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Interim Report **IR-05-054**

The GAINS Model for Greenhouse Gases – Version 1.0: Methane (CH_4)

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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 of traditional air pollution problems and 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 GAINS (**G**HG-**A**ir pollution **IN**teraction and **S**ynergies) model will allow 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. This report describes the first implementation (Version 1.0) of the model extension model to incorporate CH_4 emissions.

GAINS Version 1.0 assesses the options for reducing N_2O emissions from the various source categories. It quantifies for 43 countries/regions in Europe country-specific application potentials of the various options in the different sectors of the economy, and estimates the societal resource costs of these measures. Mitigation potentials are estimated in relation to an exogenous baseline projection that is considered to reflect current planning. The report identifies 28 control measures, ranging from animal feed changes over waste management options to various approaches for gas recovery and utilization. For each of these options, the report examines country-specific applicability and removal efficiency and determines the costs.

As a result, CH_4 emissions in Europe are estimated for the year 1990 at 63,600 kt CH_4. Assuming the penetration of emission controls as laid down in the current legislation, emissions would decline up to 2020 by 12,600 kt CH_4 per year. Full application of the presently available emission control measures could achieve an additional decline in European CH_4 emissions by 24,000 kt per year. Seventy percent of this potential could be attained at a cost of less than two billion €/year or 50 €/t CO_2–equivalent, while the further 7,000 kt CH_4/year would require costs of 12 billion €/year.

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Lena Höglund-Isaksson and Reinhard Mechler work in the Transboundary Air Pollution project of the International Institute for Applied Systems Analysis (IIASA).

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1 Introduction

1.1 Interactions between air pollution control and greenhouse gas mitigation

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

- Many of the traditional air pollutants and greenhouse gases (GHG) have common sources, offering a cost-effective potential for simultaneous improvements for both air pollution problems and climate change. For instance, climate change measures that aim at reduced fossil fuel combustion will have ancillary benefits for regional air pollutants (Syri *et al.*, 2001). In contrast, some ammonia abatement measures can lead to increased nitrous oxide (N_2O) emissions, while structural measures in agriculture could reduce both regional air pollution and climate change. Methane (CH_4) is both an ozone (O_3) precursor and a greenhouse gas. Hence, CH_4 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. As summarized by the Intergovernmental Panel on Climate Change (IPCC), changes in tropospheric ozone were found to have the third-largest positive radiative forcing after carbon dioxide (CO_2) and CH_4 (Houghton *et al.*, 2001), while sulphate aerosols exert negative forcing. Furthermore, understanding is growing on the role of carbonaceous aerosols, suggesting warming effects for black carbon and cooling effects for organic carbon.
- Other air pollutants such as ozone, nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds (VOC) act as indirect greenhouse gases influencing (e.g., via their impact on OH radicals) the lifetime of direct greenhouse gases (e.g., CH_4 and hydrofluorocarbons). Global circulation models have only begun to incorporate atmospheric chemistry and account fully for the important roles of conventional air pollutants.

It is 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 CH_4 in the atmosphere and thereby cause reduced radiative forcing. At the same time, NO_x emissions produce tropospheric ozone and increase radiative forcing. A further pathway leads to increased nitrogen deposition that may cause, via the fertilisation effect, enhanced growth of vegetation. This in turn offers an increased sink for carbon – although the net effect cannot yet be fully quantified.

Time is an important factor in the context of mitigation. While the climate change benefits (i.e., temperature decreases) take effect on the long-term, reduced air pollution will also yield benefits for human health and vegetation in the short and medium terms.

1.2 GAINS: The RAINS extension to include greenhouse gases

The Regional Air Pollution INformation and Simulation (RAINS) model has been developed at 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. To explore synergies between these environmental effects, RAINS includes 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 (GHG). 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.

The new tool is termed ‘GAINS’: **G**HG-**A**ir pollution **IN**teractions and **S**ynergies. It is not proposed at this stage to extend the GAINS model towards modelling of the climate system.

1.3 Objective of this report

The objective of this report is to describe a first version of the GAINS model (Version 1.0) related to emission control options for methane (CH_4) and associated costs. Other reports have been prepared for the other five Kyoto greenhouse gases (CO_2 , N_2O, F-gases) and are available on the Internet (http://www.iiasa.ac.at/rains/gains/index.html).

1.4 Structure of the report

This report has the following structure: Section 2 describes the general calculation methodology of the RAINS and GAINS models, and of CH_4 emissions and control costs in particular. Section 3 presents the emission factors and activity levels used for calculating sectoral emissions. In Section 4, the control options available for each sector are listed along with application rates, removal efficiencies and costs. This chapter also contains a detailed description of the assumptions made for the application rates and costs. Section 5 presents interactions between methane mitigation and the mitigation of other air pollutants. Section 6 presents the initial results of the first version of the GAINS model. Conclusions are drawn in Section 7.

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 (see Klaassen *et al.*, 2004).

This report addresses the implementation of methane (CH_4) into GAINS. Accompanying reports have been prepared for the F-gases (Tohka, 2005), for CO_2 (Klaassen *et al.*, 2005), and for nitrous oxide (Winiwarter, 2005).This section of the CH_4 report first describes the basic model concept of the RAINS model for air pollution. Subsequently, the method to calculate emissions of CH_4 is described, followed by the costing methodology.

2.2 The RAINS methodology for air pollution

The Regional Air Pollution Information and Simulation (RAINS) model developed at 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 (see Figure 2.1) that quantify 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. This optimisation mode takes 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 World Health Organisation (WHO) guideline values for ground-level ozone.

The RAINS model covers the time horizon from 1990 to 2030, with time steps of five years. Geographically, the model covers 47 countries and regions in Europe. Five of them represent sea regions, the European part of Russia is divided into four regions, and 38 are individual countries. Overall, the model extends over Europe from Ireland to the European part of Russia (West of the Ural) and Turkey. In a north to south perspective, the model covers all countries from Norway down to Malta and Cyprus.

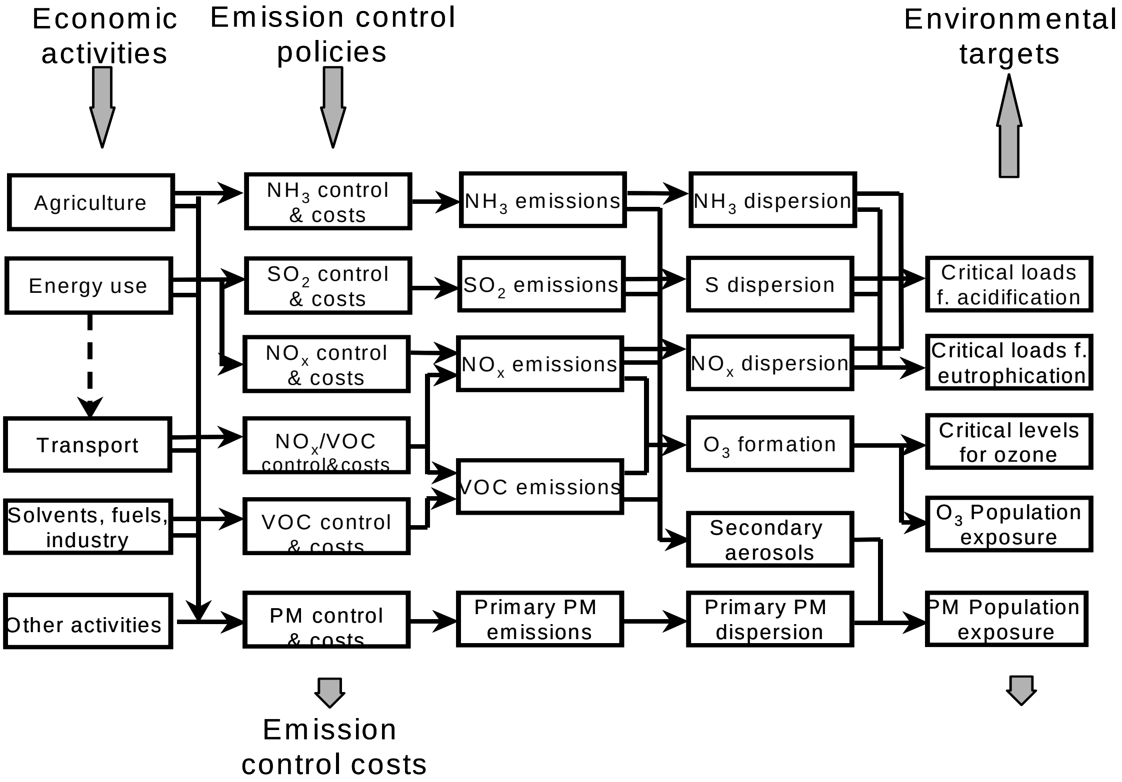

Figure 2.1: Information flow in the RAINS model

2.3 Emission calculation

The methodology adopted in GAINS 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,a,t	country, sector, activity, abatement technology
$E_{i,p}$	emissions of the specific pollutant p in country i,
A	activity in a given sector,
ef	“uncontrolled” emission factor,
eff	removal efficiency, and
X	actual implementation rate of the considered abatement.

If no emission controls are applied, the abatement efficiency equals zero ($eff = 0$) 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.

In GAINS, the business as usual scenario, the so-called “Current Legislation” (CLE) scenario, starts from the “controlled” emission factors of the base year, and modifies them following the implementation of abatement measures that are expected to result from legislation in place.

2.4 Cost calculation

2.4.1 General approach

In principle, GAINS applies the same concepts of cost calculation as the RAINS model to allow consistent evaluation of emission control costs for greenhouse gases and air pollutants. The cost evaluation in the RAINS/GAINS model attempts to quantify the values to society of the resources diverted 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 subsidies as they are transfers and not resource costs.

A central assumption in the RAINS/GAINS 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,
- operating and maintenance costs, and
- cost savings.

From these elements RAINS/GAINS calculates annual costs per unit of activity level. Subsequently, these costs are expressed per metric ton of pollutant abated. Some of the parameters are considered common to all countries. These include technology-specific data, such as removal efficiencies, unit investments costs, fixed operating and maintenance costs. Parameters used for calculating variable cost components such as the extra demand for labour, energy, and materials are also considered common to all countries.

Country-specific parameters characterise the type of capacity operated in a given country and its operation regime. They 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. Transaction costs are country-specific since they describe costs of diverse activities such as training or even information distribution required for implementation of an abatement option. All costs in RAINS/GAINS are expressed in constant € (in prices of the year 2000).

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).

2.4.2 Investment costs

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 investments 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, the coefficient *v* is used to account for the differences in flue gas volumes of the various fuels. For retrofitting pollution control devices to existing boilers, additional investments are taken into account through a 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:

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

Equation 2.1

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

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

Equation 2.2

2.4.3 Operating costs

Operating and maintenance costs (OM) include all variable costs associated with a control measure. These include operating costs of paper recycling plants, farm-scale anaerobic digestion plants, large-scale composts, and waste incineration plants, as well as costs for operating installations for recovery and utilization or flaring of gas. Apart from costs for operating control equipment, the OM costs also include waste separation and collection costs. Unless stated otherwise in the text, OM costs are assumed to consist of 80 percent labour costs and 20 percent material costs. Thus, the annual operating and maintenance cost is defined as:

$$OM = L + M = a_L * OM + a_M * OM \, ,$$

Equation 2.3

where L are annual labour costs, M are annual material costs, and α_L and α_M are their shares of total OM cost, respectively.

The material costs are not assumed to vary between countries, while labour costs are country-specific. The labour cost index from the RAINS model (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/) was used here.

2.4.4 Cost-savings

Cost-savings from CH_4 control options emerge primarily from the utilization of recovered gas and reduced gas leakages. Enteric fermentation control options imply cost-savings in the form of productivity increases. Other sources of cost-savings arise in the waste sector, where virgin pulp in paper production can be substituted for cheaper recycled pulp, good quality compost may be sold in the market, and any diversion of waste away from landfills implies saved costs from not having to landfill the waste.

When the cost-saving arise from a utilization of recovered gas or from reduced gas leakages, it is defined as follows:

$$CS = E_{ton} * g_u * p_{gas} \, ,$$

Equation 2.4

where E_{ton} is the amount of CH_4 gas recovered in tons, g_u is the share of recovered gas that is utilized and p_{gas} is the future consumer price of gas (without taxes) for power plants, retrieved from the GAINS CO_2 module (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/). This price is based for the past on International Energy Agency (IEA) statistics and for the future on the price index of the baseline projection used by the PRIMES energy model (European Commission, 2003).

Unless otherwise stated, it is assumed that the utilization rate, g_u, is 80 percent of the recovered gas use and that it is possible to find use for the recovered gas in the vicinity of the recovery installation without any need to transport the gas over long distances. In cases where E_{ton} is the amount of gas saved through reduced leakages, the utilization rate, g_u, is 100 percent. If part of the energy is utilized as heat instead of electricity (as is the case for waste incineration and farm-scale anaerobic digestion plants), the benefit is assumed to be 25 percent of the gas price.

2.4.5 Unit reduction costs

The total cost per ton of CH_4 removed is defined as the sum of the investments, operating and maintenance cost, and cost-savings per unit of CH_4 mitigated:

$$c_{ton} = \frac{\left(I^{an} + OM - CS\right)}{E_{ton}} \, .$$

Equation 2.5

3 Methane emissions

3.1 Introduction

Methane (CH_4) is the second most important greenhouse gas and accounts for 17 percent of the contribution of anthropogenic gases to an enhanced greenhouse effect (IPCC, 1996). For CH_4 a global warming potential of 21 times that of carbon dioxide (CO_2) over a 100 years time horizon has been defined (UNFCCC, 2005). Due to its relatively short average atmospheric half-life of approximately 12 years before it is consumed by a natural sink, CH_4 concentrations can be relatively quickly and easily stabilized (USEPA, 1999).

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 originate from anthropogenic sources.

Globally, the largest anthropogenic contribution to CH_4 emissions originates from enteric fermentation, followed by rive cultivation, wastewater discharge, coal mining and solid waste disposal. Since some of these sources do either not occur in Europe or are already controlled, the ranking of the important sources is different. In the EU-25, the largest contribution comes from enteric fermentation too, but then waste disposal, coal mining and natural gas distribution constitute the next largest sources (Figure 3.1).

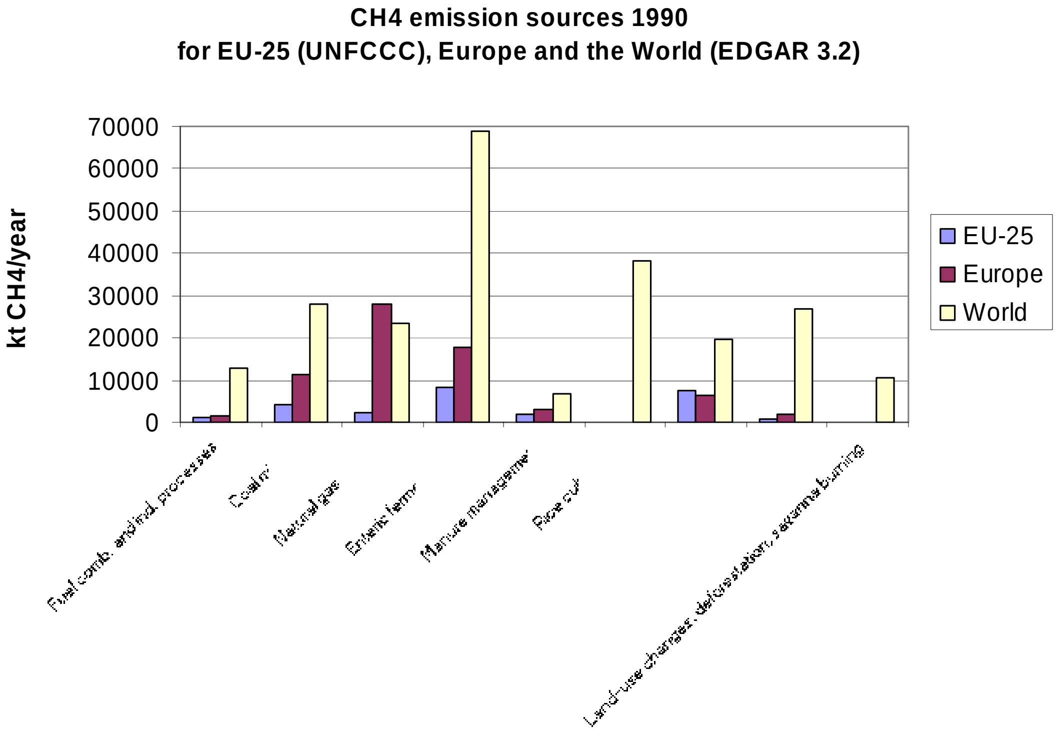

Figure 3.1: Major sources of methane (CH_4) emissions in the EU-25 and the World in 1990. Sources: Olivier *et al.* (2001) and UNFCCC (2004).

3.2 Emission source categories

Emissions of CH_4 are released from a large number of sources with a wide range of technical and economic features. Contemporary emission inventory systems, such as the inventory of the UNFCCC, distinguish more than 300 different processes causing CH_4 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. However, in reality the objective to assess abatement costs for a large number of countries, as well as the focus on emission levels in 10 to 20 years from now restricts the level of detail that can be meaningfully 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 the process-related parameters, such as future activity rates or autonomous technological progress. For an integrated assessment model focusing on the continental or global scale it is 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 manageable source categories and abatement options.

For GAINS, 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, 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 any 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 GAINS 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.

Based on these criteria, 13 source sectors have been defined for the GAINS CH_4 module Version 1.0 (Table 3.1). Other sectors with minor contributions, such as the iron and steel industry and fossil fuel combustion from stationary and mobile sources are not yet accounted for in GAINS Version 1.0.

Table 3.1: Sectors distinguished in GAINS Version 1.0 database for methane (CH_4) emissions.

GAINS sector	*GAINS sub sector*	*UNFCCC category (Houghton et al., 1997a,b)*
Livestock	Enteric fermentation	4 A
	Manure management	4 B
Rice cultivation		4 C
Waste	Biodegradable 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

3.1 Activity data

The GAINS model database includes activity data for historical years, i.e., 1990, 1995 and 2000, and five-year 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 that has been compiled from United Nations, EUROSTAT and International Energy Agency statistics. Projections of future activities have been extracted from the baseline scenario developed for the Clean Air For Europe (CAFE) program of the European Commission (Amann *et al.*, 2004). Sources of activity data that are specific for the GAINS Version 1.0 CH_4 module are listed in Table 3.2.

Table 3.2: Sources of activity data for the GAINS 1.0 CH_4 module.

Sector	Activity	Sources of activity data
Agriculture -Enteric fermentation -Manure Management	Animal numbers	RAINS database, FAO (2004)
Rice cultivation	Rice growing area	FAO (2002)
Waste - Solid	Municipal biodegradable solid waste, i.e., paper, food and garden waste	CEPI (2002), Pulp and paper international (1998), AEAT (1998), Houghton *et al.* (1997a)
- Wastewater	Population (urban in transition and developing countries)	RAINS database
Coal production	Mining	RAINS database
Gas	Gas production and consumption	RAINS database, IEA (2002a,b), Russian Federation Ministry of Energy (2003)
Oil production	Oil production and processing	IEA (2002a,b), Russian Federation Ministry of Energy (2003)
Biomass - Biomass consumption	Biomass (OS1) consumption	RAINS database
- Agricultural waste burning	Agricultural waste burned	RAINS database

3.3. Emission factors

To the maximum meaningful extent, GAINS Version 1.0 relies on emission factors provided in the revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Houghton *et al.*, 1997a,b). These guidelines provide a common methodology for estimating anthropogenic emissions of the major greenhouse gases and define explicit methodologies for calculating CH_4 emissions for all sectors. Other databases, such as the EDGAR 3.2 database (Olivier *et al.*, 2001), were also used to validate emission factors.

3.3.1 Enteric fermentation and manure management

Methane emissions from animal husbandry emerge from enteric fermentation during the digestive process of herbivores and from manure management under anaerobic conditions.

Enteric fermentation is a by-product of the digestive process of herbivores. The amount of CH_4 emissions is determined primarily by the:

- *Digestive System*: Ruminants (i.e., animals with a four compartments stomach) have the highest emissions due to the high level of fermentation that occurs in 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 (Houghton *et al.*, 1997a).

- *Level of Feed Intake*: Methane emissions are proportional to the feed intake (Houghton *et al.*, 1997a).

Table 3.3 distinguishes emission factors for enteric fermentation and for manure management. To simplify calculation procedures, the GAINS model combines these activities and applies one joint emission factor for these two processes related to one animal head.

GAINS uses the number of animals as the activity unit for emission calculation, consistent with the ammonia module of RAINS. Alternatively, activity units based on the amounts of milk, meat, or wool produced could have been used in the calculation. Such units would better reflect the effect of emissions on efficiency enhancements, which is an important aspect for the quantification of interactions with ammonia and other air pollutants.

GAINS Version 1.0 uses for the EU-15 countries, Cyprus, Malta, Norway and Switzerland the "Western European" emission factors listed in Table 3.3, and the "Eastern European" emission rates given in Houghton *et al.* (1997a) for all other countries in the European model domain. Emissions from buffaloes and camels have only been recorded for Turkey.

Table 3.3: Calculation of methane (CH_4) emissions from enteric fermentation in GAINS.

