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METHANE
THE OTHER GREENHOUSE GAS
research and policy in the Netherlands

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SUMMARY

The increase in greenhouse gases in the atmosphere leads to an increase in radiative forcing, with a possible effect on global climate. Methane is one of these greenhouse gases, the most important next to carbon dioxide. The methane concentration in the atmosphere has more than doubled (from 800 to 1720 ppbv) since the industrial revolution. During the eighties the increase slowed down. The global average increase was 12-14 ppbv per year in 1983 and 9-10 ppbv per year in 1990. The reason for this is still unclear, but is mainly attributed to an increase in OH radicals, at least over parts of the Earth's surface, causing methane to oxidize faster in these parts.

Methane is formed by geothermogenic processes in fossil organic material covered by sediments (fossil methane). With the exploitation, transport and distribution of coal, oil and gas this fossil methane escapes to the atmosphere. Incomplete burning of wood and fossil fuels is another source of methane. Methane is also formed at the surface of the Earth by bacteria in anaerobic environments, for example, in marshes and in the rumen of cattle (biogenic methane). Biogenic methane escapes from marshes through ebullition (part of it is oxidized in the water) and from cattle through belching. Landfills are another source of methane. Part of this methane is oxidized in the overlaying soil cover.

The increase in anthropogenic activities is the main reason for the increase of the methane escaping to the atmosphere. The most important sources of methane in the Netherlands are landfills, cattle, manure and the exploration, transport and distribution of oil and gas. Incomplete combustion of wood and fossil fuels is a smaller source. Wetlands are a natural source of methane, diminished since the beginning of this century by land reclamation and the lowering of the groundwater table for agriculture, as well as the accompanying dessiccation of natural wetlands.

After describing the global sources, control options and the different regional possibilities for reducing methane. The report shows emissions of methane calculated for the Netherlands for the years 1989, 1990, 1991 and 1992, using IPCC (Intergovernmental Panel for Climate Change) methodology. Results are compared with earlier estimates. Developments in the emissions for the years up to 2015 are estimated. To do this, scenarios from the third National Environmental Outlook are used. The governments aim for methane reduction is 10% of the 1990 level by the year 2000. This reduction can be concluded to take place only when waste policies and policies to reduce acid deposition and the manure surplus are effective. These policies will lead to a reduction of waste, animal numbers and manure; methane reductions will be a side effect. It is also concluded that additional policy measures for methane mitigation are feasible in the recovery of landfill gas and in the extra use of otherwise vented gas on platforms in the North Sea. Additional policies reducing cattle numbers (e.g. smaller milk quota) can be effective in methane reductions. Costs of measures are described in a companion report of De Jager and Blok (1993) developed in close cooperation with RIVM.

Finally this report shows that emissions from manure are higher than earlier estimates. Measurements taken on farms will be necessary to reduce the uncertainties in this field in the Netherlands.

SAMENVATTING

De toename van broeikasgassen in de atmosfeer leidt tot een toename van de stralingsabsorptie met een mogelijk gevolg voor het wereldklimaat. Methaan is één van deze broeikasgassen, de belangrijkste na kooldioxide. De methaanconcentratie in de atmosfeer is sterk toegenomen sinds de industriële revolutie, van 800 parts per billion by volume (ppbv) tot 1720 ppbv. Gedurende de tachtiger jaren is de methaan concentratie in de atmosfeer minder snel toegenomen dan voorheen. De wereld-gemiddelde toename was 12-14 ppbv per jaar in 1983 en 9-10 ppbv per jaar in 1990. De reden voor de afname van de groei van de methaan concentratie in de atmosfeer is nog onduidelijk, maar wordt vooral toegeschreven aan een plaatselijk toegenomen concentratie van OH radicalen, waardoor methaan plaatselijk sneller wordt afgebroken.

Methaan wordt gevormd via geothermogene processen in fossiele plantenresten die bedekt zijn geraakt met sedimenten (fossiel methaan). Dit fossiel methaan komt in de atmosfeer bij de winning en het transport van kolen, olie en gas. Methaan komt tevens vrij bij de onvolledige verbranding van hout en fossiele brandstoffen. Methaan wordt ook gevormd aan het aardoppervlak door bacteriële processen onder anaerobe omstandigheden, bijvoorbeeld in rijstvelden, moerassen (moerasgas) en in de voormaag van koeien (biogeen methaan). Biogeen methaan komt vrij door opborreling uit ondiep water, rijstvelden, moerassen of door het opboeren van gas door koeien. Tevens komt methaan uit afvalstorts vrij. Een deel van de methaan wordt geoxideerd in de bodem of in de zuurstofhoudende waterlaag van plassen voordat het naar de atmosfeer kan ontwijken.

Door de groei van de antropogene activiteiten is de hoeveelheid methaan die naar de atmosfeer ontwijkt toegenomen. De belangrijkste antropogene bronnen van methaan in Nederland zijn afvalstorts, vee, mest en de winning, distributie en onvolledige verbranding van olie en gas. Onze natte gronden en moerassen zijn een natuurlijke bron van methaan. Deze bron is afgenomen sinds het begin van deze eeuw als gevolg van de drooglegging van landbouwgronden en verdroging van natuurterreinen.

In dit rapport zijn, na een beschrijving van de wereldwijde emissies en regionale reductie opties, de emissies van methaan voor Nederland berekend voor de jaren 1989, 1990, 1991 en waar mogelijk voor 1992 volgens de methoden zoals voorgesteld door de Intergovernmental Panel for Climate Change (IPCC). Uitkomsten zijn vergeleken met eerdere schattingen. Tevens zijn de ontwikkelingen ingeschat voor de jaren tot 2015. Hierbij is uitgegaan van de scenarios van de Derde Nationale Milieuverkenning. Er is een doelstelling van de overheid voor het terugdringen van methaan emissies. In het jaar 2000 zou 10% reduktie ten opzichte van het niveau van 1990 gerealiseerd moeten worden. Dit rapport concludeert dat deze reduktie gehaald zal worden als het beleid om het afval, de verzuring en het mestoverschot terug te dringen slaagt. Dit beleid heeft namelijk als effect dat minder afval gestort wordt, de veestapel krimpt en het mest overschot afneemt. Uit dit rapport blijkt ook dat additioneel beleid voor het terugdringen van methaan vooral succes kan hebben bij stortgas winning en bij het extra gebruik van gas dat anders wordt afgeblazen op platforms in de Noordzee. Additioneel beleid dat de rundveestapel terugdringt (krimpende melkquota) kan een belangrijk effect hebben op de methaan emissies. Kosten van maatregelen worden beschreven in een rapport van De Jager en Blok (1993) dat in nauwe samenwerking is ontstaan.

De emissies uit mest zijn hoger dan eerdere schattingen. Metingen in praktijk situaties zijn nodig om uitsluitsel te geven over de onzekerheden in de actuele emissies in Nederland.

1. GENERAL INTRODUCTION

If present emission trends for greenhouse gases continue, global climate is predicted to change. One of the most important gases contributing to global warming is methane (CH_4). With a current concentration of 1.72 ppmv (parts per million by volume, or 1720 ppbv, parts per billion by volume) methane is both naturally occurring and influenced by human activities. At this concentration methane exerts a strong influence on the Earth's climate and the chemistry of the troposphere and stratosphere. Methane plays a direct role in climate. It is an effective greenhouse gas because it traps part of the outgoing infrared radiation of the Earth. Methane also plays an indirect role in climate as it reacts with hydroxyl radicals (OH) in the troposphere, thereby increasing tropospheric ozone (O_3) and carbon monoxide (CO), an ozone precursor. Methane in the stratosphere is a major source of formaldehyde (CH_2O), H_2 and stratospheric water vapour, thereby affecting the radiation balance. Methane is the most abundant hydrocarbon in the atmosphere and therefore (together with CO) the major regulator of OH radicals, the primary sink for most atmospheric pollutants (Tyler, 1991).

The methane concentration in the atmosphere is increasing at a rate of about 1% per year (Steele *et al.*, 1992). This increase is thought to be related to a rise in the human population and the accompanying activities. The recent increase can be explained by increases in several methane sources, decreases in methane sinks or a combination of the two. The increase in methane concentration has very recently slowed down. As sources are not suspected to have diminished yet, it is thought that the OH radical concentration has increased, at least in parts of the Earth's troposhere (Prinn *et al.*, 1992).

1.1 Origin of methane

Methane is formed in the Earth's interior and at the Earth's surface. The first major type of formation is a thermogenic process in buried carbon. The second is a biological process performed by strict anaerobic bacteria at or near the Earth's surface (e.g. in wetlands and the intestinal tracts of some animal types). Fossil methane is emitted during the mining and transport processes that bring coal, lignite, petroleum and natural gas hydrocarbons (including methane) to the surface. Some methane is also emitted during the refining of petroleum (evaporative emissions) and the burning of petroleum products for fuel (due to incomplete combustion). Biogenic methane is formed from the anaerobic fermentation of organic matter. This takes place in soils covered with water and sediments (e.g. peatlands with a high water table), in ruminants, termites and landfills.

1.2 Greenhouse warming potential

Methane has been recognized as an important greenhouse gas because of a high warming potential. The new GWP's are 11 times CO_2 equivalents when calculated over a 100-year period, or even 35 times CO_2 equivalents when calculated over a 20-year period (IPCC, 1992, Table A.2.1.). In an increasingly polluted atmosphere compounds like carbon monoxide, methane, non-methane hydrocarbons and hydro(chloro)fluorocarbons compete for hydroxyl radicals for oxidation. The hydroxyl radical is seen as the major cleaning agent of the atmosphere. In addition to its direct contribution to the enhanced greenhouse effect, methane also has indirect effects, notably through its role in the formation of tropospheric ozone - also a potent greenhouse gas - and on the water vapour content in the stratosphere. Methane in the stratosphere is also a major source of formaldehyde and hydrogen. In **Chapter 2** the methane chemistry will be discussed.

