbon capture

Options for carbon capture

Various possibilities exist to capture carbon dioxide from energy conversion processes. In principle, two basic options can be distinguished (Hendriks *et al.*, 2002; Rabitsch, 2000):

- Pre-combustion: fossil fuel is converted to a carbon rich stream;
- Post-combustion: carbon is removed from the flue gas.

Pre-combustion removal is applied within IGCC plants. In the post combustion process absorption, adsorption or separation (membrane or cryogenic) is used. While many methods are technically feasible, chemical or physical absorption seems to be most promising for natural gas and coal.

Potential for carbon capture

Carbon dioxide can be stored in underground layers such as empty oil fields, empty natural gas fields and aquifers. Remaining oil fields can be exploited with enhanced oil recovery, and for unminable coal enhanced coal bed methane recovery can be applied (Hendriks *et al.*, 2002). Studies suggest a best estimate of the global storage potential of 1660 Gt CO_2, i.e., 80 times the current net annual carbon dioxide emissions. The uncertainty ranges from 500 to 6000 Gt CO_2 per year (see Hendriks *et al.*, 2002). Riahi *et al.* (2004) propose that, with present assumptions on costs and on economic growth, between 90 and 243 Gt C might be sequestered over the period 1990-2100. This would represent 10 to 25 percent of global carbon emissions. However, only little information is available on the national or regional potentials. Hendriks *et al*. (2002) quote a storage potential of around 65 Gt CO_2 for Western Europe, 12 Gt CO_2 for Eastern Europe and 350 Gt CO_2 for the Former Soviet Union. Assuming storage for 100 years, this estimates imply an annual potential for Western and Eastern Europe of 770 Mt CO_2, i.e., between 15 and 20 percent of the European emissions in 1990. Pending the results of more detailed national studies it is assumed that storage facilities will, on the medium term, not pose a restriction on the amount of carbon captured for new power plants in Europe.

Table 3.9: Calculation of emissions from hard coal and natural gas in new power plants in RAINS before carbon capture

RAINS sectors	PP_new_HC	Power plants new, hard coal	
	PP_new_Gas	Power plants new, gas	
Activity rate	Fuel use		
Unit	PJ		
Data sources	RAINS databases		
Emission factors		Unit	Default
	Hard coal	kt CO_2/PJ	94.3
	Natural gas	kt CO_2/PJ	55.8
Data sources	Fuel use: country country-specific, based on the RAINS database. Emission factors: default values from IPCC (Houghton *et al.*, 1997).		

Costs of carbon capture

Costs of carbon capture consist of the costs of carbon separation and the costs of compression, transport and storage. In post-combustion processes, CO_2 is separated from the flue gases using amine-based solvents (the best-known process). The heat required for this process causes a loss of electric efficiency between 10 and 25 percent. To transport CO_2 efficiently by pipeline, it needs to be compressed. Transportation costs depend on the transport distance and the flow size. Storage costs are a function of the depth of storage and the type of storage. Compression costs range typically from 5 to 10 €/t CO_2 (Hendriks *et al.*, 2002; p. 14). The literature estimates on transportation and storage costs range from 6 to around 8.5 €/t CO_2 for Western Europe and from 2.5 to 15 €/t CO_2 depending on the volume stored (Hendriks *et al*., 2002; p 59; Riahi *et al*., 2004). For RAINS, costs for compression, transportation and storage are assumed at 14 €/t CO_2.

Table 3.10. Cost of power generation plus CO_2 removal in the power sector for new plants.

	Investment	Fixed O&M	O&M variable costs: C transport and storage	Net electricity generation efficiency	Carbon removal efficiency	Unit cost
	€/kW_{el}	€/kW_{el}/yr	€/t CO_2 captured	%	%	€cts/kWh
Hard coal plants with carbon capture	1788	130	14	26	85	9.8
Natural gas plants with carbon capture	1000	63	14	44	85	6.2

Data sources: Hendriks *et al.* (2002), Riahi *et al.* (2003, 2004).

The calculation of the annual costs (per kW_{el}) follows the standard methodology with the exception that cost of carbon transport and storage are included in the variable O&M costs:

$$OM^{var} = (c^t * (ef_{CO2} * \eta^r / 1000) + c^f) * (3.6 / 1000) * pf * 100 / \eta^e \quad \text{Equation 3.8}$$

where

c^f	fuel price (cost per unit; €/GJ),
c^t	costs of carbon dioxide transport and storage fuel price (costs per unit; €/tCO_2 captured),
ef_{CO2}	unabated CO_2 emission factor (kt CO_2/PJ)
pf	plant factor (annual operating hours at full load)
η^e	electricity generation efficiency (%)
η^r	CO_2 removal efficiency (%).

3.4.2 Transport

A variety of options exist to control the rapidly growing CO_2 emissions of the transport sector. In addition to lowering transport demand through non-technical measures or shifting to other modes of transport, greenhouse gas emissions can be reduced through technological measures that increase fuel efficiency or use alternative fuels that lead to lower CO_2 emissions (diesel, compressed natural gas, ethanol or hydrogen). RAINS distinguishes fuel efficiency improvements and alternative fuels.

3.4.2.1 Fuel efficiency improvements

Options for fuel efficiency improvements

A variety of technical means is available to improve the fuel efficiency, and it is beyond the scope of the RAINS integrated assessment to model all available options in detail. Instead, RAINS analyses the cost-effectiveness and environmental efficiency of a limited number of pre-defined technology packages to reduce emissions from the transport sector and compares them with potential measures in other sectors.

For **passenger cars and light duty vehicles using gasoline**, it has been decided to distinguish two technology packages that lead to more fuel-efficient cars:

The *improved gasoline car* combines a number of different measures described by Bates *et al.* (2001; p. 56) that reduce fuel consumption by approximately 25 percent compared to the year 2000 vehicles with conventional, gasoline based internal combustion engines. Such improvements can be achieved through basic engineering measures, e.g., reducing engine friction, reducing aerodynamic drag plus brake drag, and application of high strength steel bodies with lightweight interior, as well as through modified engine designs using variable valve lifting or advanced gasoline direct injection engines.

A second, more efficient option, the *advanced gasoline car,* would combine the same engineering measures with a hybrid internal combustion engine instead of a gasoline direct injection engine. This would increase fuel efficiency improvements to a range between 35 percent (Marsh *et al.*, 2002) and 44 percent (Bates *et al.*, 2001; p. 56). For further calculations in RAINS, a rounded number of 40 percent improvement is assumed compared to the average year 2000 vehicle.

Similar packages have been assumed for passenger cars and light duty vehicles using diesel:

An *improved diesel car* would incorporate a variety of basic engineering measures, lightweight interior and lightweight body structure, which are estimated to reduce fuel consumption by about 15 percent compared to the reference 2000 models (Bates *et al.*, 2001; Marsh *et al.*, 2002).

Fuel efficiency improvements of approximately 40 percent are considered feasible for *advanced diesel cars,* essentially hybrid electric vehicles with compression ignition direct injection engines (Bates *et al.*, 2001; Ogden *et al.*, 2004).

For **heavy-duty vehicles** (trucks, buses), which are currently using diesels, the following two options for fuel efficiency improvements are foreseen:

The literature discusses a variety of options that could lead to *improved diesel heavy-duty vehicles.* Reduction of rolling resistance, aerodynamics cab roofs and aerodynamic cab deflectors as well as various engine improvements are estimated to reduce fuel consumption by around 15 percent compared to vehicles of conventional design (Bates *et al.*, 2001). Since in 2000 approximately half of the trucks had already implemented deflectors or cab roof fairing (Bates *et al.*, 2001; p. 65), the improvements relative to the actual year 2000 model year would be somewhat lower. Marsh *et al.* (2002) list a set of technical measures that yield reductions of seven percent for trucks and around 14 percent for buses. Using typical European ratios between the number of trucks and buses, the average improvement for the entire category emerges at eight percent. This number is taken as a conservative estimate for the further calculations in RAINS.

For *advanced heavy-duty vehicle,* fuel efficiency improvements of 35 percent have been suggested by Marsh *et al.* (2002) based on hybrid electric traction.

Potential for fuel efficiency improvements

The introduction of more fuel-efficient vehicles is essentially limited by the availability of appropriate technology and the turnover rate of the existing fleets. It is assumed that the options outlined above will be on the market by the year 2010 and can then be applied to all new vehicles when they gradually replace the existing vehicle stock. No premature scrapping of existing vehicles is assumed in the present analysis.

Costs of fuel efficiency improvements

RAINS calculates the costs of all emission control options considering investments, operating costs and fuel costs. Thus, costs of fuel efficiency improvements must consider increased investments of such options, modified operating and maintenance costs and the savings from the reduced fuel consumption. The following paragraphs review the information on investments and operating costs for the various packages of fuel efficiency improvements.

For **passenger cars** and **light duty vehicles using gasoline**, Bates *et al.* (2001) mention additional investments of € 1,250 per car for applying the measures assumed for the *improved gasoline car*. Cost estimates for hybrid cars (the *advanced gasoline car*) are, e.g., provided by Bates *et al.* (2001), Concawe/EUcars/JRC (2003a), Marsh *et al.* (2002) and SAIC (2002), and range from an additional € 5,500 per car to nearly € 7,700 (all prices given in € 2000). Marsh *et al.* (2002; p. E-10) expect these costs to come down to around € 2,700 in the year 2020 if volume production starts. Following these arguments, RAINS assumes the lower estimate of € 2,711 as to be more representative for the time horizon of this study (2015-2020).

Cost data for **passenger cars** and **light duty vehicles using diesel** are provided by Bates *et al.* (2001), mentioning € 1,086 for the measures listed under the *improved diesel car* option that reduce fuel consumption by 16.4 percent. Marsh *et al.* (2002) expect for the year 2020 costs dropping to € 362 per car (220 UK pounds). For the time being, RAINS assumes the average of these estimates for its calculations. For the *advanced diesel car*, which essentially involves hybrid engines, estimates range from € 7,228 per car (Bates *et al.*, 2001) for the present day situation to € 2,800 for mass production in the year 2020 (Ogden, 2004). For the RAINS calculations addressing 2015 to 2020, the latter estimate is used.

There are a number of cost estimates for **heavy-duty vehicles** available. Typical measures that would achieve the fuel savings of the *improved heavy-duty vehicle* amount at present to € 1,341 per vehicle (Bates *et al.*, 2001), which leads with current fuel prices (even excluding fuel taxes) to net cost savings. Since the existence of such cost savings would suggest these measures to be included already in any baseline projection of future development, RAINS takes a more conservative assumption of € 2,700 per vehicle as proposed by Marsh *et al.* (2002) for the year 2020. For hybrid vehicles, which form part of the *advanced heavy-duty vehicle* category in RAINS, Marsh *et al.* (2002) suggest additional investments to decline from

€ 25,620 in the year 2000 down to € 6,000 for trucks and to € 8,300 for buses in the year 2020. In order to not be overly optimistic, RAINS assumes for heavy-duty trucks in 2020 additional investments of € 12,400, which reflects the envisaged lower decline in the costs of hybrid passenger cars.

The available evidence does not indicate significant differences in fixed annual operating and maintenance costs between the reference and the more fuel-efficient cars (Marsh *et al.*, 2002; Bates *et al.*, 2001; Concawe/EUcars/JRC, 2003b).

3.4.2.2 Fuel substitution

Options for fuel substitution

CO_2 emissions from transport can also be reduced through substituting gasoline and diesel with fuels that cause lower carbon emissions. For the time frame of this study, i.e., up to 2030, the most relevant options include the use of bio-diesel, the replacement of gasoline engines with diesel engines, and the use of compressed natural gas, ethanol and hydrogen fuel cells. For a comprehensive assessment it is crucial to consider such fuel substitutions from a systems perspective, i.e., to consider the emissions from well to wheel of each option and not only the emissions released from the vehicle. It is also important to consider side impacts on the emissions of other pollutants, such as nitrogen oxides (NO_x), volatile organic compounds (VOC) and fine particles (PM), which are of major concern for regional and local air quality.

Conventional diesel

Due to the higher energy efficiency of conventional diesel engines compared to gasoline engines, the replacement of gasoline driven cars with diesel cars will result in lower CO_2 emissions for the same mileage and comparable engine sizes.

Bio-diesel

Diesel can be replaced by bio-diesel at no additional investment costs. Taking into account the carbon emissions that occur during the feedstock production and transportation of diesel and bio-diesel, the net reduction in CO_2 emissions is estimated at around 65 percent (CEC, 2001; IEA, 1999). This gives an emission factor of 25.7 kg CO_2/GJ if 100 percent of the diesel used by a car would be replaced by bio-diesel. The literature generally assumes no differences in O&M costs for the different fuels.

Ethanol

For a consistent evaluation, emissions from ethanol production need to be included at some stage in the calculation, either explicitly through modelling ethanol production or by applying a modified emission factor to all consumed ethanol (the tank-to-wheel factor). The type of feedstock is crucial for the overall effectiveness of methanol.

Hendriks *et al*. (2001; p. B20) conclude that, in comparison to gasoline vehicles, life cycle avoided emissions are between 42 and 70 kg CO_2/GJ ethanol (or 61 to 100 percent of the tail-pipe emission) depending on the feedstock used (sugar beet or wheat). IEA (1999) quotes reductions in well-to-wheel emissions between 45 and 90 percent depending on the feedstock (cellulose or sugar starch).Concawe/EUcars/JRC (2003b) finds well-to-wheel carbon emissions of ethanol similar to those of gasoline if ethanol is used as blended fuel. If used as neat fuel, well-to-wheel emission could be 30 to 80 percent lower, depending on the feedstock and technology used to produce ethanol. Although tank-to-wheel emissions are comparable to gasoline, well-to-tank emissions are significantly lower for pure ethanol.

Including emissions from ethanol production in the emission factor and assuming for ethanol the average well-to-wheel emission factor 55 percent lower than that of gasoline, the adjusted life cycle emission factor of ethanol used by RAINS is 50 percent lower than the emission factor for the gasoline reference car.

Compressed natural gas

Europe and the rest of the world have used CNG (Compressed Natural Gas) vehicles for many years. Their expansion is constrained by the additional costs for the vehicle and the limited refuelling infrastructure (Concawe/EUcars/JRC, 2003a). Hence, so far CNG vehicles could only penetrate niche markets. The capacity of the current infrastructure for distribution and refuelling is, however, believed to be sufficient to allow market penetrations of up to 10 percent. An increased use of natural gas in the transport sector would necessitate further imports of natural gas from Siberia, south-west Asia or the Middles East (LNG), which would cause additional energy demand and GHG emissions for the transport of the gas.

It is unclear to what extent vehicles fuelled by compressed natural gas consume more or less fuels than their gasoline counterparts. Some sources suggest reductions of 18 percent (Marsh *et al.*, 2002), whereas others indicate increases of up to 20 percent (PRIMES). The Concawe/EUCars/JRC study (2003a; p. 30) suggests no major differences in fuel consumption (three percent more for CNG cars). RAINS assumes no difference in fuel consumption. Due to the lower carbon content of natural gas, the shift to CNG results in 20 percent lower CO_2 emissions per vehicle kilometre.

Hydrogen

While hydrogen powered cars have no tailpipe emissions of carbon, the source of hydrogen has crucial influence on the overall life cycle emissions of fuel cells. If hydrogen is produced from solar or hydropower, life cycle carbon emissions are close to zero. If natural gas is used as feedstock to produce hydrogen, and if carbon is captured and sequestered during the hydrogen production, carbon emissions are around 10 kg CO_2/GJ hydrogen produced (Ogden *et al.*, 2004). These emissions are of a comparable magnitude to the emissions from gasoline production (6.1-12 kg CO_2/GJ, IEA, 1999; p. 42), which are accounted for in the RAINS model in the refinery sector. For consistency, emissions from hydrogen production need to be included at some stage in the calculation, either explicitly through modelling hydrogen production or by applying a modified emission factor to all consumed hydrogen.

As a conservative assumption that remains valid even for large-scale hydrogen production, RAINS assumes all hydrogen to be produced from natural gas with the carbon from the production process captured and sequestered. Thus, RAINS uses an emission factor of 10 kg CO_2/GJ hydrogen produced based on Ogden *et al.* (2004) and includes the carbon sequestration costs in the fuel costs of hydrogen. For the distance-related emission factor, however, RAINS takes into account the lower fuel consumption of fuel cells.

Table 3.11: Emission factors for fuel substitution options, in grams CO_2/km

	Passenger cars and light duty trucks, gasoline	Passenger cars and light duty trucks, diesel	Heavy duty vehicles, diesel
Reference 2000 car	196	240	655
Diesel	199	240	-
Bio-diesel		84	233
Ethanol	96		
Compressed natural gas	159		555
Hydrogen fuel cell	15		

Potentials for fuel substitution

Conventional diesel

The replacement of gasoline driven cars by cars with diesel engines faces the limits imposed by the natural turnover rate of gasoline cars, since no premature scrapping is assumed, and will be constrained by the availability of diesel fuel in Europe. Consultations with the European oil industry in the course of the Clean Air for Europe (CAFE) programme of the European Commission indicated that a continued trend in the shift from gasoline to diesel demand for passenger cars in Europe could meet supply limits. There is a physical limit to the fraction of diesel that can be produced from a crude oil barrel during the refinery process without major new investments, and the projected growth in diesel demand from heavy-duty vehicles would leave little space for a major increase in the number of diesel light duty vehicles.

Bio-diesel and ethanol

The potentials for bio-diesel and ethanol are mainly determined by supply constraints. An estimate of the potential production of bio-diesel and methanol in the European countries is provided in Table 3.12. These estimates are based on productivity data of agricultural land for bio-diesel and methanol production as presented in the TERES-II study for the five largest EU countries (Hendriks *et al.*, 2001; p. B19) and combine them with country-specific data on arable land as contained in the RAINS database. Thus these estimates assume that all countries could set aside the same share of arable land for bio-diesel and methanol production as the five largest EU countries, and that the productivity (in terms of tons biofuel/hectare) is the same in all countries.

According to these estimates, which do not incorporate regional differences in climatic factors, ethanol from European production could in the EU countries substitute up to six percent of the gasoline consumption of the year 2000. The bio-diesel supply would amount to four percent of total diesel consumption in 2000. For comparison, the European Commission proposed a share of bio-fuels in total gasoline and diesel consumption of 5.75 percent in 2010 (CEC, 2001). The same document contains an optimistic scenario where the share of bio-fuels in total transport energy demand increases to seven percent in 2015 and eight percent in 2020.

Alternatively, a common market for bio-diesel and ethanol with free imports and exports across Europe could be assumed. In that case around 8.5 percent of diesel consumption in 2020 could be covered by bio-diesel and nine percent of the gasoline could be replaced by ethanol. On top of this, ethanol could be imported from outside Europe (e.g., Brazil).

Compressed natural gas

While, in principle, the resource availability of natural gas as a transport fuel will not be a limiting factor, the extension of the necessary distribution infrastructure might restrict a rapid conversion to compressed natural gas as a fuel for automotive vehicles. The European Commission (2001) and recent studies (Concawe/EUcars/JRC, 2003a) indicated the feasibility of CNG reaching a market share of 10 percent of total transport fuel consumption. This estimate is taken for the present version of the RAINS model as an upper limit.

Table 3.12: Total arable land (in 1000 hectares) and the estimated potential production of bio-diesel and ethanol (in PJ/year)

	Total arable land	Bio diesel	Ethanol
Albania	6000	21	18
Austria	1400	8	4
Byelorussia	6200	22	18
Belgium	800	4	0
Bosnia-Herzegovina	500	2	1
Bulgaria	4300	15	13
Croatia	1500	5	4
Czech Republic	3100	11	9
Denmark	2300	5	3
Estonia	1100	4	3
Finland	2200	2	5
France	18400	70	43
Germany	11800	31	58
Greece	2800	4	5
Hungary	4800	17	14
Ireland	1100	1	2
Italy	8500	48	19
Latvia	1900	7	6
Lithuania	2900	10	9
Luxembourg		0	0
Macedonia	600	2	2
Moldavia	1800	6	5
Netherlands	900	14	6
Norway	900	3	3
Poland	14100	49	42
Portugal	2000	6	3
Romania	9300	32	28
Russia	105100	365	312
Serbia Montenegro	3700	13	11
Slovakia	1500	5	4
Slovenia	200	1	1
Spain	13700	36	13
Sweden	2800	4	8
Switzerland	400	1	1
Ukraine	32700	114	97
United Kingdom	5900	23	50
Total		961	821

Hydrogen

The constraints on hydrogen used for the RAINS calculations are based on the report of the EU High-level Group for Hydrogen and Fuel Cells (EC, 2003a), which suggests for the EU-15 a market share of two percent of the passenger car fleet that could be fuelled by zero-carbon hydrogen in 2020. This number could increase to 15 percent in 2030 and 32 percent in 2040.

The market shares of alternative fuels that are presently used for the RAINS calculations are listed in Table 3.13.

Table 3.13: Maximum market penetration of alternative fuels assumed for the RAINS calculations (for the EU as a whole)

	2010	2015	2020
Bio-diesel (% of total diesel demand in transport)	6 %	8 %	8 %
Ethanol (% of gasoline in light duty vehicles)	6 %	8 %	10 %
Natural gas (% of fuel demand for light duty vehicles)	2 %	5 %	10 %
Hydrogen (% of passenger car fleet)	0 %	1 %	2 %

Costs of fuel substitution

Costs of fuel substitution in the transport sector consist of additional investments and operating costs for engine modifications and of the differences in fuel costs between the conventional and alternative fuels, which are determined by the differences in fuel prices and in fuel efficiencies.

Investments

Diesel

Diesel engines are more expensive than gasoline engines. For RAINS, the costs of shifting from gasoline to diesel are derived as the average of literature estimates provided in Bates *et al.* (2001), De Klerk *et al.* (1998) Concawe/EUcars/JRC (2003a) and Marsh *et al.* (2002).

Bio-diesel

Diesel can be replaced by bio-diesel without additional investments for the vehicle, and no indication for increased operating and maintenance costs is provided by the literature.

Ethanol

Gasoline vehicles can operate with an ethanol/gasoline mixture of up to 20 percent ethanol without additional investments (Bates *et al.*, 2001; Green and Schaefer, 2002; Van Thuyl *et al.*, 2003). Operating costs are taken from De Klerk *et al.* (1998), which are lower than the estimates of Marsh *et al.* (2002), but higher than the values given in Bates *et al.* (2001). No additional O&M costs have been reported in the literature compared to the gasoline car.

Compressed natural gas

Investments for a passenger car fuelled by compressed natural gas are reported to be around 15 percent higher than for the reference gasoline car (Bates *et al.*, 2001; de Klerk *et al.*, 1998). Cost estimates for heavy duty vehicles reveal a wide span, ranging from a 30 percent increase (Bates *et al.*, 2001) to a one percent decrease estimated for 2020 (Marsh *et al.*, 2002). RAINS relies on the estimate of Bates *et al.* (2001).