GAINS sectors	AGR_COWS	DL,DS	Dairy cattle (liquid and solid manure management)	
	AGR_BEEF	OL,OS	Other cattle (liquid and solid manure management)	
	AGR_PIGS	PL,PS	Pigs (liquid and solid manure management)	
	AGR_OTANI	SH	Sheep and goats	
	AGR_OTANI	HO	Horses	
	AGR_OTANI	BS	Buffaloes	
	AGR_OTANI	CM	Camels	
Activity rate	Number of animals			
Unit	Million animals			
Data sources	RAINS database and FAO (2004)			
Emission factors		Unit	Western Europe	Eastern Europe
	Other cattle	kt/Mheads	48.0	56.0
	Dairy cattle	kt/Mheads	100.0	81.0
	Pigs	kt/Mheads	1.5	1.5
	Sheep and goats	kt/Mheads	8.0	9.0
	Horses	kt/Mheads	18.0	18.0
	Buffaloes	kt/Mheads	..	55.0
	Camels	kt/Mheads	..	46.0
Data source	Houghton *et al.*, 1997a			

Methane emissions from manure are generated when the organic content of manure is decomposed under anaerobic conditions (Hendriks *et al.,* 1998). Temperature has an important influence on the generation of CH_4 during manure management. Consequently, different emission factors (Table 3.4) are used for regions with cool (< 15 °C), temperate (15 to 25 °C) and warm (> 25 °C) annual mean temperatures following Brink (2003) and Houghton *et al.* (1997a). Emission factors for temperate climates are used for Albania, Cyprus, Greece, Italy, Malta, Portugal, Spain and Turkey. Emission factors for cool regions are applied to all other countries.

A distinction is made between solid and liquid manure management since manure stored or treated as a liquid tends to produce more CH_4 than manure handled as a solid (Brink, 2003; p.16). National data on the use of solid and liquid manure management is taken from the RAINS ammonia module (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

Table 3.4: Calculation of methane (CH_4) emissions from manure management in GAINS.

GAINS sectors	AGR_COWS	DL	Dairy cattle with liquid manure management	
		DS	Dairy cattle with solid manure management	
	AGR_BEEF	OL	Other cattle with liquid manure management	
		OS	Other cattle with solid manure management	
	AGR_PIGS	PL	Pigs with liquid manure management	
		PS	Pigs with solid manure management	
	AGR_POULT	LH	Poultry, laying hens	
		OP	Poultry, other	
	AGR_OTANI	SH	Sheep and goats	
		HO	Horses	
		BS	Buffalo	
		CM	Camels	
Activity rate	Number of animals			
Unit	Million animals			
Data sources	Data on animal numbers are taken from the RAINS-Europe database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/) and FAO (2002)			
Emission factors		Unit	Western Europe	Eastern Europe
for cool climate	Dairy cattle, liquid	kt/Mheads	29.9	24.1
	Dairy cattle, solid	kt/Mheads	3.0	2.4
	Other cattle, liquid	kt/Mheads	11.2	11.2
	Other cattle, solid	kt/Mheads	1.1	1.1
	Pigs, liquid	kt/Mheads	5.5	5.5
	Pigs, solid	kt/Mheads	0.6	0.6
	Poultry	kt/Mheads	0.078	0.078
	Sheep and goats	kt/Mheads	0.19	0.19
	Horses	kt/Mheads	1.4	1.4
for temperate Climate	Dairy cattle, liquid	kt/Mheads	104.8	84.2
	Dairy cattle, solid	kt/Mheads	4.5	3.6
	Other cattle, liquid	kt/Mheads	39.3	39.3
	Other cattle, solid	kt/Mheads	1.7	1.7
	Pigs, liquid	kt/Mheads	19.3	19.3
	Pigs, solid	kt/Mheads	0.8	0.8
	Poultry	kt/Mheads	0.117	0.117
	Sheep and goats	kt/Mheads	0.28	0.28
	Horses	kt/Mheads	2.1	2.1
	Camels	kt/Mheads	..	1.92
	Buffaloes	kt/Mheads	..	9.0
Data sources	Houghton *et al.* (1997a) and Brink (2003)			

3.3.2 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 on agricultural practices. Thus, a theoretical range of values for CH_4 emission estimates is more realistic than any single number.

In Europe, emissions from this source are small because only a few countries grow rice (i.e., Albania, Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania, Spain and Turkey), usually in limited quantities. No future increases in rice production are anticipated as expanding of rice paddies is generally not considered feasible (Matthews, 2002). Emission factors have been derived from the IPCC guidelines (Houghton *et al.*, 1997a). The IPCC method is based on the annual harvested area and provides various country-specific factors in the guidelines. Usually, two types of rice are distinguished:

- Upland rice (approximately 10 percent of the global rice production and 15 percent of the harvested area). Since the fields are not flooded, no emissions of CH_4 occur.
- Wetland rice that is irrigated, rainfed, deepwater rice (100 percent of the rice cultivation in Europe).

Therefore, for GAINS Version 1.0 only the area where wetland rice is grown is taken into account as the relevant activity. Emission factors derived are country-specific and vary depending on the frequency of the flooding of the fields.

Table 3.5: Calculation of methane (CH_4) emissions from rice cultivation in GAINS.

GAINS sectors	AGR_ARABLE RICE
Activity rate	Harvested area
Unit	M hectares
Data source	Houghton *et al.* (1997a, p. 4.19)
Emission factors	220-440 kt/M ha
Data source	Houghton *et al.* (1997a)

3.3.3 Disposal of biodegradable solid waste

Methane from municipal solid waste is generated when biodegradable matter is anaerobically digested at a landfill. Biodegradable waste consists of paper and organic waste, where the latter includes food, garden and other organic matter. Activity rates defined for this sector are the amount of consumed paper and the amount of organic waste that ends up in the municipal waste flow (Table 3.7, Table 3.8).

Data on the amount of paper consumed in 1990, 1995 and 2002 were retrieved from Confederation of European Paper Industries (CEPI, 2002) and Pulp and Paper International (1998). In absence of country-specific statistics, the average per-capita consumption of Bulgaria and Romania (23.6 kg per person and year) was assumed for Albania, Belarus, Bosnia-Herzegovina, Macedonia, Moldavia, Russia, Serbia-Montenegro, Turkey and the

Ukraine. GAINS Version 1.0 estimates future paper consumption by using the average annual consumption increase in 1995 to 2002 (between -6 to +14 percent with an average of three percent per year) and assuming that this annual increase continues until 2015.

After 2015, paper consumption is assumed to remain constant. For Albania, Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Moldavia, Russia, Slovenia and Ukraine, where paper consumption has decreased during 1995 to 2002, a two percent annual increase corresponding to the annual increase rate for Romania has been assumed for 2005 to 2015. The estimated paper consumption is presented in Table 3.6. It is assumed that five percent of the paper consumed never ends up in the waste flow, but is scattered or burned without generating any CH_4 emissions. The residual 95 percent of paper consumed in the no-control case is assumed to end up in the waste flow that will be disposed of at a landfill.

According to AEA Technology (AEAT, 1998; p.75), potential emissions of CH_4 from landfilled paper amount to 0.205 ton CH_4 per ton of paper. Micales and Skog (1997) report considerably lower CH_4 potentials for landfilling various types of paper, with an average of 0.090 ton CH_4 per ton paper landfilled. GAINS Version 1.0 assumes an emission factor of 0.150 ton CH_4 per ton landfilled paper waste.

GAINS Version 1.0 computes the amount of organic waste by multiplying the per-capita municipal solid waste (MSW) generation rates by the population and the share of organic waste in MSW. For Western Europe, GAINS calculations use statistics on total population, while for economies in transition and for developing countries only the urban population is assumed to be participating in a MSW scheme. The per-capita generation rates of MSW specified in Houghton *et al*. (1997a) were used, applying the Russian per-capita waste generation rate to all East European countries. Population data (total/urban) is taken from the RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

In the 1990s, shares of organic waste in total municipal solid waste have varied between 21 percent and 49 percent in the EU-12 countries, with an average of 37 percent (AEAT 1998; p.58). GAINS Version 1.0 assumes this average share for all other countries. Estimated levels of organic waste are presented Table 3.6. For food and garden waste an emission factor of 0.082 ton per ton waste landfilled is assumed in GAINS 1.0, based on AEAT (1998, p.76). Note that the ‘uncontrolled’ emission factors relate to paper or organic waste landfilled on an uncontrolled landfill without waste diversion. To reflect waste diversion options, such as recycling, composting and incineration of biodegradable waste, specific control measures are considered in the GAINS calculations.

Table 3.6: Estimated paper consumption and amount of organic waste generated in Europe in terms of total and per capita consumption for 1990 and 2020.

Country	*Paper consumption*				*Organic waste generation*			
	1990		*2020*		*1990*		*2020*	
	Total kt	*kg/capita*	*Total kt*	*kg/capita*	*Total kt*	*kg/capita*	*Total kt*	*kg/capita*
Albania	85	27	111	36	408	124	442	124
Austria	1,283	158	3,033	374	949	123	1,009	123
Belarus	273	27	359	36	1,274	124	1,181	124
Belgium	2,090	204	4,940	482	1,721	173	1,826	173
Bosnia-H..	108	27	142	36	535	124	527	124
Bulgaria	276	34	349	43	1,083	124	826	124
Croatia	118	27	246	55	561	124	568	124
Cyprus	28	36	92	117	77	113	96	113
Czech Rep.	547	53	1,727	168	1,287	124	1,227	124
Denmark	1,068	201	1,585	298	874	170	947	170
Estonia	60	44	119	87	195	124	138	124
Finland	1,387	268	2,175	420	1,132	227	1,206	227
France	8,752	148	14,227	240	5,752	99	6,384	99
Germany	15,461	188	24,970	303	9,185	116	9,604	116
Greece	635	58	1,873	172	1,545	152	1,700	152
Hungary	557	56	1,332	133	1,287	124	1,126	124
Ireland	356	93	766	200	457	130	582	130
Italy	7,084	123	15,751	274	6,227	110	6,215	110
Latvia	77	32	156	66	332	124	263	124
Lithuania	110	31	165	47	459	124	410	124
Luxembourg	89	204	217	499	77	201	103	201
Macedonia	46	23	64	32	237	124	258	124
Malta	18	47	60	154	41	113	47	113
Moldavia	117	27	153	36	542	124	510	124
Netherlands	3,050	192	4,346	273	3,362	225	3,914	225
Norway	639	143	1,002	224	793	187	889	187
Poland	907	23	4,318	112	4,733	124	4,678	124
Portugal	758	76	1,489	149	1,268	128	1,351	128
Romania	514	23	491	22	2,882	124	2,609	124
Russia. (KALI)	23	27	31	36	125	124	109	124
Russia.(KOLK)	164	27	215	36	875	124	765	124
Russia.(REMR)	2,464	27	3,240	36	13,144	124	11,495	124
Russia.(SPET)	88	27	116	36	469	124	410	124
Serbia-M.	305	29	477	45	1,261	124	1,266	124
Slovakia	288	53	596	111	658	124	667	124
Slovenia	238	120	336	169	248	124	234	124
Spain	4,341	107	10,293	253	6,177	159	6,483	159
Sweden	1,961	221	2,755	311	1,154	135	1,235	135
Switzerland	1,448	202	1,876	261	985	147	1,063	147
Turkey	1,112	16	1,701	25	6,378	113	9,510	113
Ukraine	1,352	27	1,778	36	6,443	124	5,150	124
UK	9,361	159	14,292	243	7,984	139	8,669	139

Sources: CEPA (2002), Pulp and Paper International (1998), AEAT (1998, p.75), Houghton *et al.* (1997a, p.6.9).

Table 3.7: Calculation of methane (CH_4) emissions from landfilled paper waste in GAINS.

GAINS sector	WASTE_PA NOF
Activity	Paper waste
Unit	Kt paper waste generated per year
Data sources	CEPI (2002) and Pulp & Paper International (1998)
Emission factors	Generation of CH_4 from landfilled paper waste
Unit	kt CH_4 per kt paper waste
Data range	0.150
Data sources	AEAT (1998, p.75), Micales and Skog (1997)

Table 3.8: Calculation of methane (CH_4) emissions from landfilled organic waste in GAINS.

GAINS sector	WASTE_OR NOF
Activity	Organic waste
Unit	kt organic waste generated per year
Data sources	Houghton *et al.* (1997a, p.6.6), AEAT (1998, p.58)
Emission factors	Generation of CH_4 from landfilled organic waste
Unit	kt CH_4 per kt organic waste
Data range	0.082
Data sources	AEAT (1998, p.76)

3.3.4 Wastewater treatment

Under anaerobic conditions the handling of wastewater streams with high organic content can cause large amounts of CH_4 emissions. In developed countries, most municipal and industrial wastewater is collected and treated aerobically in open lagoons with very low CH_4 emissions (IEA-GHG, 1998). This is reflected in lower emission factors for Western Europe than for Eastern Europe (UNFCCC, 2005), where the infrastructure for treatment is less developed.

Anaerobic digestion occurs primarily when large amounts of wastewater are collected and handled in an anaerobic environment. In Eastern Europe, wastewater is primarily collected from the urban population, while wastewater in rural areas is handled to a lesser extent and with less generation of CH_4 in an anaerobic environment.

The IPCC default methodology for calculating emissions from sewage (Houghton *et al.*, 1997a) requires detailed data, e.g., on sector specific industrial outputs in the different countries. Such data is not readily available and for GAINS Version 1.0, emission factors per inhabitant have been calculated from data submitted by the member states to the UNFCCC (2005). Emission factors have been calculated for each country by taking the mean of the submitted values for 1990, 1995 and 2000. Whenever national submissions are missing, the mean emission factor of the respective country group has been used (see Table 3.9).

Table 3.9: Calculation of methane (CH_4) emissions from wastewater treatment in GAINS.

GAINS sector	WASTE_SW	NOF			
Activity rate	Total population				
Unit	Million people				
Data sources	RAINS databases (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/)				
Emission factors		Unit	Country group	Range	Mean
	Wastewater treatment	kt/ M people	EU-15, Norway, Switzerland, except Greece, Portugal, Spain	0.20-1.76	0.69
			Greece, Portugal, Spain	2.25-4.05	3.40
			EU New Member States	2.57-7.67	4.31
			Non-EU	3.62-4.81	4.21
Data sources	Based on mean of 1990, 1995 and 2000 values contained in the UNFCCC (2005) database, estimating sewage emissions per inhabitant				

3.3.5 Coal mining

The formation of coal produces CH_4 that is released to the atmosphere when coal is mined, where CH_4 releases are higher for underground mining. In addition, there are emissions from post-mining activities such as coal processing, transportation and utilization. GAINS Version 1.0 uses country-specific emission factors, considering the fraction of underground mining in each country and applying the appropriate emission factors for underground and surface mining as well as for post-mining activities (Table 3.10). National data on the mining structures were taken from EDGAR (Olivier *et al.*, 1996).

Table 3.10: Calculation of methane (CH_4) emissions from coal mining in GAINS.

GAINS sectors	MINE-BC	NOF	Mining of brown coal	
	MINE-HC	NOF	Mining of hard coal	
Activity rate	Amount of coal mined			
Unit	Mt coal mined per year			
Data sources	RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/)			
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 weigh IPCC emission factors given in Houghton *et al.* (1997a)			

3.3.6 Production of natural gas

During gas production, CH_4 emissions occur at the well as fugitive and other maintenance emissions. Data for the gas production has been retrieved from the RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/) for the EU-25 countries. For non-EU-25 countries, statistics have been derived from International Energy Agency (IEA, 2002a,b). Provincial production data for Russia are based on gas production forecasts of the Russian Federation Ministry of Energy (2003, p.72). (The model domain of GAINS-Europe includes only the European territory of the Russian Federation west of the Ural.

Since most of the Russian gas production takes place outside the present GAINS modelling domain and is thus not included in GAINS Version 1.0. Emission factors were adopted from the IPCC guidelines (Houghton *et al.*, 1997a, p.1.121) – see Table 3.11. Whenever ranges are given, GAINS Version 1.0 assumes the median value of the range.

Table 3.11: Calculation of methane (CH_4) emissions from gas production in GAINS.

GAINS sector	PROD GAS	Production of natural gas			
Activity rate	Amount of gas produced				
Unit	PJ per year				
Data sources	RAINS databases, IEA (2002) and Russian Federation Ministry of Energy (2003, p.72)				
Emission factors	Emission source	Western Europe	FSU and Eastern Europe	Rest of World[a]	Unit
	Fugitive and other maintenance emissions	0.021	0.245	0.263	kt/PJ produced
Data sources	Houghton *et al.*, 1997a,p.1.121				

[a] Value used for Turkey

3.3.7 Leakage during transmission and distribution of natural gas

Losses of natural gas during its transport and final use are an important source of CH_4 emissions. Emissions are calculated for the distribution to the end consumers and for the long-distance transmission processes (for gas producing countries). The IPCC guidelines recommend emission factors for losses during transport and distribution as CH_4 lost per unit of gas *consumed* for the Western European countries and per unit of gas *produced* for Former Soviet Union and Eastern European countries. To reflect these differences, the IPCC guidelines provide different (ranges of) emission factors for Western and Eastern European countries. Emission factors used in GAINS represent the mean of the specified ranges (Table 3.12).

Data on gas consumption and production has been retrieved from the RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/) and from IEA (2002a,b). Regional data for Russia on gas production was obtained from the Russian Federation Ministry of Energy (2003). For Russia, losses are calculated based on the total volume of gas produced in the European part of Russia and Western Siberia. Although gas fields in Western Siberia are outside of the area targeted in this study, almost all gas produced in the region is transported westwards for consumption in Russia or Europe. Thus, these emissions have been included in GAINS.

Table 3.12: Calculation of methane (CH_4) emissions from gas distribution in GAINS.

GAINS sectors	GAS CON_COMB	Petroleum refinery –combustion		
	GAS CON_LOSS	Petroleum refinery –losses during transmission		
	GAS IN_BO	Industry -combustion in boilers		
	GAS IN_OCTOT	Industry –other combustion		
	GAS PP_EX_OTH	Power and district heating plants		
	GAS PP_NEW	Power and district heating plants –new		
	GAS DOM	Combustion in residential/commercial sector		
	GAS NONEN	Non-energy use of gas		
	GAS TRANS	Gas *produced* in the Former Soviet Union, and Eastern European countries. Gas *consumed* for EU-15, Norway and Switzerland.		
Activity rate	Amount of gas consumed or produced			
Unit	PJ per year			
Data sources	RAINS database, IEA Statistics (2002) and Russian Federation Ministry of Energy (2003, p.72)			
	Emission factors:			
Emission source:	Western Europe	FSU and Eastern Europe	Rest of World	Unit
Leakage at industrial and power plants	0	0.2795	0.2055[a]	kt/PJ consumed
Leakage from consumption in residential sector	0	0.1395	0.1615[a]	kt/PJ consumed
Processing, transport and distribution	0.1025	0.458	0.288	kt/PJ produced *or* consumed
Data sources	Houghton *et al.*, 1997a			

[a] These values include emissions from processing, transport and distribution

3.3.8 Crude oil production

During crude oil production, CH_4 emissions arise from venting/flaring and as fugitive/maintenance emissions. For Western Europe, the IPCC guidelines (Houghton *et al.*, 1997a, p.1.30) report a range for the emission factor for oil production of 0.0013-0.008 kt/PJ. For all other countries a corresponding range of 0.0003-0.0015 kt/PJ is given. GAINS Version 1.0 uses the mean values of these ranges as emission factors for oil production (Table 3.13). The “Western European” values have been used for EU-15, Cyprus, Malta, Norway and Switzerland.

Table 3.13: Calculation of methane (CH_4) emissions from oil production in GAINS.

GAINS sector	PROD	CRU		
Activity rate	Amount of crude oil produced			
Unit	PJ per year			
Data sources	IEA energy statistics (2000a, 2000b), Russian Federation Ministry of Energy (2003) for data on Russian regions.			
Emission factors		Unit	Western Europe	Former Soviet Union, Eastern Europe and Rest of World
	Oil production	kt/PJ	0.005	0.003
Data source	Houghton *et al.* (1997a, p.1.30)			

3.3.9 Crude oil transportation, storage and refining

Methane emissions occur during oil transportation, refining and storage. The IPCC guidelines (Houghton *et al.*, 1997a; p.1.30) provide emission factors for oil transportation based on the amount of oil transported, while emission factors for refining and storage are based on the amount of oil refined. Since it was not possible to find data on the amount of oil shipped by tankers, GAIN Version 1.0 assumes that the amount corresponds to the amount of oil refined. Thus, the emission factors reported by IPCC for oil transported, refined and stored have been added up, resulting in a range of 0.0365-0.0975 kt/Mt. The mean value of this range has been used in the GAINS estimates (Table 3.14).

Table 3.14: Calculation of methane (CH_4) emissions from oil production in GAINS.

GAINS sectors	PR_REF	NOF	
Activity rate	Amount of oil input to refineries		
Unit	Mt per year		
Data sources	IEA energy statistics (2000a, 2000b)		
Emission factors		Unit	All regions
	Oil refined	kt/Mt	0.0678
Data sources	Houghton *et al.* (1997a, p.1.30)		

3.3.10 Biomass burning

In GAINS Version 1.0, biomass consumption comprises the burning of biomass (e.g., crop residues), wood and charcoal for energy purposes. GAINS Version 1.0 does not include biomass burning for non-energy purposes, e.g., natural forest fires or burning of savannas.

Table 3.15: Calculation of methane (CH_4) emissions from biomass burning in GAINS.

GAINS sectors	CON_COMB	OS1	Petroleum refineries –combustion	
	IN_BO	OS1	Industry -combustion in boilers	
	IN_OCTOT	OS1	Industry –other combustion	
	PP_EX_OTH	OS1	Power and district heating plants	
	PP_NEW	OS1	Power and district heating plants –New	
	DOM	OS1	Combustion in residential/commercial sector	
Activity rate	Amount of biomass burned			
Unit	PJ/year			
Data sources	RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/)			
Emission factor			Unit	
	CON_COMB		kt/PJ	0.03
	IN_BO		kt/PJ	0.03
	IN_OCTOT		kt/PJ	0.03
	PP_EX_OTH		kt/PJ	0.03
	PP_NEW		kt/PJ	0.03
	DOM		kt/PJ	0.3
Data sources	Houghton *et al.*, 1997a, p. 1.4.2			

3.3.11 Burning of agricultural waste

Methane emissions also originate from (open) burning of agricultural waste. A global emission factor based on work done by Masui *et al.* (2001) is used for GAINS Version 1.0 (Table 3.16).