Methane is a major greenhouse gas, second only to carbon dioxide. Increasing methane concentra-

tions will change the distribution and concentration of tropospheric ozone, directly affecting tropospheric air quality. Furthermore, methane has an indirect effect through its oxidation in the stratosphere to water vapour: enhanced water vapour in the stratosphere results in greater warming. However, this effect depends critically on the vertical profile of the change in water vapour (IPCC, 1992). The old Global Warming Potential (GWP) published in the first IPCC Scientific Assessment report (IPCC, 1990) is now seen as inappropriate (IPCC, 1992), because the magnitude of the indirect radiative effect is uncertain. It is still believed that the indirect effect is "positive", which means extra warming.

1.3 Methane emissions

Determining methane fluxes from chamber experiments is one method used to estimate source strengths in, for instance, rice paddies, landfills and natural wetlands. Masts with measuring devices at different heights are used to calculate methane fluxes from areas of several hundred square metres using an eddy correlation method. For taking measurements over even larger areas, measuring devices are loaded into airplanes. Remote sensing of methane fluxes from the Earth with satellites is in the experimental phase. Individual flux values for specific regions can be extrapolated to national or global values by determining the national or global distribution and area of similar regions. For national estimates of emissions, activity levels are usually multiplied by emission factors derived from the above-mentioned experimental research. Because there are many gaps in knowledge about the processes that lead to methane releases in different environments, these emission factors are generally uncertain. **In Chapter 3** the Global sources and sinks of methane will be discussed.

1.4 Policy response

International discussions on the policy response to climate change have focused so far on CFCs and carbon dioxide. The phasing out of CFCs started with the agreements in the Montreal Protocol and the London and Copenhagen Amendments. Now the focus is on carbon dioxide control. To date little attention has been paid to the other greenhouse gases, e.g. methane and nitrous oxide, partly because of the gaps in knowledge about their sources and sinks. Nevertheless, during the 1980s they caused approximately 20% of the calculated enhanced radiative forcing. Methane contributed 13% and nitrous oxide 6% (IPCC, 1990). The United Nations Framework Convention on Climate Change mentions returning emissions of 'carbon dioxide and other greenhouse gases', not just carbon dioxide alone, to earlier levels; thus allowing for the implemention of methane controls in lieu of possibly more difficult reductions of carbon dioxide emissions. No decision has yet been made nationally or internationally on whether to formally follow a comprehensive approach to climate change that would include all sources and sinks of all greenhouse gases in an integrated way, or that the different gases would be treated separately in a "parallel approach". In **Chapter 4** options for reductions of methane emissions will be discussed. Here a first attempt is made to calculate what the different regions in the world may contribute to methane reductions in the different source-sectors.

1.5 National emission inventories and policy development.

Under the Convention named above, countries have made two obligations relevant to this report:

1. To carry out a national inventory of net greenhouse gas emissions and sinks.
2. To submit a set of national policies and measures addressing climate change to the parties of the Convention.

The scientific working group (WG1) of IPCC, in cooperation with UNEP and OECD, is currently undertaking a Programme on National Inventories for Greenhouse Gas Emissions and Sinks. In a concerted action, UNEP, OECD and IPCC are developing a common basic methodology intended to serve as guidelines for these inventories (OECD, 1991). In different workshops on this methodology it was concluded that expert meetings are necessary to reduce the range of uncertainty in the estimates. By mid-1993 an internationally accepted methodology should lead to national estimates of greenhouse gas emissions to be used in international negotiations for a policy response to climate change. International cooperation was considered indispensable for preparing guidelines for inventories, with the ultimate goal of arriving at global coverage of national estimates by mid-1993. Some preliminary results for methane will be presented **in Chapter 5.**

UNEP coordinates the initiatives of many developing countries in setting up country studies in response to climate change. These country studies are carried out within the framework of the Convention on Climate Change. This Convention had been signed by 155 governments worldwide by mid-September 1992. The Convention calls on signatories from industrial countries to return emissions of greenhouse gases to earlier levels. Several countries have already set specific targets and timetables for greenhouse gas emission reductions they hope to achieve. Most countries are in the process of collecting key information and evaluating the most appropriate courses of action.

Emission control measures necessary to arrive at a stabilization of the atmospheric concentrations were found to be comparatively small due to the relatively short atmospheric lifetime of methane. So, policy measures to reduce methane emissions will have a relatively large impact (Harriss *et al.*; Rotmans, 1991; Rotmans *et al.*, 1992). According to IPCC (1990) methane emissions have to be reduced by 15-20% to stabilize concentrations at 1990 levels.

1.6 This document

In 1991 RIVM prepared an initial inventory of greenhouse gas emissions in the Netherlands (Van den Born *et al.*, 1991). This report was used to set priorities for experimental research on the theme of 'causes' in the Netherlands National Research Programme on Global Air Pollution and Climate Change. It also formed the basis for a preliminary policy by the Dutch government to control national emissions of greenhouse gases: for methane an emission reduction of 10% of 1990 levels by 2000 was agreed upon in the Climate Policy Memorandum (VROM, 1992). Since the publication of the first inventory several developments important for methane research and control policies, have taken place:

- the Science working group (WG1) of the IPCC has developed preliminary guidelines for national emission inventories;
- a Framework Convention on Climate Change was signed in which regular reporting of emissions is required and which allows for comprehensive controls and monitoring of greenhouse gases rather than carbon dioxide alone;
- new insights were acquired on the subject of sources and sinks of methane globally and for the Netherlands, and more information became available about options for methane emission control.

Therefore, the aims of the current document are:

1. To give an updated overview of the scientific knowledge on the sources, atmospheric behaviour and radiative effect of methane;
2. To test the methodology recommended by the IPCC for national emission inventories and to compare results with earlier greenhouse gas emission estimates for the Netherlands;

3. To make an inventory of the options for abatement of methane emissions and to assess their global potential;
4. To assess the effects of current policies and the needs of additional policies for methane emission abatement in the Netherlands, including the costs.
5. To identify gaps in knowledge that may be addressed by the National Research Programme on Global Air Pollution and Climate Change.

The report is thus intended to provide the Netherlands National Research Programme on Global Air Pollution and Climate Change with information to further help in designing the programme for the themes B (causes) and E (sustainable solutions). For the government, the report can support the implementation of current policies and the consideration of additional response measures to address the causes of methane emissions in the Netherlands. The information in this report is also used for the publication of RIVM's Third Environmental Outlook (RIVM, 1993).

After a general introduction on the importance of methane as a greenhouse gas in Chapter 1, the atmospheric chemistry of methane, including modelling efforts for IPCC, are described in Chapter 2. Global estimates of sources and sinks of methane are surveyed in Chapter 3. Global options for emission reductions and their potential effectiveness are described in Chapter 4. In Chapter 5 some preliminary results of the IPCC programme on national inventories of sources and sinks of greenhouse gases are given, including as an example, some national methane emission estimates in 1988/1990 for selected countries that have submitted data to the IPCC. An updated national inventory of sources and sinks for methane in the Netherlands is given for the period 1980-1992 in Chapter 6. Since the national emissions in the Netherlands are dominated by a small number of sources, this chapter focuses on these sources, notably oil and gas, ruminants, animal waste, landfills, and natural soils and wetlands. In Chapter 7 different scenarios for the economic development up to 2015 will be used to calculate the expected future emissions for alternative growth paths for the Netherlands. National additional options for reducing emissions will be presented in the same chapter. Information on the costs of measures can be found in a separate report that was developed in close cooperation with RIVM (De Jager and Blok, 1993). Finally, conclusions and recommendations are given in Chapter 8.

2. ATMOSPHERIC CHEMISTRY

2.1 Introduction

Comprehensive measurements of atmospheric concentrations of methane show that methane levels are increasing substantially. This is important from the perspective of global climate change, since, in the eighties, methane accounted for about 13% of the global warming (IPCC, 1990). This estimate is based on the direct radiative forcing caused by concentration changes over the period 1980-1990.

Methane effectively absorbs the infrared radiation from the Earth; also the atmospheric residence time of methane is long enough, about 10 years (longer than any other hydrocarbon), to allow it to absorb infrared radiation over a long period (IPCC, 1992). On the other hand, the atmospheric residence time is short enough in order to make emission control policies effective on reasonable time scales. The effectiveness of control policies can be considerable since the total amount of methane in the atmosphere is largely influenced by humans, accounting for two-thirds of the present-day emissions of methane (IPCC, 1990). Methane is, along with carbon monoxide and nitrogen oxides, an important source of tropospheric ozone, another important greenhouse gas and in high concentrations potentially detrimental to flora and fauna. Moreover, methane affects the self-cleaning capacity of the troposphere. The atmospheric chemistry governing the composition of the troposphere is very complex and not yet fully understood. Any realistic description of the chemical composition of the troposphere will include at least methane, hydroxyl radicals, carbon monoxide, ozone and nitrogen oxides, along with a broad variety of processes.

2.2 Atmospheric concentrations

Estimates of atmospheric methane concentrations during the past 160,000 years, as derived from measurements on air bubbles trapped in polar ice indicate that methane was relatively constant at about 300 ppbv during glacial periods and rose during interglacials to about 600 ppbv (Raynaud *et al.*,1988; Chappellaz *et al.*, 1990). Over the past 250 years, however, methane concentrations have increased rapidly (Pearman *et al.*, 1986). The present atmospheric concentration of methane is 1720 ppbv, more than double its pre-industrial value of about 800 ppbv. Recent data verify that the rate of growth of the concentration has slowed down during the past decades (Steele *et al.*, 1992). This growth decreased from about 20 ppbv per year (1.3%) in the late seventies to about 13 ppbv per year (0.75%) in 1983 and about 9-10 ppbv per year in 1990. If this deceleration continues steadily, global atmospheric methane levels will rise to a maximum of 1770 ppbv in 2006 and decline thereafter (Steele *et al.*, 1992). The deceleration of the global methane growth rate is dominated by what has occurred in the latitude band of 30°-90° North. There are no satisfactory explanations for this rapid decline in the methane growth rate. It could be due to an increase in tropospheric hydroxyl (Prinn *et al.*, 1992).