Hydrogen

A large range of cost estimates is provided in the literature for hydrogen fuelled cars. Costs depend on the technology and fuel chosen: methanol with on board reforming to hydrogen, hydrogen produced from natural gas or gasoline with on-board production of hydrogen.

Estimates of additional investments in comparison to a conventional gasoline car range from around € 2,200/car to around € 10,000/car (Marsh *et al.*, 2002; Jung, 1999; Padro and Putsche, 1999; Bates *et al.*, 2001; Ogden *et al.*, 2004, Concawe/EUcars/JRC, 2003a), depending on the technology (current, advanced, improved) and when the technology will be employed. For mass production, average investment costs are estimated at around € 2,600/car (Ogden *et al.*, 2004; Marsh *et al.*, 2002; Jung, 1999). Concawe/EUcars/JRC (2003a, p. 36) estimates the investments (retail price) of the hydrogen fuel cell in 2010 to be € 9,583 higher than the conventional gasoline car. RAINS uses € 4,500 as the costs for 2015/2020, assuming some progress in reducing costs while mass production will not have fully started by that date. Obviously, these cost estimates are loaded with large uncertainties, especially in relation to the speed at which the technology will gain a sufficiently high market share.

Also for heavy duty vehicles, the literature provides a wide range of cost estimates. Marsh *et al.* (2002) list for the year 2000 a 70 percent difference in investments, which however is expected to disappear until 2020. Bates *et al.* (2001) suggest investments to be 37 percent higher than for conventional heavy-duty trucks. In absence of more information, RAINS adopts the average of these estimates for its calculations.

Fuel prices

Gasoline, diesel

The RAINS model contains databases with scenario- and country-specific prices for gasoline, gas and diesel, free of taxes. These data are used to determine price differences whenever appropriate.

Bio-diesel

Production costs of bio-diesel are estimates at around 15 €/GJ (Hendriks *et al.*, 2001; Van Thuijl *et al.*, 2003).

Ethanol

Costs estimates for the production of ethanol range from 5 €/GJ to 21 €/GJ (Hendriks *et al.*, 2001; Van Thuyl *et al.*, 2003). Estimates depend on the feedstock used (sugar starch, wheat or lignocellulose), the volume of production and the year of implementation. For modest production increases, a price of 12.5 €/GJ seems plausible.

Compressed natural gas

No estimates of the costs of compressed natural gas were found in the literature, so that the gas prices for the transport sector as contained in the RAINS database have been used.

Hydrogen

Ybema *et al.* (1995) estimated the costs of producing hydrogen at around 10 €/GJ. Adding 65 percent transportation costs (IEA, 1999), the price at the pump (excluding taxes) should be around 16 €/GJ. Padro and Putsche (1999) provide a range of estimates for hydrogen prices at the pump. Depending on the number of cars per day and the technology (liquid hydrogen or compressed natural gas), costs range from 11.3 to 28.7 $/GJ. For large stations with sufficiently large number of cars per day, average costs amount around 15€/GJ. Ogden *et al.* (2004) estimate a pump price of 15.3 $/GJ for steam reforming using natural gas and of 17 $/GJ if CO_2 is captured and sequestered. For RAINS a price of 17 €/GJ is adopted. This price includes carbon capture and is therefore consistent with the assumption made for the emission coefficient for CO_2.

Table 3.14: Fuel prices excluding taxes (in the year 2000) (future prices are scenario specific)

Fuel	Price [€/GJ]
Gasoline	Country-specific (7.1-18.8)
Diesel	Country-specific (5.9-17.1)
Bio-diesel	14.5
Compressed natural gas	Country-specific (6.1-13.7)
Ethanol	12.5
Hydrogen	17

Cost calculation for efficiency improvements and fuel substitution

Investments

The cost evaluation for mobile sources follows the same basic approach as for stationary sources. The most important difference is that the investment costs are given per vehicle, not per unit of production capacity. The number of vehicles is computed in RAINS from the total annual fuel consumption by a given vehicle category and average fuel consumption per vehicle per year.

The following description uses the indices *i, j*, and *t* to indicate the nature of the parameters:

i	denotes the country,
j	the transport (sub)sector/vehicle category,
t	the technology.

The costs of applying control devices to the transport sources include:

- additional investment costs,
- increase in maintenance costs expressed as a percentage of total investments, and
- change in fuel cost resulting from the inclusion of emission control.

The additional investment costs $I_{i,j,t}$ are given in €/vehicle and are available separately for each technology and vehicle category. They are annualised using the equation:

$$I^{an}_{i,j,t} = I_{j,t} \cdot \frac{(1+q)^{lt_{i,j,k}} \cdot q}{(1+q)^{lt_{i,j,k}} - 1} \qquad \text{Equation 3.9}$$

where:

$lt_{i,j,t}$	lifetime of control equipment.

Operating costs

The increase in maintenance costs (fixed costs) is expressed as a percentage *f* of total investments:

$$OM^{fix}_{i,j,t} = I_{i,j,t} \cdot f_t \qquad \text{Equation 3.10}$$

The change in fuel cost can be caused by change in fuel type (in case of fuel substitution) or through changes in fuel consumption (when moving to a more fuel efficient car) or both combined. It can be calculated as follows:

$$OM\,\mathrm{var}^{e}_{i,j,t}(t) = fuel_{i,j,a} * c^{f}_{i,j,a} \text{ - } fuel_{i,j,a} * c^{f}_{i,j,r} \qquad \text{Equation 3.11}$$

where:

$fuel_{i,j,r}(t)$	fuel consumption of the reference car at time *t*,
$fuel_{i,j,a}(t)$	fuel consumption of the alternative car at time *t*,
$c^{f}_{i,j,r}(t)$	fuel price of the reference fuel used by the reference car (net of taxes) in country *i* and sector *j* in year *t*,
$c^{f}_{i,j,a}(t)$	fuel price of the alternative fuel used by the alternative car (net of taxes) in country *i* and sector *j* in year *t*.

The annual fuel consumption per vehicle is a function of the consumption in the base year (t_0=1990), of the (autonomous) fuel efficiency improvement, and the change in activity per vehicle (i.e., change in annual kilometres driven) relative to the base year:

$$fuel_{i,j}(t) = fuel_{i,j}(t_0) * fe_{i,j}(t) * \Delta ac_{i,j}(t) \qquad \text{Equation 3.12}$$

where

$fe_{i,,j}(t)$	fuel efficiency improvement in time step *t* relative to the base year,
$\Delta ac_{i,,j}(t)$	change in activity per vehicle in time step *t* relative to the base year.

Unit reduction costs

The unit costs of abatement ce_{PJ} (per car) add up to

$$ce_{car,i,j,t}(t) = I^{an}_{i,j,a} + OM^{fix}_{i,j,a} + OM^{e}_{i,j,t}(t) \qquad \text{Equation 3.13}$$

These costs can be related to the emission reductions achieved, i.e., the difference in CO_2 emissions of the reference car and the alternative vehicle. The costs per unit of CO_2 abated are as follows:

$$cn_{i,j,t}(t) = \frac{ce_{car,i,j,a}(t)}{ef_{i,j,r} * fuel_{i,j,r} - ef_{,j,a} * fuel_{i,j,a}} \qquad \text{Equation 3.14}$$

The most important factors leading to differences among countries in unit abatement costs are the annual energy consumption per vehicle and fuel prices.

3.4.2.3 Summary of control options

Table 3.15 to Table 3.17 summarise the CO_2 control options for gasoline passenger cars, diesel passenger cars and diesel heavy-duty vehicles, respectively.

Table 3.15: CO_2 control options for passenger and light-duty vehicles using gasoline

	Additional investment [€/car]	Fuel consumption1)		CO_2 emission factor	
		[l/100km]	Change (%)	[kg CO_2/GJ]	[g/km]
Reference gasoline car 2000	0	8.0	0	68.6	192
Efficiency improvements:					
Improved gasoline car	1250	6.0	-25	68.6	144
Advanced gasoline/hybrid car	2711	4.8	-40	68.6	115
Fuel substitution:					
Conventional diesel	1340	6.8	-15	73.4	188
Bio-diesel2)	-	-	-	-	-
Ethanol (100%)	0	8.0	0	34.3	96
Compressed natural gas	1800	8.0	0	56.1	159
Hydrogen fuel cell	4500	4.4	-55	10.0	15

Notes:

1) Fuel consumption is given in gasoline equivalents and refers to the year 2000.

2) Because of limited supply potential of bio-diesel, RAINS models only its replacement for conventional diesel.

Table 3.16: CO_2 control options for passenger and light-duty vehicles (passenger cars) using diesel

	Additional investment [€/car]	Fuel consumption[1)]		CO_2 emission factor	
		[l/100km]	Change	[kg CO_2/GJ]	[g/km]
Reference diesel car 2000	0	8.7	0	73.4	240
Efficiency improvements:					
Improved diesel car	725	7.5	-15%	73.4	207
Advanced diesel/hybrid car	2800	5.3	-40%	73.4	146
Fuel substitution:					
Bio-diesel (100%)	0	8.7	0	25.7	84

Notes: 1) Fuel consumption refers to the year 2000

Table 3.17: CO_2 control options for heavy-duty vehicles (HDV) using diesel

	Additional investment [€/car]	Fuel consumption[1)]		CO_2 emission factor	
		[l/100km]	Change[3)]	[kg CO_2/GJ]	[g/km]
Reference HDV 2000	0	24.1	0	73.4	665
Efficiency improvements:					
Improved HDV	2717	22.2	-8 %	73.4	610
Advanced HDV	12400	15.6	-35 %	73.4	430
Fuel substitution:					
Bio-diesel (100%)	0	24.1	0	25.7	233
Compressed natural gas	11630	27.0	+12 %	54.7	555
Hydrogen fuel cell	37877	17.5	-28 %	10.0	66

Note: 1) Fuel consumption refers to the year 2000.

3.4.3 Domestic sector

A wide range of options exist to reduce the CO_2 emission from the domestic sector:

- Energy end use savings (insulation of houses and office buildings, more efficient electric appliances and lighting as well as office equipment and cooling devices).
- Fuel substitution: from oil and coal to gas and from fossil fuels to renewables (biomass, geothermal heat and solar energy).

Information on the costs and efficiencies of these options is to a large degree available (Hendriks *et al.*, 2001), but data on the extent to which these options have already been implemented in the past, or will be implemented in the future, is more scarce. In the first phase of this study, two options for reducing CO_2 emissions from the domestic sector have been examined so far: electricity savings and shifting from oil to biomass.

3.4.3.1 *Efficiency improvements*

A variety of options exist to reduce electricity consumption of domestic appliances (Joosen and Blok, 2001). These range from compact fluorescent lamps to efficient cold (e.g., fridges), wet (washing machines) and brown (e.g., television) appliances. For the scope of the RAINS analysis, it is impractical and also not necessary to quantify each specific option in detail. Instead, a limited number of packages of measures were formulated that show distinct differences in emission reductions and costs. For the time being, on the basis of the average share of the electricity consumption of these appliances, two packages are distinguished (see Table 3.18):

- Introduction of compact fluorescent lamps,
- more efficient household appliances. This group contains appliances as discussed in Joosen and Blok (2001).

For each of these options, the potential energy savings are calculated as the electricity demand for lighting (or appliances) in households times the electricity saved through this option times the potential applicability of the option. Since electricity demand for lighting in households is not directly available from energy statistics, it is estimated in RAINS based on the total domestic electricity demand as given in the energy statistics/projections and a (country-specific) share for lighting purposes as provided in Joosen and Blok (2001). The maximum application potential is assumed as a function of time, starting from the present country-specific application rates and converging to the maximum rate of application (see Joosen and Blok, 2001).

Table 3.18: Two packages of electricity saving measures in households

Options	Investments [Million €/PJ electricity saved]	Lifetime [years]	Cost [€cts/kWh electricity saved]	Electricity saved
Compact fluorescent lamps	5.9	8	0.3	60%
Efficient appliances	220.6	15	7.1	50%

With the present data on electricity prices and efficiency improvements, negative costs are calculated for compact fluorescent lamps, suggesting that their full application already in any (cost-optimised) baseline projection. It will thus be necessary to thoroughly check the potential for the additional application potential for any energy projection that will be used in RAINS as a starting point.

For calculating the net costs of reduced electricity demand, the avoided costs for electricity production need to be considered. For RAINS it is assumed that electricity savings reduce first the operation of fossil fuel fired plants, so that the net costs of the savings are calculated from the annualised investment costs for the saving options minus the costs of the avoided electricity production from fossil fuel fired plants. Thus, the costs per ton CO_2 avoided depend on the fuel saved.

3.4.3.2 Fuel substitution

For the preliminary assessment, substitution of new oil heating systems for single family houses by biomass heating using pellets has been implemented. In line with the IPCC guidelines (Houghton *et al.*, 1997) the CO_2 emissions from biomass are calculated as zero, assuming that the biomass is produced in sustainable way.

Data used to determine the costs of this option are provided in Table 3.19, based on studies of Pelletsverband Austria (2003), Consumer Information Monthly (Anonymous, 2002) and Müller *et al.*, 1998. For the replaced fuel, i.e., light fuel oil, prices for households (IEA, 2003a) excluding VAT and other fuel taxes are taken.

Table 3.19: Costs and reduction of shifting from oil to biomass in households

	Unit	Oil-heating	Biomass pellets
Size of the house	m^2	150	150
Heat demand	kWh/yr	13000	13000
Fuel input	GJ/yr	58.50	58.50
Size of heating	kW	10.4	10.4
Efficiency	%	80	80
Investment	€/stove	8258	10683
Fuel price	€/GJ	8.60	8.29
Heat value	GJ/ton	43.3	18
Lifetime	years	20	20
Capital costs	€/year	607.62	786.06
Fuel costs	€/year	503.10	484.79
Total costs	€/year	1110.7	1270.8
Cost/GJ	€/year	18.99	21.72
CO_2 emissions /year	kg/year	4293.9	0
Cost per tCO_2 avoided	€/tCO_2		37.3

3.5 Interactions with other emissions

A number of cases have been identified where emissions of carbon dioxide and related emission control options influence emissions of other greenhouse gases and air pollutants, and vice versa (Table 3.20). The combustion of coal and gas leads to emissions of methane during the production of coal and gas and during transportation of natural gas. Shifting away from coal will also reduce methane emissions. Increasing gas use will have the opposite effect. Burning biomass might increase PM, NO_2 and VOC emissions depending on the control measures applied.

In the transport sector shifting to natural gas increases methane emission. Shifting to diesel could increase PM emissions depending on the control technology. Fuel substitution towards biofuels (ethanol and biomass) might increase N_2O and ammonia emissions due to the increased use of fertiliser. Fuel efficiency improvements will reduce all pollutants. In the domestic sector shifting to biomass might increase the emissions of various pollutants. It will be important to address these interactions in the further course of this study.

Table 3.20: Carbon dioxide emitting sectors and interactions with emissions of other air pollutants

Sector		Important interactions with other gases
Power plants/Industry/ Domestic sector	Coal combustion/production	CH_4
	Gas combustion/production	CH_4
	Biomass burning	PM, NO_x, VOC, CH_4
	Fuel efficiency/ renewables (except biomass)	All
Transport	Shift to natural gas	CH_4
	Shift to diesel	PM
	Shift to bio diesel/ethanol	N_2O
	Fuel efficiency changes	All
Industrial processes	Lime production/limestone use	$SO_{2,}$

3.6 Preliminary results

3.6.1 Emission inventories

Table 3.21 compares the preliminary RAINS estimates for 1990 and 2020 with the official national submissions to the UNFCCC. For Europe the RAINS models estimates total emissions at 6675 Mt CO_2 in 1990. For those countries for which the UNFCCC reports data the RAINS estimate is 2% below the official estimates for 1990. For those countries that submitted data to the UNFCCC, the RAINS estimate for 2000 is 2% below the emissions reported to the UNFCCC. RAINS estimates correspond reasonably well to the national submissions to the UNFCCC with the exceptions of a few countries and analysis of the differences is needed.

Table 3.21: CO_2 emission estimates (Mt CO_2)

	1990				2000	
	RAINS	UNFCCC	EDGAR	ECOFYS	RAINS	UNFCCC
Albania	6		7		4	
Austria	59	62	65	68	62	66
Belarus	115	126	209		74	73
Belgium	112	118	125	115	124	127
Bosnia-H.	22		15		21	
Bulgaria	82	84	73		47	
Croatia	22	23	36		23	
Cyprus	6				8	
Czech Republic	159	164	160		123	128
Denmark	56	53	55	54	55	53
Estonia	33	38	56		15	17
Finland	60	62	61	53	68	62
France	392	394	408	379	412	402
Germany	1007	1015	1067	979	859	858
Greece	81	84	81	79	97	104
Hungary	68	67	76		59	59
Ireland	33	32	33	32	43	44
Italy	433	440	446	418	463	463
Latvia	22	24	33		7	7
Lithuania	36	40	118		12	
Luxembourg	11	11	13		10	
Macedonia	12		11		11	
Malta	2		3		3	
Moldavia	29		47		23	
Netherlands	163	160	184	156	179	174
Norway	30	35	48		35	
Poland	364	381	367		313	315
Portugal	46	44	47	43	67	63
Romania	174	173	191		93	
Russia_Kaliningrad	9				7	
Russia_Kola-Karel.	30				20	
Russia_Remaining	979				706	
Russia_StPetersburg	68				48	
Serbia-Montenegro	63		91		49	
Slovak Republic	63	60	58		36	42
Slovenia	15	14	13		15	
Spain	229	227	238	220	317	307
Sweden	55	56	59	55	70	56
Switzerland	47	44	48		49	44
Ukraine	674	704	837		399	
United Kingdom	589	584	615	582	574	543
Turkey	148		156		225	
Total	6675	5318	6145		5897	4005

Sources: UNFCCC estimates for 1990 and 2000 based on UNFCCC database of emissions (UNFCCC, 2004) and the latest national communications from Bulgaria, Hungary, Poland and Romania for the 1990 data (http://www.unfccc.int/) as well as EDGAR (2004).

Figure 3.1 shows the distribution of the CO_2 emissions over the sectors in 1990 (RAINS estimate). In sum, fuel combustion (power plants, industry, conversion, domestic, transport and conversion losses) is responsible for 95 percent of the emissions in 1990, while industrial processes and non-energy use of fuels make up the remaining five percent. These numbers correspond reasonably well to the sector allocation of the emissions for European countries in the UNFCCC database.

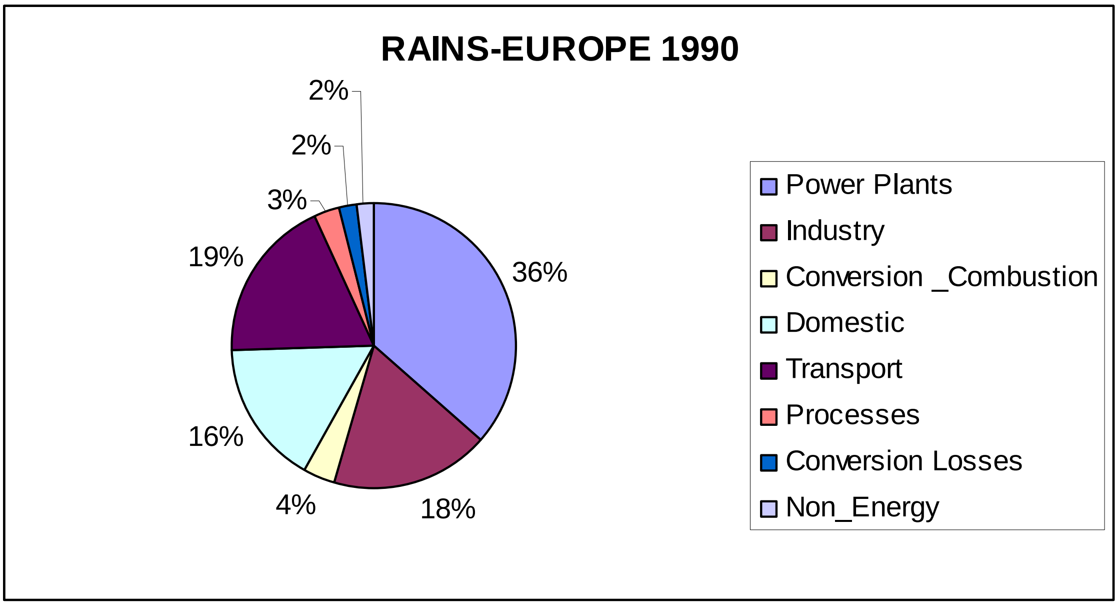

Figure 3.1: Sectoral distribution of CO_2 emissions estimated by RAINS for 1990

3.6.2 Emission projections

The RAINS model allows estimating future emissions of the various pollutants including CO_2. The initial estimate is based on future activity levels as developed for the baseline projection of the EU-CAFE (Clean Air For Europe) programme by the PRIMES model for the EU-25 countries and on national submissions (from the RAINS database) for the other countries. These projections provide future fuel consumption by sector and fuel type as well as production forecasts of industrial processes, in particular for cement and lime. Details on projected fuel consumption and production levels are available from the RAINS website (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/MainPageEmco.htm).

Table 3.21 shows the resulting CO_2 emissions for Europe. Total European CO_2 emissions are expected to first drop in the business-as-usual case (with no additional climate policies) from around 6675 Mt CO_2 in 1990 to 6379 Mt CO_2 in 2010. Afterwards, they increase to 6897 Mt in 2020 and 7583 Mt CO_2 in 2030. For comparison, the emissions in the EU-25 are expected to increase to 4157 Mt in 2010, 4499 Mt in 2020 and 4822 Mt CO_2 in 2030. The Kyoto Protocol commitments for the EU 25 would require a reduction of approximately eight percent in 2010, i.e., a reduction of roughly 400 Mt CO_2.

Table 3.22: Preliminary estimates of the development of CO_2 emissions between 1990 and 2030 under the baseline projections no additional climate policies, in Mt CO_2.