Table 3.16: Calculation of methane (CH_4) emissions from burning of agricultural waste in GAINS.

GAINS sector	WASTE_AGR	NOF	Burning of agricultural waste	
Activity rate	Amount of waste burned			
Unit	Mt/year			
Data sources	RAINS database (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/)			
Emission factor			Unit	
	Agricultural waste burning		kt/Mt	0.0012
Data sources	Masui *et al*. (2001)			

4 Emission control options and costs

The GAINS Version 1.0 model distinguishes several abatement options to reduce CH_4 emissions from anthropogenic sources. Their removal efficiencies, costs and application potentials were determined based on the available literature data.

4.1 Enteric fermentation

The literature reports on a wide range of measures that could reduce CH_4 emissions from enteric fermentation. GAINS Version 1.0 distinguishes five groups of measures:

- autonomous increases in agricultural productivity,
- increased feed intake,
- changes to more non-SC in diet,
- replacement of roughage for concentrate, and
- use of propionate precursors.

4.1.1 Autonomous increases in agricultural productivity

There are ongoing productivity increases in milk production achieved through increased feed intake, increased penetration of genetically modified high yielding animals, and various changes in the diet. An increased level of feed intake and a change to a non-structural carbohydrates concentrates (NSC) diet have effects on both emissions and productivity.

GAINS Version 1.0 uses animal activity data from the RAINS database. Inherent in these activity data is an assumed future decline in cattle numbers in the EU, which is driven partly by autonomous increases in productivity and quota limits on milk production, and partly as an effect of the reformed Common Agricultural Policy (CAP) adopted by the EU in July 2003 (http://europa.eu.int/comm/agriculture/capreform/index_en.htm). The animal projections in RAINS have been developed through national communications with the member states within the Clean Air for Europe (CAFE) Programme. The effects of the CAP reform on animal numbers are therefore included only to the extent that such effects are reflected in the Member States own projections. Projected average annual growth rates in RAINS animal numbers between 2000 and 2020 are presented in Table 4.1.

Table 4.1: Average annual growth rates in RAINS animal numbers 2000-2020.

Region	Animal category	Average annual growth rate 2000-2020 (%)
EU-New Member States	Beef cattle	-0.30
	Dairy cows	-0.63
	Pigs	+0.05
	Laying hens and poultry	+1.17
	Sheep	+1.08
EU-15, Norway, and Switzerland	Beef cattle	-0.56
	Dairy cows	-0.81
	Pigs	+0.44
	Laying hens and poultry	+0.52
	Sheep	-0.26
Europe outside EU	Beef cattle	+0.37
	Dairy cows	+0.02
	Pigs	+1.14
	Laying hens and poultry	+0.50
	Sheep	0.00

Beyond the reductions in CH_4 emissions from these productivity improvements, additional decreases in CH_4 emissions are possible through various dietary adjustments (Table 4.2). Such adjustments include increasing the general feed intake, introducing more fat and non-structural carbohydrates in the feed and changes in feed composition by replacing roughage with concentrates. All these changes demand controlled feeding of concentrates. As an approximation of the share of cattle fed indoor to outdoor, data on the number of housing days per year from the RAINS ammonia module were used (Klimont and Brink, 2003).

Literature suggests in principle further reductions in CH_4 emissions possible from high-yielding, genetically improved animals. Since the literature does not provide quantitative estimates on the effect of this option on CH_4 emissions, it is not yet considered in GAINS.

Table 4.2: Mitigation options for methane (CH_4) emissions from enteric fermentation considered in GAINS.

Control option	*GAINS technology abbreviation*	*Application CLE (%)*	*Applicability*	*Removal efficiency (%)*	
				Western Europe	*Eastern Europe*
Increased feed intake	INCRFEED	No further implementation	Dairy: Stall fed cattle in countries with milk prod <4 tons/cow/year. Non-dairy: Stall fed cattle in all countries except EU-15, Norway, Switzerland, Malta and Cyprus.	Dairy cows: 8% Non-dairy cows: 10%	Dairy cows: 13% Non-dairy cows: 8%
Change to more NSC in diet	NSCDIET	No further implementation	Dairy: Stall fed cattle in all countries. Non-dairy: Stall fed cattle in all countries.	13 % for dairy 8 % for non-dairy	11 % for dairy , 8 % for non-dairy
Replacement of roughage for concentrate	CONCENTR	No further implementation	Dairy and non-dairy: Stall fed cattle in all countries except EU-15, Norway, Switzerland, Malta and Cyprus.	6.2 % for dairy, 8.2 % for non-dairy	12.4 % for dairy, 5.4 % for non-dairy
Propionate precursors	PROPPREC	No implementation	All roughage/forage fed cattle from 2010 onwards	25 % dairy 10 % non-dairy	25 % dairy 10 % non-dairy

4.1.2 Increased feed intake

Gerbens (1998, p.21) calculates the effects of increasing the feed intake by one kilogram dry matter/day/animal (Table 4.3). It turns out that for constant levels of milk and meat production per country/region, overall CH_4 emissions are lower due to the combined effect of livestock reductions and the metabolic change in the rumen with formation of less acetate and more propionate (a so-called VFA-shift).

Increased feed intake is only applicable to indoor fed animals with a current average feed intake below voluntary feed intake. Thus GAINS Version 1.0 assumes that increasing feed intake is applicable for stall fed dairy cattle in countries with an average milk production below 4 tons/cow/year (see Table 4.4), and for stall fed non-dairy cattle in all countries except the EU-15, Norway, Switzerland, Malta and Cyprus. Based on Gerbens *et al.* (1998) it is assumed that this option will reduce CH_4 emissions from dairy cows by eight percent in Western Europe and by 13 percent in Eastern Europe (Table 4.3). For non-dairy cattle, CH_4 emissions are assumed 10 percent lower in Western Europe and five percent lower in Eastern Europe (Table 4.3).

Table 4.3: Effects of increasing the feed intake by kilogram dry matter/day/animal. Source: Gerbens (1998, p.27)

	Emission reduction per region (%)		*Livestock reduction (and assumed reduction in marginal cost of production) (%)*	
	Western Europe	*Eastern Europe*	*Western Europe*	*Eastern Europe*
Dairy/Milk	7.8	13.2	10.8	16.6
Non-dairy/Beef	9.6	5.4	14.1	8.8

The ***cost of increasing feed intake*** consists of two components: the cost for additional fodder and the cost savings from a lower number of animals producing the same amount of milk or meat. The cost of increasing the feed intake by one kg dry matter/day/animal is measured as the price of fodder adjusted for an assumed dry matter content of 90 percent. For the EU-15, the average price of fodder weighted by the quantity of different fodders consumed was calculated based on the prices for feed maize, feed oats, feed barley, and feed wheat in 1995 to 2000 (European Commission, 2004b).

An average price of 116 €/t fodder was used for the EU-15, Switzerland and Norway. For the New Member States and other Eastern European countries, the average price of barley was taken as an approximation for the price of fodder, assuming that barley is a cereal mainly used as fodder (FAO, 2004). The average price of barley for EU New Member countries was found to be 99 €/t fodder, and this price is adopted as fodder price in all of Eastern Europe.

The average increase in the operating cost per ton CH_4 reduced in country *i* is calculated as:

$$OM_{ton,\,j} = \left[\frac{p_{fodder;\,i}}{0.90} * F * 365 * n_{animal;\,i} * (1 - r_{livestock}) \right] * \left[r_{emisson} * ef * n_{animal} \right]^{-1} \quad \text{Equation 4.1}$$

where	p_{fodder}	fodder price in €/t,
	F	increase in fodder consumption in t dry matter/animal/day,
	n_{animal}	number of animals in country before option implemented,
	$r_{livestock}$	livestock reduction from option implementation in %,
	$r_{emission}$	emission reduction from option implementation in %, and
	ef	no control emission factor for enteric fermentation.

Cost-savings are measured as a reduction in production cost when less livestock can produce the same amount of milk or beef. Producer prices of milk and beef for the year 2000 were adopted from FAO (2004). Assuming a competitive market for milk and meat, prices reflect the marginal costs of production. To express the cost-saving from the productivity increase in monetary terms, it has been defined as the marginal cost times the livestock reduction. This is taken to correspond to the costs saved when the same amount of milk or beef can be produced with less livestock. No autonomous productivity increase is assumed to take place and, unless a control option is implemented, the productivity of the animals is assumed to remain constant at the 2000 level.

The production of meat for the stock of beef cattle in place (not the animals slaughtered) is measured as the amount of meat produced in 2000 divided by the beef cattle stock in the same year (FAO, 2004). Production per animal and prices of milk and meat are presented in Table 4.4.

The cost-saving from increased productivity per ton of CH_4 reduced in country *i* is calculated as:

$$CS_{ton;i} = \underbrace{p_{milk/beef;i} * r_{livestock}}_{\substack{Cost\_reduction \\ per\_ton\_product}} * \underbrace{m_{milk/beef;i} * \frac{1}{1- r_{livestock}}}_{\substack{Product\_t/animal \\ after\_option\_implemented}} * \underbrace{n_{animal;i} * (1- r_{livestock})}_{\substack{Animal\_number \\ after\_option\_implemented}} * \underbrace{\left[r_{emission} * ef * n_{animal}\right]^{1}}_{Total\_emission\_reduction}$$

Equation 4.2

where $p_{milk/beef}$ price of milk or beef in €/t,

m milk or beef produced per animal before option implemented,

n_{animal} number of animals in country before option implemented,

$r_{livestock}$ livestock reduction due to option implementation in %,

$r_{emission}$ emission reduction due to option implementation in %, and

ef no control emission factor for enteric fermentation.

The ***average cost per emitted unit of CH_4*** for increasing the feed intake is found to vary widely between countries, as well as between dairy and non-dairy cattle. This is mainly caused by the large variations in the cost-savings from increased production.

For dairy cows in Western Europe, the costs vary from -29,800 to -10,400 €/t CH_4. For dairy cows in Eastern Europe, the range is from -11,800 to -100 €/t CH_4. For non-dairy cattle, costs range from -18,200 to +1,200 €/t CH_4 for Western Europe and from +150 to +11,000 €/t CH_4 for Eastern Europe. Using the same assumptions as for emission and livestock reductions (but without country-specific assumptions on animal productivity or prices of milk, beef and fodder), Gerbens (1998 p.20) yields average cost-savings of -2,815 €/t CH_4 for Eastern Europe and -969 €/t CH_4 for Western Europe.

Table 4.4: Milk and meat production per animal, producer prices of domestically produced meat and milk and consumer price of fodder used for cost calculations.

	Milk production 2000	*Beef production 2000*	*Milk price 2000*	*Beef price 2000*	*Fodder price*
	[t/cow/year]	*[t/cattle/year]*	*[€/t]*	*[€/t]*	*[€/t]*
Albania	2.84	0.072	281	2,113	99
Austria	5.14	0.131	288	2,925	113
Belarus	2.14	0.097	140	1,370	99
Belgium	5.85	0.114	298	2,918	111
Bosnia-H..	1.42	0.041	281	2,113	99
Bulgaria	3.13	0.164	173	903	99
Croatia	1.59	0.127	281	2,113	99
Cyprus	6.11	0.144	305	2,437	99
Czech Rep.	4.35	0.057	204	2,045	99
Denmark	7.37	0.116	327	2,079	108
Estonia	2.72	0.044	170	888	99
Finland	6.71	0.129	340	4,392	104
France	4.17	0.113	286	5,841	117
Germany	4.88	0.117	314	2,162	111
Greece	4.26	0.173	338	3,550	135
Hungary	3.97	0.104	242	1,521	99
Ireland	4.26	0.103	269	3,030	119
Italy	6.17	0.231	358	3,928	126
Latvia	2.34	0.090	154	1,077	99
Lithuania	2.35	0.056	121	948	99
Luxembourg	5.63	0.084	319	2,918	116
Macedonia	3.15	0.029	281	2,113	99
Malta	4.80	0.179	338	3,550	99
Moldavia	1.38	0.032	140	1,370	99
Netherlands	7.11	0.149	320	2,841	115
Norway	4.43	0.240	357	2,233	116
Poland	2.97	0.071	195	1,442	99
Portugal	5.55	0.105	288	3,961	126
Romania	2.94	0.057	138	2,132	99
Russia (KALI)	2.14	0.097	140	1,370	99
Russia.(KOLK)	2.14	0.097	140	1,370	99
Russia.(REMR)	2.14	0.097	140	1,370	99
Russia.(SPET)	2.14	0.097	140	1,370	99
Serbia-M.	1.78	0.199	281	2,113	99
Slovakia	3.15	0.086	198	1,881	99
Slovenia	3.23	0.137	244	2,324	99
Spain	4.70	0.139	272	3,357	124
Sweden	6.59	0.115	357	2,233	109
Switzerland	5.18	0.131	491	5,431	116
Turkey	1.63	0.032	381	6,527	99
Ukraine	1.66	0.063	140	1,370	99
UK	4.92	0.087	269	3,030	106

Sources: FAO (2004), European Commission (2004b).

4.1.3 Diet with increased non-structural concentrates (NSC)

More fat and non-structural carbohydrates (NSC) in the feed cause lower CH_4 emissions of animal. This change in the composition of concentrates to more NSC involves a change towards less fibers and more starch and sugars in the concentrates. Based on Gerbens *et al.* (1998), such dietary changes could be applied to all stall-fed cattle. Associated productivity increases allow for constant production levels a reduction of livestock between 0.3 and 1.0 percent, and would reduce total CH_4 emissions for constant production levels between 7.8 and 13.1 percent (Table 4.5). GAINS Version 1.0 relates these emission reductions to the original animal numbers used as activity variables.

Table 4.5: Effects of replacing 25 percent of a structural carbohydrates (SC) diet with non-structural carbohydrates (NSC concentrate).

	Emission reduction per region (%)		*Livestock reduction (and assumed reduction in marginal cost of production) (%)*	
	Western Europe	*Eastern Europe*	*Western Europe*	*Eastern Europe*
Dairy/Milk	13.1	10.8	1.0	0.8
Non-dairy/Beef	7.8	8.2	0.7	0.3

Source: Gerbens (1998, p.30)

The cost of replacing 25 percent of structural carbohydrates (SC) diet with NSC consists of two components: the additional costs of switching to a more expensive type of fodder and the cost savings due to increased productivity when less livestock can produce the same amount of milk or beef. For the first component, the cost of replacing 25 percent of a structural carbohydrates (SC) diet with NSC is measured as the price difference between SC and NSC concentrates times the amount of feed replaced.

Each dairy animal is assumed to consume 15 kg dry matter per day, while each non-dairy animal is assumed to consume 10 kg dry matter per day (Smink *et al.*, 2004; Teagasc, 2004; Kaert *et al.*, 2003). The average concentrate feed in the diet is assumed to be 50 percent for stall fed animals (Gerbens, 1998, p.30). The price of NSC (147 €/t concentrate) was taken from Gerbens (1998, p.24) and converted into year 2000 Euro, and assumed constant for all countries. The price of an SC diet is assumed to be the same as the average fodder price presented in Table 4.4.

The cost increase from changing the diet per ton of CH_4 reduced in country *i* is calculated as:

$$OM_{ton\,:\,i} = \left[0.25 * d * \left(p_{NSC} - \frac{p_{fodder\,;\,i}}{0.90} \right) * n_{animal\,:\,i} * (1 - r_{livestock}) \right] * \left[r_{emission} * ef * n_{animal\,:\,i} \right]$$

Equation 4.3

where p_{NSC} price of NQSC concentrate (=147 €/t dry matter),

p_{fodder} fodder price in €/t,

d annual consumption of feed in t dry matter per animal,

n_{animal} number of animals in country before option implemented,

$r_{livestock}$ livestock reduction from option implementation in %,
$r_{emission}$ emission reduction from option implementation in %, and
ef no control emission factor for enteric fermentation.

Cost-savings from this option are defined in the same way as for the previous option and are specified in Equation 4.2. Just as for the previous option, total costs of this option vary between countries, as well as between dairy and non-dairy cattle.

For dairy cows, average costs are calculated between -600 and +1,200 €/t CH_4 for Western Europe and +2,800 to +3,500 €/t CH_4 for Eastern Europe. For non-dairy cows, the average costs are estimated at +300 to +5,200 €/t CH_4 for Western Europe and +4,500 to +4,700 €/t CH_4 for Eastern Europe. The main reasons for these differences are variations in fodder prices, productivity increases and attainable emission reductions. Without country-specific assumptions about prices and animal productivity (and assuming the price of NSC to be the same as for SC concentrate), Gerbens (1998, p.24) found cost-savings of -269 €/t CH_4 for Eastern Europe and -308 €/t CH_4 for Western Europe.

4.1.4 Replacement of roughage with concentrate

Replacement of roughage with concentrate is a further option to reduce CH_4 emissions from livestock farming. Gerbens (1998) estimates reduction potentials between 5 and 12 percent, depending on a number of factors (Table 4.6).

Table 4.6: Effects of increasing the concentrate intake by 1 kg dry matter per day and reducing the intake of roughage by 0.5 kg dry matter per day. Source: Gerbens (1998, p.28).

	Emission reduction per region (%)		*Livestock reduction (and assumed reduction in marginal cost of production) (%)*	
	Western Europe	*Eastern Europe*	*Western Europe*	*Eastern Europe*
Dairy/Milk	6.2	12.4	6.6	15.0
Non-dairy/Beef	8.2	5.4	8.7	7.8

The cost of replacing 0.5 kg dry matter of roughage per day with 1 kg dry matter of concentrate is measured as the sum of the cost of replacing the feed and the cost-saving of the resulting productivity increase. Gerbens (1998, p.23) uses a price of roughage, which is 63 percent of the concentrate price. Adopting this assumption and using the average fodder price in kg dry matter as the price of concentrates, the increase in the variable cost is defined as:

$$OM_{ton\,:\,i} = \left[(1 - 0.5 * 0.63) * \frac{p_{fodder\,;\,i}}{0.90} * F * 365 * n_{animal\,:\,i} * (1 - r_{livestock}) \right] * \left[r_{emission} * ef * n_{animal\,:\,i} \right]^{-1}$$

Equation 4.4

where	p_{fodder}	fodder price in €/t,
	F	increase in fodder consumption in t dry matter/animal/day,
	n_{animal}	number of animals in country before option implemented,
	$r_{livestock}$	livestock reduction from option implementation in %,
	$r_{emission}$	emission reduction from option implementation in %, and
	ef	no control emission factor for enteric fermentation.

The cost-savings from this option are defined in the same way as for the two previous options and are specified in Equation 4.2. Once gain, costs of this option vary between countries, as well as between dairy and non-dairy cattle.

For dairy cows, the average cost range from -24,500 to -9,500 €/t CH_4 for Western Europe and from -13,100 to -1,900 €/t CH_4 for Eastern Europe. For non-dairy cows, average cost vary from -15,600 to -1,400 €/t CH_4 for Western Europe and between -2,200 and 7,400 €/t CH_4 for Eastern Europe. Main reasons for the fluctuations are variations in fodder prices, productivity increases and attainable emission reductions. Without country-specific assumptions about prices and animal productivity, Gerbens (1998, p.28) found total costs of -8,258 €/t CH_4 for Eastern Europe and -5,648 €/t CH_4 for Western Europe.

4.1.5 Propionate precursors

A third option (still at a research stage and not yet commercially available) is to introduce grass varieties with high levels of malate and fumarate, which rumen microbes use to produce propionate instead of CH_4 (ECCP, 2003, Annex II). If found satisfactory, these propionate precursors have a potential for use in the EU (ECCP, 2003), where the introduction of the Common Agricultural Policy is expected to lead to an increased use of roughage feed. AEAT (2001a) estimates the removal efficiency at 25 percent of CH_4 emissions from dairy cattle and 10 percent from non-dairy cattle when an 80g supplement is given per day and animal. Allowing for a reduction in other feed costs, costs are estimated at 527 €/t CH_4 for dairy cattle and 1,100 €/t CH_4 for non-dairy cattle.

It is assumed that propionate precursors could be applied to all roughage/forage fed cattle in all regions from 2020 and onwards. The share of roughage/forage fed animals is assumed to correspond to the share of animals feeding outdoor, i.e., the average share of days in a year spent outdoor for cows and cattle given by the RAINS ammonia module (Klimont and Brink, 2003).

Table 4.7: Costs for measures to reduce methane (CH_4) emissions from enteric fermentation in GAINS.

Control option		*Investments [€/t $_{CH4}$]*	*O&M cost [€/t CH_4]*	*Cost savings [€/t CH_4]*	*Total cost [€/t CH_4]*
Autonomous productivity increases		0	0	0	0
Increased feed intake	Dairy	0	3,132	-14,886 to -3,236	-11,754 to -104
	Non-dairy	0	12,109	-11,958 to -1,136	151 to 10,972
Change to more NSC in diet	Dairy	0	621-3,725	-1,942 to -191	-599 to 3,534
	Non-dairy	0	1,452 to 5,808	-1,693 to -26	301 to 5,154
Replacement of roughage with concentrates.	Dairy	0	1,257	-14,319 to -3,113	-13,061 to -1,856
	Non-dairy	0	8,385	-10,599 to -1,007	-2,214 to 7,378
Propionate precursors	Dairy	0	527	0	527
	Non-dairy	0	1,100	0	1,100

4.2 Manure management

Methane emissions from manure can be reduced through anaerobic digestion of the manure in a closed vessel. The process generates CH_4 that can then be utilized as an energy source, where 95 percent of the generated CH_4 is captured (AEAT, 1998, p.33). However, the process itself produces more CH_4, and consequently, a lower removal efficiency of 80 percent of the original CH_4 potential is assumed.