2.3 Sinks

The main sink of methane (80%) is the reaction with hydroxyl radicals in the troposphere. Vaghjiani and Ravishankara (1991) have recently shown that the rate at which methane is oxidized by hydroxyl radicals had been overestimated by up to 25%. This research has been important in reassessing the global budget of methane. The reassessment has been summarized by Crutzen (1991) and IPCC (1992). The current annual removal of methane by hydroxyl radicals is estimated to be 420 Tg (range 340-500 Tg). The annual uptake by soils has been estimated at 30 Tg (range 15-45 Tg) in the IPCC Supplement and at 40 Tg (range 20-60 Tg) by Reeburgh *et al.* (1992). The photochemical removal in the stratosphere is estimated at 10 Tg/yr (range 5-15 Tg/yr) (Crutzen,

1991) up to 60 Tg/yr (Warneck, 1988). Recent soil flux measurements indicate that changes in land use or enhanced fertilizer input are decreasing the uptake potential by soils (Keller *et al.*, 1990, Scharffe *et al.*, 1990, Mosier *et al.*, 1991). The estimated atmospheric lifetime of methane is 10 years (IPCC, 1992).

2.4 Global budget

The present global budget of methane is estimated from the atmospheric concentration, the magnitude of its sources and sinks and its rate of accumulation in the atmosphere. A total annual emission of about 515 Tg, of which 360 Tg is anthropogenic, is now calculated. As these budgets tend to change with increasing scientific knowledge, the most recent "consensus" that has been published is presented (IPCC, 1992) in Table 2.1.

Table 2.1. Estimated global sources and sinks of methane (Tg/yr) with ranges in parentheses

Sources		
Natural		
- Wetlands	115	(100-200)
- Termites*	20	(10-50)
- Ocean	10	(5-20)
- Fresh water	5	(1-25)
- Methane hydrate	5	(0-5)
Total natural	155	
Anthropogenic		
- Coal mining	50	
Natural gas and Petroleum Industry*	50	
Total fossil	100	(70-125)
- Rice*	60	(20-150)
- Enteric fermentation	80	(65-100)
- Animal wastes*	25	(20-30)
- Domestic sewage treatm*	25	?
- Landfills*	30	(20-70)
- Biomass burning	40	(20-80)
Total anthropogenic	360	
Total biogenic	410	(280-705)
Total fossil	100	(70-125)
Total natural	155	
Total anthropogenic	360	
Total natural + anthropogenic	515	
Sinks		
Atmospheric removal* (tropospheric and stratospheric)	470	(420-520)
Removal by soils	30	(15-45)
Atmospheric increase (10 ppbv/yr)	32	(28-37)

* revised estimates since IPCC 1990. Source: IPCC, 1992

The methane is emitted by fossil and biogenic sources. The methane originating from fossil sources, the so-called dead carbon, is ^{14}C free. Some studies to date have been directed to the ^{14}C content of atmospheric methane (Whalen *et al.*, 1989; Manning *et al.*, 1990 and Quay *et al.*, 1991). The methane from fossil sources is estimated by these authors to be 21±3%, 25±4% and 16%, respectively. So an estimated 20% of total annual methane emissions (ca. 100 Tg) are from fossil sources, such as coal, oil and natural gas. A very small part may also stem from clathrate (also called hydrates in sediments) destabilization (0-5 Tg). This information on fossil carbon can be used to constrain source strengths (as, for example, in Cicerone and Oremland, 1988), but it is otherwise not in accordance with most former global budget estimates where 85-95% atmospheric methane is of modern biogenic origin. A missing anthropogenic source of fossil methane of about 50 Tg is therefore suspected.

In estimating the relative contribution of the sources, different approaches can be used. To date there have been some studies conducted to establish isotopic fingerprints of methane from different sources (Lowe *et al.*, 1991). A more direct method is to estimate emissions from direct measurements at sources combined with data on activities and emission factors. This method is followed in the International Programme on National Inventories of Sources and Sinks of Greenhouse Gases by the IPCC (OECD, 1992).

2.5 Processes affecting methane in the atmosphere

By far the largest amount of atmospheric methane can be found in the troposphere, the well-mixed part of the atmosphere below 15 km. Within the troposphere methane is a well-mixed trace gas. As a result, the interhemispheric gradient of methane is small, the difference between the average concentrations of the northern and the southern hemispheres being only 100 ppbv (6% of the global average concentration). The major sink for tropospheric methane (CH_4) is the oxidation by the hydroxyl radical (OH). Fig. 2.1 gives an overview of the most important processes affecting the atmospheric concentration of methane. The resulting CH_3 initiates a chain of reactions (see, for example, Logan *et al.* 1981 for the details on chemical reactions), ultimately leading to 80% carbon monoxide and 20% other products.

$$\begin{aligned} CH_4 + OH &\rightarrow CH_3 + H_2O \\ &\vdots \\ &\rightarrow CO + products \end{aligned} \qquad (1)$$

The hydroxyl radical is the major atmospheric cleaning agent, a very reactive atmospheric compound which effectively destructs many of the reactive atmospheric compounds, such as NO_2, carbon monoxide (CO), methane, non-methane hydrocarbons and hydro(chloro)fluorocarbons. The lifetime of hydroxyl is only a few seconds. The interactions between methane, hydroxyl and carbon monoxide are of special interest.

$$CO + OH \rightarrow CO_2 + H \qquad (2)$$

Hydroxyl radicals account for over 90% of both the methane loss and the carbon monoxide loss, while the oxidation of methane is an important source of carbon monoxide (Logan *et al.*, 1981). The other 10% is a soil sink. Methane and carbon monoxide together are responsible for over 90% of the hydroxyl loss. The OH loss caused by carbon monoxide is about three times the loss caused by methane (Logan *et al.*, 1981). It is very unclear what the historical trend of the hydroxyl concentration is. Recent findings indicate a slight increase in atmospheric OH (Prinn *et al.*, 1992).

Clearly, carbon monoxide and hydroxyl concentrations need to be known to estimate methane concentrations. The relatively well-known carbon monoxide sources can be split into direct emissions (fossil-fuel use, biomass burning etc.) and atmospheric oxidation of methane, as well as of non-methane hydrocarbons. The atmospheric source strength of hydroxyl radicals is much less certain. The hydroxyl radical is produced by the reaction of an energetically excited oxygen atom ($O(^1D)$ with water vapour (H_2O).

$$O_3 + radiation \rightarrow O_2 + O(^1D) \quad (3)$$

$$O(^1D) + H_2O \rightarrow 2\,OH \quad (4)$$

The sun's radiation photodissociates ozone, producing excited oxygen atoms. The two main sources of ozone in the troposphere are the downward transport of ozone from the stratosphere (above about 15 km) and photochemical production.

The photochemical production of ozone is influenced by nitrogen oxides and hydrocarbons (CO, CH_4, and non-methane hydrocarbons, NMHC). An important part of these ozone precursor emissions is of anthropogenic origin and thus concentrated in industrialized areas and places with high biomass burning. Furthermore, nitrogen oxides have a lifetime of some days, NMHC of some days to weeks and carbon monoxide of some months. As these lifetimes are all shorter than the mixing time of the global troposphere, tropospheric ozone is unevenly distributed over the globe.

CFCs and nitrous oxide are both precursors of stratospheric radicals, depleting stratospheric ozone. In this way they affect the ozone layer and thus the levels of the radiation required for the photolysis of tropospheric ozone. CFC replacements such as HCFCs and HFCs do not have such a large impact on stratospheric ozone because they are mainly destroyed by oxidation by hydroxyl in the troposphere. The influence on the hydroxyl concentration is (still) relatively small, so they do not influence the methane oxidation by hydroxyl radicals yet.

The complexity of the interactions can be illustrated by the sensitivity of the system to small additional emissions of nitrogen oxides. In a relatively unpolluted area such an additional emission will increase the concentration of hydroxyl, but in a more severely polluted region such an additional emission will lead to a decreased concentration of hydroxyl. The heterogeneity, the sensitivity and the large number of compounds and processes involved in the complex of chemical interactions in the troposphere are some of the main causes for the large uncertainties in the simulation results (Guthrie and Yarwood, 1991; Thompson and Steward, 1991).

Feedback mechanisms will play an important role in determining future concentrations of methane. Temperature feedbacks can both accelerate and decelerate the rate of increase of atmospheric methane. Rising temperatures, in combination with stable or increased precipitation, enhance microbial activity and, thus, the emission of methane from natural wetlands and flooded rice fields. Indirectly, higher temperatures affect the stability of methane hydrates, giving rise to a positive feedback mechanism. Recent insights indicate that this feedback will probably only materialize on a geological time scale (MacDonald, 1990).