	1990	2000	2010	2020	2030
Albania	6	4	5	7	9
Austria	59	62	66	73	77
Belgium	112	124	124	132	159
Bosnia-H.	22	21	26	31	38
Bulgaria	82	47	50	53	59
Croatia	22	23	25	27	30
Cyprus	6	8	9	10	11
Czech Republic	159	123	104	103	109
Denmark	56	55	49	48	49
Estonia	33	15	16	15	15
Finland	60	68	68	72	76
France	392	412	446	490	501
Germany	1007	859	920	992	1013
Greece	81	97	118	126	131
Hungary	68	59	64	71	82
Ireland	33	43	50	53	55
Italy	433	463	464	482	507
Latvia	22	7	9	11	12
Lithuania	36	12	18	23	26
Luxembourg	11	10	13	14	16
Macedonia	12	11	13	15	19
Malta	2	3	4	4	4
Moldavia	29	23	24	22	22
Netherlands	163	179	189	200	228
Norway	30	35	42	45	44
Poland	364	313	321	352	393
Portugal	46	67	79	92	106
Romania	174	93	104	115	135
Russia_Kaliningrad	9	7	7	7	8
Russia_Kola-Karelia	30	20	24	24	26
Russia_Remaining	979	706	856	873	907
Russia_StPetersburg	68	48	56	55	58
Serbia-Montenegro	63	49	70	92	122
Slovak Republic	63	36	41	48	54
Slovenia	15	15	17	18	21
Spain	229	317	343	383	408
Sweden	55	70	79	94	128
Switzerland	47	49	52	57	65
Ukraine	674	399	417	419	462
United Kingdom	589	574	548	594	644
Turkey	148	225	286	393	578
Grand total	6675	5897	6380	6898	7583
Of which EU-25	4090	3989	4158	4499	4822

In this preliminary projection, the share of the transport sector is expected to increase over time from 19 to 27 percent, while the power sector (including district heating) maintains a constant share. The contribution of industry and the conversion sector is expected to decrease.

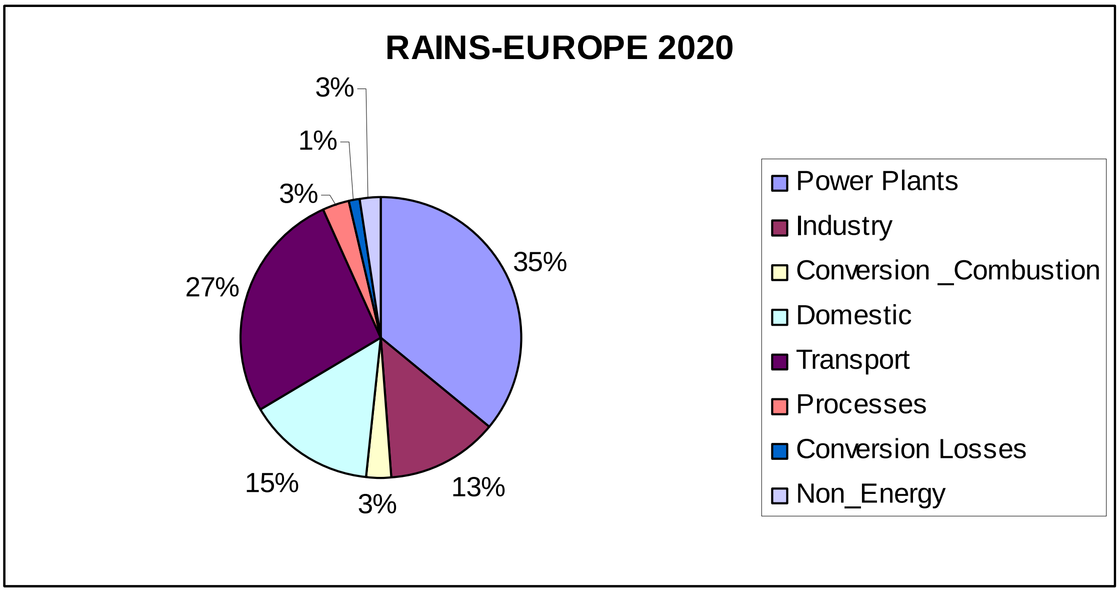

Figure 3.2: Sectoral distribution of CO_2 emissions estimated by RAINS for 2020

3.6.3 Costs

Table 3.23 ranks the options to control CO_2 emissions in the power plant, domestic and transport sectors according to their average costs (for options up to 15 €/t CO_2). These cost estimates are based on average fuel prices and operating hours; considerable differences may occur between countries. Nevertheless, the results indicate that a number of low costs options exist. Among these are typical electricity savings in households (HH) and fuel shifts away from heavy fuel oil. The costs heavily depend on the assumed fuel prices and the extent to which these options (electricity savings) are already assumed as part of the baseline projection.

Table 3.23: Options to control CO_2 emissions with average costs below 15 €/t CO_2

Sector	Sub sector	Abatement option	€/tCO_2
POWER PLANTS_NEW	GAS	Electricity savings HH1	-100
POWER PLANTS_NEW	HFO	Electricity savings HH1	-77
POWER PLANTS_EXIST	HFO	Electricity savings HH1	-64
POWER PLANTS_NEW	HFO	Gas	-42
POWER PLANTS_NEW	BC	Electricity savings HH1	-31
POWER PLANTS_NEW	HFO	Nuclear	-24
POWER PLANTS_NEW	HFO	Wind-onshore	-23
POWER PLANTS_EXIST	HFO	Gas	-22
POWER PLANTS_EXIST	BC	Electricity savings HH1	-21
POWER PLANTS_EXIST	HC	Electricity savings HH1	-21
POWER PLANTS_EXIST	HFO	Nuclear	-15
POWER PLANTS_EXIST	HFO	Wind offshore	-13
POWER PLANTS_NEW	HFO	Wind offshore	-2
POWER PLANTS_NEW	HFO	Hydro	-1
POWER PLANTS_EXIST	HFO	Biomass	1
POWER PLANTS_NEW	GAS	Nuclear	3
POWER PLANTS_NEW	HC	Electricity savings HH1	3
POWER PLANTS_EXIST	HFO	Wind onshore	6
POWER PLANTS_NEW	HC	Nuclear	6
POWER PLANTS_NEW	GAS	Wind onshore	6
POWER PLANTS_NEW	BC	Nuclear	7
POWER PLANTS_NEW	HC	CHP, gas	8
POWER PLANTS_NEW	BC	Wind onshore	8
POWER PLANTS_NEW	BC	Gas	8
POWER PLANTS_NEW	HFO	Electricity savings HH2	10
POWER PLANTS_NEW	HFO	Other renewables	11
TRANSPORT_HDV	MD	HDV diesel improved	14

Explanations: BC: brown coal, HC: hard coal, HFO: heavy fuel oil, GSL: gasoline, MD: diesel, LDV: light duty vehicles, HDV: heavy duty vehicles, HH1: compact fluorescent lamps, HH2: efficient household appliances.

Table 3.24 summarises the options that costs between 15 and 40 €/t avoided. These include improvements in fuel efficiency of diesel passenger cars, heavy duty trucks and buses.

Table 3.24: Options to control CO_2 with average costs between 15 and 40 €/t CO_2

Sector	Sub sector	Abatement option	€/tCO_2
POWER PLANTS_NEW	HFO	Biomass	16
POWER PLANTS_EXIST	HFO	Electricity savings HH2	17
POWER PLANTS_EXIST	BC	Nuclear	17
TRANSPORT_HDV	MD	HDV diesel hybrid	18
POWER PLANTS_EXIST	BC	Wind onshore	18
POWER PLANTS_EXIST	HFO	Other renewables	19
POWER PLANTS_EXIST	HC	Nuclear	22
POWER PLANTS_EXIST	HC	Wind onshore	23
POWER PLANTS_NEW	BC	Wind offshore	23
POWER PLANTS_EXIST	HFO	Hydro	24
POWER PLANTS_NEW	BC	Hydro	24
POWER PLANTS_EXIST	BC	Biomass	25
POWER PLANTS_NEW	HC	Biomass	26
POWER PLANTS_NEW	BC	Biomass	27
POWER PLANTS_NEW	HC	Carbon capture	29
POWER PLANTS_EXIST	HC	Biomass	30
POWER PLANTS_NEW	BC	Electricity savings HH2	32
TRANSPORT_LDV	MD	LDV diesel improved	33
POWER PLANTS_NEW	BC	Other renewables	33
POWER PLANTS_EXIST	BC	Wind offshore	33
POWER PLANTS_EXIST	BC	Hydro	34
POWER PLANTS_NEW	HC	Other renewables	35
DOMESTIC	MD	Shift to biomass	37
POWER PLANTS_EXIST	HC	Wind offshore	40

Explanations: BC: brown coal, HC: hard coal, HFO: heavy fuel oil, GSL: gasoline, MD: diesel, LDV: light duty vehicles, HDV: heavy duty vehicles, HH1: compact fluorescent lamps, HH2: efficient household appliances.

Table 3.25 lists the more expensive control options, e.g., for existing power plants and renewable energy forms (e.g., solar PV) as well as most of the options in the transport sector. Note that in the RAINS cost formulation, fuel taxes are not included since they are transfer payments: although car owners save these costs, tax payers are confronted with the loss in tax revenues so the net gain for society as a whole is zero. In practice, fuel taxes make up a significant part (up to 80 percent) of the price paid by the consumer.

Table 3.25: CO_2 control options with average costs exceeding 40 €/tCO_2

Sector	Sub-sector	Abatement option	€/tCO_2
POWER PLANTS_EXIST	BC	Electricity savings HH2	42
POWER PLANTS_NEW	HC	Gas	42
POWER PLANTS_EXIST	BC	Other renewables	43
POWER PLANTS_NEW	GAS	Wind-offshore	47
POWER PLANTS_NEW	HC	Wind-onshore	47
POWER PLANTS_EXIST	BC	Gas	48
POWER PLANTS_EXIST	HC	Electricity savings HH2	49
POWER PLANTS_EXIST	HC	Other renewables	50
POWER PLANTS_NEW	GAS	Hydro	50
POWER PLANTS_EXIST	HC	Hydro	55
POWER PLANTS_EXIST	HC	Gas	61
POWER PLANTS_NEW	HC	Wind offshore	64
POWER PLANTS_NEW	HC	Hydro	65
POWER PLANTS_NEW	GAS	Electricity savings HH2	69
POWER PLANTS_NEW	GAS	Biomass	70
POWER PLANTS_NEW	GAS	Other renewables	73
POWER PLANTS_NEW	HC	Electricity savings HH2	77
POWER PLANTS_NEW	HC	IGCC	78
TRANSPORT_LDV	MD	LDV diesel hybrid	96
TRANSPORT_LDV	GSL	LDV gasoline to CNG	123
TRANSPORT_LDV	GSL	LDV Gasoline improved	124
TRANSPORT_HDV	MD	HDV diesel to bio-diesel	136
TRANSPORT_LDV	MD	LDV diesel to bio-diesel	136
TRANSPORT_LDV	GSL	LDV gasoline to 20% ethanol	146
TRANSPORT_HDV	MD	HDV diesel to hydrogen fuel cell	196
TRANSPORT_LDV	GSL	LDV gasoline to hydrogen fuel cell	209
TRANSPORT_HDV	MD	HDV diesel CNG	212
TRANSPORT_LDV	GSL	LDV gasoline hybrid	216
POWER PLANTS_NEW	BC	Solar PV	242
POWER PLANTS_EXIST	BC	Solar PV	252
POWER PLANTS_EXIST	HC	Solar PV	284
POWER PLANTS_EXIST	HFO	Solar PV	290
POWER PLANTS_NEW	HFO	Solar PV	299
POWER PLANTS_NEW	HC	Solar PV	309
TRANSPORT_LDV	GSL	LDV gasoline to diesel	365
POWER PLANTS_NEW	GAS	Solar PV	637

Explanations: BC: brown coal, HC: hard coal, HFO: heavy fuel oil, GSL: gasoline, MD: diesel, LDV: light duty vehicles, HDV: heavy duty vehicles, HH1: compact fluorescent lamps, HH2: efficient household appliances.

3.7 Conclusions

This chapter describes the RAINS methodology for estimating CO_2 emissions and the possibilities and cost for reducing these emissions. Emissions estimates from fuel combustion in the various sectors and industrial process emissions correspond very well to the UNFCCC and EDGAR data. A preliminary forecast for 2010 suggests a five percent decline in European CO_2 emissions (mainly from non-EU countries) compared to 1990. In 2020, emissions would increase to three percent above their 1990 levels in a no-control scenario.

Up to now, 86 options for controlling CO_2 emissions were identified for the power plant, transport and domestic sector and their potential and costs were estimated. Further work will add further control options from the industrial sector.

4 Methane

4.1 Introduction

Methane (CH_4) is the second most important greenhouse gas and accounts for approximately 20 percent of the direct radiative forcing from greenhouse gases. Methane has a global warming potential of 23 times that of CO_2 over a 100 years time horizon (Houghton *et al.*, 2001). Due to its relatively short average atmospheric lifetime of approximately 12 years before it is consumed by a natural sink, methane concentrations can be relatively quickly and easily stabilised (US EPA, 1999). Many of the available options to reduce methane emissions involve recovery of emissions for use as an energy source. Where this re-use is applicable, these benefits can reduce control costs considerably (US-EPA, 1999). This chapter provides an overview of the major sources of methane emissions, outlines the methodology for estimating anthropogenic methane emissions, the technical reduction potential to reduce these emissions, and the associated costs for a time horizon of 1990-2030. The spatial scale is the country level.

Methane emissions arise from natural (e.g., wetlands) and anthropogenic sources (e.g., agriculture, landfills, and natural gas emissions). Of the estimated global emissions of 600 Mt in 2000, slightly over half of the emissions originated from anthropogenic sources.

Figure 4.1 shows the contributions of the major sources of methane emissions for the EU-25, Europe and the World in 1990 as shares of total emissions in the respective regions based on UNFCCC contributions (EU-25, Europe) and the EDGAR 3.2 database by RIVM. According to these estimates, the largest contribution in the EU-25 comes from enteric fermentation followed by waste disposal, coal mining, production and distribution of oil and natural gas, and manure management, while other sources make less important contributions. For global emissions the order is different with more emissions from oil and gas extraction, rice cultivation and wastewater than in the EU.

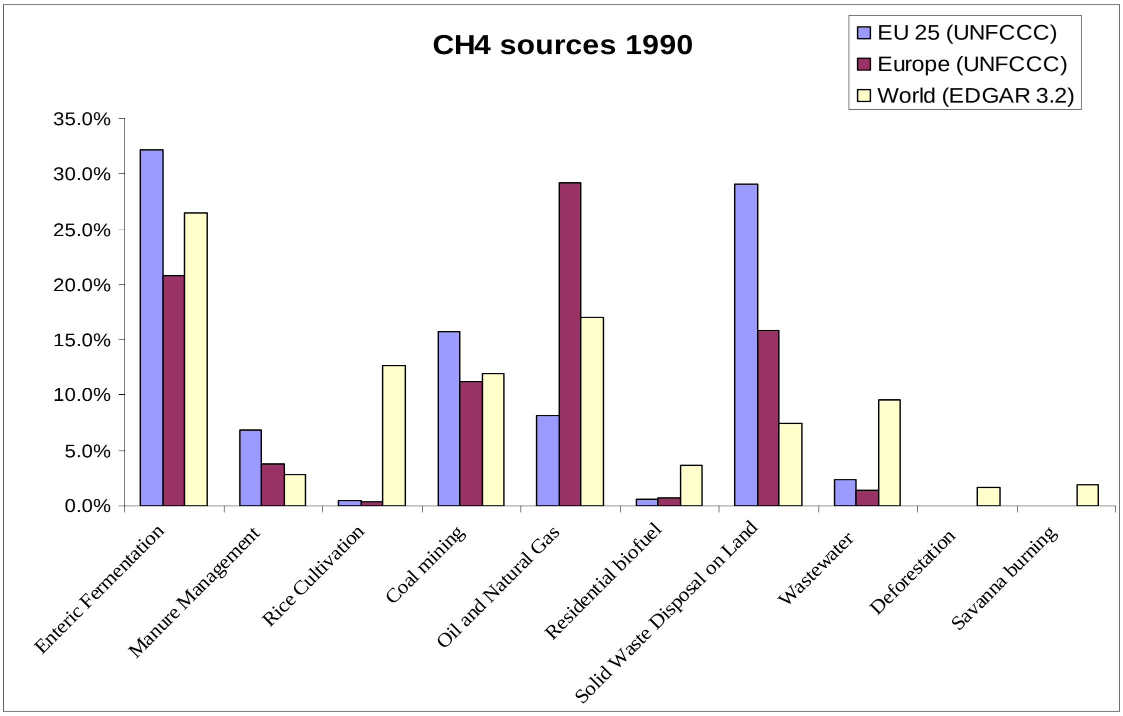

Figure 4.1: Major sources of methane emissions in EU-25, Europe, and the World in 1990 (shares in total emissions). Sources: UNFCCC 2003, Olivier *et al.* 2001.

4.2 Emission source categories

Emissions of methane are released from a large number of sources featuring a wide range of technical and economic differences. Conventional emission inventory systems, such as the inventory of the United Nations Framework Convention on Climate Change (UNFCCC), distinguish more than 300 different processes causing various types of methane emissions. The UNFCCC database contains emission inventories for Annex I and non-Annex I countries for the years 1990 to 2000 that are based on national submissions (*national communications*). EDGAR 3.2 (Olivier *et al.*, 2001) is the most comprehensive global database providing sector specific methane estimates on a country level for 1990 and 1995.

The main sectors contributing to methane emissions are listed in Table 4.1. Other sectors, such as the iron steel industry and fossil fuel combustion from stationary and mobile sources, make minor contributions and are not yet accounted for in this study.

Table 4.1: Sectors distinguished in the RAINS database for methane emissions.

RAINS sector	Rains sub sector	UNFCC category
Livestock	Enteric fermentation	4 A
	Manure management	4 B
Rice cultivation		4 C
Waste	Solid waste	6 A
	Wastewater	6 B
Coal mining		1 B1
Gas	Gas production	1 B2
	Gas consumption	1 B2
Oil production		1 B2
Biomass	Biomass consumption	1 A1
	Agricultural waste burning	4 F
	Savannah burning	4 E
	Forest burning	5 A

Table 4.2 lists the sources of activity data used for RAINS.

Table 4.2: Origin of activity data for methane used in RAINS.

Sector	Activity	Source of activity data
Livestock -Enteric fermentation -Manure Management	Animal numbers	RAINS databases
Rice cultivation	Area rice fields	1990 values from Houghton *et al.* 1997a kept constant
Waste - Solid	Municipal solid waste disposal	UN 2000, World Bank 2001, Houghton *et al.*, 1997b
- Wastewater	Population (urban in transition and developing countries)	UN 2000, World Bank 2001
Coal production	Mining	RAINS databases
Gas	Gas production	PRIMES projections
	Gas consumption	RAINS databases
Oil production	Oil production	PRIMES projections
Biomass - Biomass consumption	Biomass (OS1) consumption	RAINS databases
- Agricultural waste burning	Agricultural waste burned	RAINS databases

4.3 Emission factors

RAINS relies to the maximum possible extent on emission factors provided in the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (Houghton *et al.*, 1997a; Houghton *et al.*, 1997b). These guidelines establish a common methodology for estimating anthropogenic emissions of the major greenhouse gases and define explicit methodologies for calculating methane emissions for all sectors. In addition, other databases such as the EDGAR 3.2 database (Olivier *et al.*, 2001) were used to validate and, where necessary, adjust emission factors.

4.3.1 *Enteric fermentation*

Enteric fermentation is a by-product of the digestive process of herbivores. The amount of methane emissions is determined primarily by (Houghton *et al.*, 1997b)

- the digestive system. Ruminants (i.e., animals with a four compartments stomach) have the highest emissions, because a high amount of fermentation that produces methane occurs within the rumen. Main ruminants are cattle, buffalo, goats, sheep and camels. Pseudo-ruminants (i.e., horses, mules, asses, which have stomachs with three compartments) and monogastric animals (e.g., swine) have lower emissions as less fermentation takes place in their digestive systems.
- the level of feed intake. Methane emissions are proportional to feed intake.

Table 4.3: Calculation of emissions from enteric fermentation in RAINS

RAINS sectors	AGR_COWS	Dairy cattle		
	AGR_BEEFS	Other cattle		
	AGR_PIG	Pigs		
	AGR_OTANI	Other animals (horses, sheep, goats, etc.)		
Activity rate	Number of animals			
Unit	1000 animals			
Data sources	Data on animal numbers are taken from the RAINS-Europe database and FAO (2002).			
Emission factors		Unit	Western Europe	Eastern Europe
	Other cattle	kg/head	48.0	56.0
	Dairy cattle	kg/head	100.0	81.0
	Pigs	kg/head	1.5	1.5
	Sheep and goats	kg/head	8.0	9.0
	Horses	kg/head	18.0	18.0
	Dairy cattle, liquid	kg/head	29.9	24.1
Data sources	Brink *et al*. (2002), based on Houghton *et al.* 1997b			

4.3.2 Manure management

The decomposition of organic fractions of manure under anaerobic conditions produces methane (Hendriks *et al.*, 1998). Because temperature has an important influence on manure management, emission factors differ for cool (< 15°C), temperate (15-25°C) and warm (> 25°C) annual mean temperatures. For RAINS emission factors for temperate climate are used for Albania, Italy, Greece, Portugal and Spain, while for all other countries in Europe the factors for the cool region are applied. Also, a differentiation is made between solid and liquid manure management.

Table 4.4: Calculation of emissions from manure management in RAINS

RAINS sectors	AGR_COWS	Dairy cattle, solid and liquid manure management		
	AGR_BEEFS	Other cattle, solid and liquid manure management		
	AGR_PIG	Pigs, solid and liquid manure management		
	AGR_POULT	Poultry		
	AGR_OTANI	Other animals (horses, sheep, goats, etc.)		
Activity rate	Number of animals			
Unit	1000 animals			
Data sources	Data on animal numbers are taken from the RAINS-Europe database and FAO (FAO, 2002).			
Emission factors		Unit	Western Europe	Eastern Europe
for cool climate	Dairy cattle, liquid	kg/head	29.9	24.1
	Dairy cattle, solid	kg/head	3.0	2.4
	Other cattle, liquid	kg/head	11.2	11.2
	Other cattle, solid	kg/head	1.1	1.1
	Pigs, liquid	kg/head	5.5	5.5
	Pigs, solid	kg/head	0.6	0.6
	Poultry	kg/head	0.078	0.078
	Sheep and goats	kg/head	0.19	0.19
	Horses	kg/head	1.4	1.4
for temperate	Dairy cattle, liquid	kg/head	104.8	84.2
Climate	Dairy cattle, solid	kg/head	4.5	3.6
	Other cattle, liquid	kg/head	39.3	39.3
	Other cattle, solid	kg/head	1.7	1.7
	Pigs, liquid	kg/head	19.3	19.3
	Pigs, solid	kg/head	0.8	0.8
	Poultry	kg/head	0.117	0.117
	Sheep and goats	kg/head	0.28	0.28
	Horses	kg/head	2.1	2.1
Data sources	Brink *et al*. (2002), based on Houghton *et al.* (1997b)			

4.3.3 Rice cultivation

Emissions from rice cultivation result from the anaerobic decomposition of organic material in rice fields. Methane is released into the atmosphere mainly by diffusive transport through the rice plants during the growing season. Emissions depend on the season, soil type, soil texture, use of organic matter and fertiliser, climate, soil and paddy characteristics as well as agricultural practices. Thus, in theory a range of values for methane emission estimates is more realistic than a single number. Emissions in the EU are small because only a limited number of countries grow rice (i.e. France, Greece, Hungary, Italy, Portugal, and Spain).