Current farm-scale anaerobic digestion (biogas) plants have a minimum size of 100 dairy cows, 200 beef cattle or 1000 pigs. Centralized anaerobic digestion (AD) plants serving many farms are only feasible in areas with very intensive animal farming since long distance transport is costly and increases emissions of both CH_4 and carbon oxides. Farm-scale digesters do not have these limitations and are more generally applicable than centralized plants. Hence, the applicability and costs for the AD option assumed here are based on farm-scale digesters. Emissions per animal vary with temperature and manure management method (liquid or solid). The control cost per unit of reduced emissions will vary with these parameters. Anaerobic digestion is only considered to be feasible for liquid manure management, since emissions from solid manure management are much too low to justify the use of AD (AEAT, 1998, p.41).

For GAINS Version 1.0, it is assumed that anaerobic digesters can only be applied to farms above a minimum size (i.e., 100 dairy cattle, 200 beef cattle, or 1000 pigs per farm) as stated for the EU-15 by AEAT (1998, p.45). Due to a lack of data for Eastern Europe, the farm size distribution of Greece is assumed for this region. As a consequence, it is assumed that 15 percent of dairy cow farms have 100 animals or more, 24 percent of beef cattle farms have 200 animals or more, and 71 percent of pig farms have 1000 animals or more.

Costs for installing AD are based on Italian cost data for the installation of a farm-scale AD plant (AEAT, 1998, p.37). The plant is designed to handle 22,000 t manure/year generating 180 MWh electricity and 440 MWh heat per year. Investments are estimated at 72,600 € or

5,344 €/year when annualized over a 20 years lifetime of the equipment. Operating and maintenance costs are estimated at 4,539 €/year, whereof 39 percent are labour costs. The utilized energy (i.e. electricity and heating) is regarded as a cost-saving.

Housing adaptation is an option to primarily reduce ammonia emissions from pig farms. This implies installing a manure slide and storage system or a manure rinsing system, which regularly empties the manure cellar or stable floor. As an additional effect, methanogenesis is retarded and 10 percent of CH_4 emissions are removed (Hendriks *et al*., 1998, p.36). Installing a manure slide and storage system requires investments of 100-500 €/pig (Hendriks *et al*., 1998). A manure rinsing system needs an investment of 70-350 €/pig. With a lifetime of 20 years, annualized investment costs are calculated at 5-37 €/pig/year. The emission factor for pigs is 5.5 kg CH_4/animal and the removal efficiency of this option is 10 percent. Thus, if housing adaptation is adopted exclusively as an option to control CH_4, the annualized investment costs are estimated in the range of 9,400-66,900 €/t CH_4 removed.

Table 4.8: Mitigation options for manure management considered in GAINS.

Option	*GAINS acronym*	*Type of animal/ Climate/ Manure management*	*Maximum applicability*	*Removal efficiency (%)*
Farm-scale anaerobic digestion plant	FARM_AD	Dairy cows/cool/liquid	0-84 %	80 %
		Dairy cows/temp/liquid	11-42 %	80 %
		Beef cattle/ cool/liquid	4-96 %	80 %
		Beef cattle/temp/liquid	0-54 %	80 %
		Pigs/cool/liquid	12-95 %	80 %
		Pigs/temperate/liquid	52-82 %	80 %
Housing adaptation	SA	Pigs/liquid	24-91 %	10 %

Source: AEAT (1998) and Hendriks *et al.* (1998)

Table 4.9: Costs for the mitigation options for manure management in GAINS.

Option	*GAINS technology abbreviation*	*Type of animal/ Climate/ Manure management*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost savings [€/t CH_4]*	*Total cost [€/t CH_4]*
Farm-scale anaerobic digestion plant	FARM_AD	Dairy cows/cool/liquid	145	80-144	-200 to -14	74 to 223
		Dairy cows/temp/liquid	41	23-36	-53 to -18	20 to 58
		Beef cattle/ cool/liquid	191	106-191	-266 to -19	98 to 294
		Beef cattle/temp/liquid	54	30-48	-70 to -23	27 to 76
		Pigs/cool/liquid	84	46-84	-117 to -8	43 to 129
		Pigs/temperate/liquid	21	12-19	-27 to -9	10 to 30
Housing adaptation	SA	Pigs/liquid	9,400-66,900	0	0	9,400-66,900

Source: AEAT (1998) and Hendriks *et al.* (1998)

4.3 Rice cultivation

Methane emissions vary significantly between rice strains. Low CH_4 emitting rice strains can be applied to reduce CH_4 emissions from rice paddies (IEA, 1998). While it is estimated that a careful selection of strains could reduce emissions between 20 and 30 percent, no information on current and potential application potentials could be derived. Lacking more detailed knowledge, it is assumed that such low CH_4 emitting rice strains could be used at all water-based rice fields in Europe.

Table 4.10: Control option for rice cultivation considered in GAINS.

Option	*Applicability*	*Removal efficiency [%]*	*Investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost savings [€/t CH_4]*	*Total cost [€/t CH_4]*
Alternative rice strains	100 %	25	0	47	0	47

Source: IEA (1998)

4.4 Disposal of biodegradable solid waste

Methane emissions are generated when biodegradable waste is digested anaerobically in landfills. GAINS distinguishes two classes of biodegradable waste, i.e., paper and organic waste. Emissions may be reduced by diverting paper and organic waste away from landfills through paper recycling, composting, incineration or biogasification. Alternatively, landfill emissions can be reduced by applying various landfill control options. These options have been applied in two stages. Firstly, waste diversion options are applied. In the second stage, landfill control options can be applied to the residual biodegradable waste that is landfilled.

4.4.1 Paper waste

Of the total paper consumed in a given country, 95 percent is assumed to end up in the municipal waste flow. The residual five percent is assumed to be scattered or burned without generating CH_4.

GAINS considers the following mitigation options for CH_4 emissions from paper waste:

- Paper recycling
- Incineration
- Landfill, capping
- Landfill, with gas recovery through gas utilization
- Landfill, with gas recovery through flaring
- Landfill, combined capping and gas recovery with utilization
- Landfill, combined capping and gas recovery with flaring

The waste management options available to treat the paper in the waste flow are recycling, incineration or landfilling. Landfills can be capped and the residual landfill emissions of CH_4 can be recovered and either flared or utilized as an energy source.

Figure 4.1 illustrates the flow of waste paper for the various mitigation options considered in GAINS. Removal efficiencies and application rates for the various mitigation options are presented in Table 4.11.

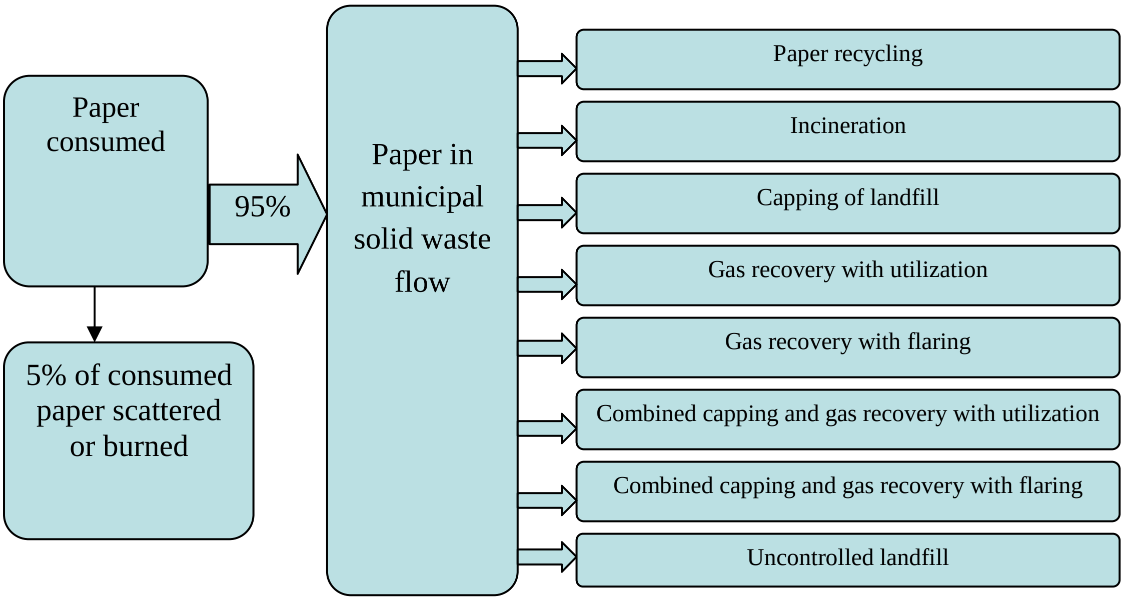

Figure 4.1: Flow of waste paper for the waste management options used in GAINS.

Diverting paper waste from landfills through ***collection and recycling of paper*** is assumed to remove 80 percent of the CH_4 emissions generated by the paper if landfilled (AEAT, 1998, p.63). This takes into consideration a 10 percent loss of the used paper during the de-inking process and an organic content of the resulting sludge amounting of at least 50 percent. This sludge is then assumed to be incinerated (Bresky, 2004), thereby removing 80 percent of the CH_4 contained in the sludge. It also considers fugitive emissions during collection, transportation and storage of waste paper before incineration, so that the net reduction efficiency of paper incineration is calculated at 80 percent in relation to the uncontrolled landfill reference case.

Paper waste that is not diverted away from the waste stream is assumed to be land filled. ***Methane emissions from landfills*** can be controlled by capping the landfill, recovering the gas, and flaring or utilizing it as an energy source. Capping of landfills is assumed to be a prerequisite for landfill gas recovery. Removal efficiencies for landfill capping and gas recovery are provided by AEAT (2001b) (1998, p.85-86). Oxidation of CH_4 from capping of the landfill varies from 10 to 50 percent for different types of capping (AEAT, 2001b, p.50). A mean oxidation rate of 30 percent is assumed for GAINS. The maximum recovery rate of CH_4 from landfills is 70 percent (AEAT, 2001b, p.19). Accordingly, the resulting maximum removal efficiency from a capped landfill with gas recovery is 79 percent (i.e., 0.3 + 0.7 * 0.7).

To estimate the maximum applicability for paper recycling, a maximum collection rate of 75 percent of paper consumed or 79 percent of paper waste is assumed to be attainable in all countries. According to CEPI (2003), 19 percent of paper consumed is non-collectable and/or non-recyclable paper. In addition, some paper finds secondary uses or is simply not economically viable to collect. Hence, a maximum collection rate of 75 percent appears feasible. Current collection rates exceed or are close to 70 percent in Finland, Germany, Netherlands, Sweden, Latvia, Norway and Switzerland. Less than 40 percent is collected in Cyprus, Greece, Ireland, Estonia, Lithuania, Poland, Bulgaria, and Romania (CEPI, 2003).

Thus, there is scope for increasing the collection rates in many of the European countries. For GAINS, it is further assumed that all of the residual paper waste can be incinerated. In principle, all landfills can be equipped with one of the mitigation technologies listed above.

The costs of diverting paper waste away from landfills through increasing collection and recycling rates consist of the increased costs for collection including the time spent by individuals separating paper waste from other waste and increased transportation costs. Cost-savings arise from the revenues of using recovered pulp instead of virgin pulp in paper production and from the foregone cost of landfilling when less paper waste is land filled. AEAT (1998, p.75) presents cost estimates for a UK de-inking plant producing 200 t/day of recovered pulp of a quality equal to virgin pulp. Investments are estimated at 35 €/t pulp produced or 171 €/t avoided CH_4, assuming that paper would have generated 0.205 t CH_4/t paper if land filled. O&M costs are estimated at 97 €/t pulp or 473 €/t CH_4 reduced.

Collection costs of recovered paper are estimated at 58 €/t assuming a 10 percent yield loss and the UK collection rate of 40 percent (AEAT, 1998, p.75). For the EU-25, marginal collection costs are assumed to increase according to the following equation: $MC=11.7e^{4s}$, where s is the collection rate. This implies that a 40 percent collection rate is reached at a marginal collection cost of 58 €/t paper collected (i.e., the UK collection cost). The marginal cost is then assumed to increase exponentially reaching 235 €/t paper collected at the maximum collection rate of 75 percent. With this collection cost relationship, the total cost of recycling paper turns positive at the maximum collection rate of 75 percent. Above this maximum collection rate, the paper industry does not consider it economically viable to collect and recycle paper for use in paper production (CEPI, 2002).

For countries outside the EU-25, GAINS assumes collection costs to increase at a much faster rate. The marginal cost relationship is set to $MC=57.6e^{5s}$, which implies that a positive total cost of recycling is rendered for expected CLE collection rates of about 30 percent in 2020. Thus, at a collection rate of 40 percent, the marginal collection cost will be 426 €/t paper and reach 2,449 €/t paper at a 75 percent collection rate. There are two reasons for assuming considerably higher collection costs for non-EU25 countries. First, the current waste collection infrastructure is poorer and development is usually costly. Second, collection costs in Western Europe are estimated assuming a zero cost to households for separating paper waste from other waste before disposal. The opportunity cost for the extra time households spend on paper waste separation is to spend the time on something else (e.g., work or leisure).

However, experience shows high collection rates in Western European households, suggesting a (possibly immaterial) value attributed by households to waste recycling. Benefits are likely to be linked to environmental awareness, social acceptance, and to the contribution to environmental improvement. Such benefits are likely to be lower in transitional and developing countries, where environmental education and awareness is lower, GDP/capita is lower, and households need to spend their time on more immediate concerns. Paper waste may also be valuable to the households for secondary uses (e.g., as burning material). To attain paper collection rates in these countries that are comparable to the collection rates attainable in Western Europe, paper collectors may need to compensate the households for paper separation work. Such compensation is hardly economically viable when carried out on a larger scale.

Cost-saving from using recovered instead of virgin pulp for paper production are derived from the price of virgin pulp. Mean prices for virgin pulp for the United Nations Economic

Commission for Europe (UNECE) area were calculated for the years 1990, 1995, and 1998 to 2002 using import and export quantities and values for virgin pulp from FAO (2004). Over these years the mean price for virgin pulp in the UNECE area has fluctuated between 433 and 645 €/t. Assuming the lower value of 433 €/t and a CH_4 generation rate of landfilled paper of 0.205 t CH_4/t paper, the virgin pulp price corresponds to a cost-saving of 2,112 €/t CH_4 when recycled paper is used in paper production instead of virgin pulp. The cost-saving of avoided landfilling of paper is estimated at 98 €/t CH_4. The CH_4 emission factor of paper is 0.205 t CH_4/t paper and the cost of landfilling is assumed to be 20 €/t waste (AEAT, 1998, p.76).

The cost of incinerating paper was calculated based on cost data from a UK waste incineration plant reported by Patel and Higham (1996) and referred to by AEAT (1998, p.77). This plant has a capacity to burn 200,000 t waste/year to produce and sell 324 TJ electricity and 324 TJ heat per year. Investments are reported at 51 million € or 3.7 million €/year when annualized over an equipment lifetime of 20 years. Operating and maintenance costs are estimated at 3.8 million €/year. Cost-savings from electricity and heat generation were calculated assuming the same heat value of paper waste as of municipal solid waste. The electricity generated is valued using the power plant price of gas for a corresponding amount of energy (assuming gas contains 50 GJ/t CH_4). The price of heat is assumed to be 25 percent of the price of electricity. The avoided cost of landfilling paper is counted as a cost-saving and assumed at 20 €/t paper.

Costs for landfill capping are based on data collected by AEAT (2001b, p.51) for a typical UK landfill of 62,500 m^2 (250 m x 250 m) with a capacity to landfill one million tonnes waste over a lifetime of 50 years. Over its entire lifetime, such a landfill is assumed to generate 72,000 t CH_4 or 1,440 t CH_4/year. Investment are 29 €/m^2, and operating and maintenance cost amount to 2,433 €/year. Capping reduces fugitive emissions from the landfill by 30 percent. This reduction corresponds to annualized investment costs of 195 €/t CH_4 and operating and maintenance cost of 5.63 €/t CH_4.

When the landfill is capped, the gas can be recovered to be flared or utilized as an energy source. Costs of installing a flaring facility or a boiler have been reported by AEAT (1998, p.78) based on UK data. The flaring facility is assumed to have a lifetime of 10 years and a capacity to burn 500 m^3 landfill gas/hour. With 98 percent availability and for 0.727 kg CH_4/m^3 landfill gas, the facility will burn 1,073 t CH_4/year. Assuming a removal efficiency of 80 percent, annualized investment costs amount to 17 €/t CH_4 and operating and maintenance cost to 8 €/t CH_4.

Instead of flaring, the recovered gas can be utilized as an energy source. Costs of installing a typical boiler for gas utilization in the UK was reported by AEAT (1998, p.78). The boiler has a capacity to burn 3.01 million m^3 CH_4/year or 2,139 t CH_4/year. This implies that one boiler would be enough for the typical landfill generating 1,440 t CH_4/year. The lifetime of the equipment is assumed to be 20 years. Investments amount to 90,800 € or 3 €/t CH_4 when annualized. Operating and maintenance cost are estimated at 10,400 €/year or 5 €/t CH_4. Eighty percent of the recovered gas can be utilized as energy. A lower and more variable quality of the recovered gas reduces its value in comparison with pure natural gas. Therefore the value of recovered CH_4 is assumed to correspond to 50 percent of the natural gas price.

Table 4.11: Waste diversion as control options to reduce methane (CH_4) emissions from paper waste in GAINS 1.0.

Option	*GAINS acronym*	*Maximum applicability*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost savings [€/t CH_4]*	*Total costs [€/t CH_4]*
Paper recycling	PAP_REC	79 %	80 %	171	394-4318[b]	-2210	-1645 to +2279
Incineration	PAP_INC	100 %	80 %	91	53-132	-168 to -102	+2 to +95
Capping of landfill	PAP_CAP	100 %	30 %	195	3-8	0	+198 to +203
Gas recovery with utilization[c]	PAP_USE1	100 %	70 %	3	3-7	-142 to -10	-133 to -4
Gas recovery with flaring[c]	PAP_FLA1	100 %	70 %	17	5-11	0	+22 to +28
Combined capping and gas recovery with utilization	PAP_USE2	100 %	79 %	198	6-15	-142 to -10	+69 to +194
Combined capping and gas recovery with flaring	PAP_FLA2	100 %	79 %	212	8-18	0	+220 to +231

[a] Country- and year specific. [b] Includes O&M and collection costs. [c] Only applicable to capped landfills. [d] Assumed maximum application rate when options are mutually exclusive. Sources: AEAT (1998, 2001b)

4.4.2 Organic waste

The GAINS category "Organic waste" includes organic matter from food and garden waste that ends up in the municipal solid waste flow. Some organic waste never reaches the municipal waste flow because it is treated in domestic composts. Home composts are assumed to be too small to generate any CH_4 emissions. Methane emissions from organic waste disposed in uncontrolled landfills can be reduced by large-scale composting, incineration, biogasification, capping of landfill, and landfilling with or without utilization of recovered gas (Figure 4.2). Table 4.12 summarizes removal efficiencies and maximum application potentials.

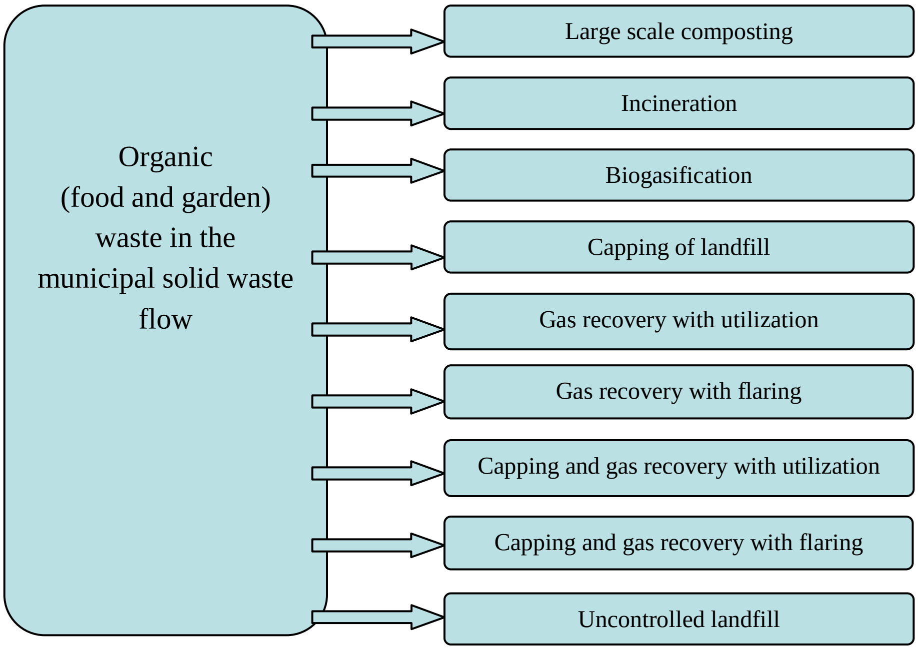

Figure 4.2: Options for treatment of organic wasted distinguished in GAINS.

The “Composting” option in GAINS includes large scale composts that diverting organic matter that would otherwise end up in the municipal solid waste disposal. These composts are assumed to eliminate 80 percent of the CH_4 emissions that would have occurred if the same waste had been landfilled. For incineration and biogasification, assumed removal efficiencies are 80 percent of CH_4 emissions generated otherwise (AEAT, 1998, p.69).