At present, the total atmospheric chemistry can be seen as a positive feedback. Higher concentrations of methane may lead to lower hydroxyl concentrations. This increases the methane lifetime, thereby the rate of methane increase. As a result of this, the GWP value for methane may

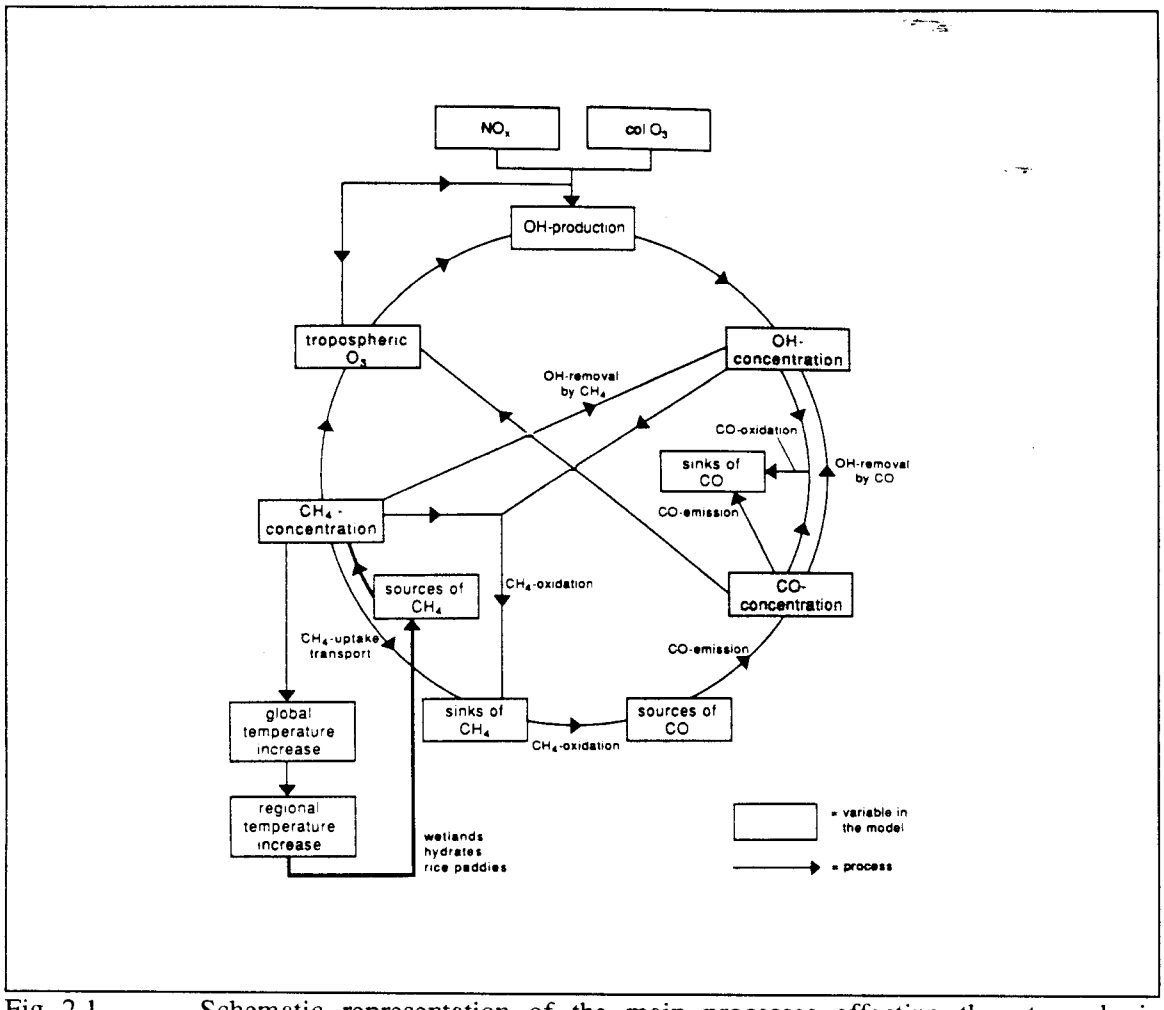


Fig. 2.1. Schematic representation of the main processes affecting the atmospheric concentration of methane as represented in the methane module of the IMAGE model.

rise. The same holds for some other compounds like HCFCs and HFCs. According to Prinn however OH radicals may have increased because of NO_x releases in originally clean areas.

A feedback mechanism which can be either positive or negative involves the stratosphere. Oxidation of methane affects the oxidizing capacity of the stratosphere, favouring ozone in the lower stratosphere and depleting ozone in the upper stratosphere. Methane production is acting as a sink for chlorine in the stratosphere, thereby reducing the ozone destruction.

Negative feedbacks play a significant role as well. Rising temperatures will increase tropospheric water vapour (a hydroxyl precursor). Rising temperatures will also affect reaction rates and, as a result, favour methane in the reaction with hydroxyl relative to carbon monoxide, enhancing the methane sink. Furthermore, rising temperatures will increase microbial activity in soils, possibly enhancing the soil sink of methane.

Another feedback mechanism involves tropospheric ozone. Both methane and carbon monoxide act as precursors for tropospheric ozone. Ozone is a precursor of hydroxyl and thus enhances the sink of methane. Here an additional indirect positive feedback is caused by tropospheric ozone acting as a greenhouse gas.

Some of the above feedbacks will only materialize when the system changes significantly, while the order of importance of the different feedback mechanisms will depend strongly on future developments. The relative importance of the different feedback mechanisms is still under consideration.

2.6 Global atmospheric models to simulate methane concentrations

The perturbation of the tropospheric burden of CH_4, O_3, OH and their related species is studied by means of measurements and atmospheric chemical simulation models. The evaluation of past, and in particular, future concentration trends by applying models requires parameterizations (= simplified representations of atmospheric processes) that can simulate changes on a global scale for a long time frame. In general, the chemistry and physics in a model are, depending on the correctness of simulated results, assessed according to their validity for future predictions, present state of the atmosphere and past trends.

Photochemical global models applied in research on the atmospheric budget of CH_4 necessarily contain simplifications, both in chemistry and dynamics (= representation of atmospheric transport); moreover, they need to be computationally efficient. This leads to difficulties since a model that can accurately simulate the global troposphere will have to represent processes on geographical scales of 100 km^2 up to continental scales and time scales ranging from a few years to decades. To improve this situation, the identification of systematic errors and the calibration of each individual parameterization with appropriate observations should be part of the process of model development. Such an approach could finally lead to a better estimate of model uncertainty limits when interpreting results of scenario runs.

In order to tackle problems on spatial and temporal variation, several methods are followed. The first method is to adopt a set of OH distributions calculated from a comprehensive transport model and to recalibrate or scale the OH fields with chemical losses proportional to OH (e.g. Fung *et al.*, 1991). A second approach for deriving an average global CH_4 budget is to use a tropospheric photochemical model for an appropriate range of global conditions (Mayer *et al.*, 1982; Crutzen and Gidel, 1983; Khalil and Rasmussen, 1983; Blake, 1984; Jones and Pyle, 1984; Fraser *et al.*, 1986; Isaksen and Hov, 1987; Wahlen *et al.*, 1989; Quay *et al.*, 1991; Taylor *et al.*, 1991).

Changes in the atmospheric composition were calculated with 1-, 2- and 3-dimensional models (1D, 2D, 3D).

1D Models

The 1D models, representing only vertical profiles of trace gases, are useful in studying the sensitivity of the chemical composition to processes that are reasonably parameterized to one dimension, e.g. radiation. These models are especially good for trace gases with long lifetimes. Because of the relatively simple dynamics it is possible to include the effect of the dependence atmospheric radiative processes have on height. Thompson and Cicerone (1986) and Thompson and Steward (1990) applied a 1D model to calculate the regional effects of global change for several typical chemical regimes. A global picture is acquired by averaging effects over the typical chemical regions. Horizontal transport cannot be taken into account in these models.

2D Models

The global troposphere was studied extensively with 2D zonally averaged models (latitude versus height) during the seventies and eighties. In order to perform scenario calculations, these represented the best balance between the extent of detailed parameterizations of atmospheric processes and computer efficiency. The 2D models necessarily neglect longitudinal variations in

atmospheric parameters, including mixing times, temperature, moisture, cloudiness, precipitation, solar insulation, stratospheric intrusions, emissions and deposition. These variables are treated as being zonally averaged. This approach is inadequate for representing extremes in emissions of short-lived nitrogen oxides (NO_x) and hydrocarbons (HCs) and their subsequent O_3 formation. Furthermore, the comparison of model results with measurements can be performed for long-lived zonally well-mixed components like methane.

Another type of 2D model is the longitude versus height-parameterization (Reeves, 1989; Solberg, 1988). These models usually represent a zonal band in the northern hemisphere. However, such 'channel' models are designed to study effects of emissions in highly industrialized regions and are less adequate to calculating effects of CH_4 emissions on the remote atmosphere.

In a recent study a 'semi 2D' version was created by averaging the variation in emissions over longitudinal zones in a 3D model (Kanakidou, 1992). This work demonstrated that zonal averaging of NO_x and HC emissions may result in an overestimate in O_3 and OH concentrations at northern mid-latitudes and in the tropics. In fact, zonally averaged 2D models usually overpredict O_3 concentrations. The OH overestimate implies an underestimate in the amount of CH_4 for which OH is the dominant photochemical sink. This would consequently lead to an error in a climate model calculating the radiative forcing from CH_4.

3D Models

As discussed above, a number of atmospheric compounds (e.g. CO) have short lifetimes. Therefore the analyses of all chemical processes in the atmosphere requires global 3D models with high spatial and temporal resolutions. Models that account for all factors including heterogeneous processes (chemical processes taking place at and in aerosols, clouds, rain droplets and particles) have, however, not yet been developed. The current 3D models describe the dynamics of the atmosphere in a more realistic way than their 2D counterparts. So far, only part of the chemical species and processes have been described in these models. The development of powerful and fast computers parallels the development of these 3D models. The new generation 3D models on chemistry and transport in the atmosphere are often based on a global circulation model (GCM), frequently a weather forecast model. These models are expected to produce more accurate simulations because of their spatial resolution. Even with these models, however, for integrations over longer time periods, processes on scales smaller than the grid size must be parameterized.

The development of models with a more detailed spatial resolution requires input emission data with similar spatial resolution. An important project in this respect is the IGBP-GEIA (International Geosphere Biosphere Project - Global Emission Inventory Activity). In this project the source strength of various trace gases is estimated on a 1° x 1° spatial resolution (Baars *et al.*, 1991).

2.7 IPCC emission scenarios

Simulating the composition of the atmosphere requires emission figures as input data. A full description of the relevant emissions is often called a scenario. The term is used both for descriptions of emission levels in a specific situation and for descriptions giving emission levels in a certain time-interval. The first type of scenario is used in equilibrium studies and is common in, for instance, climate simulation. The second type of scenario, used in time-dependent runs, is common, for instance, in policy studies.

In 1990 the IPCC defined a set of five scenarios of the second type (described in IPCC, 1991). These scenarios are used in many modelling studies. The scenarios describe the emissions of the main greenhouse gases emitted from the biosphere (CO_2, N_2O, CH_4, CFCs), as well as the

emissions of NO_x and CO from 1985 to 2100. The scenarios are meant to represent some very different possible futures.