Emission factors were derived from the IPCC guidelines (Houghton *et al.*, 1997b). The IPCC method relates to the annual harvested area and provides country-specific factors, which are listed in the guidelines. Usually, two types of rice are distinguished:

- Upland rice (approximately 10 percent of global rice production and 15 percent of harvested area). Since the fields are not flooded, no emissions of methane occur.
- Wetland rice: irrigated, rain fed, deepwater rice.

Thus, only the area where wetland rice is grown is taken into account as the relevant activity. Emission factors derived are country-specific and a range of values is indicated in Table 4.5.

Table 4.5: Calculation of emissions from rice cultivation in RAINS

RAINS sectors	AGR_RICE	Rice paddies
Activity rate	Harvested area	
Unit	1000 hectares	
Data sources	FAO (2002)	
Emission factors	0.038-0.650 kt/1000 ha	
Data sources	Country-specific, based on Houghton *et al.* (1997b)	

4.3.4 Solid waste disposal in landfills

Methane emissions from waste and wastewater are caused by the anaerobic decomposition of organic matter by methanogenic bacteria in solid waste disposal sites and during the handling of wastewater streams with high contents of organic material. In developing countries, the majority of emissions arise due to low standards for wastewater treatment and disposal technologies, while in industrialised countries the dominating emission sources are landfills and a larger degradable content of solid waste.

To calculate emissions from solid waste disposal, RAINS applies per-capita emission factors for the total population for Western European countries. For transition and developing countries, this calculation is performed only for the urban population. Emission factors are based on the theoretical gas yield methodology using a mass balance approach developed by Bingemer and Crutzen (1987). The estimated degradable organic carbon content of the waste is used to gauge the methane generation potential, assuming that all methane is released in the same year as the waste is land filled. This is a reasonable approximation if the amount of land filled waste and the composition rates remain relatively constant over time.

Table 4.6: Calculation of emissions from solid waste disposal in RAINS

RAINS sectors	Municipal solid waste disposal		
Activity rate	Municipal solid waste disposal		
Unit	Million tons		
Data sources	Houghton *et al.*, 1997b		
Emission factors		Unit	
	Solid waste disposal	kt/million tons waste	24.02-120.55
Data sources	Country-specific, based on Houghton *et al.*, 1997b		

4.3.5 Wastewater treatment

The handling of wastewater streams with high organic content under anaerobic conditions causes large amounts of methane emissions. If wastewater is treated aerobically, no emissions arise. Wastewater handling methods differ between developed and developing countries. In most developed and transition countries, wastewater is treated aerobically without methane emissions or in centralised aerobic wastewater treatment plants and lagoons, where emissions are small. In many developing countries, wastewater is often discharged directly into the water or treated anaerobically.

For sewage, the IPCC default methodology requires a detailed accounting, for which in-depth information, e.g., on sector specific industrial outputs, is necessary. As the present study addresses European countries where the bulk of wastewater is treated aerobically, emissions are simply calculated as a function of population.

Table 4.7: Calculation of emissions from wastewater treatment in RAINS

RAINS sectors	Wastewater			
Activity rate	Total population in Western Europe, urban population for transition countries			
Unit	Million people			
Data sources	RAINS databases			
Emission factors		Unit	Western Europe	Eastern Europe
	Waste water treatment	kt/million people	0.00083	0.00560
Data sources	Country-specific, based on 1990 values contained in the UNFCCC and EDGAR databases, estimating sewage emissions per head			

4.3.6 Coal mining

The process of coal formation produces methane, which is released to the atmosphere when coal is mined. Methane release is higher for underground mining. In addition, there are emissions from post-mining activities such as coal processing, transportation and utilisation.

RAINS uses country-specific emission factors, taking into account the fraction of underground mining in each country and applying the appropriate emission factors for underground and surface mining as well as post-mining activities. National data on the mining structures were taken from EDGAR (Olivier *et al.*, 1996).

Table 4.8: Calculation of emissions from coal mining in RAINS

RAINS sectors	MINE-BC	Mining of brown coal	
	MINE-HC	Mining of hard coal	
Activity rate	Amount of coal mined		
Unit	1000 tons of coal mined		
Data sources	RAINS databases		
Emission factors		Unit	
	Coal mining	kt/Mt	0.9-23.9
Data sources	Using coal production structures as documented in Olivier *et al.* (1996; p. 116) to weight IPCC emission factors given in Houghton *et al.*, 1997b		

4.3.7 Production of natural gas

During gas production, methane emissions occur at the well and from venting and flaring.

Table 4.9: Calculation of emissions from gas production in RAINS

RAINS sectors	GAS_PROD	Production of natural gas		
Activity rate	Amount of gas produced			
Unit	PJ			
Data sources	RAINS databases			
Emission factors		Unit	Western Europe	Eastern Europe
	Gas production	kt/PJ	0.015-0.027	0.146-0.344
Data sources	Houghton *et al.*, 1997b			

4.3.8 Processing, transport and distribution of natural gas

Losses of natural gas during transport and final use are an important source of methane emissions. RAINS calculates these emissions based on gas consumption figures. Emissions are calculated for the distribution to the end consumers and, for gas producing countries, for the long-distance transmission processes. To reflect these differences, the IPCC guidelines provide different (ranges of) emission factors for Western and Eastern European countries. For RAINS, the average emission factors calculated from these ranges are used.

Table 4.10: Calculation of emissions from gas distribution in RAINS

RAINS sectors	CON_COM IN_BO, IN_OC, IN_OCTOT	Gas use in refineries and industry		
	PP_EX_OTH PP_EX_WB, PP_NEW	Gas use in power stations		
	DOM	Gas use in the residential and commercial sector		
	NONEN	Gas use for non-energetic purposes		
	GAS_PROD	Gas produced		
Activity rate	Amount of gas consumed and produced			
Unit	PJ			
Data sources	RAINS databases			
Emission factors		Unit	Western Europe	Eastern Europe
	Gas processing, transport and distribution	kt/PJ gas consumed	0.072-0.133	
		kt/PJ gas produced		0.288-0.628
	Leakages at industrial & power plants	kt/PJ gas consumed		0.087-0.384
	Leakage in the residential and commercial sectors	kt/PJ gas consumed		0.087-0.384
Data sources	Houghton *et al.*, 1997b			

4.3.9 Crude oil production

In crude oil production, methane emissions occur mainly during oil production due to leakage of the associated gas emissions. Regional emission factors from the IPCC guidelines are listed in Table 4.11.

Table 4.11: Calculation of emissions from oil production in RAINS

RAINS sectors	OIL_PROD	Crude oil production		
Activity rate	Amount of crude oil produced			
Unit	PJ			
Data sources	IEA energy statistics (2000a, 2000b)			
Emission factors		Unit	Western Europe	Eastern Europe
	Oil production	kt/PJ	0.0013-0.0035	0.003-0.014
Data sources	Houghton *et al.*, 1997b			

4.3.10 Biomass burning

Biomass consumption comprises the burning of biomass, wood and charcoal for energy purposes. For the time being, RAINS does not include biomass burning for non-energy purposes, e.g., natural forest fires, burning of savannas, etc.

Table 4.12: Calculation of emissions from biomass burning in RAINS

RAINS sectors	CON_COMB, TOTAL_PP, IN_BO, IN_OC, IN_OCTOT, DOM	Biomass burning in refineries, power stations, industry and the residential sector	
Activity rate	Amount of biomass burned		
Unit	PJ		
Data sources	RAINS database		
Emission factors		Unit	
	Biomass combustion	kt/PJ	0.3
Data sources	Houghton *et al.*, 1997b		

4.3.11 Burning of agricultural waste

Methane emissions also originate from the (open) burning of agricultural waste. A global emission factor based on work done by Masui *et al.* (2001) is used for RAINS.

Table 4.13: Calculation of emissions from burning of agricultural waste in RAINS

RAINS sectors	WASTE_AGR	Burning of agricultural waste	
Activity rate	Amount of waste burned		
Unit	Million tons		
Data sources	RAINS database		
Emission factors		Unit	
	Waste_AGR	kt/Mt	0.0012
Data sources	Masui *et al*. (2001)		

4.4 Emission control options and costs

A range of options to reduce emissions of methane was identified and included in the RAINS model. The quantification of their efficiencies, their costs and application potentials is based on a wide range of literature. A number of these studies have a similar spatial (Europe) and temporal (up to 2030) focus, e.g., Hendriks *et al. (*1998 and 2001), AEAT (1998), Bates (2001) and Bates and Haworth (2001). USEPA (1998) provide a similar analysis for the United States, while IEA (1998) and Criqui (2002) have a global focus.

4.4.1 Enteric fermentation

There are a number of control options available to reduce methane emissions through dietary adjustments. The table lists the names of the options, a short description, the associated removal efficiency, annualised investment cost, annual operating and maintenance costs, as well as the total specific costs per ton methane abated.

Table 4.14: Control options for enteric fermentation

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Improved feed conversion efficiency	Mix of options: -Replacement of roughage by concentrates -Change to high fat diet - Increase feed intake - Usage of non-structural carbohydrates	10 %	-	-1790	-1790
Propionate precursors	Hydrogen generated by the fermentation process can react to produce either methane or propionate. Increasing levels of propionate precursors such as organic acids, maltase or fumarate will lead to more propionate being produced from hydrogen and less CH_4.	For dairy cows 25 %, 10 % for non-dairy cattle	-	1474 (dairy) 707 (non-dairy	1474 (dairy) 707 (non-dairy)

Sources: Hendriks *et al.* (1998), AEAT (1998)

For this report it was assumed that feed conversion improvement and the option of increasing propionate precursors can be combined, although there is some uncertainty whether combined reductions would be additive (Bates, 2001).

The high negative costs associated with the feed conversion improvement need further validation in the future. There might be additional costs, e.g., negative effects on animal health and welfare that are not included in the current cost estimates.

The implementation rates listed in Table 4.15 are taken from Bates (2001; p. 52) for the year 2010. Due to a lack of further information, the same implementation rates were assumed for the years after 2010. At this stage it is not clear whether these rates reflect the technical or the economic potentials (taking into account cost).

Table 4.15: Expected implementation of enteric fermentation control options for 2010

	Expected implementation rate in 2010
Improved feed conversion efficiency	50 %
Propionate precursors	50 %

Source: Bates (2001)

4.4.2 Manure management

Methane emissions from manure can be reduced by a regular emptying of the stable cellar and through controlled fermentation of manure under different temperature conditions. The cost of the latter option has been reduced as the methane generated can be used for heat or electricity generation (biogas). Anaerobic digestion can take place in large centralised plants or in small reactors on farms. Two kinds exist:

- Mesophilic digestion (35-40 degrees C): biogas generated on farms is used in central heating systems, which also maintains the digester temperature.
- Psychrophilic digestion (15 degrees C): no heat is added to the digester.

Because a regular emptying of the stable cellar is introduced primarily as a measure to reduce ammonia emissions, the cost of this measure as an option to reduce methane emissions is set to zero.

Table 4.16: Control options manure management

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Housing adaptation and complete emptying of stable cellar	Methanogenesis can be retarded if manure stored in (heated) stables is flushed or cleaned in regular intervals to outdoor storage	10 %	Calculated in the RAINS ammonia module	Calculated in the RAINS ammonia module	Calculated in the RAINS ammonia module
Controlled fermentation of manure	Mesophilic digestion	50 %	23	2	25
	Psychrophilic digestion	75 %	32	37	69

Source: Hendriks *et al.* (1998)

According to AEAT (1998), in 2010 and 2020 approximately 25 percent of the emissions from manure management can be avoided through controlled fermentation. Thus a 50 percent implementation rate is assumed for RAINS.

4.4.3 Rice cultivation

The literature lists low methane emitting rice strains as an option to reduce methane emissions from rice paddies (IEA, 1998). Methane emissions vary significantly between rice strains, careful selection of strains is estimated to reduce emissions by 20-30 percent. No increases in rice production and methane emissions are anticipated as expanding rice paddies is generally not considered feasible (Matthews, 2002). No information has yet been found on current and expected implementation of this option.

Table 4.17: Control option for rice cultivation

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Alternative rice strains	Alternative rice strains	25 %	-	47	47

Source: IEA (1998)

4.4.4 Solid waste disposal

Methane emissions from waste disposal may be controlled by reducing the amount of land filled waste or by reducing emissions from the landfill. The options for waste diversion include paper recycling, composting of waste, anaerobic digestion of waste, incineration of municipal solid waste destined for landfill and mechanical-biological treatment. Recovery and use of landfill gas can be achieved through flaring of landfill gas, direct use of landfill gas for heat generation, use of landfill gas to generate electricity for export, or gas upgrade and delivery to a distribution network. Landfills can be capped with a clay cap and the restoration layer above the cap can be designed with a permeable material to allow oxygen to diffuse into the layer to oxidise methane into carbon dioxide (CO_2). These options are interdependent: the more waste is diverted, the smaller are the reduction potentials from gas recovery and improved capping of landfills.

In order to maintain a manageable number of control options to be analysed in the RAINS model, nine options have been grouped together into three groups of measures with similar costs and reduction potentials (Table 4.18).

Table 4.18: Control options for methane emissions from solid waste disposal

Option	Description	Application potential	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Paper recycling	Paper recycling for paper and cardboard production	100 %	24 %	1747	-3589	-1842
Generic option for waste diversion	Composting, incineration, anaerobic digestion, mechanical-biological treatment	100 %	100 %	1671	-158	1,513
CH_4 recovery and use	Electricity generation, heat generation, gas upgrade	80 %	Remaining emissions	195	-200	-5
Landfill capping	Landfills are capped with clay cap and restoration layer above cap is designed with permeable material to allow oxygen to diffuse into layer to oxidise CH_4 into CO_2	20 %	Remaining emissions	588	35	623

Source: AEAT (1998); Bates and Haworth (2001); Hendriks *et al.* (1998)

Current market prices for used paper and transportation costs result in negative costs for paper recycling. More information will be needed to validate the result. Further analysis will also need to assess the elasticity of the market price for an increased availability of waste paper.

The European Council Directive 99/31/EC of 26 April 1999 on the land filling of waste requires a reduction of biodegradable land filled waste and control of landfill gas. This directive requires the following amount of waste (expressed as percentage of 1995 volumes) to be diverted in biodegradable municipal waste going to landfills (Hogg *et al.,* 2002: 35):

- 2006: -25 percent
- 2009: -50 percent
- 2016: -65 percent.

These targets also apply to accession countries. For countries with a heavy reliance on landfill (Greece, Ireland, Italy, Portugal, Spain, UK, Cyprus, Estonia, Hungary, Poland and Slovenia) an additional compliance period of four years is foreseen (Hogg *et al.,* 2002; p. 9). In this report, it is assumed that the targets set in the directive will be achieved. The directive also requires that all new landfill sites must have gas recovery facilities. All existing sites must have installed these facilities by 2009 (Hogg *et al.,* 2002; p. 67). As a consequence, it can be assumed that the efficiency of methane recovery from land filled waste will increase from 13 percent in 1990 to 55 percent in 2020 (Table 4.19, based on AEAT, 1998).

Table 4.19: Methane recovery from landfills as shares of landfill emissions

	1990	2000	2010	2020
	Share of emissions			
Austria	0.20	0.20	0.37	0.55
Belgium	0.12	0.12	0.37	0.55
Denmark	0.20	0.20	0.38	0.55
Finland	0.00	0.00	0.29	0.50
France	0.20	0.20	0.44	0.59
Germany	0.26	0.26	0.51	0.63
Greece	0.05	0.05	0.29	0.50
Ireland	0.05	0.05	0.29	0.50
Italy	0.10	0.10	0.39	0.56
Luxembourg	0.20	0.20	0.34	0.53
Netherlands	0.03	0.03	0.37	0.55
Portugal	0.05	0.05	0.29	0.50
Spain	0.00	0.00	0.33	0.52
Sweden	0.28	0.28	0.56	0.66
United Kingdom	0.20	0.20	0.45	0.59
EU-15 average	0.13	0.17	0.38	0.55

Source: AEAT (1998)

Due to a lack of more specific data, the EU average values are taken for accession

4.4.5 Wastewater treatment

In industrialised countries essentially all sewage is currently treated in sewage plants. In less developed countries significant amounts remain untreated. For these countries, integrated sewage systems, where the sewage is degraded aerobically, is seen as a viable option for reducing methane emissions.

There is high degree of uncertainty concerning the share of the sewage treatment cost that can be attributed exclusively to methane abatement, as sewage treatment is undertaken mainly for other reasons. IEA-GHG (1998) discusses a range of 50-2,000 US-$ per ton methane abated. Until better information is found, 100 €/t abated CH_4 is assumed as a first estimate.

Table 4.20: Control option for wastewater handling

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Integrated sewage system	Collection of sewage in integrated sewage system involves aerobic degradation step	90 %	n.a.	n.a.	100

Source: IEA (1998)

4.4.6 Coal mining

Methane emissions from coalmines can be reduced through upgrading existing mines or building new mines with more efficient methane recovery (AEAT, 1998; p. 107). Because all coalmines are already equipped with some sort of methane recovery, an upgrade from a 30 percent efficiency to an 80 percent efficient recovery is considered for this study (Table 4.21). The recovered methane can be used for heat and electricity generation and therefore, depending on the gas price, the net costs for methane recovery are typically reported to be negative (e.g., AEAT, 1998).

Table 4.21: Control option for coal mining

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Upgrade or new installation with 80 % recovery	From 30 to 80 % recovery and utilisation	80 %	2768	-2839	-71

Source: AEAT (1998)

According to AEAT (1998), the currently installed equipment captures typically 30 percent of the emissions in the EU, but 70 percent in Germany. It is assumed that the recovery can be increased by 2020 to 50 percent (80 percent in Germany).

4.4.7 Gas production

Emissions can be controlled during production and processing (increased gas utilisation) of methane.

Table 4.22: Control options for gas production

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Increased gas utilisation, Stage 1	Increased gas utilisation on offshore platforms, e.g., for power generation instead of venting	20 %	92	-152	-60
Further increased gas utilisation, Stage 2	More advanced gas utilisation on off-shore platforms	30 %	152	-145	7

Sources: Hendriks *et al*. (1998, 2001); AEAT (1998)

4.4.8 Gas distribution

Emissions can be controlled during distribution and transmission (replacement of distribution network) of methane.

Table 4.23: Control options for gas distribution

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Inspection and maintenance incl. power generation for gas transport and distribution		4 %	-	-211	-211
Doubling leak control frequency for pipelines		10 %	-	1266	1266
Replacement of grey cast iron network	Replacement by modern pipes	38 %	2833	-321	2512

Sources: Hendriks *et al.* (1998), Hendriks and de Jager (2001); AEAT (1998)

Table 4.24: Current implementation (2000) of control options for the gas sector in the EU-15 (percent of 1990 emissions)

Country	Measures	CH_4 reduction (%)
Austria	Switching to suppliers with more advanced production plants and distribution networks	10 %
France	Replacement of distribution network and improvement of operating practices	23 %
Germany	Modernisation of pipeline networks	19 %
Italy	Maintenance and replacement of old network	10 %
Netherlands	Maintenance and replacement of old network	13 %
UK	Introduction of leakage control strategy	23 % of gas distribution (=86 % of emissions), thus 20 %

Source: AEAT (1998)

4.4.9 Oil production

Methane associated with oil production can be flared or used for energy recovery. Negative costs are estimated for the latter option due to the benefits of utilizing methane as an energy source (Table 4.25). No information has yet been found on the current and expected implementation of this option.

Table 4.25: Control options for methane emissions of associated gas from oil production

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Flaring	Flaring rather than venting	23 %	271	126	397
Use	Use of associated gas for sale or electricity generation (mix)	27 %	1777	-1974	-197

Source: AEAT (1998)

4.4.10 Agricultural waste burning

A control option for agricultural waste burning already considered in RAINS is a ban on open burning of agricultural waste (Klimont *et al.,* 2000).

Table 4.26: Control options for agricultural waste burning

Option	Description	Removal efficiency	Annualised investments (€/t abated CH_4)	Annual O&M costs (€/t abated CH_4)	Specific costs (€/ton abated CH_4)
Ban	Ban on open burning of agricultural or residential waste	100 %	Calculated in the RAINS VOC model		

Source: Klimont *et al.* (2000)

4.5 Interactions with other emissions

A number of cases have been identified where emissions of methane and related emission control options influence emissions of other greenhouse gases and air pollutants, and vice versa. During treatment of manure, N_2O and NH_3 are emitted together with methane and when wastewater is discharged, methane and nitrous oxide (N_2O) emissions are released. Waste disposal, gas production, distribution and consumption, and oil production and refining are processes during which both methane and volatile organic compounds (VOC) are emitted. Agricultural waste burning causes emissions of methane, particulate matter (PM), nitrogen oxides (NO_x) and VOC. It will be important to capture these interactions in the further course of this study.

Table 4.27: Methane emitting sectors and interactions with emissions of other air pollutants

Sector		Interactions with other gases
Agriculture	Enteric fermentation	
	Manure management	NH_3, N_2O
	Rice cultivation	
Waste	Solid waste	VOC
	Wastewater	N_2O
Fugitive emissions in energy sector	Gas production, processing and distribution	VOC
	Coal mining	
	Oil production and refinery	VOC
Biomass burning	Field burning of agricultural residues	PM, NO_x, VOC
	Residential bio-fuel combustion	CO_2

4.6 Preliminary results

4.6.1 Emission inventories

At the aggregated European level, the initial RAINS CH_4 emission estimates compare well with the UNFCCC and EDGAR inventories (Table 4.28). There are, however, discrepancies to some national estimates, which need further exploration. The sectoral origin of methane emissions in Europe in 1990 is shown in Figure 4.2. According to the preliminary RAINS estimates, 34 percent originated from enteric fermentation, followed by waste disposal (28 percent) and coal mining (18 percent).