GAINS Version 1.0 assumes that all other organic waste that is not diverted away from the waste stream will be landfilled. Emissions from landfills can be controlled by capping the landfill, recovering the gas with flaring or utilizing the gas as energy. Landfill capping can be a control option of its own, but is also assumed to be a prerequisite for gas recovery. Removal efficiencies for landfill capping and gas recovery were provided by AEAT (1998, pp.85-86).

GAINS Version 1.0 assumes that in principle each option can be applied to 100 percent of organic waste, with the exception of large-scale composting. According to AEAT (1998, p.9), the potential maximum production of compost from organic waste is estimated for the EU-15 to vary between 49 and 124 kg per person and year, with a mean of 80 kg per person and year. Thus, it is assumed that the maximum amount of organic waste that can be composted is 80 kg per person and year in all countries.

Cost data for composting were adopted from AEAT (1998, p.66). Cost estimates are given for a large tunnel composting plant located in the Netherlands composting 25,000 t/ year. The plant has a capital investment of 2.98 million € and an expected lifetime of 15 years. Operating and maintenance cost are estimated at 25 €/t waste composted and the costs of source separating the waste is estimated at 8.2 €/t waste. The process is assumed to produce 7,000 t of poor quality material and 10,000 t of compost. Fifty percent of the poor quality material will have to be landfilled at an assumed cost of 20 €/t waste (AEAT, 1998, p.76). Fifty percent of the compost produced is assumed to be of a quality high enough to be sold at the market at a price of 4 €/t. The residual compost is of a poorer quality and given away for free. Cost-savings arise from avoided costs of landfill disposal calculated to 500,000 €/year. Costs and cost-savings per unit of CH_4 reduced are determined against the alternative of an uncontrolled landfill with a CH_4 generation rate of 0.082 t CH_4/t organic waste.

Costs of incinerating organic waste were calculated based on the same data as used for calculating costs for incinerating paper. The only difference in the calculation is that organic waste is assumed to generate 0.082 ton CH_4 per ton organic waste when landfilled instead of 0.205 t CH_4 generated per ton paper waste. It should be pointed out that costs for waste incineration used for GAINS 1.0 are based on data from 1996 and may underestimate the current costs for the EU due to the introduction of stricter environmental regulations for waste incineration in 2000. The New Directive (2000/76/EC) on waste incineration published on 28 December 2000 implies considerably stricter limits on emissions of various pollutants from waste incineration plants in the EU.

The costs of biogasification reported by AEAT (1998, p.77) are based on the costs for a UK plant processing 50,000 t waste/year and producing 8,000 MWh/year of electricity. Investments are estimated at 7.1 million € or 641,000 €/year assuming a 15 years lifetime of the equipment. Operating and maintenance cost are estimated at 1.07 M€/year. Costs for source-separated collection are estimated at 8.2 €/ton or 410,000 €/year. Overall, the process generates 5,000 t of poor quality material that is assumed to be landfilled at a cost of 20 €/t waste. It also generates 3,000 t of liquor that is assumed to have a secondary use at 50 percent at a zero disposal cost, while the residual 50 percent is disposed of in a landfill. The process is assumed to produce 34,500 t compost/year where 50 percent is assumed to be of a high quality and sold at a price of 4 €/t. It is assumed to be possible to find secondary use at no cost for the residual 50 percent of low quality compost. Avoided costs of not having to landfill the waste (while it is biogasified instead) are estimated at 20 €/t waste. The power plant price of gas was used for determining the cost-savings from selling the electricity generated during the process.

The cost of landfill control options are calculated in the same way for landfilled organic waste as presented for landfilled paper waste in Section 4.4.1. Table 4.12 presents costs for capping and gas recovery options separately, as well as for the combined options “capping with gas recovered and utilized” and “capping with gas recovered and flared”.

Table 4.12: Waste diversion as control options to reduce methane (CH_4) emissions from organic waste in GAINS 1.0.

Option	*GAINS acronym*	*Maximum application potential*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M cost [€/t CH_4]*	*Cost savings [€/t CH_4]*	*Total cost [€/t CH_4]*
Large scale composting	ORG_COMP	19-65 %	80 %	131	258-520	-254	135-397
Incineration	ORG_INC	100 %	80 %	228	131-330	-175 to -12	248-481
Biogasification	ORG_BIO	100 %	80 %	156	236-544	-311 to -264	100-399
Capping of landfill	ORG_CAP	100 %	30 %	195	3-8	0	198-203
Gas recovery with utilization[c]	ORG_USE1	100 %	70 %	3	3-7	-142 to -10	-133 to -4
Gas recovery with flaring[c]	ORG_FLA1	100 %	70 %	17	5-11	0	22-28
Combined capping and gas recovery with utilization	ORG_USE2	100 %	79 %	198	6-15	-142 to -10	69-194
Combined capping and gas recovery with flaring	ORG_FLA2	100 %	79 %	212	8-19	0	220-231

[a] Country and year specific. [b] Assumed max application rate when options are mutually exclusive. [c] Only applicable to capped landfills. Sources: AEAT (1998, 2001b)

4.5 Wastewater treatment

Wastewater treatment has primarily been introduced for public health concerns and to reduce emissions causing water eutrophication. Treatment requires that large amounts of sewage is collected and treated for the population at large. Under anaerobic conditions, this process generates methane emissions. In developed countries, treatment is usually undertaken in open lagoons under aerobic conditions and CH_4 generation is minimal.

An end-product of the treatment process is sludge, which needs to be disposed of either through composting, aerobic or anaerobic digestion, incineration or landfilling. Methane emissions might be generated depending on the method chosen for disposal. In economies in transition and developing countries, the types of integrated systems used in the developed countries are uncommon and urban areas often rely on cess pits and septic tanks that are likely to generate CH_4 emissions. These emissions can be recovered and used (e.g., for electricity and heating in households), which would simultaneously reduce CH_4 emissions (IEA-GHG, 1998).

GAINS considers two mitigation options, i.e., integrated treatment systems in regions where such systems are not yet implemented, and facilities for CH_4 recovery and utilization where the treatment involves anaerobic digestion of sewage (Table 4.13). The introduction of integrated systems in Eastern Europe is assumed to reduce CH_4 emissions from wastewater by 85 percent. This removal efficiency is derived from the difference in IPCC emission factors for wastewater in Western and Eastern Europe (see Section 3.3.4). Installing a gas recovery and utilization facility is assumed to remove 70 percent of the CH_4 emissions (IEA_GHG, 2003; p.B-39).

GAINS assumes that gas recovery and utilization facilities are in principle applicable to all treatment plants for residential waste water. Wide-spread application of waste water treatment in the EU-25 leaves mainly the anaerobic handling of the sludge as a target for further reductions. For the non-EU-25 countries, it is assumed that integrated systems can be applied to 100 percent of wastewater in residential areas. CH_4 generated from cess pits, septic tanks and other anaerobic collection and storage of wastewater is assumed to be recovered. Fifty percent of the recovered gas is assumed to be utilized as energy and the remainder is flared.

Due to the high costs of integrated wastewater treatment systems, they would be a very expensive option for CH_4 control if all costs were allocated to this objective, ignoring all other benefits from wastewater treatment. Renzetti and Kushner (2004) quote for Canada annual operating expenditure for sewage treatment (including costs for labour, material, energy, debt charges and capital reserve funds) of 100 \$/person/year (i.e., approx. 72 €/person/year). With an emission factor for Eastern Europe of 0.0056 kt CH_4/million people and a removal efficiency of 85 percent, the corresponding cost would be about 15 million €/t CH_4 reduced.

Thus, any cost assessment of this mitigation option is thus critically dependent on the valuation of the co-benefits. Costs could range from the 15 million €/t CH_4 reduced if all costs are solely allocated to CH_4 control to no additional expenses if it is assumed that wastewater treatment is implemented mainly for other purposes. For installing gas recovery and utilization facilities in the wastewater sector, cost data are given in IEA-GHG (2003, p.B-39) for North American conditions. These estimates have been used in GAINS Version 1.0, adjusted for labour costs and gas prices. The lifetime of the equipment is assumed to be 30 years.

Table 4.13: Control options for wastewater handling in GAINS.

Option	*GAINS acronym*	*Removal efficiency*	*Maximum applicability*	*Annualized investments [€/t CH_4]*	*O&M cost €/t CH_4*	*Cost savings [€/t CH_4]*	*Total cost [€/t CH_4]*
Integrated sewage system	INT_SYS	85 %	0-87 %	n.a.	n.a.	n.a.	>1,000,000
Gas recovery and utilization	GAS_USE	70 %	100 %	284	4-13	-155 to -11	140-277

Sources: IEA-GHG (1998, 2003), Eurostat (2003), European Commission (2004c)

4.6 Coal mining

Methane emissions from coal mines can be reduced by upgrading the gas recovery of existing mines or by installing more efficient CH_4 recovery in new mines. The recovered gas can then be utilized for energy purposes. Current recovery and utilization rates for CH_4 emissions from coal mines are presented in Table 4.14 for the Former Soviet Union, Germany, Poland and the UK (AEAT, 2001c; p.38). Based on this information, recovery and utilization rates for other EU and non-EU countries were assumed. For EU countries, the gas recovery rate is assumed to be 50 percent of total emissions, whereof 25 percent is utilized as energy. GAINS Version 1.0 assumes the current gas recovery and utilization rates of the former Soviet Union, i.e., 28 percent recovered, whereof 14 percent is utilized is assumed, for the non-EU countries.

GAINS Version 1.0 considers improvements of the current capture and utilization rates as the major option for further reducing CH_4 emissions. It is assumed that it is technically possible to extend the recovery and utilization rate to on average 70 percent of total emissions from coal mines (AEAT, 2001c; p.44). A 90 percent removal efficiency of the recovered gas is assumed taking into account that some fugitive emissions will take place during the utilization of the recovered gas. It is assumed that such upgrades of the gas recovery and utilization rates from the current levels to 70 percent of total emissions are possible.

Costs of increased gas recovery and utilization from 30 to 70 percent of total emissions are estimated assuming a typical mine producing 1.7 Mt coal/year and emitting 20 kt CH_4/year (or emitting 0.012 t CH_4/t coal) (AEAT, 1998; p.101). The recovery upgrade leads to an increase in emission recovery from 6 to 10 kt CH_4/year, i.e., reducing emissions by 4 kt CH_4/year. Costs are based on the installation of a reciprocal engine, which according to AEAT (1998; p.101) is the most cost-effective measure. The lifetime of the equipment installed is 10 years.

Additional investments for the upgrade of the gas recovery from 30 to 70 percent are reported at 3.8 million € or 0.28 million €/year when annualized (AEAT, 1998; p.102). With an additional emission reduction of four kt CH_4/year, investments amount to 70 €/t CH_4 reduced. Additional operating and maintenance cost are 0.222 million €/year or 43 €/t CH_4 reduced, assuming UK labour costs. When gas utilization increases from 30 to 70 percent, cost savings per unit of CH_4 reduced are assumed at 80 percent of the gas price, assuming that 80 percent of the gas made available for utilization can be used in the vicinity of the coal mine.

Table 4.14: Methane (CH_4) captured and proportion utilized of mine gas.

	Methane captured (% of total CH_4 emitted)	*Proportion utilized (% of total CH_4 captured)*	*Source*
Former USSR	28	14	AEAT (2001c, p.38)
Germany	63	40	AEAT (2001c, p.38)
Poland	49	29	AEAT (2001c, p.38)
UK	18	20	AEAT (2001c, p.38)
Other EU	50	25	Assumed here
Other Non-EU	28	14	Assumed here

Source: AEAT (2001c, p.38)

Table 4.15: Control option for reducing methane (CH_4) emissions from coal mining in GAINS.

Option	GAINS acronym	Maximum applicability	Removal efficiency	Annualized investments [t/CH_4]	O&M costs [€/t CH_4]	Cost saving [€/t CH_4]	Total cost [€/t CH_4]
Upgraded recovery and utilization of gas from current level to 70%	CH_4_REC	70 %	100 %	118	13 to 72	-284 to -20	-107 to 112

Source: AEAT (1998, 2001c)

4.7 Gas and oil production and refinery processes

Emissions of CH_4 occur during oil and gas production and the associated refining of oil. These emissions can be controlled either by flaring (instead of venting) or by recovering the gas in order to use it for heat or electricity production. Apart from limited on-site use, it may be difficult to find use for the recovered energy in the vicinity of the gas or oil field. Oil refineries are usually located in the outskirts of urban areas and may also have problems finding use for the recovered gas in the close vicinity. Therefore, utilization of recovered gas from these activities is not considered in GAINS Version 1.0 to be a feasible option.

GAINS considers flaring as the only option for reducing emissions from oil and gas production and refinery processes. Flaring is a more emission effective measure than gas recovery and utilization. According to AEAT (1998, p.121), the removal efficiency of a flaring facility is 97 percent compared with 80 percent for a gas recovery and utilization installation. Flaring is assumed to be applicable to 100 percent of the production and processing of oil and gas.

AEAT (1998, p.124) provides cost data for flaring based on Dutch off-shore installations. Woodhill (1994) estimates the capital costs of an on-shore installation at 40 percent of the capital cost of an off-shore installation. GAINS Version applies these Dutch cost data to installations in in the Netherlands, the UK, Norway and Denmark and assumes for all other countries on-shore installations with costs of only 40 percent of the Dutch off-shore estimates. Gas prices are country-specific.

Table 4.16: Control options for oil and gas production and processes in GAINS.

Option	*GAINS acronym*		*Maximum applicability*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost-saving*	*Total cost [€/t CH_4]*
Flaring instead of venting of gas - oil/gas production	FLA_PROD	Off-shore	100 %	97 %	162	58-79	0	220-241
		On-shore	100 %	97 %	65	8-38	0	73-103
Flaring instead of venting of gas - refineries	FLA_REF	On-shore	100 %	97 %	65	8-38	0	73-103

Source: AEAT (1998)

4.8 Gas transmission and distribution

Significant CH_4 emissions occur from gas leakages during pipeline transmission and consumer distribution networks in Eastern Europe, while only marginal losses occur for Western Europe.

For Western Europe, emission estimates are based on the amount of gas consumed. They primarily arise from leakages in the distribution to the consumers. Following Houghton *et al.* (1997; p.1.30), no emissions from leakages in the industrial, power plants and residential sectors are assumed. Fugitive emissions from old consumer distribution networks make up the majority (79 percent) of emissions from gas distribution in Western Europe (AEAT, 1998; p.123). Emissions from this source can be reduced by replacing the grey cast iron networks, which were built when town gas was used instead of CH_4, by polyethylene (PE) or polyvinylchloride (PVC) networks. This measure typically removes 97 percent of fugitive emissions (AEAT, 1998, p.132). Investments have a lifetime of 20 years.

A second option is to increase the frequency of inspections and maintenance to improve leakage detection and repair. A doubling of the control frequency of gas networks in the Netherlands (from every fourth year to every second year) reduced emissions by 50 percent (AEAT, 1998; p.123). Cost estimates for a doubling of the leak control frequency of the distribution network for the Netherlands are provided in AEAT (1998, p.125). GAINS Version 1.0 uses these estimates for Western Europe, adjusting for differences in labour costs. Annualized investments are estimated at 2,036 €/t CH_4 abated. Cost-savings from reduced gas losses correspond to the gas price.

GAINS assumes that all grey cast iron pipe networks can be replaced, which would reduce 76 percent of emissions from gas distribution in Western Europe. Residual emissions could be further reduced by 50 percent through an increased control frequency of all distribution networks. Resulting application rates, removal efficiencies and costs for the control options applied for Western Europe are given in Table 4.17.

For Eastern Europe, IPCC emission factors and emission estimates are related to the amount of gas *produced* (Table 4.18). Emissions arise from leakages of gas transmission pipelines and distribution networks. In Russia, gas transmission is the most important source of CH_4 emissions, and emissions from gas compression and control systems are the major contributors to emissions from transmission (IEA Greenhouse Gas R&D Programme, June 1998). Methane emissions arise for several reasons, e.g., compressor seals are not gas-tight, valves are poorly controlled and maintained, and due to flushing with natural gas during start-ups.

Hendriks *et al*. (1998; pp.19-20) calculate for EU-15 costs of a set of measures that together reduce 90 percent of compressor emissions. These measures include no flushing at start-up, electrical start-up, and inspection and maintenance programs. The removal efficiency is 80 percent of emissions from distribution. The cost estimates for Western Europe have been applied to Eastern Europe with adjustments for different labour costs and gas prices. Cost savings from this set of measures arise due to reduced gas losses and to an efficiency increase of the equipment of 10 percent (Hendriks *et al*., 1998, p.20). For all countries except Russia, the cost of gas losses are measured as the export price of gas from Russia to the European market. Export prices for gas in 2002 from Gazprom (2002) were used as starting values. These were 60 €/t gas for the CIS member states Ukraine, Belarus, Moldavia and the Baltic states.

For all other countries, a price of 116 €/t gas has been used. The price is assumed to increase linearly by 1.8 €/year until 2020 following Kononov (2003) and assuming 0.9 t CH_4 per thousand m^3 CH_4. After 2020, the producer price is assumed constant. Thus, the price in 2000 is assumed to be 56.4 €/t rising to 92.4 €/t gas in 2020 in CIS member countries. For all other countries the gas price is assumed to increase from 112 to 148 €/t gas in 2000 to 2020. For Russia, the producer price of gas is used as a measure of the benefit of reduced gas losses during transmission. Producer prices for gas in Russia were assumed to be 36 €/t CH_4 in 2000 rising to 45 €/t CH_4 in 2020 (Makarov and Likhachev, 2002). For a valuation of the reduced gas losses in Russia, 75 percent of gas is assumed to be sold in the internal market and 25 percent to be exported to Europe (Gazprom Annual Report 2002). All other costs (investments and material costs) are assumed to be the same in Eastern and Western Europe.

Table 4.17: Control options to reduce methane (CH_4) emissions from gas distribution in Western Europe in GAINS.

Option	*GAINS acronym*	*Maximum applicability*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost-saving [€/t CH_4]*	*Total cost [€/t CH_4]*
Replacement of grey cast iron networks	REPL_NET	79 %	97 %	2,036	0	-280 to -66	1,756 to 1,970
Doubling of leak control frequency of network	CONT_NET	21 %	50 %	0	538-1,630	-355 to -84	338 to 1,394

Source: AEAT (1998, p.126), Hendriks *et al*. (1998, p.20-21)

Table 4.18: Control options to reduce methane (CH_4) emissions from gas transmission and distribution in Eastern Europe in GAINS.

Option	*GAINS acronym*	*Maximum applicability*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost-saving [€/t CH_4]*	*Total cost [€/t CH_4]*
Reduction at compressor stations	COMPRESS	100 % of transmission pipelines in FSU	80 %	75	5-16	-83 to -32	0-48
Replacement of grey cast iron networks	REPL_NET	79 % of leakage in domestic and industrial sectors	97 %	2,036	0	-245 to -20	1,791 to 2,016
Doubling of leak control frequency of network	CONT_NET	21 % of residual emissions from leakage in domestic and industrial sectors	50 %	0	349-1,310	-248 to -20	169-1,078

Source: Hendriks *et al.* (1998, p.19-20), AEAT (1998, p.122)

4.9 Agricultural waste burning

The ban on open burning of agricultural waste (Klimont *et al.*, 2000), which also leads to lower CH_4 emissions, is already implemented in the RAINS VOC module as an option to reduce VOC emissions from this source. The costs of a ban are calculated in the RAINS VOC module at 60 €/t VOC. With emission factors of 8-10 t VOC/Mt waste and 1.2 t CH_4/Mt waste, the corresponding cost for using this option to reduce CH_4 emissions is about 500 €/t CH_4, if costs were allocated to CH_4 control only. In practice, GAINS Version 1.0 takes full account of these synergies and avoids double-counting of costs.

Table 4.19: Control options for agricultural waste burning in GAINS.

Option	*GAINS acronym*	*Maximum applicability*	*Removal efficiency*	*Annualized investments [€/t CH_4]*	*O&M costs [€/t CH_4]*	*Cost-saving [€/t CH_4]*	*Total cost [€/t CH_4]*
Ban on agricultural waste burning	BAN	100 %	100 %	n.a.	n.a.	n.a.	500

Source: Klimont *et al.* (2000)

5 Interactions with other emissions

A number of cases have been identified where emissions of methane (CH_4) and related emission control options influence emissions of other greenhouse gases and air pollutants, and vice versa (Table 5.1).

During treatment of manure, nitrous oxide (N_2O) and ammonia (NH_3) are emitted together with CH_4. When wastewater is discharged, CH_4 and N_2O emissions are released. Waste disposal, gas production, distribution and consumption, and oil production and refining are processes during which both CH_4 and VOC are emitted. Agricultural waste burning causes emissions of CH_4, particulate matter (PM), nitrogen oxides (NO_x) and VOC. It will be important to capture these interactions when the findings of this study are implemented together with the other pollutants in the GAINS optimization model.

Table 5.1: Interactions of sectors in GAINS emitting methane (CH_4) with emissions of other environmental issues.

Sector		Interactions with other gases in GAINS
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, CO_2
	Coal mining	CO_2
	Oil production and refinery	VOC, CO_2
Biomass burning	Field burning of agricultural residues	PM, NO_x, VOC
	Residential bio-fuel combustion	CO_2

6 Results

6.1 Baseline emission estimates

6.1.1 GAINS estimates

With the methodology and data described in the preceding sections, GAINS computes for the entire model domain total anthropogenic methane (CH_4) emissions of 63,138 kt in 1990, and 54,659 kt for the year 2000 (Table 6.1). For 1990, EU-25 emissions are estimated at 24,099 kt and 25,080 kt for the European part of Russia. The largest contributions originate from gas transportation and agricultural activities, each source responsible for approximately one third of the total European anthropogenic CH_4 emissions.