In the *2030 High Emissions* scenario (also called the Business-as-Usual scenario) the equivalent CO_2 concentration is assumed to have doubled the pre-industrial level by 2030; the *2060 Low Emissions* scenario assumes that this doubled level will be reached by 2060. In the *Control Policies* scenario the doubling will take place by 2090, followed by a stabilization. In the *Accelerated Policies* scenario the equivalent CO_2 will stabilize somewhere below double its pre-industrial level, but economic, political and technological constraints prevent significant emission reductions in the short term. In the fifth scenario, *Alternative Accelerated Policies*, emission reductions are also assumed to be possible in the short term. The main sources of emissions and the key factors influencing these sources have been identified and estimated in the development of the scenarios. The main factors taken into account are population density, economic growth, energy supply and demand processes, control technologies, universal compliance to CFC protocols, deforestation rates and emission factors for agriculture.

All scenarios use the World Bank's population scenario (Zachariah and Vu, 1988). For economic growth both the lower and higher estimates of the World Bank (WorldBank, 1987) have been used. For the remaining key factors, related to technological development and environmental policies, specific scenario-dependent assumptions are made.

The first four scenarios resulted in two versions: one with high and one with low economic growth. The emissions arising from these two versions have been averaged in such a way that the resulting equivalent CO_2 concentrations comply with the definition of the scenario. Two models have been used to calculate these equivalent CO_2 concentrations: the Atmospheric Stabilization Framework (ASF) of the US EPA and the Integrated Model to Assess the Greenhouse Effect (IMAGE) of RIVM (Rotmans, 1990).

2.8 Methane modelling for IPCC

In the analysis of atmospheric effects of future CH_4 emission simulations for the Intergovernmental Panel of Climate Change (IPCC), several models, including GISS, GSFC, HAR, MPI, LLNL and OSLO (Guthrie and Yarwood, 1991) were applied.

The GISS model (of the Goddard Institute for Space Studies in the USA) represents processes in the atmosphere in a very simple manner in only four boxes. The parameterized chemistry is derived from explicit chemical models. The advantage of this simplified approach is that all kinds of feedback processes can be included and evaluated.

The MPI model (of the Max Planck Institute for Meteorology in Germany) goes a few steps further into the real atmosphere by representing both the northern and southern hemispheres, each of which are divided into several altitude levels. Several, simple feedback processes are implicit, while the chemical mechanism is explicit.

The HAR & OSLO models (of Harwell Laboratory in the UK and the University of Oslo) are both 2D models of latitude versus altitude and therefore show relatively realistic atmospheric transport. Both models contain a realistic chemical scheme. They are, from the point of view of computation the most expensive of the models used for the IPCC study. Therefore integrations over many decades were 'simulated' by running the model at several intermediate times in the future for a few years and interpolating between each modelled period.

GSFC (of the Goddard Space Flight Center in the USA) uses a 1D model for six 'chemically coherent regions' on Earth. The chemistry is explicitly formulated but transport processes between the regions is not implicit.

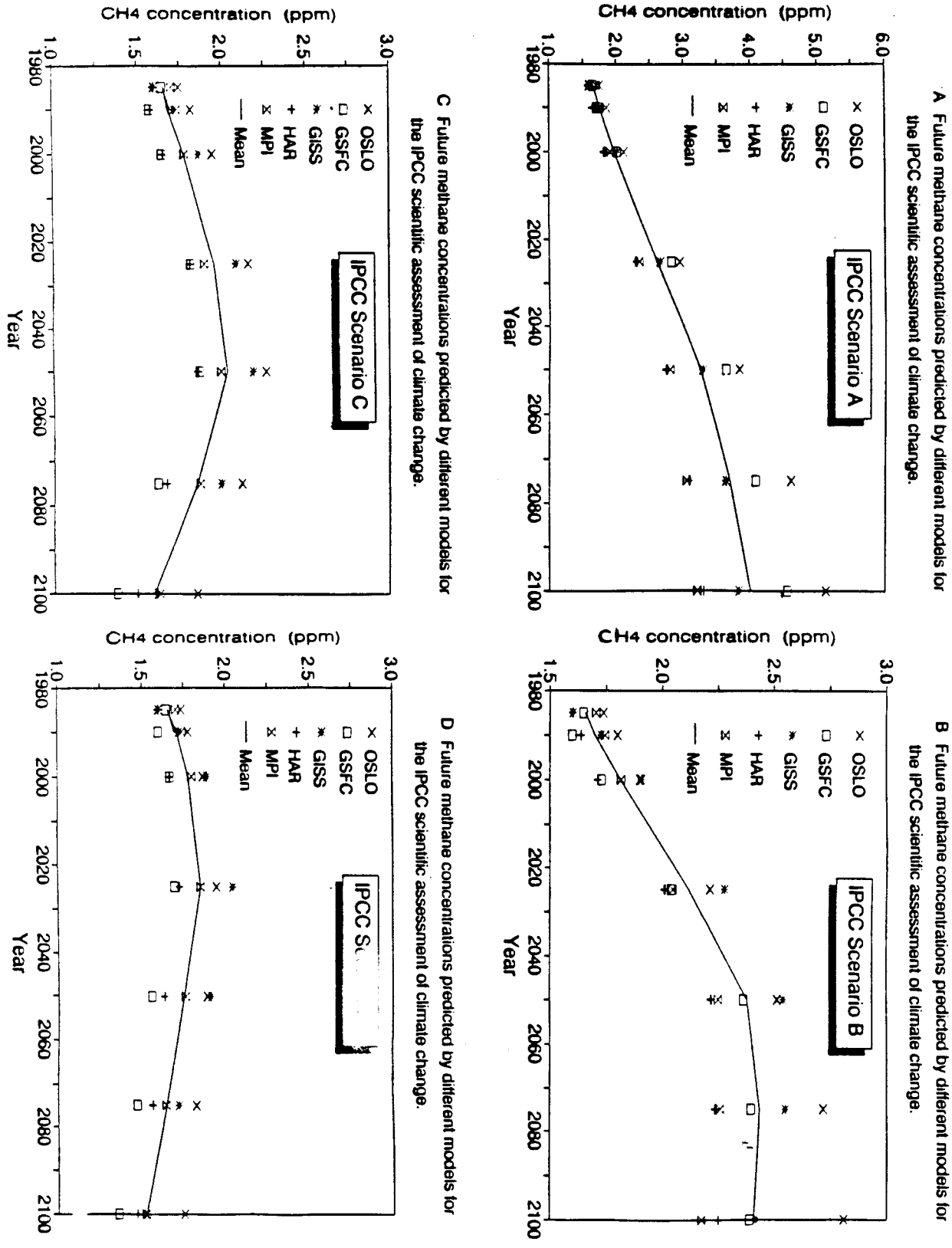
In LLNL (of the Lawrence Livermore National Laboratory in the USA) both 1D and 2D (altitude vs. latitude) modes are used. The models cover both troposhere and stratosphere and explicitly describe chemistry, transport and radiation.

The CH_4 concentrations presented in the IPCC Science Working Group report represented the average results of five of these models. They demonstrate four different approaches to the problem of representing the physics and chemistry of the atmosphere in a computationally tractable form.

The IPCC Scientific Assessment (IPCC, 1990) contains simulation results for the scenarios from the IPCC Response Strategies. The 1992 IPCC Supplementary Report (IPCC, 1992) describes an update of the 2030 High Emissions scenario with a number of variants, including the improved estimates of present-day emissions. The atmospheric chemical implications of these scenarios have not yet been analyzed in detail by IPCC. The simulation results in IPCC 1990 represent the averages of the results of five contributing modelling groups. All five calculated atmospheric concentrations of greenhouse gases resulting from the emissions according to the scenarios described above. Guthrie and Yarwood performed an intercomparison study of the methane simulations at the request of IPCC as a first step towards a model intercomparison study (Guthrie and Yarwood, 1991). They compared the methane concentrations as calculated by the individual models (see Fig. 2.2). Due to methodological differences the results of one of the six models used in their study was omitted from the intercomparison.

For the *2030 High Emissions* scenario (Fig. 2.2. A) the simulated methane concentrations increase steadily from 1.7 ppmv in 1985 to an average of 4 ppmv in 2100. The results for the individual models in 2100 range from 3.2 to 5.1 ppmv; the range gradually increases with the time interval.

Fig. 2.2. Future methane concentrations predicted by different models for the IPCC scientific assessment of climate change (Guthrie and Yarwood, 1991).



For the *2060 Low Emissions* scenario (Fig. 2.2. B) the average 2100 methane concentration simulated is 2.4 ppmv, individual results ranging between 2.15 and 2.8 ppmv. Here the results of the model start diverging in 2050. Some models show a persistence of the increasing trend up to 2100 while others show a significant decrease at the end of the time interval.

For the *Control Policies* scenario (Fig. 2.2. C) all models calculate an increasing concentration of methane up to 2 ppmv in 2050, and a decrease afterwards to 1.6 ppmv in 2100. Model results range constantly between 0.3 ppmv above and below the average value.

For the *Accelerated Policies* scenario (Fig. 2.2. D) the situation is similar. Here, the maximum methane concentration, reached in 2025, is about 1.85 ppmv. An almost linear decrease follows, ending up at 1.5 ppmv in 2100. Model results range from about 0.2 ppmv around the mean for this scenario.

2.9 Conclusions

Guthrie and Yarwood (1991) generally concluded that, at present, calculations using the models are inadequate to predict an accurate rate of possible methane concentrations, and that this inadequacy is caused by shortcomings in the model representations rather than by uncertainties in the emission estimates. Present model intercomparisons should overcome the shortcomings and lead to better possibilities for analyzing the effects of the different control policies.

A conclusion drawn from scenario studies, taking into account the possible emission reductions, is that stabilization or reduction of methane concentrations is a realistic goal for environmental policies (Rotmans *et al.*, 1992). Lelieveld and Crutzen come to the same conclusion based on studies with the Max-Planck model (Lelieveld and Crutzen, 1993). Measures directed towards control of CO_2, such as increased efficiency in use of energy, a shift to non-carbonaceous fuels and arrest of deforestation, will also contribute to the control of methane. In addition a large number of conventional emission control measures are available to limit the emissions of methane and CO.