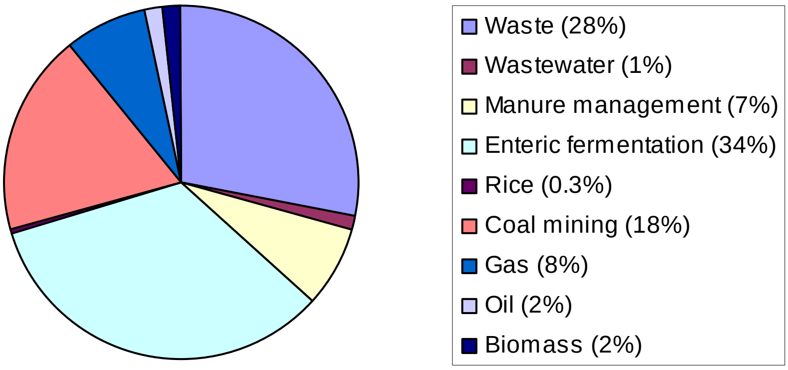

Figure 4.2: Methane baseline emissions 1990 for EU-23 by sector. Source: RAINS

4.6.2 Emission projections

Emission projections for Europe as a whole (except Cyprus, Malta and the European part of Russia) indicate that, with current legislation, methane emissions will be 18 percent lower than in 1990. The maximum feasible reduction in 2020 is 43 percent of the 1990 values.

Emission calculations for EU-23 countries render a total value of 24.6 million tons methane for 1990 and for the 2020 baseline a value of 19.4 million tons. The maximum feasible reduction (MFR) indicates a technological reduction potential of around 46 percent for 2020 (see Table 4.29).

Table 4.28: CH_4 emission estimates for 1990 and 2000 (kilotons CH_4)

	1990				2000		
	RAINS	UNFCCC	EDGAR	ECOFYS	RAINS	UNFCCC	ECOFYS
Albania	109	n.a.	105	n.a.	121	n.a.	n.a.
Austria	450	538	391	587	418	448	600
Belarus	830	n.a.	914	n.a.	631	n.a.	n.a.
Belgium	491	550	488	634	476	524	537
Bosnia-H..	115	n.a.	95	n.a.	96	n.a.	n.a.
Bulgaria	470	1334	457	n.a.	355	n.a.	n.a.
Croatia	160	182	190	n.a.	178	n.a.	n.a.
Cyprus	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Czech Rep.	1059	798	1059	n.a.	1009	510	n.a.
Denmark	272	278	269	421	336	274	409
Estonia	135	208	124	n.a.	100	118	n.a.
Finland	257	292	353	246	248	187	226
France	2783	3169	2701	3017	2525	2871	2820
Germany	5172	5273	5232	5682	3924	2885	3892
Greece	424	416	305	443	440	518	n.a.
Hungary	538	664	677	n.a.	489	553	n.a.
Ireland	628	612	551	811	606	610	837
Italy	1577	1876	2015	2329	1621	1801	2455
Latvia	176	196	206	n.a.	89	121	n.a.
Lithuania	381	378	369	n.a.	326	n.a.	n.a.
Luxembourg	22	24	12	24	23	23	22
Macedonia	71	n.a.	57	n.a.	69	n.a.	n.a.
Malta	n.a.	n.a.	5	n.a.	n.a.	n.a.	n.a.
Moldavia	179	n.a.	229	n.a.	167	n.a.	n.a.
Netherlands	1199	1292	922	1290	1183	983	971
Norway	250	307	362	n.a.	275	324	n.a.
Poland	2706	3141	4286	n.a.	2719	2183	n.a.
Portugal	417	614	355	806	421	625	714
Romania	1753	2357	2014	n.a.	1406	n.a.	n.a.
Serbia-M.	430	n.a.	614	n.a.	420	n.a.	n.a.
Slovakia	264	323	355	n.a.	207	215	n.a.
Slovenia	132	176	83	n.a.	129	n.a.	n.a.
Spain	1403	1412	1508	2181	1486	1827	2356
Sweden	322	324	365	324	240	280	284
Switzerland	209	242	229	n.a.	200	216	n.a.
Ukraine	5195	9402	6971	n.a.	4432	n.a.	n.a.
UK	3751	3645	3227	4409	3436	2427	3361
Total EUROPE	34330	40023	39381	n.a.	30801	n.a.	n.a
EU-23	24559	26199	25853	n.a.	22449	n.a.	n.a.
CO_2eq	515739	550179	542913	n.a.	471429	n.a.	n.a.
EU-15	19167	20315	18694	23204	17381	16283	n.a.
CO_2eq	402507	426615	392574	487284	365001	341943	n.a.

Sources: RAINS, UNFCCC (2003), EDGAR (2004) and ECOFYS (1998)

Table 4.29: Methane emission calculation for 1990 and 2020 (in kilotons of CH_4)

Country	1990	2020 Current legislation	2020 Maximum feasible reduction
Albania	109	145	101
Austria	450	326	202
Belarus	830	692	512
Belgium	491	411	273
Bosnia-H.	115	106	62
Bulgaria	470	388	262
Croatia	160	215	143
Cyprus	n.a.	n.a.	n.a.
Czech Republic	1,059	882	744
Denmark	272	261	205
Estonia	135	81	80
Finland	257	205	124
France	2,783	2,212	1,682
Germany	5,172	2,915	1,803
Greece	424	382	275
Hungary	538	567	410
Ireland	628	611	505
Italy	1,577	1,442	964
Latvia	176	111	93
Lithuania	381	260	222
Luxembourg	22	32	25
Macedonia	71	82	59
Malta	n.a.	n.a.	n.a.
Moldavia	179	170	122
Netherlands	1,199	879	603
Norway	250	279	160
Poland	2,706	2,963	1,880
Portugal	417	357	206
Romania	1753	1777	1406
Serbia-M.	430	464	284
Slovak Republic	264	234	158
Slovenia	132	115	73
Spain	1,403	1,380	931
Sweden	322	231	177
Switzerland	209	197	146
Ukraine	5195	4201	3011
UK	3,751	2,615	1,657
Total Europe	34330	28188	19560
EU-23 total	24559	19472	13292
EU-15 total	19168	14259	9632

A comparison of the preliminary RAINS estimates with the studies conducted by ECOFYS and AEAT shows overall similar reduction potentials for the current legislation and maximum feasible reduction cases (Table 4.30). When comparing these estimates, however, it must be kept in mind that both the ECOFYS and AEAT study are based on the national emission inventories reported for 1990 under the Second National Communications to UNFCCC. In many cases these estimates are higher than more recent inventories, because they did not fully reflect the extent at which abatement measures were already implemented in 1990. Consequently, the relative reduction potential estimated by ECOFYS and AEAT are somewhat larger than the more recent RAINS estimates, which start from a lower emission estimate for 1990.

Table 4.30: Estimated changes in methane emissions in EU-15 compared to 1990 emissions (CLE: Current legislation/business as usual; MFR: maximum technically feasible reductions).

	RAINS		ECOFYS		AEAT	
	CLE	CLE	BAU	MFR	CLE	MFR
1990-2010	-20 %	-33 %	-26 %	-50%	-9 %	-40 %
1990-2020	-25 %	-49 %				

4.6.3 Estimates of emission control costs

The measures to control methane emissions can be summarised and ranked according to their average costs per ton CO_2eq removed. Table 4.31 indicates that for a number of options exists negative net costs are calculated due to associated costs savings (e.g., from fodder cost reductions, paper recycling revenues or sales of natural gas, heat or electricity). As mentioned previously, these results depend heavily on the assumed costs and prices, both of which might change if measures are applied on a larger scale (possibly implying higher marginal costs and lower revenues).

Table 4.31: Summary of options to control methane emissions

Sector	Sub-sector	Control option	Cost €/ t CO_2eq
Waste	Municipal solid waste	Paper recycling	-88
Agriculture	Enteric fermentation	Improved feed conversion efficiency	-85
Gas	Gas distribution	Inspection and maintenance	-10
Oil	Oil production	Use of gas for sale or electricity generation	-9
Coal	Coal mining	Upgrade or new installation with 80 % recovery	-3
Gas	Gas production	Increased gas utilisation -stage 1	-3
Waste	Municipal solid waste	CH_4 recovery and use	0
Agriculture	Manure management	Regular cleaning of manure	0
Waste	Agricultural waste	Ban on open burning of agricultural waste	0
Gas	Gas production	Increased gas utilisation - Stage 2	0
Agriculture	Manure management	Controlled fermentation - Mesophilic digestion	1
Agriculture	Rice cultivation	Alternative rice strains	2
Agriculture	Manure management	Controlled fermentation - Psychrophilic digestion	3
Waste	Wastewater	Integrated sewage system	5
Oil	Oil production	Flaring rather than venting	19
Waste	Municipal solid waste	Landfill capping	30
Agriculture	Enteric fermentation	Propionate precursors -non-dairy	34
Gas	Gas distribution	Doubling leak control frequency for pipelines	60
Agriculture	Enteric fermentation	Propionate precursors -dairy cows	70
Waste	Municipal solid waste	Generic options for waste diversion (composting, incineration etc.)	72
Gas	Gas distribution	Replacement of grey cast iron network	120

4.7 Conclusions

This chapter describes the RAINS methodology to estimate emissions of methane (CH_4) emissions and the possibilities and cost for reducing these emissions. A number of preliminary conclusions can be drawn at this stage:

RAINS includes now the most important anthropogenic sources of methane emissions, i.e., livestock (enteric fermentation and manure management), rice cultivation, waste and wastewater management, coal mining, production and consumption of oil and gas, and biomass burning.

The RAINS emission estimates for Europe for 1990 and 2000 correspond well to the UNFCCC and EDGAR data. With current legislation, the preliminary forecast for 2020 suggests that CH_4 emissions in Europe might decrease by 18 percent in 2020 compared to 1990. EU-23 emissions are 23 percent lower.

Various options to control methane emissions were identified for all sources and their costs have been estimated. However, associated uncertainties are high, especially for the costs and the applicability of the various options. More research is needed to further validate this data.

Further work on the methane emissions will have to analyse in detail the validity of the negative costs options, explore the synergies with other greenhouse gases and air pollutants and to complete the database especially regarding Malta, Cyprus and the European part of Russia.

5 Nitrous oxide

5.1 Introduction

Among the more abundant climate gases, nitrous oxide (N_2O) is the one with the strongest climate forcing. On a scale of 100 years, nitrous oxide is considered to contribute 310 times as much to the greenhouse effect as the same mass of carbon dioxide. Therefore N_2O is a quite effective greenhouse gas already at low concentrations. Furthermore, nitrous oxide is to a large extent the result of biological processes which occur in soils over large areas. This and the long atmospheric residence time of approximately 120 years (Seinfeld and Pandis, 1998) allows for only small increments over the background concentrations, which are difficult to track by measurements. Since the soil processes are also poorly understood, the uncertainty associated with a considerable part of the emissions is thus very high.

Consequently, the current implementation of nitrous oxide emissions in RAINS focuses primarily on the sources that are reasonably well understood. These are, first, industrial process emissions. N_2O is also formed as a by-product of energy combustion, often as a consequence of NO_x abatement technologies. As the concept of this work is to integrate emission calculations of N_2O into the RAINS system, relevant activity numbers have been taken from the existing RAINS implementation as far as possible. The quantification of the important sector of soil emissions will be limited to general parameterisations, which are compatible to the IPCC guidelines proposed by Houghton *et al.* (1997a and b). As better results from soil models are expected to come up soon, an external pre-processor is foreseen that will allow improving the preliminary estimates in the near future.

Little information is also available in terms of abatement options and costs. Within this study, we concentrate on abatement measures that are applied to control emissions of other trace gases and that have a side-impact on nitrous oxide emissions. General features of these measures as well as the associated costs are taken from the existing databases of the RAINS model. In most of these cases, only N_2O emission factors had to be added. N_2O-specific abatement options have been found only in a handful of cases, and further work will be required to support and further develop the figures now presented in Section 5.4.

Since work is still in progress, this report describes the current state of investigations. Results presented in this report have to be considered as preliminary and may change in the further course of the project.

5.2 Nitrous oxide emission source categories

Both global and national estimates of N_2O emissions are available by source category. As a contribution to the GEIA project, a compilation of emission sources has been performed globally (Bouwman, 1995). Based on this experience, Houghton *et al.* (1997a, 1997b) have published guidelines to assess national emission estimates for N_2O. For the European Union, national estimates have been compiled from national submissions of the Member States to UNFCCC (Gugele and Ritter, 2002, Figure 5.1).

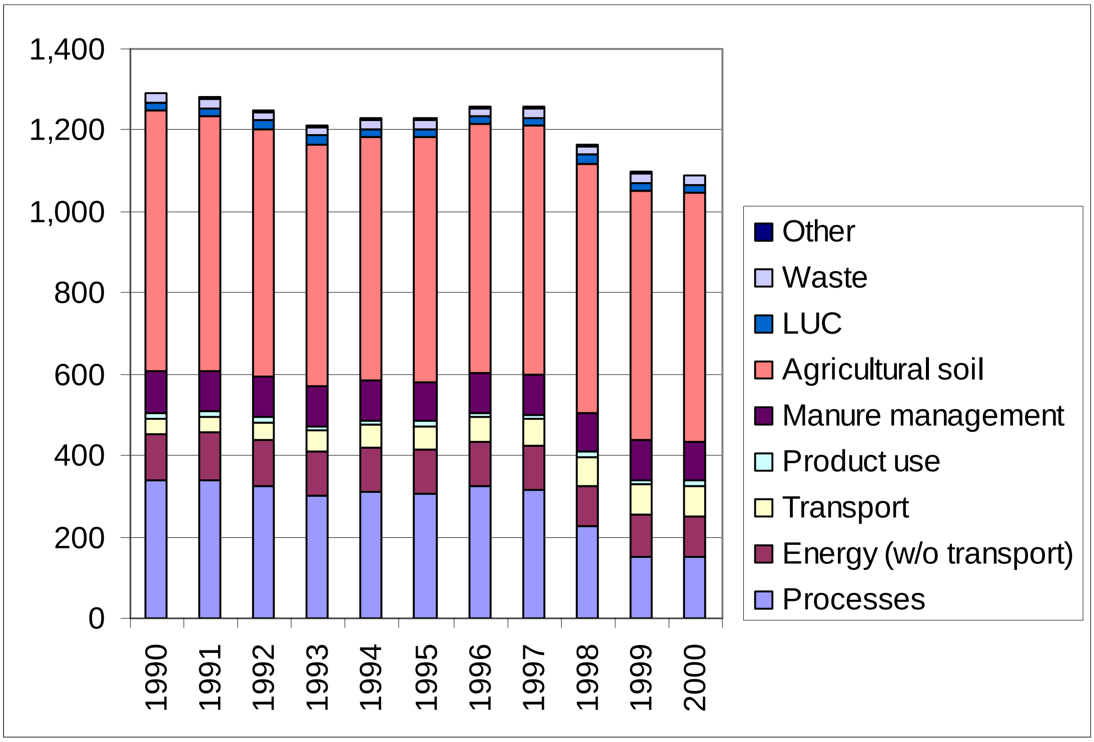

Figure 5.1: N_2O emissions from the EU-15 (Gugele and Ritter, 2002) in kt/yr.

This overview clearly identifies the most important contributors to nitrous oxide emissions in Europe. The dominant source is agriculture, in particular emissions from soils. Other important sources are industrial processes, which have strongly declined after 1997, and transport, which displays an increasing trend. The European inventory does not include N_2O emissions from oceans, since they are not allocated to individual countries. As will be discussed in the paragraphs below, the transport emissions (and the associated increase) are caused by the increased use of catalytic converters in cars, while the decrease of industrial process emissions is caused mainly by process optimisations in the production of adipic acid, where emission reductions merely are positive side-effects of process improvements.

5.3 Emission factors and emission estimates

5.3.1 Industrial processes

Nitrous oxide is formed in processes that involve nitric acid, especially when nitric acid is used as an oxidant. This is the case for the production of adipic acid, a chemical used for Nylon®

production. Emissions from this process are huge (0.3 t per t product: De Soete, 1993), such that only few installations in four countries (Germany, France, Italy and UK) make up for a significant part of total European nitrous oxide emissions. At the same time, flue gas concentrations at these plants are so high that they can be captured by specific equipment. Several options exist for such removal, and the recovered N_2O can be used as raw material for nitric acid production (Hendriks *et al.*, 1998). Within the overall process, these options may be considered cost-neutral. This technological change has started in the late 1990's, so that the introduction of N_2O recovery can be regarded as an autonomous development, driven by optimising the production process rather than environmental considerations.

Production of nitric acid is the other significant source. Concentrations of nitrous oxide in flue gases are much lower, so that control measures are less efficient and more costly. Still methods have been described (De Soete, 1993; Kuiper, 2001) for the catalytic reduction on N_2O. As the production of nitric acid (activity) is already included in RAINS, this only needs to be extended by an appropriate emission factor.

Table 5.1: Calculation of N_2O emissions from industrial processes in RAINS. An asterisk ("*") stands for all sectors/activities/technologies other than those specifically mentioned

RAINS sectors	PR_ADIP	Adipic acid production		
	PR_NIAC	Industry - Process emissions - Nitric acid plants		
Activity rate	Production			
Unit	Mt product			
Data sources	Nitric acid production is taken from the RAINS-Europe database. Adipic acid production is derived from the national communications to the UNFCCC (only applicable for DE, FR, IT, and UK, no production in other European countries).			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O/Mt product)
	Adipic acid production	Production	No control	300.0
	Adipic acid production	Production	SCR	4.5
	Nitric acid plants	Production	*	5.7
	Nitric acid plants	Production	SCR	1.14
Data sources	De Soete (1993), Kuiper (2001)			

5.3.2 Combustion in industry and power plants

In addition to the (low) emission factors of conventional boilers, specific abatement measures introduced to control the emission of NO_x have to be considered. Both fluidised bed combustion, FBC (due to the different combustion conditions, especially the lower temperature and longer residence time of combustion gases), and selective non-catalytic reduction of NO_x (SNCR) with NH_3 or urea as reducing agent prevent NO_x emissions, but favour the formation of N_2O. The respective activity data are already part of the RAINS databases, so that only emission factors have to be derived. De Soete (1993) reports on one dataset that presents measured energy-related emission factors (50 – 140 mg N_2O/MJ) for a coal fired FBC power plant. A distinct temperature dependence (lower N_2O at higher temperatures) is seen. The common practice of adding CaO leads to destruction of N_2O. This is already taken care of by developing an emission factor, which should reflect this type of abatement.

Table 5.2: Calculation of combustion emissions of N_2O in RAINS. An asterisk ("*") stands for all sectors/activities/technologies other than those specifically mentioned. Priority decreases from top to bottom, i.e., the fluidised bed emission factor is used in case this technology is implemented.

RAINS sectors	CON_COMB	Fuel production and conversion: Combustion		
	DOM	Combustion in residential/commercial sector		
	IN_BO	Industry: Combustion in boilers		
	IN_OC	Industry: Other combustion		
	PP	Power plants: Combustion		
Activity rate	Fuel consumption			
Unit	PJ			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kt N_2O / PJ)
	Industry	Heavy fuel oil, industrial boilers and other combustion	Combustion modification + Selective non-catalytic Reduction (SNCR) Oil &Gas	0.008
	*	*	Fluidised bed	0.08
	*	Brown coal/lignite	*	0.0014
	*	Hard coal	*	0.0014
	*	Derived coal	*	0.0014
	*	Heavy fuel oil	*	0.0006
	*	Medium distillates (diesel, light fuel oil)	*	0.0006
	*	Gasoline	*	0.0006
	*	Liquefied petroleum gas	*	0.0006
	*	Natural gas (incl. other gases)	*	0.0001
	*	Other solid fuels	*	0.004
Data sources	De Soete (1993), Houghton *et al.* (1997b)			

In conventional combustion installations, enhanced N_2O emissions have been systematically observed after SNCR, but only occasionally for selective catalytic reduction (SCR, De Soete, 1993). For SNCR, 50 ppm N_2O (20 – 70 for temperatures at high NO_x reduction efficiency) in flue gas has been reported after 200 ppm NO for an installation applying urea injection. Applying ammonia as reducing agent will produce about one third of this amount. Using an unabated emission factor of 0.1 t NO_x (as NO_2)/TJ for heavy fuel oil and neglecting the molecular weight differences of NO_2 and N_2O, the N_2O emissions will reach 25 kg/TJ for urea injection (or about 8 kg/TJ for NH_3 injection). As long as no additional information is available, RAINS applies this emission factor only to heavy oil as fuel.

5.3.3 Transport

A detailed description of a large number of different studies on traffic emissions, including own measurements, is presented by Jimenez *et al.* (2000). Data used here were extracted from a table showing the ratios of N_2O to CO_2 emissions and were recalculated to yield emission factors.

In order to reconcile the results of older studies, it is assumed that advancements in three-way catalysts are responsible for a change in N_2O emissions between the early generation and the new generation of catalysts. This is in line with the differentiation performed by the US EPA, and the EPA emission factors compare well with those derived by Jimenez (all as reported by Jimenez). However, the ratio between unabated (non-catalyst) and catalystequipped cars according to Jimenez is much smaller than that reported by De Soete (1993) or by Houghton *et al.* (1997b). Jimenez *et al.* (2000) provide a wide overview of the reasons why the first assessments of N_2O emissions both in dynamometer studies and in field studies tended to overestimate N_2O emissions from catalyst cars, but underestimate emissions from non-catalyst cars. Even the IPCC guidelines (Houghton *et al.*, 1997b) are based on these older studies.

For future generations of emission control at vehicles, as a first approximation no further changes in terms of N_2O emissions compared to EURO-IV are assumed. As however EURO-IV heavy duty vehicles will be the first diesel engines that have flue gas $DeNO_x$ equipment (SCR supported by urea as reducing agent), it may be possible that additional nitrous oxide is being formed. For the time being, RAINS assumes for heavy-duty vehicles equipped with EURO-IV an emission factor reported by De Soete (1993) for boilers with SNCR and urea injection. Obviously, this assumption is rather uncertain, as for boilers different residence times and other combustion temperatures (no catalyst!) apply. Also, a recent report by RICARDO plc (personal information) does only indicate a modest increase of the N_2O emission factor. An explanation for the difference to the data reported by RICARDO (where N_2O was just a side issue) will still have to be found.

Table 5.3: Calculation of N_2O traffic emissions in RAINS. An asterisk ("*") stands for all sectors/activities/technologies other than those specifically mentioned.

RAINS sectors	TRA_RD	Road transport		
	TRA_OT	Other transport		
Activity rate	Fuel consumption			
Unit	PJ			
Data sources	RAINS databases			
Emission factors	Sector	Fuel use	Abatement technology	Emission factor (kt N_2O / PJ)
	Road transport	Diesel	*	0.0018
	Heavy duty vehicles	Diesel	EURO-IV and later	0.025
	Road transport	Gasoline	*	0.0031
	Light duty vehicles, 4-stroke (excl. GDI)	Gasoline	EURO-I	0.0136
	Light duty vehicles, 4-stroke (excl. GDI)	Gasoline	EURO-II and later	0.0055
	Other transport	Medium distillates (diesel, light fuel oil)	*	0.0018
	Other transport	Gasoline	*	0.0031
Data sources	Jimenez *et al.* (2000), Houghton *et al.* (1997b)			

5.3.4 N_2O use

While the IPCC guidelines on national GHG emission inventories (Houghton *et al.*, 1997b) do not specify a methodology to assess N_2O use, an attempt was made to obtain order-of-magnitude estimates both from production figures and data on consumption/use of N_2O.