The largest single source is gas transportation and distribution in Russia, which accounts for about 25 percent of total European emissions (Figure 6.1). Waste treatment and coal mining contribute 17 and 13 percent, respectively, while all other sectors are responsible for comparably smaller shares. A different picture emerges for the EU-25 (Figure 6.2). In this region, agriculture, waste and coal mining are the dominating sources of CH_4 emissions, and only eight percent of total emissions emerge from the gas sector.

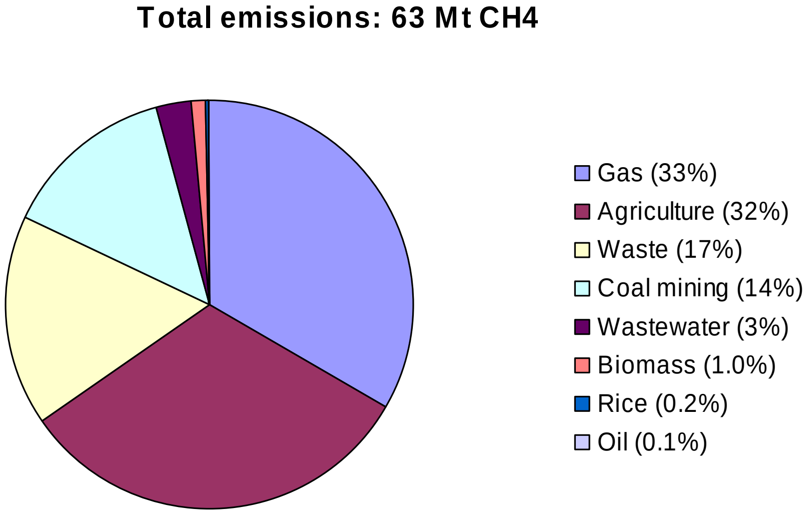

Figure 6.1: Sectoral contributions to total anthropogenic methane (CH_4) emissions as calculated by GAINS for the year 1990 for entire European model domain.

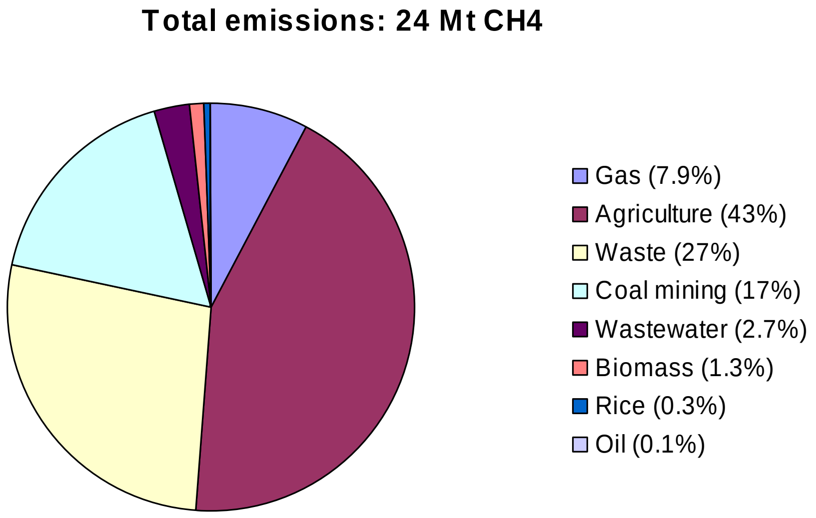

Figure 6.2: Sectoral contributions to total anthropogenic methane (CH_4) emissions as calculated by GAINS for the year 1990 for the EU-25.

6.1.2 Comparison with other emission estimates

Emission estimates for CH_4 are available from a number of different sources. This report compares the country/sector totals obtained from GAINS Version 1.0 with data from the official national communications (UNFCCC, 2005) and with the EDGAR inventory, which is a scientific emission inventory of global emissions with country and grid information (EDGAR (2004). For the comparison the UNFCCC online database as of August 2005 has been used.

The UNFCCC and the EDGAR inventories do not cover the full GAINS model domain. However, comparisons of the emissions for the EU-25 show similar emission levels for most countries (Table 6.1). For a few countries (Belarus, Bulgaria, Czech Republic, Estonia, Germany, and Ukraine), GAINS estimates for 1990 deviate by more than 30 percent from the figures reported by countries to UNFCCC (2005). Table 6.2 compares sectoral emissions of GAINS with the UNFCCC estimates. Large discrepancies between emission estimates appear for the waste sector and for coal mining. Discrepancies for the agricultural sector are small except for Germany, where agricultural emissions reported to UNFCCC are almost twice the amount calculated by GAINS 1.0.

For the Czech Republic, the UNFCCC data report considerably lower emissions from coal mining than estimated by GAINS, possibly due to the use of country-specific emission factors in the Czech inventory. Differences in the emission estimates for waste can be traced back to different calculation methods. National estimates for the waste sector as reported to UNFCCC are computed based on the amounts of municipal solid waste, which implicitly assume uniform shares of waste paper and organic waste in the total waste volume for all countries. GAINS, however, calculates emissions from this sector separately for paper and organic waste, using country-specific statistics on paper consumption and waste composition. This leads for 1990 to higher GAINS estimates for countries with high paper consumption and low recycling and incineration rates, such as Italy and Spain.

Table 6.1: Comparison of GAINS Version 1.0 estimates of methane (CH_4) emission with other emission inventories [kt CH_4].

	1990				*2000*		
	GAINS	*UNFCCC*	*EDGAR*	*ECOFYS*	*GAINS*	*UNFCCC*	*ECOFYS*
Albania	165	n.a.	105	n.a.	172	n.a.	n.a.
Austria	392	446	391	587	317	371	600
Belarus	908	666	914	n.a.	686	488	n.a.
Belgium	506	519	488	634	456	468	537
Bosnia-H..	175	n.a.	95	n.a.	148	n.a.	n.a.
Bulgaria	476	1,164	457	n.a.	329	484	n.a.
Croatia	190	182	190	n.a.	219	153	n.a.
Cyprus	25	n.a.	n.a.	n.a.	30	n.a.	n.a.
Czech Rep.	1,247	798	1,059	n.a.	965	510	n.a.
Denmark	302	259	269	421	322	273	409
Estonia	127	208	124	n.a.	68	114	n.a.
Finland	314	302	353	246	281	258	226
France	2,574	3,306	2,701	3,017	2,413	3,067	2,820
Germany	4,243	6,743	5,232	5,682	3,283	4,208	3,892
Greece	462	428	305	443	480	544	n.a.
Hungary	724	624	677	n.a.	593	471	n.a.
Ireland	564	567	551	811	569	609	837
Italy	2,189	1,771	2,015	2,329	1,773	1,691	2,455
Latvia	197	174	206	n.a.	85	104	n.a.
Lithuania	308	340	369	n.a.	168	n.a.	n.a.
Luxembourg	27	24	12	24	27	23	22
Macedonia	91	n.a.	57	n.a.	89	n.a.	n.a.
Malta	10	n.a.	5	n.a.	11	n.a.	n.a.
Moldavia	224	n.a.	229	n.a.	214	n.a.	n.a.
Netherlands	964	1,302	922	1,290	863	968	971
Norway	247	307	362	n.a.	287	334	n.a.
Poland	2,551	3,141	4,286	n.a.	2,193	2,183	n.a.
Portugal	369	402	355	806	387	409	714
Romania	2,241	2,464	2,014	n.a.	1,550	1,225	n.a.
Russia-Kalinin.	72	n.a.	n.a.	n.a.	58	n.a.	n.a.
Russia-Kola-K.	151	n.a.	n.a.	n.a.	157	n.a.	n.a.
Russia-Other	24,480	n.a.	n.a.	n.a.	21,459	n.a.	n.a.
Russia-St.Petersb.	377	n.a.	n.a.	n.a.	298	n.a.	n.a.
Serbia-M.	522	n.a.	614	n.a.	498	n.a.	n.a.
Slovakia	342	310	355	n.a.	259	214	n.a.
Slovenia	120	121	83	n.a.	103	112	n.a.
Spain	1,807	1,440	1,508	2,181	1,984	1,870	2,356
Sweden	331	317	365	324	295	281	284
Switzerland	280	238	229	n.a.	275	208	n.a.
Turkey	2,727	n.a.	n.a.	n.a.	2,778	n.a.	n.a.
Ukraine	5,711	9,402	6,971	n.a.	4,876	n.a.	n.a.
UK	3,403	3,662	3,227	4,409	2,642	2,323	3,361
Total (42 regions)	63,138	n.a.	n.a.	n.a.	54,659	n.a.	n.a.
CO_2-eq, Mton	1,326	n.a.	n.a.	n.a.	1,148	n.a.	n.a.
EU-25	24,099	27,203[a]	n.a.	n.a.	20,567	21,072[b]	n.a.
CO_2-eq, Mton	506	571[a]	n.a.	n.a.	432	443[b]	n.a.

Sources: GAINS, UNFCCC (2005), EDGAR (2004) and Hendriks *et al.* (1998)

[a] EU-25 excluding Cyprus and Malta. [b] EU-25 excluding Cyprus, Lithuania, and Malta.

Table 6.2: Comparison of sectoral methane (CH_4) emission estimates for 1990 [kt/year].

Country	*Data source*	*CH_4 emissions (kt/year)*				
		Fuels and industrial processes[a] (whereof coal mining)	*Agriculture*	*Waste (whereof wastewater)*	*Other*	*Total*
Albania	GAINS	12 (0)	95	57 (14)	0	165
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Austria	GAINS	78 (14)	205	110 (14)	0	392
	UNFCCC	*35 (1)*	*219*	*192 (14)*	*0*	*446*
Belarus	GAINS	166 (0)	562	180 (43)	0	908
	UNFCCC	*1*	*530*	*112*	*24*	*666*
Belgium	GAINS	65 (17)	265	175 (4)	0	506
	UNFCCC	*41(2)*	*342*	*132(4)*	*5*	*519*
Bosnia-Herc.	GAINS	11 (3)	90	74 (18)	0	175
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Bulgaria	GAINS	87 (23)	225	164 (42)	0	476
	UNFCCC	*233 (92)*	*273*	*658 (45)*	*0*	*1,164*
Croatia	GAINS	30 (1)	84	77 (19)	0	190
	UNFCCC	*69 (2)*	*75*	*38 (n.a.)*	*0*	*182*
Cyprus	GAINS	0 (0)	16	9 (2)	0	25
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Czech Rep.	GAINS	772 (700)	283	191 (29)	0	1247
	UNFCCC	*459 (362)*	*204*	*133 (39)*	*3*	*798*
Denmark	GAINS	18 (0)	224	60 (4)	0	302
	UNFCCC	*13 (3)*	*183*	*62 (n.a.)*	*0*	*259*
Estonia	GAINS	27 (12)	68	33 (9)	0	127
	UNFCCC	*61 (19)*	*70*	*77 (9)*	*0*	*208*
Finland	GAINS	24 (0)	107	182 (7)	0	314
	UNFCCC	*21 (1)*	*98*	*182 (7)*	*1*	*302*
France	GAINS	345 (112)	1,583	647 (44)	0	2,574
	UNFCCC	*566 (206)*	*2,185*	*578 (34)*	*-23*	*3,306*
Germany	GAINS	1,283 (953)	1,727	1,234 (52)	0	4,243
	UNFCCC	*1,931 (1,314)*	*3,206*	*1,605 (106)*	*0*	*6,743*
Greece	GAINS	37 (27)	233	191 (41)	0	462
	UNFCCC	*69 (52)*	*170*	*184 (50)*	*6*	*428*
Hungary	GAINS	332 (130)	185	206 (45)	0	724
	UNFCCC	*176 (73)*	*197*	*251 (63)*	*0*	*624*
Ireland	GAINS	11 (0)	488	65 (2)	0	564
	UNFCCC	*14 (0)*	*497*	*55 (n.a.)*	*0*	*567*
Italy	GAINS	214 (1)	1036	939 (59)	0	2,189
	UNFCCC	*403 (6)*	*839*	*521 (60)*	*8*	*1,771*
Latvia	GAINS	34 (0)	115	49 (13)	0	197
	UNFCCC	*23 (0)*	*111*	*36 (17)*	*3*	*174*
Lithuania	GAINS	50 (0)	197	62 (15)	0	308
	UNFCCC	*31 (0)*	*181*	*128 (15)*	*0*	*340*
Luxembourg	GAINS	4 (0)	16	7 (0)	0	27
	UNFCCC	*2 (0)*	*18*	*4 (0)*	*0*	*24*
Macedonia	GAINS	11 (5)	47	33 (8)	0	91
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Malta	GAINS	0 (0)	5	6 (2)	0	10
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*

Table 6.2 (continued): Comparison of sectoral methane (CH_4) emission estimates for 1990 [kt/year].

Country	*Data source*	*CH_4 emissions (kt/year)*				
		Fuels and industrial processes[a] (whereof coal mining)	*Agri-culture*	*Waste (whereof wastewater)*	*Other*	*Total*
Moldavia	GAINS	38 (0)	109	77 (18)	0	224
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Netherlands	GAINS	205 (0)	531	228 (3)	0	964
	UNFCCC	*216 (0)*	*505*	*578 (7)*	*2*	*1,302*
Norway	GAINS	66 (3)	100	81 (1)	0	247
	UNFCCC	*28 (0)*	*97*	*183 (1)*	*0*	*307*
Poland	GAINS	1,244 (1,049)	732	575 (98)	0	2,551
	UNFCCC	*1,311 (1,043)*	*863*	*966 (131)*	*1*	*3,141*
Portugal	GAINS	22 (0)	180	168 (39)	0	369
	UNFCCC	*28 (3)*	*215*	*139 (39)*	*0*	*402*
Romania	GAINS	1,179 (46)	682	380 (84)	0	2,241
	UNFCCC	*1,401 (303)*	*775*	*286 (81)*	*0*	*2,464*
Russia-Kalinin.	GAINS	17 (0)	37	17 (4)	0	72
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Russia-Kola-K.	GAINS	15 (0)	15	121 (30)	0	151
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Russia-Remain.	GAINS	19,105 (3,036)	3,558	1,818 (446)	0	24,480
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Russia-St.Peters	GAINS	183 (0)	129	65 (16)	0	377
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Serbia-M.	GAINS	120 (82)	220	181 (43)	0	522
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Slovakia	GAINS	87 (12)	136	119 (41)	0	342
	UNFCCC	*76 (24)*	*134*	*98 (48)*	*1*	*310*
Slovenia	GAINS	24 (12)	46	51 (5)	0	120
	UNFCCC	*24 (17)*	*51*	*45 (7)*	*1*	*121*
Spain	GAINS	198 (136)	879	730 (87)	0	1,807
	UNFCCC	*172 (85)*	*912*	*356 (72)*	*0*	*1,440*
Sweden	GAINS	56 (0)	148	127 (6)	0	331
	UNFCCC	*34 (0)*	*161*	*122 (0)*	*0*	*317*
Switzerland	GAINS	11 (0)	169	99 (1)	0	280
	UNFCCC	*23 (0)*	*154*	*61 (1)*	*0*	*238*
Turkey	GAINS	253 (118)	1,594	880 (237)	0	2,727
	UNFCCC	*n.a.*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Ukraine	GAINS	2,728 (1,180)	2,074	909 (219)	0	5,711
	UNFCCC	*6,256 (n.a.)*	*2,254*	*892 (n.a.)*	*0*	*9,402*
UK	GAINS	1,248 (958)	1,103	1,052 (34)	0	3,403
	UNFCCC	*1,461 (819)*	*1,034*	*1,165 (33)*	*1*	*3,662*

[a] Includes emissions from fuel combustion, fugitive emissions from fuels, and emissions from industrial processes including emissions from coal mining. Sources: GAINS 1.0 and UNFCCC (2005)

6.2 Projections of future emissions

6.2.1 Background information

The GAINS Version 1.0 baseline estimate of future CH_4 emissions relies for the 25 EU Member States on the projected activity levels of the baseline scenario of the "Energy Outlook" developed in 2003 by the Directorate General for Energy and Transport of the European Commission (Mantzos *et al.*, 2003).

The evolution of agricultural activities follows the assumptions made for the baseline scenario of the Clean Air For Europe (CAFE) programme of the European Commission (http://www.iiasa.ac.at/rains/CAFE_files/CAFE-baseline-full.pdf). As a basic assumption, these projections do not include any climate policy measures beyond those which were already in force in 2003. For the non-EU countries, national reports of activity projections have been used. Details on projected fuel consumption and production levels are available from the RAINS website (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

Future levels of emissions are critically determined by the extent to which mitigation measures will be implemented. This is reflected in GAINS by the application rates of the various control measures considered in GAINS. This report analyzes two projections of future emissions. The "Current Legislation" (CLE) case attempts to portray the 'business as usual' development taking into account mitigation measures that are currently decided and form part of national or EU-wide emission control legislation. This current legislation baseline projection is contrasted by a scenario that explores the extent to which CH_4 emissions could be lowered through full application of all mitigation measures that are currently included in GAINS Version 1.0.

6.2.2 Emissions for the current legislation scenario

For the CLE case, emissions are calculated by considering the present and future implementation of control measures that will reduce unit emissions below the level already assumed in the IPCC emission factors. For example, starting points for determining emission factors from paper waste are published emission factors for paper that is disposed of to uncontrolled landfill. For the CLE case, the current levels of paper recycling, incineration and gas recovery at landfills are taken into account, as well as expected future emission reductions from legislation requiring increased waste diversion.

For this report, the CLE case only includes (national or international) legislation in place as of end 2003. This implies that mitigation measures proposed for national or EU-wide legislation at that time are not included in the CLE-scenario presented in this report. In particular, the EU-wide legislation currently considered in the estimations of the CLE scenario for CH_4 includes:

- The EU Landfill Directive (adopted by the European Council in April 1999).
- The EU Common Agricultural Policy (adopted by the EU agricultural ministers in June 2003) has been included through the choice of control options to mitigate CH_4 emissions from enteric fermentation. Expected effects from the CAP reform on the number of animals have not yet been regarded in the activity data.
- The EU Wastewater Directives (adopted in May 1991 and February 1998).

Effects on animal numbers of the EU Nitrate Directive (adopted in December 1991) and from the reform of the EU Common Agricultural Policy have not been taken into account in the GAINS Version 1.0 baseline projection. To derive at the baseline emission projection, a number of quantitative assumptions had to be taken for individual source categories. These are described in the following sections.

The EU Landfill Directive

The EU-wide Landfill Directive (European Council Directive 99/31/EC of 26 April 1999) requires a reduction of biodegradable landfilled waste and control of landfill gas. The following amounts of biodegradable waste (expressed as percentage of the 1995 volumes) are required to be diverted from landfills (Hogg *et al.,* 2002; p.35):

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

These targets also apply to New Member 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). For the GAINS Version 1.0 baseline projection, it is assumed that the targets set in the Landfill Directive will be achieved. The required reductions are assumed to apply to both paper and organic waste. For example, a 25 percent reduction of landfilled paper waste in 2006 is assumed to be attained in addition to a 25 percent reduction of landfilled organic waste.

The 1995 amounts of landfilled paper and organic waste were calculated by applying 1995 levels of paper recycling and composting (based on the 1995 levels of paper consumption and generation of organic waste). The residual waste is either landfilled or incinerated in accordance with the current shares of municipal waste going to different waste management treatments in the EU-15, Norway and Switzerland (AEAT 2001b, p.1; Umwelt Schweiz, 2002; Statistics Norway, 2003). For all other countries, a zero incineration and composting rate has been assumed for 1995. All EU-15 countries, Norway and Switzerland are assumed to have capped landfills in 1990. The Landfill Directive also requires that all new landfill sites must have gas recovery facilities and all existing sites must have installed these facilities by 2009.

Starting from the current shares of municipal waste going to different waste management treatments in the EU-15, Norway and Switzerland (AEAT 2001b, p.1; Umwelt Schweiz, 2002; Statistics Norway, 2003), the shares will change in the baseline projection as more paper is diverted away from landfills due to increased recycling. The requirement of the Landfill Directive to equip all sites with gas recovery facilities is assumed to be met in all EU-25 countries from 2009 onwards. Country-specific shares of CH_4 recovered from landfills in 1990 for the EU-15 (AEAT 1998, p.82) have been considered, as well as a few national requirements on landfill gas recovery specified in AEAT (2001b; p.43). No gas recovery is assumed for 1990-2005 for the new EU Member States, and full compliance with the Directive is assumed for 2009 onwards. For all other countries zero landfill capping and gas recovery is considered for the CLE case.

The shares of recovered gas that is utilized or flared were calculated using information in AEAT (2001b, p.46) on the current and future capacity to utilize recovered landfill gas in EU-

15 is listed in Table 4.11. The amount of recovered and utilized CH_4 was calculated assuming a 100 percent utilisation of the capacity and the energy content of CH_4 to be 50 GJ/tonne. The resulting amount of utilized CH_4 was divided by the estimated total amount of recovered gas to obtain the shares of utilized gas presented in Table 6.3 for the EU-15. For all other countries no utilization of energy from recovered landfill gas is assumed. Recovered gas that is not utilized as energy is assumed to be flared.

Table 6.3: Share of recovered methane (CH_4) gas utilized. Assumptions based on capacity rates specified in AEAT (2001b, p.46).