3. GLOBAL SOURCES AND SINKS OF METHANE

3.1 Introduction

The major sources of atmospheric methane have been identified. However, there are considerable uncertainties about the source strengths (Cicerone and Oremland, 1988). This uncertainty arises because of the paucity of methane emission measurements and due to the wide variation in methane fluxes as a result of the intrinsic heterogeneity of the landscape, and the political, economic and cultural factors. For example, flux measurements in natural wetlands span several orders of magnitude (Sebacher *et al.*, 1986), (Whalen and Reeburgh, 1988). Extrapolation from individual flux measurements to the global budget is very difficult.

The uncertainties in the sources and sinks of methane are illustrated by the budget given by Cicerone and Oremland (1988), who presented a comprehensive survey and synthesis of the methane cycle. Many individual sources are believed to be a factor of 2. A more recent budget is given by IPCC (1992) and included in Chapter 2 of this report (Table 2.1). The global annual methane emission of about 515 Tg can be deduced from the magnitude of its sinks and the rate of atmospheric accumulation. The major loss term in the methane budget, the reaction with tropospheric OH radicals, is not defined more closely than $\pm$ 25%; the best estimates involve scaling to the lifetime of other gases such as methyl chloroform (CH_3CCl_3) (e.g. Prinn *et al.*, 1987).

The individual global sources in Table 2.1 will be discussed in the following section. The methane consumption by soils is also discussed briefly in 3.4. In Chapter 6 the strength of the Dutch sources is discussed.

3.2 Methane emissions from fossil sources

The proportion of methane from sources related to fossil carbon were estimated from studies of the ^{14}C content of atmospheric CH_4. The portion of CH_4 stemming from fossil carbon is about 20% (100 Tg) (Crutzen, 1991), although independent estimates range from 16$\pm$12% (Quay *et al.*, 1991) to 21$\pm$3% (Whalen *et al.*, 1989) and 25$\pm$4% (Manning *et al.*, 1990). The individual sources included in this 20% are the coal mining, natural gas and petroleum industries, along with CH_4 hydrates.

Oil production, transportation and distribution
The major causes of CH_4 release in oil production are venting and flaring of the gas associated with the crude oil. A mixture of crude oil, water and gas is pumped up from a well. The associated gas, mainly consisting of methane, is separated from the oil. This gas can be used on the platform, reinjected or transported to a distribution network. It is vented or flared if the other options are not economical. Worldwide venting and flaring is reduced as this gas is increasingly being used. With venting all methane is emitted. With flaring the methane is burned. Methane emissions depend on the efficiency of the flares. Nielen (1991) estimated an overall emission of 2% from land-based flares in Western Europe. Offshore oil loading operations are significant sources of direct VOC and methane emissions. In oil tankers hydrocarbons evaporate and have to be vented to avoid pressure buildup. After loading, gas recovery from the hoses and other transfer systems is very complicated so this gas is vented. The IPCC estimates that methane emissions from the oil industry are 17 Tg (range 5-30 Tg) per year (IPCC, 1992)

Gas production, transportation and distribution
An important source of methane is the natural gas industry. As natural gas is a convenient and relatively clean fuel its consumption is rapidly increasing around the world. This trend is generally

believed to continue in future, possibly enhanced by strategies to reduce carbon dioxide emissions (natural gas has a lower carbon emission factor than other fossil fuels). Recent literature shows a growth in proven reserves of natural gas from 17.5 Tm^3 in 1960 to 109 Tm^3 in 1987 and 120 Tm^3 in 1989 (Andriesse, 1991). The last estimates of the global resource of natural gas in conventional categories are between 250 and 350 Tm^3. The proven Dutch reserves are 1.9 Tm^3 natural gas. Non-conventional reserves are estimated to be far greater then conventional. Gross global production is 2.4 Tm^3 per year, so no resource constraints are expected for the short to medium term.

The causes of CH_4 losses associated with natural gas are venting and flaring during its production and maintenance, blowouts, and leaks during the transport and distribution.

Methane releases during regular production

Venting and flaring during production and treatment of natural gas is much more controlled than in petroleum production, partly because of the available infrastructure to accommodate the recovered gas. In 1988 3.9% of production was estimated to be vented or flared worldwide (Nielen, 1991). Especially during well testing and emergencies, gas is vented and/or flared. The quantities released during normal operations are sometimes recorded, but the losses taking place during testing before a concession is made is not recorded. Thus, no accurate quantitative information about the losses during production and treatment is available. All equipment operating under pressure uses safety valves to prevent overpressure in the systems. Gas thus released is led to a flare tip located away from the platform for safety reasons. The gas can either be released to the atmosphere, or burned at the flare tip. On most platforms offshore venting is still common practice. In the Norwegian part of the North Sea flaring is obligatory.

Planned flaring

Planned flaring occurs during start-up, maintenance and shut-down operations and is exempted from flare regulations. Flaring is kept to a minimum but flared quantities of gas between platforms can differ by a factor of 10. Some flaring can last for several months. The flare gas is measured by gas meters (accuracy range is about 10%) and reported daily. To avoid backflow and explosions, flare systems are constantly purged with natural gas taken fom the fuel gas system. On some platforms inert gases such as nitrogen are used. Natural gas from the fuel gas system is also used for the pilot flame.

Utilization of gas at production facilities

Natural gas is needed for various processes on the platforms:

1. as a blanket gas in storage tanks to prevent air entering which can create explosive mixtures above the stored liquids;
2. to dehydrate glycol in the glycol regeneration process;
3. to deoxygenate seawater prior to the injection of this water in the gas field.

In all these processes the gas is taken from the fuel gas system. To avoid backflow from other systems, this gas is normally vented unburned. In some cases it is burned. It is not metered separately, the flow volume is included in the fuel gas measurement.

Accidents

The pressure in gas and oil fields is many times the atmospheric pressure. Blowouts occur when the production pipe and the well are disconnected. Westergaard (1987), after analyzing many blowouts, concluded that only in 15 to 20% of the cases did fire break out. So the methane emissions are relevant. Little concluded in 1989 that 23% of worldwide methane emissions from the natural gas sector are from blowouts. The blowout frequency in the Gulf of Mexico, calculated by Westergaard, is between 0.26 and 9.60×10^{-3} per well. For the North Sea this frequency is 1.7×10^{-3} per well for exploration drillings (Westergaard, 1987). The average blowout lasts 4-8 days and emits 2.1 million m^3 gas per day (Little, 1987). Accidents like blowouts or ruptures of pipes can result in high emissions. It has, for example, been reported that the Soviet gas transmission system suffers from poor construction and operational difficulties. But also in Alaska problems have been reported with pipelines. Some of the problems originate from the extreme climatic conditions in Siberia and Alaska. Emissions have recently been estimated to be up to 3 to 5% of the Russian gas production (Rubchuk *et al.*, 1991;Bashmakov, 1992).

Transport and distribution

International studies on the methane emissions from transport and distribution of natural gas are still scarce. Emissions are frequently expressed as a percentage of the total consumption of the energy carrier. Data in the literature still vary depending on the method of estimates. Frequently estimates for methane loss in gas systems are based on the difference between gas produced and delivered.

Nielen recently summarized the relevant literature. Table 3.1 estimates global losses of natural gas.

Table 3.1. Global losses of natural gas

	Gm^3	%
Gross production of natural gas	2368.23	100.0
Gas reinjected	209.16	8.8
Gas flared and vented	92.41	3.9
Other losses	107.19	4.5
Marketed production	1959.47	82.8

Source: Nielen, 1991

Emission factors for methane as a percentage of throughput from a study coordinated by Sweden on 30 gas companies of the Alphatania Group have been in use since 1990 (EPA, 1990). The emission factors are given in Table 3.2.

Table 3.2. Emission factors from the natural gas chain (as percent throughput)

Exploration	0.0
Production (max.)	0.015
Treatment	0.001-0.002
Transport	0.001-0.13
Distribution	
-Modern network	0.03-0.3
-Old networks (max.)	1.0
End use (combustion)	0.01

The IPCC estimated the methane emissions from the gas industry at 37 Tg (range 25-42 Tg) methane per year (IPCC, 1992).

Coal exploitation and production

Coal production is spread over 50 countries. The total 1990 hard coal production worldwide in 1990 was 3481 Mt, the total brown coal and lignite production in 1990 was 1155 Mt. The major producers of hard coal in 1991 were China: 1086 Mt, USA: 823 Mt, Commonwealth of Independent States (CIS): 409 Mt, India: 222 Mt, South Africa: 177 Mt, Australia: 168 Mt, Poland: 141 Mt and the United Kingdom: 96 Mt. Colombia and Indonesia will become major producers shortly. The IEA Coal Research suggests that coal consumption will expand to 5500 Mt by the year 2000 (IEA, 1992).

Methane exists within the micropore structure of the coal, mainly as adsorbed layers. The amount of methane present is effectively a function of the available internal pore surface area - a function of coalification - and the level of competing, adsorbing or pore-blocking species, such as water; the amount of methane is, of course, a function of pressure. The translation of the in-situ methane content of coal into methane gas emission during mining is complex. It involves information on the nature of the methane storage in the coal, on the methane transmission through coal beds during mining operations and the mining itself, where degassing and ventilation practices of mines may vary.

Kirchgessner *et al.* (1992) made a global estimate of methane emissions from coal mines in 1989 using country specific information on coal depth and in-situ methane content of coal. Their methane estimate from coal mining was 46 Tg/yr. IPCC (1992) estimated 35 (range 25-47) Tg/yr.