Information provided by the Swiss engineering company SOCSIL indicate that N_2O production may be significant. The company reports having installed globally more than 100 N_2O production units, at standard sizes between 25 and 300 kg/hr (www.socsil.ch). Assuming half of the installations to be in the European Union, and an average production of 100 kg/hr during 8000 hours per year suggests a total annual production of 40 kt. With the assumption that most of N_2O is used directly (in medicine or as propellant in food industry), virtually all of the N_2O that is produced will eventually be emitted to the atmosphere; N_2O remains in the human body only for a short time and is not metabolised.

This calculation suggests a contribution of about three percent of the total N_2O emissions in the EU-15, while the national greenhouse gas inventories collectively report only about one percent from this sector. On a per-capita basis (per 378 Mio inhabitants), an estimate of 0.105 kg per inhabitant for medical purposes and the food industry may be considered an upper limit. In the German report to UNFCCC, N_2O emissions from “solvent and other product use” amount to 6 kt per year or 0.076 kg/inhabitant, indicating reasonably good agreement (see http://ghg.unfccc.int/).

For EU-15, the situation is quite different however. Gugele and Ritter (2002) report 11 kt N_2O from the same sector, just a quarter of the estimate derived from potential production and about a third (on a per-capita-basis) of the German situation. Looking at the data in detail (again according to http://ghg.unfccc.int/), it becomes evident that Germany contributes more than half in this sector, France one third of the German number, while Italy and UK do not report any emissions. Even if it is beyond the task of this study to assess emissions, we understand that emissions from this source simply have not been reported by the countries, and we apply the population-based emission factor from Germany. According to the information available we assume the majority of emissions to be associated with N_2O use for medical purposes. The emission factor may however only apply to countries at a certain standard of medical care. This can not explain the differences for EU-15, but it may be useful at a later stage of development to scale German emissions by GDP per capita instead of per capita alone. This remains an option only for the future, however.

To reduce emissions of N_2O from medical use and the food industry, RAINS considers the option of replacement (e.g. by Xe or intravenous application of anaesthetics).

Table 5.4: Calculation of emissions due to application of N_2O in RAINS.

RAINS sectors	N_2O_USE	Use of N_2O		
Activity rate	Population			
Unit	Million inhabitants			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor [kg N_2O/person]
	Use of N_2O	Population	No control	0.076
	Use of N_2O	Population	Replacement	0
Data sources	German report to the UNFCCC (2000), www.SOCSIL.com (2003)			

5.3.5 Sewage treatment plants

The contribution of sewage treatment plants to nitrous oxide emissions is fairly small (see also Figure 5.1). The main reason to include it specifically is the fact that Hendriks *et al.* (1998) provide specific options for emission abatement from this source. Because of the low overall importance of N_2O emissions from sewage treatment plants, RAINS estimates uncontrolled emissions on a per-capita basis. Total emissions were taken from the official EU database submitted to UNFCCC (Gugele and Ritter, 2002), which presents a number that is three times as high as that by Hendriks *et al.* (1998). In terms of abatement, the reduction factor suggested by Hendriks has nevertheless been applied.

Table 5.5: Calculation of N_2O emissions from sewage treatment plants in RAINS

RAINS sectors	SEW_TREAT	Sewage treatment		
Activity rate	Population			
Unit	Million inhabitants			
Data sources	RAINS databases			
Emission factors	Sector	Activity	Abatement technology	Emission factor (kg N_2O/person)
	Sewage treatment	Population	No Control	0.051
	Sewage treatment	Population	Process optimisation	0.031
Data sources	Gugele and Ritter (2002), Hendriks *et al.* (1998)			

5.3.6 Agriculture

Microbial processes in soil and in manure (nitrification and denitrification processes) are considered the dominant sources of nitrous oxide emissions in Europe. One key parameter influencing the amount of N_2O emissions is the availability of nitrogen. The IPCC emission reporting guidelines (Houghton *et al.*, 1997b) recommend a uniform emission factor related to nitrogen input. The uncertainty of emission calculations based on this approach was estimated at two orders of magnitude (1997).

While the IPCC guidelines provide details on how to account for other forms of nitrogen losses and for ‘indirect’ emissions resulting from such losses, the contribution from atmospheric deposition of nitrogen is not considered. However, the amount of nitrogen deposition is directly influenced by air pollution control, and this mechanism might form an important interaction between air pollution control and emissions of greenhouse gases. Thus, the methodology recommended in the IPCC guidelines has been modified to consider the impact of changes in nitrogen deposition on N_2O emissions. Not only the nitrogen input due to agricultural practice is now considered, but also atmospheric deposition. Moreover, as atmospheric deposition also affects forests, emissions from forests are also included.

In the present preliminary implementation, default values have been used for atmospheric deposition (20 kg N/ha/year, for both agricultural land and forest area) and for nitrogen input from inorganic fertilisers (100 kg N/ha/year, calculated for agricultural land only) throughout Europe. In the future, nitrogen deposition from the atmosphere will be calculated within RAINS at a 50*50 km spatial resolution, distinguishing deposition to forests and to agricultural land. Similarly, average values of nitrogen excretion per animal as given in the IPCC guidelines have been used as a default for the nitrogen input from spreading of manure or from grazing animals (Table 5.7). In the future, this will be replaced by country-specific data.

It is further assumed that 1.5 percent of all nitrogen entering the soil is emitted as N_2O. This number is simplified from the IPCC recommended multi-stage approach, where different factors ranging from one to 2.5 percent are used for different fractions of nitrogen input. As not only the uncertainty given with these factors is extremely high, but also the differentiation into fractions is unreliable, this simplification seems acceptable as a first estimate.

Nitrogen input is, however, only one factor influencing N_2O emissions. Other parameters that may drastically modify N_2O emissions are soil pH and soil texture, but also exposure to freeze-thaw cycles, which trigger the most striking emission peaks. Currently, soil models are being developed that will allow describing this behaviour. The EU-funded project NOFRETETE (http://195.127.136.75/nofretete/) will provide results for forest soils upon its completion, expected in late 2004. For agricultural soils, similar results are expected from the EU-funded project INSEA. These activities will provide parameterisations for the respective soil properties, which can then be combined with soil databases to derive country-specific parameter values for the emission calculation in RAINS. This procedure should provide significantly higher data quality, if appropriate model results were available in time.

Table 5.6: Calculation of area-specific agricultural N_2O emissions in RAINS

RAINS sectors	AGR_ARABLE	Agriculture: Ploughing, tilling, harvesting		
	AGR_HISTO	Histosols (NEW)		
	AGR_FOREST	Forests (NEW)		
Activity rate	Area			
Unit	Million hectares			
Data sources	RAINS data bases, Simpson *et al.* (1999) based on EUROSTAT data			
Emission factors	Source category	Activity	Abatement technology	Emission factor [kt $N_2O/10^6$ ha]
	Histosols	Land area	No control	7
	Histosols	Land area	Laying fallow	0.5
	Forests	Land area	No control	0.472
	Agriculture: Ploughing, tilling, harvesting	Land area	*	2.832
Data sources	Houghton *et al.* (1997b), adapted			

Specific attention has been given by IPCC to organic soils (histosols). These soils are characterised by important anoxic zones, which together with the availability of carbon lead to excessive activity of microbes. Under crop, these soils allow for a prolific N_2O production. For the initial RAINS implementation, IPCC emission factors are used (Table 5.6).

The emission factors presented in Table 5.6 and Table 5.7 describe the uncontrolled situation. For the sources marked with asterisks for abatement measures, a few options exist for changing the emission factors. N_2O emissions from livestock might change as a consequence of measures for reducing other emissions, especially NH_3. Data on these options are taken from an in-depth analysis of Brink *et al.* (2001), who provide correction factors for the uncontrolled N_2O emission factors (Table 5.8). There are a few options to control specifically N_2O emissions. Information on these options is poor; the main data source is the report by Hendriks *et al.* (1998).

Table 5.7: Calculation of animal number-specific agricultural N_2O emissions in RAINS.

RAINS sectors	AGR_BEEF	Agriculture: Livestock – other cattle		
	AGR_COWS	Agriculture: Livestock – dairy cattle		
	AGR_OTANI	Agriculture: Livestock – other animals		
	AGR_PIG	Agriculture: Livestock – pigs		
	AGR_POULT	Agriculture: Livestock – poultry		
Activity rate	Animal number			
Unit	1000 heads			
Data sources	RAINS databases			
Emission factors	Source category	Activity	Abatement measure	Emission factor [kt N_2O/1000 heads]
	Other cattle	Animal number	*	0.001416
	Dairy cattle	Animal number	*	0.002124
	Other animals	Animal number	*	0.000590
	Pigs	Animal number	*	0.000472
	Poultry	Animal number	*	0.000014
Data sources	Houghton *et al.* (1997b), adapted			

Table 5.8: Options to change N_2O from agriculture and their efficiencies. Removal efficiencies apply to several combinations of source sector/activity (see asterisks in tables above).

Sector	Activity	Abatement measure	Removal efficiency
Agriculture		Soil testing	3 %
Agriculture: Livestock		Feed modification	10 %
Agriculture: Livestock		Deep injection of manure	-100 % (increase)
Agriculture		Fertiliser timing	5 %
Agriculture		Nitrification inhibitor	5%
Data sources: Brink *et al.* (2001), Hendriks *et al.* (1998)			

It is possible that the efficiencies presented in Table 5.8 underestimate the reduction potential, as the figures presented for removal efficiencies implicitly assume that the measure is only applicable to a small part of the sector. A detailed description is however not available in the original literature. Due to lack of information, for nitrification inhibition efficiency equal to the other measures at this source is assumed. Further work is necessary to confirm and revise these initial estimates and assumptions.

5.4 Options and cost of controlling nitrous oxide

A number of measures have been identified that are available to change emissions of N_2O. Most of the options do not focus primarily on nitrous oxides, but aim at the control of other pollutants (NO_x, NH_3). Since these measures are already addressed in other parts of the RAINS model, the costs of these options do not need to be re-discussed here. Four options were found that specifically address N_2O; these include selective catalytic reduction in industrial plants, optimisation of sewage treatment, replacing N_2O use as anaesthetics, and the optimised application of fertiliser.

Relatively well understood are options to control industrial process emissions. Even if the emissions from adipic acid production have been abolished by now, it is still important to keep the sector in order to show the temporal change. Nitric acid production has also been covered in detail by Kuiper (2001). The current level of abatement in the individual countries remains to be estimated.

Data on sewage treatment and N_2O use will need to be refined to incorporate additional literature sources. Especially the replacement of N_2O by Xenon is extremely expensive, and it should be expected that cheaper alternatives for medical use of N_2O should become available

More work is required to get a better understanding of the potential measures within the agricultural sector. The currently included options assume that emissions depend linearly on the nitrogen availability. Reducing the amount of nitrogen available in soil, as long as plants do not immediately take it up, is seen as the main key to emission reductions. As the same action needs to be implemented for the water framework directive (Council Directive 2000/60/EC), a thorough review of the literature on water quality will have to be conducted.

The costs of control options in the agricultural sector include costs of crop losses, which are strongly depending on subsidies. With the proposed changes of the Common Agricultural Policy of the EU, subsidies will shift from supporting crop volumes to support the maintenance of agricultural area and thus will become partly independent of crops. Crop losses – in terms of the national economy – can then be only estimated from world market prices of crops. The cost data presented in Table 5.9 derived from Hendriks *et al.* (1998) refer to present market conditions and thus need to be re-evaluated for modified agricultural subsidies.

Table 5.9: Overview of options genuinely implemented for controlling N_2O emissions

Abatement Option	Emission reduction	Costs [€/t N_2O]
Processes: Adipic acid – SCR	95 %	0
Processes: Nitric acid – SCR	80 %	130
Sewage treatment: optimisation	40 %	0
N_2O use: replace by Xe	100 %	200,000
Agriculture: Soil testing to optimise nitrogen input	3 %	-20,000*
Agriculture: Fertiliser timing to avoid availability of excess nitrogen	5 %	6000*
Agriculture: Application of nitrification inhibitors	to be assessed	to be assessed
Agriculture: Discontinue cultivation of histosols	1 %	to be assessed

* These cost figures depend on assumptions concerning agricultural policy and on synergies with other environmental legislation, specifically the water directive.

5.5 Interactions with other pollutants

Emissions of nitrous oxide are linked to emissions of other pollutants in two areas. They occur in the formation and destruction of gaseous nitrogen oxides, and they are an intrinsic part in the soil nitrogen cycle.

Nitrogen oxides formation during combustion processes is favoured by very high temperatures. Longer residence times and lower temperatures, which are typical for fluidised bed combustion, suppress nitrogen oxide formation but may increase nitrous oxide formation. In a similar way, one side product of the destruction of nitrogen oxides in end-of-the-pipe installations (catalytic as well as non-catalytic) is nitrous oxide.

In soils, microbial processes that produce *inter alia* nitrous oxide rely on the availability of mineralised nitrogen. One important pathway of nitrogen input is spreading of manure, which is also responsible for considerable ammonia emissions and some methane emissions. Measures on ammonia abatement (deep injection of manure) will decrease ammonia emissions, but increase excess nitrogen in soils (i.e., nitrogen which is not used by plants) and consequently also nitrous oxide formation. Reducing manure application to a level that accounts for the increased availability of nitrogen may counterbalance this adverse effect. Excess nitrogen also leads to nitrate leaching into groundwater, linking measures to safeguard water quality with climate measures.

Table 5.10: Interactions of sectors emitting nitrous oxide with emissions of other gases

Sector		Important interactions with other gases
Power plants/Industry	SCR and NCSR technologies	NO_x
	Fluidised bed combustion	NO_x
Transport	Catalytic converter	NO_x
Agriculture	Manure spreading (deep injection)	NH_3 (CH_4)

5.6 Preliminary results

5.6.1 Emission inventories and projections

Information on emissions of nitrous oxide has been organised as a database, applying the activity factors from the RAINS model where applicable. First comparisons of historic emissions were made for the national submissions of Austria and Germany according to the data available from the UNFCCC (www.unfccc.int). Without any adaptation of the model, data agree within 20 percent, far better than the uncertainty margins for N_2O emissions. Agreement should not be mistaken as an indication of reflecting a real world situation. Instead, the comparison demonstrates that the RAINS model in this form is able to emulate the more detailed IPCC approach. Forecasts of the emissions are not yet available, but can readily be made since the activities are already included in the RAINS database.

5.6.2 Costs

Table 5.11 gives a preliminary overview of the possible options to control nitrous oxide emissions from a variety of sectors. Bearing in mind the significant uncertainty regarding the actual emissions in a number of sectors, the table suggests that several options are available at relatively low cost. Note that the options for the industrial sector are already being implemented, to a certain degree.

Table 5.11: Overview of N_2O control options and their costs

Sector	Sub sector	Abatement option	Average cost [€/tCO_2]
Agriculture	Soil	Soil testing to optimise N-input	-65
Industry	Adipic acid	Selective catalytic reduction	0
Waste	Sewage treatment	Optimisation	0
Industry	Nitric acid	Selective catalytic reduction	0
Agriculture	Fertiliser use	Fertiliser timing to avoid excess nitrogen	19
Waste	N_2O use	Replace by Xenon	645
Agriculture	Fertiliser use	Apply nitrification inhibitors	n.a.
Agriculture	Soils	Discontinue cultivation of histosols	n.a.

5.7 Conclusions

The implementation of nitrous oxide emissions into the RAINS database already at this stage allows summarising a few major results:

Nitrous oxide from soils is generally considered the most important source, followed by industrial process emissions.

Reduction of nitrous oxide has not attracted major attention in the past. Available abatement measures are in most cases not focussed towards nitrous oxide as such, but a side effect of other reduction targets. In a case where N_2O emissions were considered specifically (in adipic acid production), even economical advantages of abatement were identified.

Nitrous oxide emissions can successfully be integrated into the RAINS database, at least emulating the existing inventorying approaches.

Still considerable work is required to assess estimates of abatement costs, and to adapt the scarce available information for use in RAINS. Furthermore, the influence of existing environmental and general policy regulations on measures and costs needs to be included in the framework. This relates specifically to the influence of the common agricultural policy reform in the EU, and to the limitations of nitrogen input to soils implied by the water framework directive. Finally, the coverage of emissions will be extended towards covering also non-agricultural soils. N_2O emissions from these soils derive from atmospheric deposition of NO_x, which is clearly caused by anthropogenic sources. Further literature studies and coherence to the expected changes of the IPCC methodology will be fundamental in developing the RAINS equivalent of this sector.

6 HFC, PFC and SF_6

6.1 Introduction

The man-made greenhouse gases hydrofluorocarbons (HFC), perfluorocarbon (PFC) and sulphur hexafluoride (SF_6) are usually summarised under the title F-gases. These F-gases account for approximately one percent of the direct radiative forcing from greenhouse gases, but business as usual scenarios suggest a rapid increase in their importance. Harnisch and Hendriks (2000), for example, estimate that in year 2010 F-gases could account for 2.9 percent of the EU-15’s greenhouse gas emissions, because they are increasingly used in air conditioning, refrigeration, foam and aerosol applications as substitute for chlorofluorocarbons (CFCs), which are banned by the Montreal Protocol

This chapter first describes the emission source categories, then the emission factors and methodology used for estimating the current and future emission of the three F-gases. Subsequently, it gives an overview of the options and cost to control these emissions. Finally, some initial results are shown.

6.2 Emission source categories

Sources, magnitudes and projections of future F-gas emissions differ significantly between countries and estimates, mainly due to structural differences and the timing of the substitution of ozone depleting substances. According to the EDGAR inventory (RIVM/TNO, 2004; Olivier, 2002), two-thirds of the global HFC emissions in 1995 (126 Mt CO_2eq.) result from the production of HCF-22. The remainder results from various usages of HCFs. Around 70 percent of global PFC emissions (99 Mt CO_2eq. comes from primary aluminium production. The rest results from the usage of PFC. Some two-thirds of global SF_6 emissions (144 Mt CO_2eq.) result from the manufacturing of electric equipment, equipment use in utilities and other electrical equipment use. The rest comes from a variety of sources such as the production of magnesium. The uncertainty in individual national estimates is significant. Data available from UNFCCC databases (UNFCCC, 2004) give total Annex I emissions for HFC (124 Mt CO_2eq), PFCs (78 Mt CO_2eq) and SF_6 (100 Mt CO_{2eq}) In 1995, 60 percent of the countries submitted data. Some countries have provided inventories in the common reporting format (CRF) with great details also on the sector-specific split. Most European countries, however, have not provided this information in sufficient detail, so that it is difficult to conclude about the importance of individual sources for the European emissions. Bearing this in mind, Table 6.1 summarises the most important anthropogenic activities that lead to emissions of F-gases and indicates their importance.

Table 6.1: Estimated importance of the sources of HFC, PFC and SF_6 emissions

	HFC	PFC	SF_6	Level of importance
HCFC-22 production	HCF-23			1
Industrial refrigeration	blend			1
Commercial refrigeration (supermarkets, etc.)	R-404a			3
Transport refrigeration	R-404a			1
Stationary air-conditioning	blend			2
Small hermetic refrigerators	R-143a			3
Mobile air-conditioning	R-143a			1
Aerosols	R-143a			2
One component foam	blend			1
Other foams	blend			1
Manufacturing and distribution	x			3
Other use of HFC	blend			3
Primary aluminium production		x		1
Semiconductor industry, PFC use in CVD and etching		x		1
High (and mid) voltage switches			x	1
Magnesium production			x	2
Manufacturing and distribution of SF_6			x	3
Other use of SF_6			x	3

Source: RIVM/TNO (2004), Harnisch and Hendriks (2002) and own estimates.

6.3 Emission factors and emissions of F-gases

6.3.1 HFC emissions

During the 1990s, many sectors that formerly used CFC changed rapidly to applications employing HFC to comply with the Montreal Protocol and its subsequent amendments demanding a phase out of ozone depleting substances (ODS).

The IPCC Guidelines for National Greenhouse Gas Inventories (Tier 2: Advanced Methodology for Estimating Emissions) (Houghton *et al.*, 1997a and 1997b) introduce two different methods to estimate emissions: a “bottom-up” and a “top-down” approach. The recommended method depends on the quality of the statistics and data available. In the “bottom-up” approach, the emissions of each individual HFC and PFC chemical are calculated based on equipment numbers or detailed use data. Alternatively, in the “top-down” approach emissions are estimated based on the levels of consumption and the emission characteristics related to various processes and equipment, taking current service and recovery practices into account. For the RAINS model, the “top-down” approach offers sufficient detail. Activities that emit HFC have been divided into 12 different sectors. Six of these are related to refrigeration and air conditioning. In the remainder, each of these sectors will be discussed.

6.3.1.1 HCFC-22 production

HCFC-22 is a gas used in refrigeration and air-conditioning systems, in foam manufacturing as a blend component of blowing agents, and in the manufacturing of synthetic polymers. Because it is an ozone depleting substance, most developed countries are phasing out HCFC-22 from most end-uses with the exception of the use as chemical feedstock.

The production of HCFC-22 involves the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) using antimony pentachloride ($SbCl_5$) as a catalyst. This process generates HFC-23 as a by-product, but the amount varies depending on plant-specific conditions and the amount of HCFC-22 produced. HFC-23 has a global warming potential (GWP) of 11,700 over a 100-year time horizon, so its potential impact on climate change is significant.

With the implementation of the Montreal Protocol, HCFC consumption is gradually eliminated, with reductions from the 1986 base-year levels of 35 percent, 65 percent, and 90 percent in 2004, 2010, and 2015, respectively. Final HCFC consumption phase-out will occur in 2020 (2040 for developing countries).

To calculate HFC emissions, RAINS applies emission factors related to the volume of HCFC-22 production. Activity data are based on reported production levels for historic years (Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999) and UNEP's phase out schedule for CFC and HCFC products for future years (UNEP, 1997). Country specific emission factors are presented in Table 6.2.

Table 6.2: Calculation of HFC emissions from HCFC production in RAINS

RAINS sectors	HCFC-22	HCFC-22 production		
Activity rate	HCFC-22 production			
Unit	Tons per year			
Data sources	Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999			
Emission factors				
Sector	Emission control	Emission factor [t HCFC-22/ t HCFC-22 produced]	GWP	Emission factor [t CO_2eq/ t HCFC-22 produced]
HCFC-22	No control	0.02	11,700	2,340
HCFC-22	Post combustion	0.001	11,700	11.7
Data sources	Harnisch and Hendriks (2000), AEAT (2003)			

In post combustion, emitted HFC-23 is thermally oxidised to CO_2, hydrogen fluoride (HF), and water) with an after-burner.