Country	*Gas recovery capacity (MW)*		*Assumed share of recovered gas utilized*	
	1996	*2010*	*1995*	*2010*
Austria	10	2	5.9 %	2.3 %
Belgium	2	27	0.5 %	13.9 %
Denmark	10	23	0.21 %	0.94 %
Finland	0	11	0 %	4.9 %
France	20	69	1.7 %	11.2 %
Germany	170	286	8.3 %	27.9 %
Greece	0	12	0 %	3.9 %
Ireland	12	11	7.3 %	8.5 %
Italy	10	160	0.4 %	8.4 %
Luxembourg	0	1	0 %	12.4 %
Netherlands	120	100	48.3 %	77.2 %
Portugal	0	2	0 %	0.8 %
Spain	5	27	0.3 %	2.3 %
Sweden	49	20	26.7 %	21.6 %
UK	145	589	4.8 %	25.4 %

The provisions of the Landfill Directive are reflected in the CLE scenario for composting and incineration of municipal organic waste. Current shares of municipal solid waste composted were derived for the the EU-15, Switzerland and Norway from AEAT (2001b, p.1), Umwelt Schweiz (2002), Statistics Norway (2003). For all other countries, no composting of municipal solid waste is assumed to take place in the base year. These levels of landfilled organic waste have been applied as a baseline for the reduction targets set out in the Landfill Directive. Organic waste that is not composted is assumed to be either incinerated or landfilled.

Shares of incinerated and landfilled waste are based on the waste treatment routes for municipal solid waste presented in AEAT (2001b, p.1), Umwelt Schweiz (2002), and Statistics Norway (2003). As for landfilled paper waste, application rates for landfill control options were adopted assuming that requirements to equip all landfill sites with gas recovery facilities set out in the Landfill Directive are met. In addition, country-specific shares of CH_4 recovered from landfills in 1990 for the EU-15 (AEAT 1998, p.82) have been considered, as well as the national requirements on landfill gas recovery specified in AEAT (2001b, p.43). For the new Member States, no gas recovery units are reported up to 2005. However, they need to fulfil the requirements set out in the Landfill Directive by 2009. For all other countries, no gas recovery is assumed in the CLE case. The shares of recovered gas that is utilized or flared were calculated using the same assumptions as for paper waste.

Livestock

The current legislation projection assumes the option “increased feed intake” to be implemented already for stall fed dairy cows in Western Europe. For Eastern Europe, countries with an average milk production of less than 4 ton/cow/year (see Table 4.4) are assumed to still have the potential to apply the option to stall fed cows. For non-dairy cattle, the option is assumed to form part of current legislation for all stall fed cattle in the EU-15, Norway, Switzerland, Cyprus and Malta, but not in the other regions.

In a similar way, “change to a NSC diet” is assumed to be part of ongoing practices for stall fed dairy cows in EU-15, Norway and Switzerland (ECCP, 2003, Annex II).

Replacement of roughage for concentrates is part of the current legislation projection for stall fed cows and non-dairy cattle in EU-15, Norway and Switzerland.

No application of propionate precursors is assumed in the current legislation case.

Sewage treatment

Integrated sewage treatment with aerobic treatment represents current practice in all EU-15 countries. For the new EU Member and Candidate countries, Eurostat (2003) has provided data on the share of the residential population connected to public wastewater treatment system in 2000. This has been used as a measure of the extent of current wastewater treatment (Table 6.4). For Latvia and Lithuania, the fraction reported for Estonia is assumed (i.e., 69 percent). Albania, Belarus, Russia, Romania, the former Yugoslav Republics, Moldavia, and Ukraine were assumed to have the same fraction of the urban population connected to a public wastewater treatment scheme as Bulgaria (i.e., 37 percent).

Wastewater treatment is regulated primarily through the adoption of the Council Directive (91/271/EEC) of 21 May 1991 and the amendment by the Commission Directive (98/15/EC) of 27 February 1998. These directives require from 1999 all Member States to have wastewater facilities available for all urban areas with a population over 10,000 people and where the effluents are discharged into sensitive areas. The directives also stipulate that by the end of 2000 wastewater treatment facilities are required for all urban areas with a population over 15,000 people.

Finally, the directives state that by the end of 2005, a collection and treatment system must be provided in all urban areas with a population between 2,000 and 15,000 people (European Commission, 2004), applying also to the New Member states. New Member countries are assumed to fulfil the requirements set out in the Wastewater Directives (i.e., application of integrated systems in urban areas will increase to 100 percent by 2005). In the CLE case, no further application of integrated systems is assumed outside the EU-25, and no application of gas recovery and utilization from wastewater handling is assumed.

Table 6.4: Share of the residential population connected to a public wastewater treatment system in 2000 in the EU Accession Candidate countries.

Country	*Percent of residential population connected to public wastewater treatment in 2000*
Bulgaria	37 %
Cyprus	35 %
Czech Rep.	64 %
Estonia	69 %
Hungary	32 %
Latvia	n.a. (69 %)
Lithuania	n.a. (69 %)
Malta	13 %
Poland	53 %
Romania	n.a.
Slovak Rep.	49 % (1998)
Slovenia	30 % (1999)
Turkey	17 % (1998)

Source: Eurostat (2003, p.199)

Coal mines

The current legislation case assumes the present rates of methane capture and utilization to prevail in the future, and no further autonomous improvements are assumed.

Gas flaring

AEAT (1998, p.30) assumes in their business-as-usual projection flaring undertaken on a voluntary basis and fully implemented by 2010 in the EU-15. This assumption is based on information about the situation in the two major oil and gas producing countries in the EU-15, i.e., the Netherlands and the UK. In these countries, oil and gas producing companies have implemented various measures to recover and utilize methane. In the Netherlands, such measures are estimated to reduce CH_4 emissions from on- and off-shore oil and gas production by 30 percent in the year 2000 compared with the 1990 level.

In the current legislation (CLE) case, no control measures are assumed to be applied in the gas and oil production sectors for non-EU-15 countries. For EU-15, a 30 percent reduction from the 1990 level is assumed to take place between 1990 and 2000, and to continue until 100 percent in 2010, even in absence of any further legal requirements. These autonomous reductions are reflected by the lower emission factor for Western Europe.

Gas distribution

For 1990, no mitigation measures for reduction CH_4 losses from gas distribution are reported for the entire model domain. Since then, targeted network improvements have been implemented at distribution networks in Austria, France, Germany, Ireland, Italy, Netherlands, and the UK (AEAT, 1998; p.131). Assuming a replacement rate of the old networks of three percent per year (i.e., the current replacement rate in Ireland) and starting from 1995, emissions from this source are assumed to be successively reduced until the networks will be fully replaced by 2030. For 50 percent of non-replaced networks, the control frequency is assumed to be doubled in these countries.

Pipelines in the Former Soviet Union are assumed to be refurbished at a rate of one percent per year starting from year 2000. This corresponds to the share of pipeline length refurbished in Russia in the year 2002 (Gazprom Annual Report, 2002). No control of leakages of emissions from residential and industrial consumer networks is assumed in the CLE case.

Burning of agricultural waste

The current legislation case considers the ban on open burning of agricultural waste as specified in national legislations in the Czech Republic, Denmark, Finland, France, Germany, Ireland, Luxembourg, the Netherlands, Spain, Sweden and the UK.

6.2.3 Emissions in 2020 for the current legislation scenario

With the assumptions on the implementation of the measures described above, the GAINS Version 1.0 model projects CH_4 emissions in the model domain to decline between 1990 and 2020 by 20 percent (Table 6.5). In 2020, the largest share of anthropogenic CH_4 emissions is expected to originate from the gas sector (36 percent), followed by agriculture (32 percent), waste (16 percent) and coal mining (11 percent) (Figure 6.3).

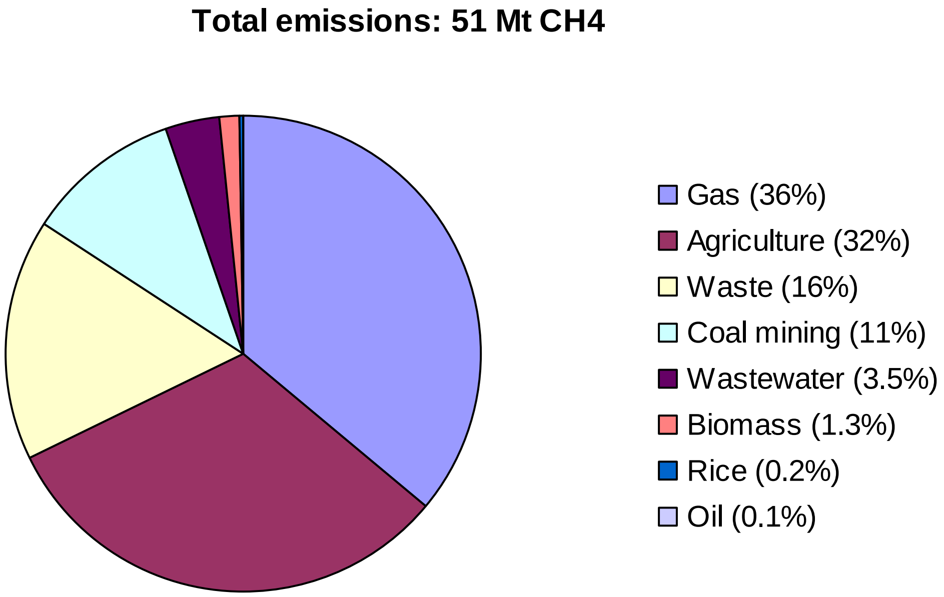

Figure 6.3: Sectoral contribution to methane (CH_4) emissions for the current legislation (CLE) case in the year 2020 for GAINS model domain.

Table 6.5: GAINS estimates of methane (CH_4) emission calculation for 1990 and 2020 for the "Current Legislation" (CLE) and "Maximum reduction" (MTFR) cases [kt CH_4]

Country	*1990*	*Current legislation (CLE) 2020*	*Maximum reduction scenario (MTFR) 2020*
Albania	165	199	121
Austria	392	327	289
Belarus	908	748	379
Belgium	506	512	366
Bosnia-H.	175	169	80
Bulgaria	476	347	173
Croatia	190	257	120
Cyprus	25	26	20
Czech Rep.	1,247	576	358
Denmark	302	328	225
Estonia	127	51	31
Finland	314	214	179
France	2,574	2,060	1,788
Germany	4,243	2,523	2,115
Greece	462	397	303
Hungary	724	407	237
Ireland	564	519	443
Italy	2,189	1,735	1,357
Latvia	197	69	47
Lithuania	308	138	90
Luxembourg	27	28	20
Macedonia	91	101	57
Malta	10	7	6
Moldavia	224	215	105
Netherlands	964	740	525
Norway	247	258	143
Poland	2,551	1,609	1,029
Portugal	369	344	249
Romania	2,241	1,856	1,186
Russia – Kaliningrad	72	60	27
Russia - Kola-K.	151	151	38
Russia - Remaining European area	24,480	20,281	6,757
Russia – St. Petersburg	377	305	118
Serbia-M.	522	563	290
Slovakia	342	196	102
Slovenia	120	80	51
Spain	1,807	1,729	1,226
Sweden	331	289	246
Switzerland	280	291	203
Turkey	2,727	3,463	1,892
Ukraine	5,711	4,918	2,415
UK	3,403	1,879	1,498
Total model domain	63,138	50,962	26,904
CO_2-eq, Mton	1,326	1,070	565
EU-25	24,099	16,781	12,800
CO_2-eq, Mton	506	352	269

In the EU-25, anthropogenic CH_4 emissions are computed to decline by 30 percent between 1990 and 2020 for the current legislation case. Largest reductions are expected to take place for gas distribution and waste treatment, so that in 2020, agriculture, where a smaller mitigation potential exists, will gain the dominating share (49 percent) of methane sources.

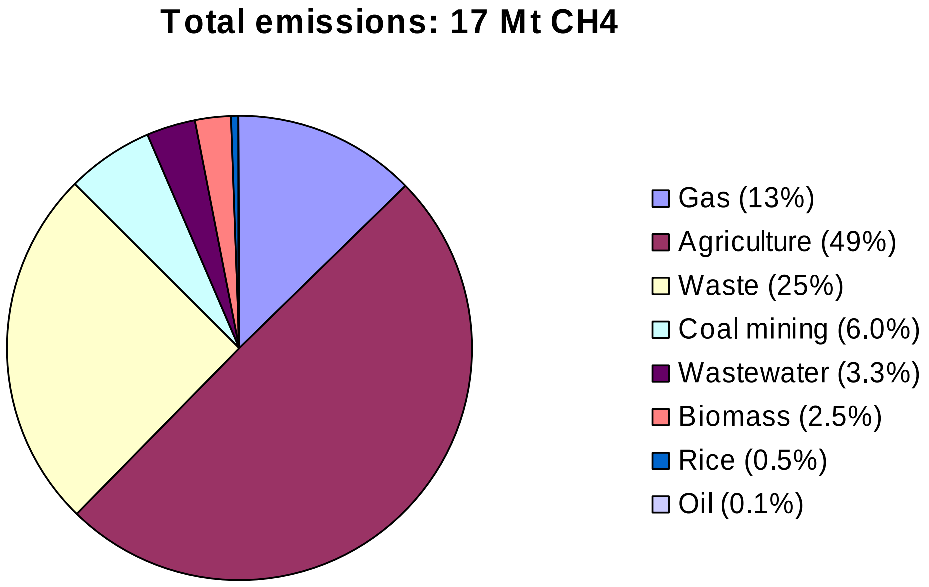

Figure 6.4: Sectoral contributions to methane (CH_4) emissions for the current legislation (CLE) case in the year 2020 for the EU-25.

6.2.4 Mitigation potential from the maximum application of the options

This case is also known as the maximum technically feasible reduction (MTFR) scenario. With maximum application of the technical control measures that are considered in GAINS Version 1.0, CH_4 emissions could be reduced in 2020 by 53 percent below 1990 emission level (Table 6.5). The largest technical potentials for further reductions exist in the gas and waste sectors (see Figure 6.5 and Table 6.6).

Important control options include measures to reduce leakages from gas pipelines (mainly in Russia) and to increase the diversion of biodegradable waste from landfills. There is only little potential for further emission reductions in the agricultural sector. For the EU-25, maximum application of the measures in the GAINS database could reduce CH_4 emissions by 2020 by 47 percent, mainly through further measures in the gas and agriculture sectors (Figure 6.6).

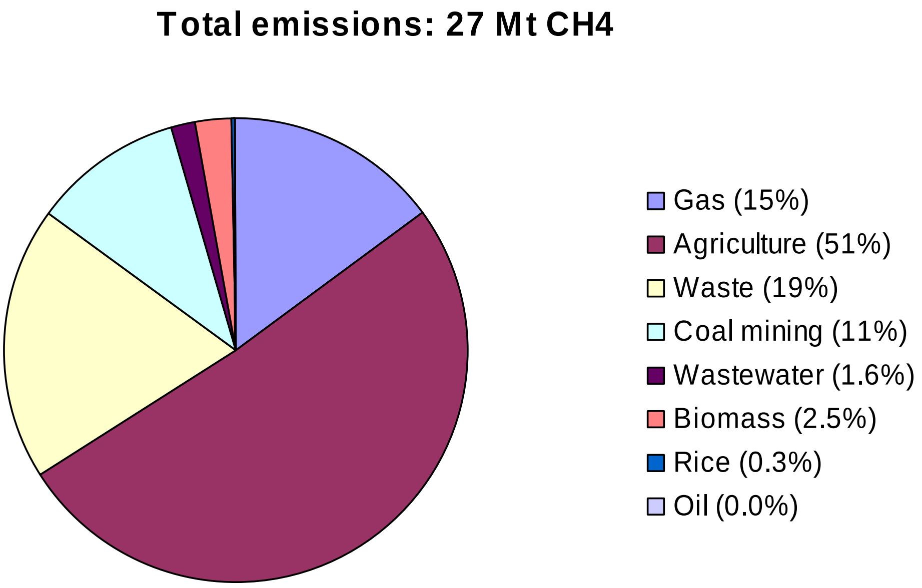

Figure 6.5: Sectoral contributions to methane (CH_4) emissions for the maximum application (MTFR) case in the year 2020 for the European model domain.

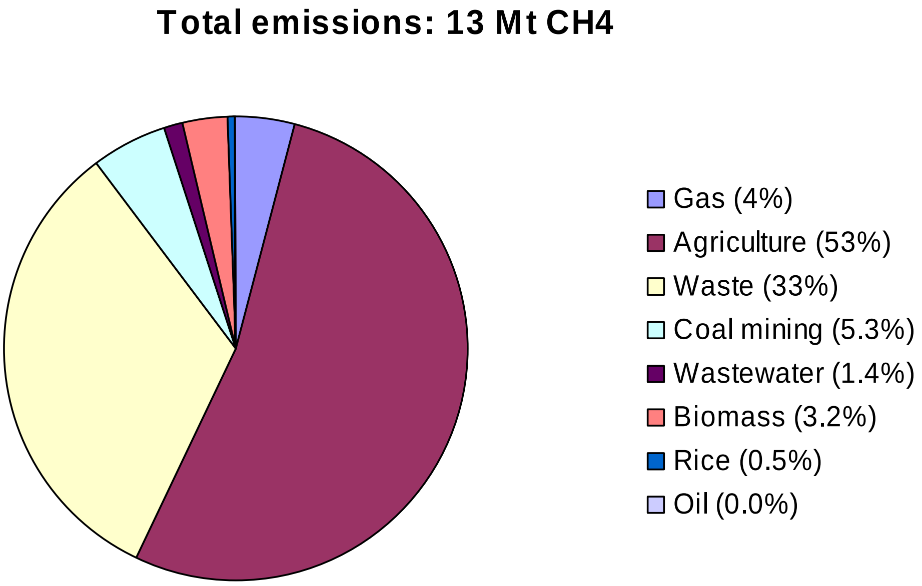

Figure 6.6: Sectoral contributions to methane (CH_4) emissions for the maximum application (MTFR) case in the year 2020 for the EU-25.

Table 6.6: Sectoral changes in methane (CH_4) emissions in the entire GAINS model domain: (a) between 1990 and the current legislation (CLE) case in 2020, and (b) between 1990 and the maximum technically feasible reductions (MTFR) case in 2020 [kt CH_4/year].

Sector	*Emission change between 1990 and 2020 with current legislation (CLE)*	*Maximum technically feasible emission reductions between 1990 and 2020 (MTFR)*
Agriculture	-4016	-6517
Biomass	+49	+49
Gas	-2757	-17061
Coal mining	-3177	-5754
Oil	+2	-60
Rice cultivation	+10	-20
Biodegradable solid waste	-2185	-5400
Wastewater	+100	-1470
Total	-12176	-36234

Table 6.7: Sectoral changes in methane (CH_4) emissions in the EU-25: (a) between 1990 and the current legislation (CLE) case in 2020, and (b) between 1990 and the maximum technically feasible reductions (MTFR) case in 2020 [kt CH_4/year].

Sector	*Emission change between 1990 and 2020 with current legislation (CLE)*	*Maximum technically feasible emission reductions between 1990 and 2020 (MTFR)*
Agriculture	-2153	-3644
Biomass	+103	+103
Gas	+251	-1384
Coal mining	-3138	-3463
Oil	-3	-23
Rice cultivation	0	-21
Biodegradable solid waste	-2288	-2396
Wastewater	-90	-471
Total	-7318	-11300

Table 6.8: Sectoral changes in methane (CH_4) emissions in the EU-15: (a) between 1990 and the current legislation (CLE) case in 2020, and (b) between 1990 and the maximum technically feasible reductions (MTFR) case in 2020 [kt CH_4/year].

Sector	*Emission change between 1990 and 2020 with current legislation (CLE)*	*Maximum technically feasible emission reductions between 1990 and 2020 (MTFR)*
Agriculture	-1255	-2620
Biomass	+83	+83
Gas	-34	-965
Coal mining	-1980	-2052
Oil	-3	-23
Rice cultivation	0	-20
Biodegradable solid waste	-1660	-1753
Wastewater	+24	-269
Total	-4825	-7619

Table 6.9: Sectoral changes in methane (CH_4) emissions in the EU-15: (a) between 1990 and the current legislation (CLE) case in 2010, and (b) between 1990 and the maximum technically feasible reductions (MTFR) case in 2010 [kt CH_4/year].

Sector	*Emission change between 1990 and 2020 with current legislation (CLE)*	*Maximum technically feasible emission reductions between 1990 and 2020 (MTFR)*
Agriculture	-820	-1978
Biomass	+79	+79
Gas	+144	-1102
Coal mining	-1728	-1889
Oil	+3	-23
Rice cultivation	0	-20
Biodegradable solid waste	-1862	-2034
Wastewater	+23	-269
Total	-4161	-7235

For 2020, the GAINS Version 1.0 baseline projection attributes for the EU-25 an emission decline of 7,300 kt to the implementation of current legislation (Table 6.7). These reductions emerge primarily from productivity increases in the agricultural sector, from the decreasing amount of coal production, and from the provisions of the Landfill Directive.

The GAINS baseline projection has been compared with the assessments performed in 1998 by ECOFYS (Hendriks *et al.*, 1998) and AEAT (1998). Since these estimates are not available for all countries, only the estimates for the EU-15 are compared here. Table 6.10 reveals larger emission reductions for the GAINS projection compared to the study by AEAT. This more optimistic GAINS estimate is to a large extent related to the Landfill Directive, which is included in the GAINS projection, but was not considered by the assessment of AEAT in 1998 (1998, p.156). At that time, the AEAT study did not assume changes in landfilling practices, so that the fraction of waste that is disposed of to landfills in 1990 was assumed constant until 2010. Excluding the emission changes in the solid waste sector, GAINS projects a 18 percent reduction from the other sources, which is still higher than the AEAT estimate (9 percent), but lower than the reduction estimated by ECOFYS (26 percent).