Methane hydrates (clathrates)

Clathrates or methane hydrates are ice crystals in cubic form with methane molecules locked in. Methane in clathrates is highly concentrated. One cubic metre of clathrates can contain up to 170 m^3 of methane gas at standard conditions (st) ([MacDonald, 1990a #155], 1990). Limited data from oceanic drilling and seismic exploration lead to a rough estimate of 11,000 Gt of carbon stored in clathrates in carbon-rich sediments on continental shelves and in ocean basins. Some 400 Gt of carbon are estimated to be enclosed in clathrates in permafrost regions of the world. MacDonald estimates the clathrate volume in continental shelves and basins to be about 1 million km^3. This equals about 20,000 Tm^3 methane. In permafrost regions the clathrate gas potential may be about 750 Tm^3 methane ([MacDonald, 1990 #155, 1990a; 1990 #386], 1990b).

Methane clathrates are potential reserves of exploitable natural gas. Methane hydrates are considered to be relatively minor sources of methane (~5 Tg; Table 3.1), but global warming may lead to increased emissions. They are a potentially large source if they come into production. Future methods for natural gas production from clathrates therefore would have to be leak-free to prevent emissions.

Minor sources of fossil methane
A minor source of fossil methane is incomplete combustion of oil, gas and coal. Worldwide this source is estimated at 2 Tg/yr. Finally, freshwater systems and the oceans are believed to release methane that is of a non-biogenic origin. Since this source is relatively small and cannot readily be influenced by humans, we will limit the discussion on these sources by giving the IPCC estimated source strength: 5 (range 1-25) Tg/yr for freshwater and 10 (range 5-20) Tg/yr for the oceans.

3.3 Methane emissions from non-fossil sources

Enteric fermentation
Methane is formed in the rumen by methanogenic bacteria under anaerobic conditions. This process enables ruminants to utilize the energy in low-quality feeds with high cellulose content.

Early data on methane yields by cows, sheep, goats, horses and elephants were published in 1938 by Ritzman and Benedict (1938). They found a range of 4-7% gross energy intake for ruminants fed on maintenance level. The methane release rates in ruminants were lower when fed with protein-rich feeds and higher when fed with straw. Horses and elephants had methane emissions of 1.5-3%. Blaxter and Clapperton (1965) found that at maintenance level, methane release increased from 7.5 to 9% when the digestibility of the feed was raised from 65 to 95%. Methane release of 6.5 to 7% was independent of the digestibility at twice the maintenance level and decreased from 6 to 5% at three times maintenance level when the feed digestibility was changed from 60 to 90%. In developing countries a large proportion of the feeds consists of low-quality straw and fodder. Krishna *et al.* (1978) estimated 9% methane yields in Indian cattle fed at maintenance level or slightly above with low-quality feed.

The worldwide spectacular growth of herds since the fifties gave rise to a growing methane emission from this source. According to Lerner *et al.* (1988) 76% of methane emissions from livestock is from the northern hemisphere. Important concentrations of livestock, and thus of emissions, are found in the USA, the CIS, Europe and southern Asia. The global annual methane release from wild and domestic animals, and from humans, was estimated to be about 80 Tg/yr (range 65-100 Tg/yr). The mean annual increase in CH_4 emissions from domestic animals and humans over the years 1966-1986 was 0.6 Tg, or 0.75% per year (Crutzen *et al.*, 1986). For domestic animals alone Crutzen estimated the methane emissions to be 74 Tg/yr. Lerner *et al.* (1988) made a global grid-based database (1° x 1°) on methane emissions from livestock. Emissions of more than 5000 kg/km^2/yr were found in small regions such as the Benelux, Bangladesh, parts of northern India and New Zealand. They found that half the annual global emissions are from only five countries: India, the CIS, Brazil, the USA and China.

Animal waste
Because the quantity of animal waste worldwide is large and because animal waste is composed primarily of organic material, the potential for methane emissions from this source is great. The actual methane emissions are primarily dependent on the management systems. When waste is kept in contact with oxygen or spread on the fields, methane emissions are minimal and degradation produces carbon dioxide immediately. When waste is kept in anaerobic environments long enough, for example, in waste lagoons or collectors, methane production is predominant. It is evident that

methane production from animal waste can be usefully applied. In many countries, like China, methane production is stimulated by adding straw to biogas digesters for a maximum yield of gas for domestic use. Often, these systems are leaky and some of the gas produced is lost.

World methane emissions from animal waste systems were estimated by Cicerone and Oremland (1988) at 65-100 Tg/yr. In 1990 a new estimate was made by Casada and Safley, which was substantially lower. Casada and Safley came to 28.4 Tg/yr for livestock waste and poultry manure. The IPCC (1992) estimated 25±5 Tg/yr.

Methane is a primary decomposition product of the anaerobic degradation of organic material. There are numerous experimentally determined methane yields from animal waste recorded in the literature. Most of these are cited by Casada and Safley (1990). These yields are for livestock and poultry feeding, and management practices found in the United States, Western Europe and China. Lerner *et al.* (1988) investigated the global distribution of livestock methane emissions. It is expected that the emissions from animal waste will exhibit a similar global distribution. Casada and Safley (1990) estimated that if all of the world's livestock and poultry manure were anaerobically digested, 167 Tg/yr of methane would be produced. However, it is estimated that less than 10% of this manure actually undergoes anaerobic digestion. A detailed inventory of waste management systems for each animal waste type could more accurately estimate the methane emissions from livestock waste.

Landfills

Methane emissions from landfills are growing rapidly because of a growing world population, a growing waste generation per capita and growing urbanization, especially in developing countries (Bingemer and Crutzen, 1987). In the developed countries waste is partly dumped in sanitary landfills. Sometimes the waste is isolated from the underlying soil with plastic foils or with bentonitic clay layers. The waste is dumped in so-called compartments isolated from each other at the base. The waste is compacted to reduce the volume. Thus anaerobic decomposition is stimulated in which methanogenic bacteria degrade the organic fraction of the waste. After a compartment is filled the waste is covered with soil or clay.

In rural areas in developing countries waste is mainly dumped in open pits. This waste is usually not compacted. Here, aerobic degradation of the organic fraction dominates. Methane emissions are expected to be low under these circumstances. Sanitary landfills, however, can be found around the cities. A study in India found 0.6 m^3 of gas per hour emitted from wells in a landfill in New Delhi. For this location a theoretical maximum of waste gas was calculated to be between 150-265 m^3/t of municipal solid waste (with 30-50% methane), which is comparable to northern hemisphere potentials (Bhide *et al.*, 1990).

The global emission of methane from landfills and waste dumps is estimated to be 30 Tg/yr (range 20-70 Tg/yr) (IPCC, 1992). Different authors have made world estimates of methane emissions from landfills. IPCC/OECD summarized the methods used for waste gas calculations (OECD, 1991).

Bingemer and Crutzen (1987) used a simple mass balance approach in which an instantaneous release of methane is assumed to enter the atmosphere after landfilling. They assumed all methane produced to be emitted to the atmosphere, so no oxidation is assumed in the soil cover. For developing countries only the urban population was considered, as sanitary landfilling is assumed to occur in urban areas, while open dumping occurs in rural areas. Bingemer and Crutzen came to an estimated methane release of 50 Tg/yr (range 30-70 Tg/yr).Ahuja (1990) introduced a new factor in this method, important in dryer climates in developing countries. For India he assumed

that 31% is wet and 69% is dry refuse. He assumed that the dry refuse could not emit methane. Orlich (1989) and Richards (1990) estimated the emissions for countries on the basis of a regression analysis of waste generated per capita and GNP. The global source thus estimated was 32.7 Tg/yr.

Natural wetlands
In wetlands methane is formed by microbial decomposition of organic matter in the anaerobic zone; this occurs in natural wetlands and agricultural areas. Methane is formed by methanogenic organisms. Aselmann and Crutzen (1989) calculated that 2-7% of net primary productivity in wetlands is emitted as methane; Whiting *et al.* (1991) found a 5% emission from their measurements.

Anaerobic conditions can be found at different places on the Earth's surface: in the soil column of wet soils, under the bottom of shallow lakes, in peatlands, on the continental shelves etc. Above the zone where conditions are strictly anaerobic, an aerobic zone is found. Methane that diffuses upwards is partly oxidized by methanotrophic microbes in this zone. If methane diffuses upwards through a water column most of it is oxidized. The net budget between methanogenesis and methanotrophy determines the site as a source or a sink for atmospheric methane. Apart from diffusive processes, methane can escape by ebullition (emission by bubbles through a water column or the stems of reed, rice and other water plants in marshes, lakes, shallow lagoons etc.). In swamps and rice paddies most of the net emissions are from bubbles or stem flow (up to 90% of the emissions). In salty sediments and in the presence of sulphate, practically no methane is formed.

Global analyses have been made by various authors (e.g. Aselmann and Crutzen (1989); Matthews and Fung (1987). Aselmann and Crutzen (1989) used average values for methane in the range of 15-300 mg/m^2 per day and calculated a global emission of 40-160 Tg/yr. Matthews and Fung used values in the range of 30-200 mg/m^2 per year. Aselmann and Crutzen also give a methane emission as a fraction of primary production. Assuming that 2-7% of NPP is emitted as methane, the global emission would be 75-420 Tg/yr. The IPCC, (1992) estimates a total source strength of 115 (range 100-200) Tg CH_4/yr.

Wetland rice paddies
Emissions from rice are related to the period that the paddies are flooded. Calculations of the world methane emissions from rice have shown different outcomes because of a lack of data concerning the area under irrigated, rainfed, deep-water and upland rice. Only the irrigated rice has significant emissions. FAO statistics on harvested area of rice are not subdivided into different systems. The IRRI (1988) has information on the area of wetland rice. Only 80.10^6 million ha. harvested wetland rice are potential sources of methane. Neue *et al.* (1990) estimated a global emission of only 25-60 Tg/yr compared to 40-160 Tg/yr as estimated by Matthews and Fung in 1987. Matthews *et al.* (1991) did not attempt to make an update of their 1987 estimate. Instead they evaluated the temporal and spatial distribution of emissions from a hypothetical annual source of 100 Tg methane.