6.3.1.2 Cooling and stationary air conditioning

For the RAINS calculations, this sector is divided into five sub-sectors, distinguishing cooling for domestic, commercial, industrial and transport purposes as well as stationary air-conditioning. Some sectors, which make only minor contributions to total emissions such as artificial ice rinks, professional kitchens refrigeration machines and some smaller air condition equipment, are included in the category "Other use of HFC".

For cooling purposes, different refrigerants were used in the past. CFC-12 (R-12) was used for a temperature range from 0°C to +10°C, the CFC/HCFC blend R-502 for low temperatures between -25°C and -10°C. HCFC-22 (R-22), the quantitatively most important refrigerant, was used for medium temperatures and for the majority of air-conditioning systems.

Because of the phase-out of ozone depleting substances, CFCs and HCFCs are replaced, mainly with the different HFC compounds described in Table 6.1. The phase-out schedule depends on the country's status in the Montreal Protocol. Developing countries (Article 5 Parties) are entitled to a grace period before phase-out measures have to be implemented. For developed countries the target years for stabilizing consumption levels are 1989 for CFCs and 1996 for HCFCs. Developing countries have to stabilise their consumption of CFCs in 1990 and HFCs in 2016. Developed countries have to completely phase out CFC in 1996 and HFC in 2030. Developing countries have to stop using CFCs in 2010 and HCFCs in 2040.

Table 6.3: Calculation of HFC emissions from cooling and stationary air conditioning in RAINS

RAINS sectors	REF_DOM	Domestic small hermetic refrigerators
	REF_COM	Commercial refrigeration
	REF_IND	Industrial refrigeration, including food and agricultural
	REF_TRANS	Refrigeration during transport
	AIRCON	Stationary air conditioning using water chilling
Activity rate	Refrigerant use in new equipment	
	Number of scrapped equipment/stock	
Unit	HFC tons/year	
Data sources	Annual emission inventories of the Parties submitted to the UNFCCC (http://unfccc.int/program/mis/ghg/submis2003.html), Harnisch and Hendriks, 2000, Oinonen and Soimakallio (2001).	

Activity data for the year 2000 have been compiled from various sources (Harnisch and Hendriks, 2000; AEAT, 2003; Schwarz and Leisewitz, 1999; National Communications), assuming an average charge per installation as listed in Table 6.5. Estimates of the average charge size are based on Houghton *et al.* (1997b), Pedersen (1998) and Oinonen and Soimakallio (2001). For the future, the growth rates and market penetration of cooling and air conditioning as listed in Table 6.4 have been assumed. For stationary air conditioning, the growth relates to the installed amount of refrigerant. These Europe-wide default data could be refined by country-specific estimates, if relevant information becomes available.

Table 6.4: Average market growth (use in new equipment) in percent per year

RAINS sector	1995-1999	2000-2010	2010-2020	2020-2030
REF_DOM	Sales statistics or HH	HH	HH	HH
REF_COM	60	2	2	2
REF_IND	60	0	0	0
REF_TRANS	60	0	0	0
AIRCON	22	22	22	0.6

HH: calculated from the number of households, assuming that every households purchases (on average) 0.105 small hermetic units per year

The activity levels in this approach consist of the so-called refrigerant bank. This bank describes the average annual stock of refrigerants for a particular application as a function of the (past) sales of refrigerant and the scrapping rate of the application. Because of the complex nature of refrigerant banks, three stages during the life cycle of a refrigerant are distinguished for the calculation of emissions: (i) during installation/manufacture, (ii) during the lifetime of the product and (iii) at the end of life. Losses during manufacture and installations are negligible compared to other losses. In almost all refrigerant/air-conditioning sectors, equipment must be annually refilled with new refrigerant, causing significant emissions, typically 15 percent of the charge per year. HFC emissions thus are determined by the losses of refrigerant during the various stages of the life cycle (Table 6.5). In view of the complex nature of the refrigerant banks, the possibility to arrive at a reduced-form model to be used in RAINS is being investigated.

Table 6.5 Assumed losses in refrigerants during the life cycle for the different sub-sectors (percent of total charge)

	REF_DOM	REF_COM	REF_ TRANS	REF_IND	AIRCON
Losses during product life (per year)	1 %	20 %	32.5 %	15 %	10 %
Losses at decommissioning, no control	100 %	100 %	100 %	100 %	100 %
Losses at decommissioning with recovery of refrigerant	20 %	15 %	25 %	15 %	15 %
Lifetime losses per year, no control	9.3 %	30.0 %	47 %	21.7 %	16.7 %
Lifetime losses per year, with recovery	2.7 %	21. 5 %	36 %	16.0 %	11.0 %
Mean lifetime of equipment	12 yrs	10 yrs	7 yrs	15 yrs	15 yrs
Average GWP of refrigerant	1,300	2,700	2,700	2,200	2,600
Average refrigerant charge [kg/unit]	0.1	30/300	6	80	60g/m^3*

*average charge of refrigerant per cooled m^3

With the data provided in Table 6.5, emission factors can be calculated for each sub-sector. Yearly emissions are calculated from the emissions of the refrigerant bank using the emission factor. Decommissioning emissions are calculated from refrigerant use in a specific year, which will depend on the life time of the specific equipment and the percentage of the equipment scraped in that year. For instance, with a lifetime of 12 years, decommission emissions are based on use of HCF in new equipment 12 years ago.

It is important to distinguish the differences in the global warming potentials (GWP) of the refrigerants used in different sectors. Assuming a GWP calculated for 100 years, the emission factors listed in Table 6.6 can be determined. Since the choice of a particular GWP is subject to policy preferences (as is the choice of the GWP concept as such), RAINS allows using different GWP for its analysis.

Table 6.6: Calculation of HFC emission factors from cooling stationary air conditioning

Sector	Abatement measure	Emission factor [t HFC/year/ t charge/bank]	GWP (100 years)	Emission factor [t CO_2eq/year/ t charge/bank]
REF_DOM	No control	0.01/0.09	1,300	13/117
	Recovery	0.01/0.03	1,300	13/39
REF_COM	No control	0.2/0.35	2,700	540/945
	Recovery	0.2/0.18	2,700	540/468
REF_TRANS	No control	0.33/0.47	2,700	891/1269
	Recovery	0.33/0.36	2,700	891/972
REF_IND	No control	0.15/0.22	2,200	330/484
	Recovery	0.15/0.16	2,200	330/352
AIRCON	No control	0.11/0.16	2,600	286/416
	Recovery	0.11/0.11	2,600	286/288

Emission factors change during the lifetime of the stock, when at the end of its life equipment is land filled or recycled and the refrigerant recovered. Until the first generation of the HFC equipment has reached the end of its life time, only product lifetime emissions are counted. By default, this period is assumed to last until 2010, but depends in principle on the lifetime of the equipment.

6.3.1.3 Mobile air conditioning

Emissions from mobile air conditioning have been in the centre of EU legislative attention because of the growing share of cars with air-conditioning and the high life-cycle emissions of mobile air conditioners. As for stationary sources, the major emissions are caused by leakage and losses during the replacement of the refrigerant during the lifetime of the vehicle and at the end of the vehicle's life.

Table 6.7: Calculation of HFC emissions from cooling and stationary air conditioning in RAINS

RAINS sectors	MAC	Mobile air conditioning
Activity rate	Number of vehicles	
	Number of scabbed vehicles with air condition	
Unit	Vehicles	
Data sources	RAINS databases on vehicle numbers, Oinonen and Soimakallio (2001) and AEAT (2003) for the market share of air-conditioned cars	

In the past, the share of air-conditioned cars was lower in Europe than in Japan and the United States. Currently, 50 percent of all new vehicles sold in Europe have air-conditioning; compared to almost 100 percent in the US and Japan, and the share is expected to sharply increase in Europe. Estimates on the future penetration for Fennoscandia, i.e., Finland, Sweden and Denmark, are based on Oinonen and Soimakallio (2001), while for the other European countries the projections of AEAT (2003) have been used. For non-EU-25 countries with cold climates such as Russia and the Ukraine, appropriate estimates of the shares will have to be made.

Table 6.8: Market share of HFC-134a air-conditioners in new cars and their average charge

	1990	1995	2000	2005	2010	2015	2020	2025	2030
Fennoscandia [%]	0	5	38	50	50	50	50	50	50
Rest of Europe [%]	0	15	50	70	75	75	75	75	75
Average charge size [kg]	1.2	1.1	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Equipment lifetime [years]	12	12	12	12	12	12	12	12	12

The average charge size per vehicle is assumed to diminish linearly between 1993 and 1999 from 1.2 kg to 0.67 kg. Lifetime emissions for mobile air conditioning equipment are assumed to be 15 percent of the banked amount per year and 100 percent at the end of the life in the no-control case. Recovering the refrigerant at the end-of-life can reduce losses to 20 percent of the end of life emissions. Table 6.9 lists the resulting emission factors for mobile air conditioning calculated with the 100-year GWP of 1,300 for HFC-134a.

Table 6.9: Calculation of HFC emission factors from mobile air conditioning

Sector	Abatement measure	Emission factor [t HFC-134a/ year/t charge	GWP	Emission factor [t CO_2eq/year/ t charge]
MAC	No control	0.15/0.22	1,300	260/286
	Recycling	0.15/0.16	1,300	260/208

6.3.1.4 Aerosols

HFC emissions from aerosols are mainly released from aerosol propellant cans and metered dose inhalers that are used for medical purposes such as asthma inhalers. In these applications HFC is used as propellant so that it vaporises immediately. RAINS uses the amount of emissions itself as the activity (unit: HFC emissions ton/year). Emission estimates and activity forecasts are based on the national communications to the UNFCCC as well as on Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001).

Table 6.10: Calculation of HFC emissions from aerosol use in RAINS

RAINS sectors	AERO	Aerosol use		
Activity rate	HFC emissions as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	National communications to UNFCCC, Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)			
Emission factors				
Sector	Emission control	Emission factor [t HFC/t HFC emitted]	GWP	Emission factor [t CO_2eq/t HFC emitted]
Aerosol use	No control	1.0	1,300	1,300

6.3.1.5 Polyurethane one component foam (OCF)

The main application of polyurethane (PU) one component foam is to fill cavities and joints when installing inner fixtures in housing construction. Because OCF foams come in pressurised canisters and cylinders, they are also called aerosol foams. OCF blowing agents are typically gaseous, as they function as a blowing agent and as a propellant for the foam. They volatilise upon application, except for small residues, which remain for at most one year in the hardened foam (Schwarz and Leisewitz, 1999).

Table 6.11: Calculation of HFC emissions from one component foam (OCF) in RAINS

RAINS sectors	OCF	Polyurethane one component foam		
Activity rate	HFC emissions from OCF as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	National communications to UNFCCC, Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), Poulsen (2001)			
Emission factors				
Sector	Emission control	Emission factor [t HFC/ t HFC emitted]	GWP	Emission factor [t CO_2eq/ t HFC emitted]
Aerosol use	No control	1.0	1,300	1,300

Because there are country-specific variations of the composition of HFC blend inside the can, emissions (expressed in tons HFC/year) rather than can production were used as activity. The full volume of HFC inside the can was assumed to vaporise immediately. Emission estimates and activity forecasts are based on the national communications to UNFCCC as well as on Harnisch and Schwarz (2003), Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003), the web site of the Austrian Environmental Protection Agency and

Poulsen (2001). For accession countries, CFC substitution was estimated to start five years later.

6.3.1.6 Other foams

This sector includes about ten different polyurethane foam types (PU appliances, PU/PIR/Phen laminates, PU disc panel, PU cont panel, PU blocks, PU spray, PU pipe in pipe, XPS) and extruded polystyrene (XPS). RAINS uses emissions itself as the activity (unit: HFC emissions ton/year). Emission estimates are based on the national communications to the UNFCCC.

The average growth for the whole sector is assumed at 2.3 percent per year. This number takes into account the assumed average market growth of this sector, the ratio between hydrocarbons and HFCs in foam cells, differences in product life times (from 15-50 years) and differences in production, lifetime and disposal emissions. For accession countries, CFC substitution is assumed to start five years later.

Table 6.12: Calculation of HFC emissions from other foams in RAINS

RAINS sectors	OF	Other polyurethane foams		
Activity rate	HFC emissions from other foams and XPS foam as reported to UNFCCC			
Unit	HFC tons/year			
Data sources	National communications to UNFCCC			
Sector	Emission control	Emission factor [t HFC/ t HFC emitted]	GWP	Emission factor [t CO_2eq/ t HFC used]
Other foams	No control	1.0	815	815

6.3.1.7 Production and distribution of HFC

Production and distribution of HFC is associated with certain losses. RAINS applies the use of HFC as a surrogate activity variable and applies an emission factor that is related to the annual volume of total HFC use.

Table 6.13: Calculation of HFC emissions from production and distribution of HFCs in RAINS

RAINS sectors	MANDIST_HFC	HFC production		
Activity rate	HFC use			
Unit	HFC tons/year			
Data sources	National communications to UNFCCC			
Sector	Emission control	Emission factor [t HFC/t HFC used]	GWP	Emission factor [t CO_2eq/t HFC used]
Other foams	No control	0.01	1,300	13

6.3.1.8 Other HFC emission sources

This sector includes all other emission sources of HFC that are not described above. These include fire extinguishers, solvents, some air conditioning and refrigerator applications (artificial ice rinks e.g.) and so forth. RAINS uses as activity variables for this sector HFC emissions. Both past and future emissions of this sector are based on the national communications to UNFCCC.

Table 6.14: Calculation of HFC emissions from production and distribution of HFCs in RAINS

RAINS sectors	HFC_OTHER	Other HFC applications		
Activity rate	HFC emissions from different applications ton/year			
Unit	HFC tons/year			
Data sources	National communications to UNFCCC			
Sector	Emission control	Emission factor [t HFC/t HFC reported]	GWP	Emission factor [t CO_2eq/t HFC used]
Other foams	No control	1	1,300	1,300

6.3.2 PFC emissions

Two important sectors emit PFC (CF_4 and C_2F_8): primary aluminium production and the semiconductor industry.

6.3.2.1 Primary aluminium production

Primary aluminium production has been identified as a major anthropogenic source of emissions of two perfluorocarbon compounds (PFC): tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). These compounds are potent global warming gases compared to carbon dioxide (CO_2) and have long atmospheric lifetimes. The two PFCs, CF_4 and C_2F_6, have the equivalent greenhouse gas warming potentials of 6,500 and 9,200 times that of CO_2, respectively. During normal operating conditions, an electrolytic cell used to produce aluminium does not generate measurable amounts of PFC. They are only produced during brief upset conditions known as "anode effects". These conditions occur when the level of aluminium oxide (the raw material for primary aluminium) drops too low and the electrolytic bath itself begins to undergo electrolysis. Since the aluminium oxide level in the electrolytic bath cannot be directly measured, surrogates such as cell electrical resistance or voltage are most often used in modern facilities to ensure that the aluminium in the electrolytic bath is maintained at the correct level.

The activity variable used to calculate emissions from this source is the volume of aluminium production. Activity data are based on UN statistics and data on the production technologies from the aluminium industry website (http://www.aluminium.net/smelters) and are, together with projections, already part of the existing RAINS database.

Emission factors depend on the production technology (Table 6.15) and on a number of site-specific conditions. The International Aluminium Institute (IAI, 2002) has published lower emission factors than the ones shown in the table, indicating that considerable variations exist even between smelters using the same technology. The study covers all smelters in the EU-25, but does neither provide site-specific nor country-specific emission factors, so that the values of Table 6.15 are used for RAINS.

Table 6.15: Calculation of PFC emissions from aluminium production in RAINS

RAINS sectors	PR_ALUM	Aluminium production
Activity rate	Primary aluminium production	
Unit	PFC tons (as CF_4eq.)/year	
Data sources	RAINS databases	
Emission factors		
Technology		Emission factor [kg CF_4eq./ton Al]
Point feeder prebake	PFPB	0.06
Centre worked prebake	CWPB	0.4
Side worked prebake	SWPB	1.9
Vertical stud Söderberg	VSS	0.7
Horizontal stud Söderberg	HSS	0.7

With data from the Aluminium Industry website (http://www.aluminium.net/smelters) on the shares of the different aluminium production technologies in the European countries (Table 6.16), country-specific emission factors have been calculated (Table 6.17).

Table 6.16: The share of different primary aluminium production technologies in Europe (countries, which are not mentioned, do not have primary aluminium production). Source: http://www.aluminium.net/smelters

	1995				2000		
	PFPB	SWPB	CWPB	VSS	PFPB	SWPB	VSS
Bosnia-H.	0 %	0 %		0 %	100 %	0 %	0 %
France	79 %	21 %					
Germany	31 %	20 %	50 %		88 %	12 %	
Greece	100 %				100 %		
Hungary				100 %			100 %
Italy	100 %				100 %		
Netherlands	38 %	63 %			36 %	64 %	
Norway					50 %		50 %
Poland					50 %		50 %
Romania					100 %		
Russia	12 %			88 %	12 %		88 %
Slovak Republic	100 %				100 %		
Slovenia	100 %				100 %		
Spain		55 %		45 %	54 %		45 %
Sweden	25 %			75 %	25 %		75 %
Ukraine				100 %			100 %
Serbia-M.	100 %				100 %		
United Kingdom	96 %			4 %	96 %		4 %

Table 6.17: Calculation of PFC emissions from aluminium production in RAINS

Country	Abatement technology	Emission factor [t PFC/t PFC reported]	GWP	Emission factor [t CO_2eq/t PFC produced]
Bosnia-H.	PFPB	0.06	6,500	390
France	PFPB	0.44	6,500	2,893
Germany	PFPB	0.27	6,500	1,766
Greece	PFPB	0.06	6,500	390
Hungary	No control	0.70	6,500	4,550
Italy	PFPB	0.06	6,500	390
Netherlands	PFPB	1.23	6,500	8,056
Norway	PFPB	0.38	6,500	2,470
Poland	PFPB	0.38	6,500	2,470
Romania	PFPB	0.06	6,500	390
Russia	PFPB	0.62	6,500	4,042
Slovak Republic	PFPB	0.06	6,500	390
Slovenia	PFPB	0.06	6,500	390
Spain	PFPB	0.23	6,500	1,526
Sweden	PFPB	0.57	6,500	3,753
Ukraine	No control	0.70	6,500	4,550
Serbia-M.	PFPB	0.06	6,500	390
United Kingdom	PFPB	0.09	6,500	570

6.3.2.2 Semiconductor industry, PFC use in CVD and etching

The semiconductor industry uses HFC-23, CF_4, C_2F_6, C_3F_8, c-C_4F_8, SF_6 and NF_3 in two production processes: plasma etching thin films (etch) and plasma cleaning chemical vapour deposition (CVD) tool chambers. Because in many cases the amount of PFC use would directly indicate the production rate of the company, this information is confidential. RAINS uses as activity variables for this sector the volume of PFC emissions. Data is derived from national communications to the UNFCCC as well as on Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001).

Table 6.18: Calculation of PFC emissions from the semiconductor industry RAINS

RAINS sectors	PFC_SEMICOND	PFC use in semiconductor industry
Activity rate	PFC emissions	
Unit	Tons/year	
Data sources	National communications to the UNFCCC as well as on Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001).	

Sector	Emission control	Emission factor [t HFC/t HFC reported]	GWP	Emission factor [t CO_2eq/t HFC used]
PFC_SEMICOND	No control	1	6,500	6,500

6.3.3 SF_6 Emissions

SF_6 emissions arise from high and mid voltage switches, magnesium production and casting and other applications using SF_6.

6.3.3.1 High and mid voltage switches

SF_6 is a manufactured gas, used mainly as an electrical insulator in the transmission and distribution equipment of electric systems. The use of SF_6 in electrical transmission and distribution equipment slowly increased between 1970’s and the mid-1990’s, with new SF_6 equipment gradually replacing older oil and compressed air systems. Suitable alternatives to SF_6 do not exist for these applications as oil and compressed air systems suffer from safety and reliability problems (AEAT, 2003).

Most of the SF_6 is stored in gas-insulated switchgears for high and mid-voltage electric networks. The consumption of SF_6 depends on the age of the gas insulated switchgear (GIS), (since older models leak more than newer ones), the size of the transport network as well as recycling practices of “old” SF_6.

Although specialised methods for the estimation of SF_6 emissions from electrical equipment have been developed (Schaefer *et al.*, 2002), implementation of these methods would need significant information on transmission network length and the age and size of utilities, which is not readily available at the European scale. Therefore, RAINS uses as activity variables for this sector the amount of SF_6 emissions. Emission factors rates have been taken from the national communications to the UNFCCC and from other country reports from the German Federal Environmental Agency (Schwarz and Leisewitz, 1999), VTT Energy (Finland) (Oinonen and Soimakallio, 2001), AEAT (AEAT, 2003) and Poulsen (2001). In cases when countries have not reported their emissions, US-EPA estimates (US EPA, 2001b) are used.

Table 6.19: Calculation of SF_6 emissions from the high and mid voltage switches

RAINS sectors	GIS	SF_6 use in high and mid voltage switches		
Activity rate	SF_6 emission from switches			
Unit	Tons/year			
Data sources	National communications to the UNFCCC as well as on Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001)			
Sector	Emission control	Emission factor [t HFC/t HFC reported]	GWP	Emission factor [t CO_2eq/t HFC used]
GIS	No control	1	23,900	23,900

6.3.3.2 Magnesium production and magnesium casting

Casting and production of primary and secondary magnesium are well known sources of atmospheric emissions of SF_6. SF_6 is used as a shielding gas in magnesium foundries to protect the molten magnesium from re-oxidizing whilst it is running to best cast in ingots. Activity data on the volume of processed magnesium is taken from the World Mineral Statistics (Taylor *et al.*, 2003), UN statistics and the national communications to UNFCCC. In RAINS, the change of the activity levels over time is scenario-dependent, following the production index of non-ferrous metals.

The emission factor of 1 kg SF_6/ton of processed metal is based on the average emission factors published in Schwarz and Leisewitz (1999) and Oinonen and Soimakallio (2001).

Table 6.20: Calculation of SF_6 emissions from magnesium production and casting in RAINS

RAINS sectors	PR_MAGN	Magnesium production and casting		
Activity rate	Magnesium processed			
Unit	Tons/year			
Data sources	National communications to the UNFCCC as well as Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001)			
Sector	Emission control	Emission factor [kg SF_6/t magnesium processed]	GWP	Emission factor [t CO_2eq/t HFC used]
PR_MAGN	No control	1	23,900	23,900

6.3.3.3 Other sources for SF_6 emissions

Some European countries are using significant amounts of SF_6 in tires and soundproof windows. Some sport equipment manufacturers use SF_6 also in tennis balls and sport shoes, but this use is relatively small and emissions are hard to forecast. RAINS uses as activity variables for this sector the amount of SF_6 emissions as reported by countries to UNFCCC. Emissions from these other sources are taken from the national communications to the UNFCCC or from other national reports (Schwarz and Leisewitz, 1999; Oinonen and Soimakallio, 2001; AEAT, 2003; Poulsen, 2001).