Table 6.10: Comparison of changes in methane (CH_4) emissions between 1990 and 2010 for the EU-15 from different sources [kt CH_4].

	GAINS		*ECOFYS*		*AEAT*	
	CLE	*MTFR*	*CLE*	*MTFR*	*CLE*	*MTFR*
1990	18,451		23,742		23,349	
2010	14,287	11,213	17,338	11,386	21,348	16,153
Change 1990-2010	-23 %	-39 %	-26 %	-50%	-9 %	-31 %

6.3 Costs estimates

6.3.1 Unit costs of mitigation

Table 6.11 summarizes the cost estimates for the CH_4 mitigation options considered in GAINS Version 1.0. The available control options are ranked by their average cost expressed as the mean over all years and all countries. Negative costs are calculated for five control measures. These are the increased feed intake or a replacement of roughage for concentrates for dairy cows in Eastern Europe, paper recycling, upgrade of the recovery and utilization of gas from coal mines, and recovery and utilization of gas from landfills that are already capped.

All cost estimates involve uncertainties. Most often, estimates are based on a small number of data source reporting cost estimates for a single or a very small number of actual installations. Although GAINS Version 1.0 has adjusted such reports for differences, e.g., in prices and wages between countries, still large uncertainties remain. For some options, no case studies exist and estimates are instead based on references from the literature. Fur such options no cost range is specified.

In Table 6.12, emission reduction potentials in 2020 and costs are specified for each control option. GAINS estimates that reductions of 24,000 kt/year are possible in 2020 on top of reductions that can be expected from current legislation. The total cost of these reductions is about 14,000 € per year. Reductions of about 18,000 kt per year are possible at a total cost of about 1.5 billion € per year or less than 1,050 €/t CH_4 (or 50 €/t CO_2-equiv.). An additional reduction of about 6,000 kt CH_4/year can be achieved at a total cost of 12 billion €/year.

Table 6.11: Unit costs of the control options considered in GAINS (mean of all countries and for the years 1990-2030).

Control option	*GAINS*	*Costs [€/t CH_4]*	
	acronym	*Mean*	*Range*
Ent. ferm: Repl. roughage for concentrates –dairy cows E.Europe	CONCENTR	-6,194	-13,061 to -1,856
Ent. ferm: Increased feed intake –dairy cows E.Europe	INCRFEED	-4,615	-11,754 to -104
Waste: Paper recycling	PAP_REC	-445	-1,645 to 2,280
Waste: utilization of gas from paper waste deposited on capped landfill	PAP_USE1	-70	-133 to -4
Waste: utilization of gas from organic waste deposited on capped landfill	ORG_USE1	-70	-133 to -4
Coal mining: Upgraded gas recovery and utilization	CH4_REC	-5	-115 to 111
Ent. ferm: Autonomous efficiency increase in milk and meat prod.	AUTONOM	0	no range
Manure management: Farm-scale AD –pigs/temperate	FARM_AD	17	8 to 30
Waste: flaring of gas from paper waste deposited on capped landfill	PAP_FLA1	23	22 to 28
Waste: flaring of gas from organic waste deposited on capped landfill	ORG_FLA1	23	22 to 28
Gas transmission –Reduction at compressor stations in FSU	COMPRESS	27	-3 to 48
Waste: Paper incineration	PAP_INC	31	-11 to 95
Manure management: Farm-scale AD –dairy cows/temperate	FARM_AD	33	16 to 58
Manure management: Farm-scale AD –beef cattle/temperate	FARM_AD	43	21 to 76
Rice cultivation: Alternative rice strains	ALT_RICE	47	No range
Manure management: Farm-scale AD –pigs/cool	FARM_AD	81	33 to 129
Oil and gas: Flaring instead of venting –onshore refinery	FLA_REF	81	73 to 100
Oil and gas: Flaring instead of venting –onshore production	FLA_PROD	81	73 to 100
Waste: capping of landfill *and* utilization of gas from paper waste	PAP_USE2	130	68 to 194
Waste: capping of landfill *and* utilization of gas from organic waste	ORG_USE2	130	68 to 194
Manure management: Farm-scale AD –dairy cows/cool	FARM_AD	139	57 to 223
Manure management: Farm-scale AD –beef cattle/cool	FARM_AD	184	76 to 294
Waste: biogasification of organic waste	ORG_BIO	193	91 to 395
Waste: landfill capping of paper waste	PAP_CAP	200	198 to 203
Waste: landfill capping of organic waste	ORG_CAP	200	198 to 203
Wastewater: Gas recovery and utilization	GAS_USE	207	139 to 277
Waste: composting of organic waste	ORG_COMP	210	135 to 372
Waste: capping of landfill *and* flaring of gas from paper waste	PAP_FLA2	223	220 to 230
Waste: capping of landfill *and* flaring of gas from organic waste	ORG_FLA2	223	220 to 230
Oil and gas: Flaring instead of venting –offshore production	FLA_PROD	232	220 to 241
Gas distribution: Doubling leak control frequency E. Europe	CONT_NET	258	117 to 679
Waste: Organic waste incineration	ORG_INC	322	216 to 481
Agricultural waste burning: Ban	BAN	500	No range
Enteric fermentation: Propionate precursors –dairy cows	PROPPREC	527	No range
Gas distribution: Doubling leak control frequency W. Europe	CONT_NET	891	248 to 1,394
Enteric fermentation: Propionate precursors –beef cattle	PROPPREC	1,100	No range
Gas distribution: Replacement grey cast iron networks W. Europe	REPL_NET	1,869	1,756 to 1,970
Gas distribution: Replacement grey cast iron networks E. Europe	REPL_NET	1,897	1,791 to 2,016
Enteric ferm.: Change to NSC diet –dairy cows E. and W. Europe	NSCDIET	1,945	1,607 to 2,293
Enteric ferm: Change to NSC diet –beef cattle E. and W. Europe	NSCDIET	3,963	301 to 5,154
Enteric ferm: Repl. roughage for concentr. –beef cattle E. Europe	CONCENTR	4,475	-2,214 to 7,378
Enteric ferm: Increased feed intake –beef cattle E. Europe	INCRFEED	7,698	151 to 10,972
Manure management: Housing adaptation –pigs/liquid manure	HO_ADAP	38,150	9,400 to 66,900
Wastewater: Integrated sewage system	INT_SYS	> 1M	No range

Table 6.12: Costs and emission reductions for individual CH4 mitigation measures in the entire model domain (42 regions) in 2020.

Control option	GAINS technology abbrev.	Marginal cost [€/t CH_4]	Emissions abated[a] (kt CH_4)	Total cost[b] (M€/yr)	Incremental mitigation (MFR) on top of CLE [kt CH_4]	Incremental costs on top of CLE [M€/year]
Baseline (CLE) emissions 1990					63,573	
Current legislation emission level (CLE)					50,962	0
Enteric ferm: Increased feed intake –dairy cows	INCRFEED	-13,006	0	0	65	-220
Enteric ferm: Repl. roughage for concentrates –dairy cows	CONCENTR	-12,268	0	0	62	-313
Enteric ferm: Repl. roughage for concentrates –beef cattle	CONCENTR	-547	0	0	28	116
Coal mining: Upgraded gas recovery and utilization	CH4_REC	-38	2,328	7	2,578	70
Gas transmission –Reduction at compressor stations in FSU	COMPRESS	-31	1,984	77	7,935	306
Waste: Paper recycling	PAP_REC	3	10,661	393	503	29
Waste: Paper incineration	PAP_INC	23	1,566	67	1,402	53
Rice cultivation: Alternative rice strains	ALT_RICE	47	0	0	29	1
Manure management: Farm-scale AD –pigs	FARM_AD	57	0	0	816	42
Oil refinery: Flaring instead of venting	FLA_REF	81	0	0	2	0
Oil production: Flaring instead of venting	FLA_PROD	95	0	0	61	12
Gas production: Flaring instead of venting	FLA_PROD	95	0	0	1,303	118
Manure management: Farm-scale AD –dairy cows	FARM_AD	99	0	0	188	21
Waste: capping of landfill *and* utilization of gas from paper waste	PAP_USE2	113	362	42	-362[c]	0
Waste: capping of landfill *and* utilization of gas from organic waste	ORG_USE2	113	264	31	-264[c]	0
Manure management: Farm-scale AD –beef cattle	FARM_AD	131	0	0	175	24
Waste: biogasification of organic waste	ORG_BIO	188	0	0	2,417	515
Wastewater: Gas recovery and utilization	GAS_USE	189	0	0	296	52
Waste: landfill capping of paper waste	PAP_CAP	200	2	0	-2[c]	0
Waste: landfill capping of organic waste	ORG_CAP	200	13	3	-13[c]	0
Waste: composting of organic waste	ORG_COMP	210	2,255	613	1,737	270
Waste: capping of landfill *and* flaring of gas from paper waste	PAP_FLA2	223	756	171	-756[c]	0
Waste: capping of landfill *and* flaring of gas from organic waste	ORG_FLA2	223	769	173	-769[c]	0
Waste: Organic waste incineration	ORG_INC	301	680	248	-680[c]	0
Agricultural waste burning: Ban	BAN	500	0	0	0.04	0.02
Gas distribution: Doubling leak control frequency	CONT_NET	508	200	184	571	177
Enteric fermentation: Propionate precursors –dairy cows	PROPPREC	527	0	0	498	262
Enteric fermentation: Propionate precursors –beef cattle	PROPPREC	1,100	0	0	235	258
Enteric ferm: Increased feed intake –beef cattle	INCRFEED	1,566	0	0	28	205
Enteric ferm.: Change to NSC diet –dairy cows	NSCDIET	1,845	0	0	172	197
Gas distribution: Replacement grey cast iron networks W. Europe	REPL_NET	1,852	1,128	2,078	4,495	8,551
Enteric ferm: Change to NSC diet –beef cattle	NSCDIET	3,958	0	0	168	568
Manure management: Housing adaptation –pigs/liquid manure	HO_ADAP	38,150	0	0	67	2,539
Wastewater: Integrated sewage system	INT_SYS	> 1M	101	101,294	719	718,652
Sum of emission reduction and costs			23,068	105,381	24,058	732,582
Sum when methane mitigation costs for integrated sewage treatment set to zero.			23,068	4,087	24,058	13,930

[a] Reductions compared to a completely unabated situation, i.e. reductions in place already in 1990 also included.

[b] Costs for total reductions including reductions in place already in 1990.

[c] Additional emissions reductions are negative, because the application of these control options in the current legislation case (CLE) are substituted for other options in order to attain the maximum feasible reduction case.

6.3.2 Cost estimates for individual countries

For each country, costs for implementing the "current legislation" as well as for applying all measures contained in the GAINS Version 1.0 database can be estimated by combining the unit costs presented above with the country-specific application factor.

With unit costs given in

Table 6.11 and the interpretation of which measures are included in national legislation, national mitigation costs are presented in Table 6.13 for the current legislation (CLE) and the maximum application (MTFR) cases for the year 2020. As mentioned before, these estimates do not consider side impacts from other emission control measures directed at other pollutants, and consequently do not include such costs.

Overall, the CLE costs are estimated at 4 billion €/year, while the GAINS Version 1.0 databases hold further measures at total costs of 14 billion €/year, which could reduce twice as much CH_4 emissions.

Table 6.13: GAINS Version 1.0 estimates of national emission reductions and mitigation costs for methane (CH_4) for the year 2020.

	Emission reduction CLE[a] [kt CH_4]	Cost CLE[b] [mio €/year]	Emission reduction MTFR additional to CLE [kt CH_4]	Cost of measures MTFR in addition to CLE [mio €/year][c]
Albania	4	0.3	78.1	35.1
Austria	442	87.8	37.5	117.0
Belarus	15	1.0	368.9	377.4
Belgium	680	88.4	145.6	275.2
Bosnia- Herzegov.	6	0.3	88.6	42.3
Bulgaria	16	-1.1	173.9	98.9
Croatia	10	0.6	137.0	73.4
Cyprus	18	0.7	6.1	11.7
Czech Republic	473	-22.0	218.4	223.5
Denmark	243	31.9	102.4	178.0
Estonia	24	-0.1	19.7	25.7
Finland	324	59.7	35.4	87.3
France	2,210	542.3	271.7	383.5
Germany	3,962	979.4	408.6	830.9
Greece	342	13.3	93.3	93.9
Hungary	281	-2.0	169.4	220.9
Ireland	148	55.4	76.6	83.8
Italy	2,441	690.9	378.3	381.6
Latvia	37	1.5	22.5	28.5
Lithuania	49	2.1	47.5	66.0
Luxembourg	31	4.7	8.1	14.4
Macedonia	4	0.0	44.5	24.1
Malta	11	0.2	1.1	1.9
Moldova	6	0.4	110.3	91.7
Netherlands	898	381.8	214.5	309.7
Norway	171	24.2	114.7	100.6
Poland	1,205	-43.0	579.7	470.4
Portugal	256	3.0	94.6	171.4
Romania	22	-1.5	669.9	443.6
Russia-Kaliningr.	1	0.1	32.6	35.2
Russia-Kola-K	8	0.6	112.8	53.8
Remaining Russia	3,079	133.8	13,523.9	4,358.4
Russia-St.Petersb.	4	0.3	186.7	245.0
Serbia-Monten.	45	-0.9	273.2	89.9
Slovakia	135	-0.2	93.4	131.3
Slovenia	57	2.6	29.1	46.9
Spain	1,610	140.9	502.8	864.0
Sweden	394	54.7	43.6	87.5
Switzerland	242	37.5	88.6	96.1
Turkey	108	0.9	1,570.9	477.1
Ukraine	513	23.3	2,502.5	1756.0
UK	2,543	793.7	381.1	426.6
Total	23,068	4,087	24,058	13,930

[a] Reductions in 2020 compared with unregulated emission level, i.e. including emission reductions present already in 1990.

[b] Costs in 2020 include costs for reductions in place already in 1990.

[c] Costs assume a zero cost for methane mitigation from extended integrated sewage treatment.

6.3.3 Cost functions

The relation between emission control costs and the associated emission control potentials can be displayed in form of cost functions. Cost functions are specific to each source region reflecting the different relative contributions from the different emission sources. Figure 6.7 presents such cost functions for the European part of Russia, France and Turkey for the year 2020, showing the measures that remain after implementation of the current legislation. These curves present for different levels of emission reductions (relative to the emissions in the year 1990) marginal abatement costs in €/t CO_2–equivalent.

For Russia and France, cost curves start from levels below the 1990 emissions, while Turkey starts from higher emissions than 1990. For France, reductions due to a phase out of coal mining, improved gas distribution networks, and compliance with the Landfill Directive are accounted for in the CLE. Further limited reduction potentials exist in the agricultural sector and from gas distribution. For Russia, main reductions in CLE result from falling livestock numbers and a limited refurbishing of gas transmission pipelines. Further reduction potentials are possible through more extensive improvements of gas transmission pipelines, upgraded gas recovery from coal mining, and from the waste and wastewater sectors. The increase in Turkish methane emissions in 2020 is expected to come primarily from increased gas use and from increasing amounts of landfilled waste and wastewater. Technically feasible additional reductions are possible primarily from the same sectors.

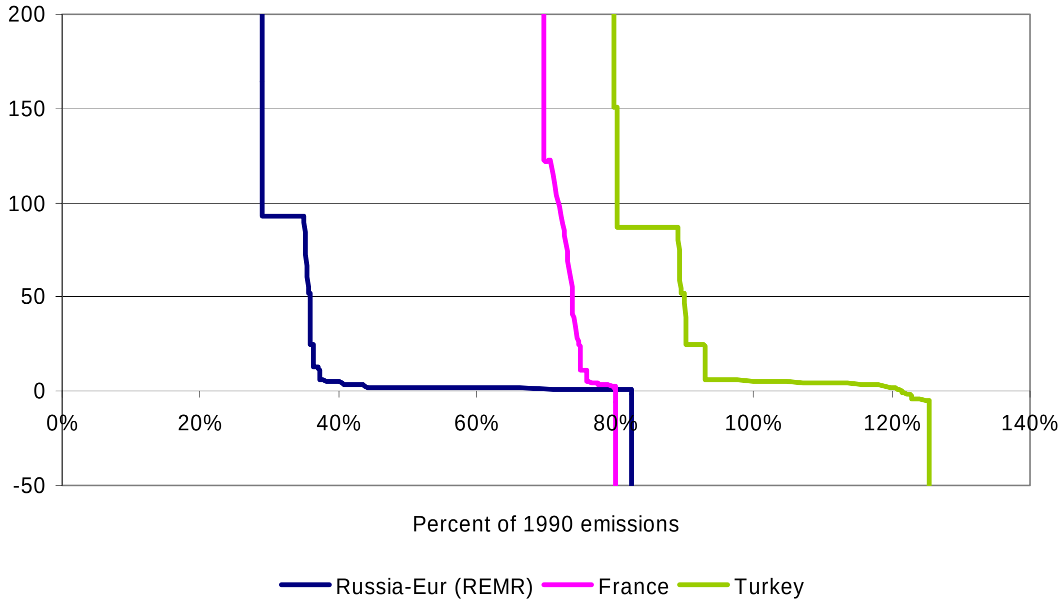

Figure 6.7: National cost curves for methane (CH_4) mitigation for the year 2020 for Russia, France and Turkey. These curves present marginal abatement costs (€/t CO_2–equivalent) in relation to the emission levels in the year 1990.

Table 6.14 presents an example of a country-specific cost-function. In this case, the underlying information for the Czech Republic is presented, but similar cost functions are available for all regions. At maximum, full application of the GAINS measures (MTFR case) would achieve a reduction of more than 218 kt out of totally 473 kt CH_4. Only three options are available at moderate costs (i.e., at less than 3,000 €/t CH_4, which is about 12 €/t CO_2-eq.). Still, these three options cover more than one third of the total mitigation potential.

Table 6.14. Costs and emission reductions for individual CH_4 mitigation measures in the Czech Republic in 2020.

		Unit costs [€/t CH_4]	Emissions abated [kt CH_4]	Total costs [M €/yr]	Incremental abatement [kt CH_4]	Incremental costs [M €/year]
Enteric fermentation	Dairy cows: switch to concentrate feed	-12,644	0	0	0.5	-6.4
Solid waste	Paper recycling	-154	155	-24.0	0.1	-0.0
Coal mining	Methane recovery and use	-86	189	-16.2	76	-6.4
Solid waste	Paper incineration	0.6	25	0	16	0.0
Manure management	Pigs: Farm-scale AD	43	0	0	11	0.5
Manure management	Dairy cows: Farm-scale AD	74	0	0	0.9	0.1
Oil production	Flaring	77	0	0	0.0	0.0
Gas production	Flaring	77	0	0	1.0	0.1
Oil refinery	Flaring	77	0	0	0.0	0.0
Manure management	Beef cattle: Farm-scale AD	98	0	0	0.5	0.0
Solid waste	Biogasification of organic waste	130	0	0	29	3.7
Wastewater	Gas recovery and use	167	0	0	12	2.0
Solid waste	Large-scale composting of organic waste	167	51	9	0.8	0.1
Solid waste	Landfill gas recovery with flaring	221	44	3	-43.6	0
Gas distribution	Increased control frequency of network	283	0	0	12.9	3.6
Enteric fermentation	Dairy cows: proprionate precursors	527	0	0	2.5	1.3
Enteric fermentation	Beef cattle: proprionate precursors	1100	0	0	1.3	1.5
Gas distribution	Replacement of grey cast iron networks	1815	0	0	94.0	170.6
Enteric fermentation	Dairy cows: switch to NSC-diet	2,874	0	0	0.4	1.3
Enteric fermentation	Beef cattle: switch to NSC-diet	4,606	0	0	2.5	11.6
Manure management	Pigs: Stable adaptation	38,150	0	0	1.0	39.9
Wastewater	Integrated sewage treatment	>1 M	8.4	8,392	0	0

7 Conclusions

GAINS Version 1.0 assesses present and future emissions of methane (CH_4) from anthropogenic sources in Europe and estimates the available potential for mitigation and the associated costs. From the first implementation, the following conclusions can be drawn:

- Highest CH_4 emissions in Europe are estimated from the production and distribution of natural gas. While for all of Europe these sources contribute approximately one third to total emissions, Russian emissions alone account for some 25 percent of total European CH_4 emissions.
- The second largest source of CH_4 emissions relates to agricultural activities. In the EU-25, agriculture is estimated to contribute 43 percent to total CH_4 emissions. Other important contributors are waste treatment and coal mining.
- Continuing autonomous improvements in agricultural productivity coupled with livestock reductions in milk production and progressing implementation of European legislation on waste landfills are expected to lead to lower CH_4 emissions in the coming decades. Additional factors that will lead to lower CH_4 emissions in the future are improved gas distribution networks and lower coal production in Western Europe. For the entire model domain, the baseline emission projections suggests for 2020 a resulting decline in CH_4 emissions of 20 percent, while stricter legislation in the EU-25 is expected to reduce CH_4 emissions by 30 percent.
- There exist a number of mitigation options to reduce emissions of CH_4 at all sources. Further emission reductions would be technically feasible through, in particular, reduced gas leakages from gas transmission pipelines and distribution networks, extended waste diversion and higher landfill standards in non-EU countries. However, there is only a little potential for further reductions in emissions from enteric fermentation and manure management in the agricultural sector.
- For some of these mitigation options, comparably low costs are calculated. In addition to the “current legislation”, the GAINS Version 1.0 assessment identifies measures that could further reduce European CH_4 emissions in 2020 by 17 million tons of CH_4 (i.e., by one third of the baseline level) at marginal costs below 20 €/t CO_2-equivalent.
- The remaining mitigation potential (on top of current legislation) is associated with higher costs. However, since some of these options address other critical issues at the same time (e.g., treatment of wastewater), they might materialize in the future.

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