Table 6.21: Calculation of SF_6 emissions from other sources in RAINS

RAINS sectors	SF6_OTHER	Other sources of SF_6 emissions
Activity rate	Reported emissions of SF6	
Unit	Tons/year	
Data sources	National communications to the UNFCCC as well as on Schwarz and Leisewitz (1999), Oinonen and Soimakallio (2001), AEAT (2003) and Poulsen (2001)	

Sector	Emission control	Emission factor [t HFC/t HFC reported]	GWP	Emission factor [t CO_2eq/t HFC used]
SF_6_OTHER	No control	1	23,900	23,900

6.4 Options and costs of controlling F-gases

6.4.1 Options and costs of controlling HFC emissions

Table 6.22 presents the abatement options for reducing HFC emissions that have been identified for this study. All data apply for present technology. The potential application assumes that the measures are implemented in 2004 (except mobile air conditioning 2007). Potential inconsistencies with cost assumptions adopted for the control of other greenhouse gases in RAINS need to be sorted out in the next phase of the study.

Table 6.22: Abatement options for HFC emissions, estimated penetration (potential application in 2020) and the technically feasible emission reduction for each option.

Source	Activity, unit	Abatement measure	Potential application	Emission reduction
HCFC-22 production	HCFC-22 production, ton	Post combustion	100 %	95 %
Industrial refrigeration	Refrigerant bank, ton HFC	Good practice	100 %	80 %
		Process modifications	100 %	92 %
Commercial refrigeration	Refrigerant bank, ton HFC	Good practice	100 %	48 %
		Process modifications	75 %	80 %
Transport refrigeration	Refrigerant bank, ton HFC	Good practice	100 %	32 %
Stationary air conditioning	Refrigerant bank, ton HFC	Process modifications	100 %	100 %
		Good practice	100 %	50 %
Household refrigeration	Refrigerant bank, ton HFC	Recollection	100 %	90 %
		Alternatives	100 %	100 %
Mobile air co	Refrigerant bank, ton HFC	Alternatives	100 %	100 %
		Good practice	100 %	70 %
One component foam	Emissions as CO_2eq.	Alternatives	90 %	90 %
Other foams	Emissions as CO_2eq.	Alternatives	15 %	15 %

Thermal oxidation (i.e., the process of oxidizing HFC-23 to CO_2, hydrogen fluoride (HF), and water) is a demonstrated technology for the destruction of halogenated organic compounds. Good practice means leak prevention and end of life recollection of the refrigerant. Process modification includes change of the process type from ordinary to secondary loop systems and alternative refrigerants. Secondary loop systems pump cold brine solutions through a second set of loops away from the refrigeration equipment and into areas to be cooled. These systems require a significantly lower refrigerant charge, have lower leak rates, and can allow the use of flammable or toxic refrigerants. The primary disadvantage of the secondary loop system is a loss of energy efficiency (US EPA, 2001a).

The alternative refrigerant for mobile air conditioning is CO_2, for one component foam alternative blowing agent would mean changing R-134a partly to R-152a or to hydrocarbons. In the foams- sector the alternative for XPS would be $CO_{2.}$

Table 6.23: Costs of HFC reduction options (Harnisch and Hendriks 2000; Heijnes *et al.* 1999; US EPA 2001a; Oinonen and Soimakallio 2001; Pedersen 1998).

Sector	Technology	Investment (€/activity unit)	Electricity use (% change)	Maintenance costs (€/activity/year)	Average costs (€/t CO_2 eq.)
PR_HCF23	Post combustion	15,000	-	2,000	0.3
REF_IND	Good practice	3,333	0	5,000	11
	Process modifications	51,192	3	2,500	11
REF_COM	Good practice	10,000	0	2,500	8
	Process modifications	100,000	10-20	2,500	28
REF_TRANS	Good practice	12,500	0	5,000	6
AIRCON	Process modifications	80,000	20	3,000	34
	Good practice	8,333	0	3,000	28
REF_DOM	Recollection	150,000	0	0	103
	Alternatives	166,667	0	0	141[a]
MAC	Alternatives	76,923	0	0	16
	Good practice	3,333	0	0	5
OCF	Alternatives	0.4	0	0	0
OF	Alternatives	4.9	0	0	6

[a] Cost takes into account that isobuthane would not need to be recollected according to the Directive 2002/96/EC (EU, 2003) on waste of electric and electronic equipment.

The data in Table 6.23 are based on EPA (2001a), Oinonen and Soimakallio (2001), Harnisch and Hendriks (2000), Little (1999), Pedersen (2001) and Kaapola (1989). If there was a significant difference between the costs estimates, the most recent data was used. In the preliminary cost estimates, the average cost for energy is estimated to be 6.7 cents per kWh and an average use of energy per ton of HFC is assumed of 430 MWh/year.

6.4.2 Options and costs of controlling PFC emissions

6.4.2.1 Primary aluminium production

The reduction of the frequency and duration of anode effects has dual benefits. It reduces PFC emissions and optimises process efficiency. Costs for process improvements are presented in Table 6.24. The annualised investment costs are average estimates; investment costs vary depending on technical aspects and the life time of the plant. Note that in a large number of countries the technology conversions took place already in the past.

Table 6.24: Specific costs for conversion and retrofitting of smelter capacity (Harnisch and Hendriks, 2000).

Abatement measure	Removal efficiency (%)	Annualised investment costs [€/t aluminium]	Annual O&M [€/t aluminium])
VSS to PFPB conversion	86 %	2,200	0
VSS retrofitting	26 %	100	-10
SWPB to PFPB conversion	97 %	530	-75

6.4.2.2 Semiconductor manufacture

In absence of detailed information on activity data for PFC use in the semiconductor industry, it was assumed that limiting PFC use and increasing NF_3 use in chemical vapour deposition (CVD) chambers could lead to a 10 percent reduction of PFC emission in this sector from 2010 onwards. This is in agreement with the process line age structure estimates done in Harnisch *et al*. (2000). CVD chamber cleaning use covers approximately 60 percent of total PFC use in year 2010 (Harnisch and Hendriks, 2000).

It is estimated that additional investment costs for NF_3 use would be € 70,000 per chamber (Harnisch *et al*., 2000), resulting in average costs between € 156,000–169,000/ton CF_4 used (Harnisch and Hendriks, 2000; Oinonen and Soimakallio, 2001). The potential application for this abatement option is estimated to cover the total CVD part of this sector.

6.4.3 Options and costs of controlling SF_6 emissions

Table 6.25 presents the main options for reducing SF_6 emissions. Good practice for high and mid voltage switchgears (GIS) means leakage reduction and recycling of recollected SF_6 from end of life switchgear. Alternatives for magnesium production and casting means change from SF_6 to SO_2, and alternatives in sector “SF_6 other” means a phase-out of SF_6 for tires and sound proof windows.

Table 6.25: Abatement options for SF_6 emissions and the estimated reduction potential from the baseline in year 2020 if measures are implemented in 2004.

	Abatement technology	Application potential	Emission reduction
High and mid voltage switches	Good practice	100 %	84 %
Magnesium production and casting	Alternatives	Country-specific	100 %
SF_6 Other	Alternatives	100 %	100 %

The average costs of good practice measures like leakage reduction, regular checking routines of switches and end of life recollection of SF_6 are estimated at € 19,000/banked ton of SF_6. Changing SF_6 to SO_2 is estimated to cost on average € 7,170/used SF_6 ton. Alternatives for tires and soundproof windows have negative costs (Harnisch and Schwarz 2003), but to be on the conservative side zero costs are assumed for RAINS. Costs are based on Harnisch and Hendriks (2000) and Oinonen and Soimakallio (2001).

6.5 Interactions with other pollutants

Direct interactions with other pollutants exist for primary aluminium production, which is also a source of particulate matter emissions. Abatement options that affect PFC emissions also affect CO_2 emissions. Other interactions are more indirect. For example the use of alternative refrigerants will consume more electricity.

Table 6.26 Interactions between F-gases and other pollutants

F-gas	Activity	Other pollutants
HFC	Use as refrigerant	CO_2
	Air conditioning	CO_2
PFC	Aluminium production	CH_4, CO_2, NO_x, VOC, SO_2
SF6	Switches	CO_2
	Magnesium production	NO_x, VOC, SO_2

6.6 Preliminary results

6.6.1 Emission inventories

The initial RAINS estimate for 1995 for the EU-23 results in total F-gas emissions of 0.7 Mt CO_2eq (Table 6.27). To the extent that national data are available and comparable, the preliminary RAINS estimates show reasonable agreement with national data, although in some cases major discrepancies occur. These can be traced back to differences in activity data for the refrigerant sector. Also different emission factors, especially for sectors with high GWP F-gases such as HCFC-22 production and primary aluminium production, lead to differences in emission estimates.

As of now, the implementation of the RAINS model is only partly completed for non EU-23 countries. Country-specific data have been collected for the most important sectors, where activity data is published (HCFC-22 production, primary aluminium production and magnesium production). Because very little is known about HFC use in non EU-23 countries, estimates for these countries are more uncertain and are hampered by lack of data. The exception is HCFC-22, for which data are generally good.

Table 6.27: Emission estimates for HFC, PFC and SF_6 for 1995 [Mt CO_2eq]

	HCFs			PFCs			SF_6		
	RAINS	UNFCCC	ECOFYS	RAINS	UNFCCC	ECOFYS	RAINS	UNFCCC	ECOFYS
Austria	0.7	0.5	0.5	0.0	0.0	0.1	1.2	1.2	0.1
Belgium	0.1	0.3	0.6	0.0	n.a.	0.0	0.4	0.2	0.0
Czech Republic	0.1	0.0	n.a.	0.0	n.a.	n.a.	0.0	0.2	n.a.
Denmark	0.3	0.2	n.a.	0.0	0.0	0.0	0.0	0.1	0.0
Estonia	0.0	n.a.	n.a.	0.0	n.a.	n.a.	0.0	n.a.	n.a.
Finland	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
France	4.0	1.3	7.3	1.4	1.3	1.5	1.0	2.3	1.9
Germany	5.1	3.1	14.2	2.2	1.8	1.5	6.0	6.2	1.4
Greece	0.7	3.4	0.9	0.1	0.1	0.0	0.0	0.0	0.0
Hungary	0.0	n.a.	n.a.	0.1	n.a.	n.a.	0.0	n.a.	n.a.
Ireland	0.0	0.0	0.2	0.1	0.1	0.0	0.0	0.1	0.0
Italy	4.4	0.7	6.9	0.2	0.3	0.2	0.5	0.5	0.5
Latvia	0.0	n.a.	n.a.	0.0	n.a.	n.a.	0.0	n.a.	n.a.
Lithuania	0.0	n.a.	n.a.	0.0	n.a.	n.a.	0.0	n.a.	n.a.
Luxembourg	0.0	n.a.	n.a.	0.0	n.a.	n.a.	0.0	n.a.	n.a.
Netherlands	5.0	6.0	6.3	1.8	1.9	2.2	0.2	0.4	0.2
Poland	0.1	0.0	n.a.	0.1	0.8	n.a.	0.0	0.0	n.a.
Portugal	0.0	0.0	0.3	0.2	0.2	0.0	0.1	0.0	0.0
Slovakia	0.0	0.0	n.a.	0.0	0.1	n.a.	0.0	0.0	n.a.
Slovenia	0.0	n.a.	n.a.	0.6	n.a.	n.a.	0.0	n.a.	n.a.
Spain	4.2	4.6	5.4	3.2	0.8	n.a.	0.2	0.1	0.2
Sweden	0.1	0.1	0.5	0.3	0.4	0.5	0.2	0.1	0.2
UK	6.6	15.2	8.9	0.7	1.1	0.7	0.9	1.1	1.0
Total	31.4			11			9.2		

Source: UNFCCC national submissions (http://unfccc.int), Blok *et al.* (2001)

6.6.2 Emission projections

To test the RAINS methodology, two scenarios were created: a baseline without any legislation on the control of F-gases and the current legislation scenario. Both the baseline and current legislation take into account the expected change in technology for new investments, while assuming frozen technology for existing applications in future emissions forecasts and the ODS phase out plan of the Montreal Protocol. The end of life collection of HFC refrigerants obligated by Directive 2000/53/EC on end-of-life vehicles (EU, 2002) and Directive 2002/96/EC on waste from electric and electronic equipment (EU, 2003) were only included in the current legislation scenario CLE.

Table 6.28 shows the baseline estimates for the three F-gases for the EU-23. Nearly 80 percent of the expected F-gas emissions are HFC and around 16 percent come from PFC.

Table 6.28: Country-specific HFC, PFC and SF_6 emissions in the baseline in 2020 in EU-23 in Mt CO_2eq

	HFC	PFC	SF_6	SUM
Austria	4.2	0.4	0.6	5.2
Belgium	4.0	0.3	0.2	4.5
Czech Republic	3.7	0.0	0.0	3.7
Denmark	1.9	0.3	0.1	2.3
Estonia	1.5	0.0	0.1	1.6
Finland	3.0	0.2	0.2	3.4
France	19.3	2.9	1.0	25.2
Germany	33.8	5.9	4.6	44.3
Greece	2.0	0.3	0.0	2.3
Hungary	2.1	0.1	0.0	2.2
Ireland	1.4	0.1	0.0	1.5
Italy	15.6	1.3	0.6	17.5
Latvia	1.1	0.0	0.0	1.1
Lithuania	1.6	0.0	0.0	1.6
Luxembourg	0.6	0.0	0.0	0.6
Netherlands	5.6	4.2	0.2	10.0
Poland	5.4	0.1	0.0	5.5
Portugal	3.3	0.2	0.1	3.6
Slovak Republic	1.3	0.0	0.0	1.3
Slovenia	0.8	0.9	0.0	1.7
Spain	9.2	6.0	0.4	15.6
Sweden	3.9	1.3	0.1	5.3
UK	18.6	4.4	0.7	23.7
Total EU-23	144.0	29.0	9.1	182.1

Figure 6.1 presents the level and distribution of the F-gas emissions in 2020 for the baseline and CLE scenario. The following abbreviations are used: GIS includes SF_6 emissions from electrical equipment, foams include one component foam and foam sectors, REF and SAC include all refrigeration and stationary air conditioning sectors, other HFC include aerosols, distribution and installing emissions and the category other sectors.

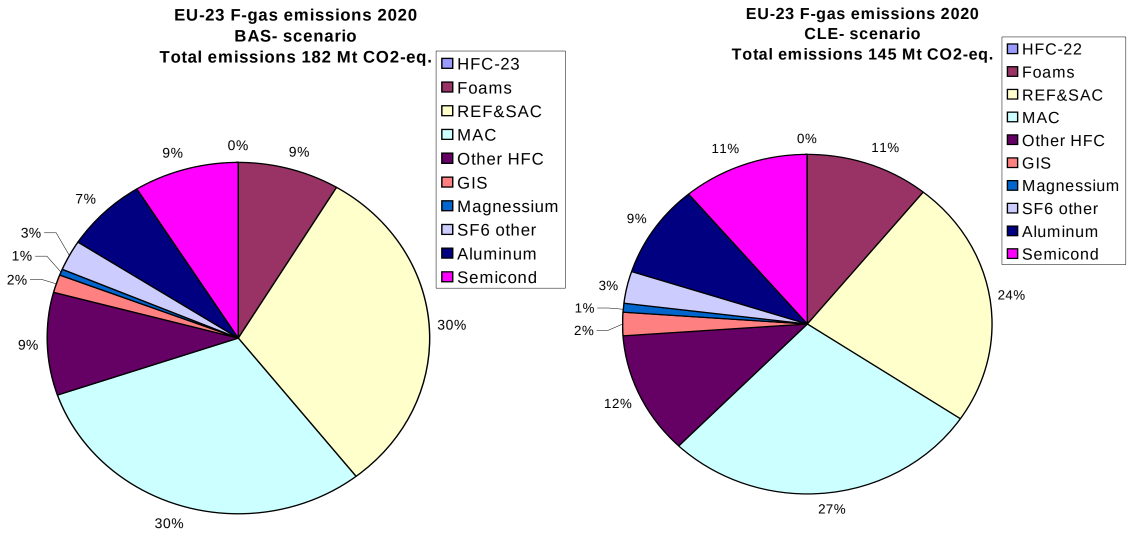

Figure 6.1: EU-23 F-gas emissions in 2020 for the baseline and CLE scenarios

6.6.3 Costs

A number of relatively cheap options exist to control the emissions of F-gases (see Table 6.29). The average costs presented in the table are only indicative since they depend, to some degree, on the production technologies used in a specific country.

Table 6.29: Overview of options to control F-gas emissions and their costs

Sector	Control option description	Average costs [€/t CO_2eq]
HCFC-22 production	Post combustion (HCFC-22 production)	0
Magnesium production and casting	Alternatives (magnesium processing)	0
One component foam	Alternatives (alternative propellants for one component foam)	1
Electrical equipment SF6	Good practice and recollection (Gas insulated switch gears, GIS)	5
Mobile air conditioning	Good practice and recollection	5
Other foams	Alternatives (alternative blowing agents)	6
Commercial refrigeration	Good practice and recollection	8
Industrial refrigeration	Good practice and recollection	11
Transport refrigeration	Good practice and recollection	11
Industrial refrigeration	Alternatives	16
Mobile air-conditioning	Alternatives	27
Stationary air co	Good practice and recollection	28
Semiconductor industry	Alternatives	28
Commercial refrigeration	Alternatives	28
Stationary air conditioning	Alternatives	34
Small hermetic refrigerators	Recollection	103
Small hermetic refrigerators	Alternatives	231

6.7 Conclusions

A methodology has been developed to estimate emissions of HCF, PFC and SF_6 and the possibilities and cost for reducing these emissions. Emission factors and activity data were identified for the most relevant sectors emitting F-gases, but further work is needed especially for Eastern European countries to arrive at robust estimates. The uncertainty surrounding the estimates is large. Preliminary results for the EU-23 show that the total emissions of the three F- gases might increase in the future from 51 Mt CO_2eq in 1995 to around 182 Mt CO_2eq in 2020. Current legislation should limit the increase to 145 Mt CO_2eq, in 2020. 25 to 30 percent of the emissions are expected to originate from mobile air conditioners and 25 to 30 percent from stationary refrigerants.

Nearly 20 control options (excluding electricity savings) and their costs were identified. Most of these are geared towards controlling HFC emissions; the remaining options focus on PFC emissions from primary aluminium production, PFC emissions from the semiconductor industry and a variety of SF_6 sources.

Because of large differences (and inconsistencies) in country-specific activity data, the activity data for some sectors (SF_6 from switches and HFC from foam) need to be verified.

7 Conclusions

Many of the traditional air pollutants and greenhouse gases have common sources, offering a cost-effective potential for simultaneous improvements for both traditional air pollution problems as well as climate change. A methodology has been developed to extend the RAINS integrated assessment model to explore synergies and trade-offs between the control of greenhouse gases and air pollution. With this extension, the RAINS model allows now the assessment of emission control costs for the six greenhouse gases covered under the Kyoto Protocol (CO_2, CH_4, N_2O and the three F-gases) together with the emissions of air pollutants SO_2, NO_x, VOC, NH_3 and PM.

The methodology enables a consistent evaluation of emission control costs for the greenhouse gases and air pollutants, so that costs can be readily compared across the pollutants. The methodology also allows for the first time to analyse the potential and costs of fuel substitution measures for the reduction of pollution, so that these structural changes can be compared with add-on emission control measures on a consistent basis. Furthermore, a concept has been developed that permits the design of multi-pollutant/multi-effect strategies to simultaneously meet environmental targets for air quality and greenhouse gas reductions in the most cost-effective way. This methodology will also allow exploring the scope of economic instruments (joint implementation, carbon trading, and pollution taxes) for reaching cost-effective emission reductions.

In the first phase of the study, emissions, costs and control potentials for the six greenhouse gases covered in the Kyoto Protocol have been estimated and implemented in the RAINS model. To the maximum meaningful and feasible extent, emission estimates are based on methodologies and emission factors proposed by the IPCC emission reporting guidelines. Even the provisional emission estimates of RAINS match reasonably well with other emission inventories, such as the national submissions to UNFCCC, although certain discrepancies at the sectoral level remain to be resolved.

A large number of options for controlling greenhouse gas emissions have been compiled from the literature. However, for a European integrated assessment it is imperative to keep the analysis manageable, which calls for a well founded level of aggregation of detailed information. Thus, up to now approximately 150 (groups of) control options for the six greenhouse gases have been developed and implemented in the RAINS model for the European countries. While for many measures a wealth of information is available which allows a robust assessment of emission control potentials and costs, large uncertainties remain especially for some of the non-CO_2 greenhouse gases.

The control options that are presently included in the RAINS model span a wide range of cost-effectiveness. There are certain advanced technical measures for all gases that will involve very high costs (several hundreds of €/ton CO_2 equivalent), even anticipating future technical progress that will lower the costs. There is a considerable number of measures for all greenhouse gases that can reduce greenhouse gases at low costs (up to 40 €/ton CO_2 equivalent) that constitute a realistic and sizeable potential for emission reductions. Many options for substituting solid and liquid fuels by less carbon intensive fuels fall into this group.

Finally, there are a number of options identified for which negative costs are calculated, if major side impacts (cost savings) are calculated. These include, inter alia, some energy conservation measures and options that recover greenhouse gases and use them for combustion to substitute other fuel use. It needs to be clarified if and why such options that lead to cost savings are not applied in the (presumably cost-minimised) baseline projection. A number of explanations (higher interest rates applied by individual consumers than for the macro-economic analysis, lack of knowledge, and other implementation barriers) have been suggested that need to be further explored to confirm the abatement potentials estimated by RAINS.

The extended RAINS model also allows projections of future greenhouse gas emissions for a range of exogenous driving forces (e.g., economic development, etc.), consistent with projections of air pollution emissions. Based on the energy outlook developed by the Directorate General for Energy and Transport of the European Commission (EC, 2003b), the RAINS model suggests for the 23 EU countries (15 Member States and the Acceding Countries excluding Cyprus and Malta) an increase of CO_2 emissions from 1995 to 2020 by 16 percent, if no further measures to reduce greenhouse gas emissions were taken. For methane, a 20 percent decline is estimated, mainly due to legislative improvements for landfills, increased gas recovery in coal mines and the declines in coal production and livestock numbers.

The extended RAINS model framework will offer a tool to systematically investigate economic and environmental synergies between greenhouse gas mitigation and air pollution control while avoiding negative side impacts. Further work is necessary to complete the implementation of the RAINS model for all European countries and sectors and to refine the analytical tools for identifying emission control strategies that achieve the largest environmental benefits at lowest costs.

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