Neue *et al.* (1990) in their analysis considered the major rice ecologies (irrigated, rainfed, deep-water and upland) of the global rice area harvested in 1988. They also considered soil factors, like temperature, texture, redox potential, acidity and salinity, controlling the emissions in their analysis. They assumed an average methane emission of 200-500 mg/m^2 during an average growing season of 130 days. First, second and third crops in rice have average growing seasons of 120, 110 and 80 days, respectively (OECD, 1991).

Biomass burning
Recently, biomass burning and land-use changes have been recognized as important sources of methane, especially in countries with deforestation and savanna burning. Methane emission from biomass burning depends on two parameters: the amount of biomass burned and the emission factor for each ecosystem and each type of burning. Methane is emitted especially during smoldering combustion. This means that emission factors are higher for forest fires and firewood combustion than for savanna fires or agricultural waste burning. During the eighties many research campaigns were conducted, especially in the tropics, to study trace gas and partical emissions from vegetation fires in different ecosystems. Several books were published with information overviews on biomass burning and its atmospheric and ecological consequences (Goldammer, 1990 and Levine, 1991). Whatever the type of combustion, the main compound emitted is CO_2. The methane emission is expressed relative to CO_2 emissions. The emission factor is highest in smoldering fires. The total global emission is estimated by the IPCC to be 40 (range 20-80) Tg/yr.

Minor biogenic sources
In addition to the major anthropogenic sources influenced by human activities mentioned above, several less important sources can be distinguished. Under anaerobic conditions, methane is released during domestic sewage treatment. This applies to wastewater lagoons and other anaerobic treatment methods. IPCC estimated this source to be 25 Tg/yr worldwide. The emissions are predominantly expected in warmer countries. In some industrialized countries the methane is captured and used in the sewage treatment process. Another minor source of methane is found in termites, where methane is formed in the hind gut. Difficulties arise in estimating the termite biomass on earth. The IPCC estimates that termites emit 20 (range 10-50) Tg/yr. A change in termite population may be a function of landuse changes, for example, savanna turned into permanent agricultural areas.

3.4 Forest soils acting as methane sinks

Atmospheric methane is taken up by well-drained soils (Crill, 1991; Mosier *et al.*, 1991; Whalen *et al.*, 1991; Steudler *et al.*, 1989; Keller *et al.*, 1986). Crill (1991) found an annual methane consumption of 600 mg/m^2 and a carbon dioxide production of about 2 kg/m^2 in temperate woodland soils. Whalen (1991) found an annual methane consumption of 0-63 mg/m^2 taiga; this comsumption is smaller than the previous boreal forest measurements of Steudler (1989). Taiga has even been considered a source of methane by Matthews and Fung (1987) and by Sebacher *et al.* (1986), because of high bog and fen emissions. High resolution databases will be needed to estimate the actual temporal and spatial distribution of the methanogenic and methanotrophic soil sites.

Steudler *et al.* (1989) summarized measurements of methane consumption in different ecosystems. More recent measurements of methane consumption were reported by Crill, 1991 and Whalen *et al.*, 1991. Since Harriss *et al.* first published direct measurements of methane uptake by forest soils in 1982, more knowledge has been gained about the processes involved. Remarkable is that the most rapid rates, from Alaska to the Amazon, seldom exceed 6 mg/m^2 per day, which is 2190 mg/m^2 per year. In temperate climates temperature plays a role mainly in the spring when microbial populations and gradients become established after the spring thaw. Temperature is less important once the oxidizing system becomes diffusionally controlled. This means that oxidation is faster than the supply of methane from the atmosphere into the soil. If methane oxidation is limited by diffusion for more than six months, soil texture and moisture are important. Higher fluxes were observed in sandy soils. Soil moisture acts as a barrier to diffusion and increases the degree of anaerobiosis. As microsites become anoxic, the balance shifts towards methane production (Crill, 1991).

Worldwide consumption of methane by soils has been estimated by different authors. The IPCC (1992) summarized these estimates. Soil consumption is about 30 (15-45) Tg/yr. Methane oxidation also appears to be influenced by nitrogen deposition rates. Different authors observed reduction of methane uptake in fertilized forest soils and in grazed and fertilized pasture (Crill, 1991; Keller *et al.*, 1990; Mosier *et al.*, 1991; Steudler *et al.*, 1989). There are observations that nitrifying bacteria are capable of oxidizing methane (Crill, 1991). Competitive interactions between different groups of organisms in the soil are possible.

3.5 Conclusion

The global budget is still uncertain. The major sources of methane are: oil and gas production and distribution, coal production, enteric fermentation in ruminants, animal waste, landfills, natural wetlands, wetland rice and biomass burning and smoldering. Consumption of methane by soils is relatively small.

4. OPTIONS FOR REDUCTIONS OF METHANE EMISSIONS: GLOBAL ESTIMATES

4.1 Introduction

Methane reductions can significantly further the aim of reducing global warming. In 1990 methane was responsible for 13% of the total global warming impact of all greenhouse gases, making it the second most important of the greenhouse gases. Carbon dioxide was responsible for 61% and the CFCs 11% (based on GWPs integrated over a 100-year time horizon (IPCC, 1990)). The anthropogenic emissions are relatively large: more than 60%. For several anthropogenic sources the possibilities for reducing methane are many. Compared to the other greenhouse gases, methane has a relatively short lifetime in the atmosphere. Along with a high specific warming potential (the GWP of methane is 11 times that of carbon dioxide for a 100-year or 35 times for a 20-year period), this means that reductions of emissions have a relatively large effect in a relatively short period of time. With the phasing out of CFC emissions by the year 2000 methane reductions will have relatively even greater effects.

Therefore methane provides important policy options for overall greenhouse gas reductions. As discussed in Chapter 2, reductions of 10 to 20% are necessary in order to stabilize the atmospheric concentration in the next few decades (Rotmans *et al.*, 1992). The exact reduction necessary for atmospheric stabilization of the methane concentration depends on the emissions of other gases that play a role in atmospheric methane chemistry.

For policy makers at national and international levels it is interesting to have an idea about the regional potentials for methane emission controls that can be evaluated against controls for the other greenhouse gases like CO_2. In this chapter regional potential reductions have been calculated. Knowledge on regional differences is important in the negotiations about response strategies in the Framework Convention on Climate Change. Emission scenarios for methane over the period 1990-2100 were published by the IPCC (1992). The results for the period up to 2025 have been used in this chapter to estimate potential regional reductions in the coming future. The USEPA has estimated global reduction potentials. This work has been used as a starting point.

4.2 Reduction potentials on the global scale

Methane emissions are partly natural, partly anthropogenic. The anthropogenic sources, like fossil-fuel production and use, landfills and wastes, have large potentials to be reduced. A carbon dioxide control policy aiming at reducing fossil fuel combustion and deforestation will have the reduction of methane emission as a side-effect. In addition, specific cost-effective reductions of methane emissions are possible since methane from these sources can be recovered and used as an energy carrier. Generally, these options are in line with traditional technological emission reduction methods with add-on technology or process changes. Thus, these may be less controversial than addressing basic human activities such as fossil fuel combustion and land conversion requiring major revisions of production and consumption structures. Lashof made an inventory of possible reductions of emissions from the different sources worldwide (Lashof, 1991). After his inventory, the IPCC revised the global budget because new information had become available (IPCC, 1992). Emission estimates from coal, oil and gas were revised upwards and thus absolute reduction potentials from coal, oil and gas may therefore even be higher than estimated by Lashof. The EPA produced a report within the US/Japan Working Group on Methane on technological options for reducing methane emissions (EPA, 1992). Detailed information is now available on the quality of the measures. Table 4.1 summarizes the opportunities worldwide for reduction according to the EPA. Below, the different options will be briefly discussed, after which a preliminary regional assessment of methane control options is presented.

Table 4.1. Technological options for reducing methane emissions from different source-sectors

Source strategies	Current emissions (Tg CH_4/yr)	Methane reductions potential (%)	Availability of technique	Capital needs
Coal mining	50	30-90		
-Gob-well recovery			now	low
-Pre-mining degasification			now	medium/high
-Ventilation air use			demonstration	low
-Integrated recovery			now	medium/high
Oil and natural gas	50	20-80		
-Flaring			now	low
-Compressor operation			now	medium
-Detection/repair			now	low/medium
-Low-emission technologies			now	low
Enteric fermentation	80	25-75		
-Feed processing			now	low/medium
-Strategic supplementation			now	low
-Production enhancing agents			now	medium
-Genetic improvement			now	medium
-Reproduction improvement			now	medium
Animal waste	25	25-80		
-Covered lagoons			now	low/medium
-Advanced digesters			now	medium
Rice cultivation	60	10-30	after 2000	low
Landfills	30	50-90		
-Recovery			now	medium
-Organic waste reduction			now	low/medium
-Waste reduction			now	low/medium
Waste water	25	up to 80	now	low/medium
Biomass burning	40	unknown	demonstration	

Source: EPA, 1992 (EPA, US/Japan Working Group on Methane)

4.3 Options for methane control by source category

Coal mining

Two options are available to reduce methane emissions from coal mining. Less coal could be produced, or the methane releases during coal mining operations could be avoided or captured. The first option may include a fuel shift to other fuels, or the closing down of gassy mines, in favour

of mining less gassy coals. In addition, there are many technological options to preventing the release of methane during mining operations or using the gas for energy purposes.

Techniques for removing methane from the mine have been developed primarily for safety reasons. These techniques have been adapted in some places to recover methane so that the fuel is not wasted. Methane emissions from particularly gassy mines can be reduced by 70% with available techniques. Benefits of most techniques are improved safety in the mines and the use of an otherwise wasted clean energy source. If additional techniques become available even 90% can be recovered. The following techniques are promising in coalbed methane abatement:

- Enhanced gob-well recovery: the recovery of gas that is emitted in the area of the mine where the roof has collapsed after coal extraction. If this gas is removed before entering the mine, ventilation can be reduced.
- Pre-mining degasification: the extraction of gas before the coal is mined. This can be done from the surface or inside the mine. When using surface drilling there is an increased recovery of the gas. This technique is, however, more expensive.
- Ventilation air use: air can be used for combustion in turbines or boilers. This technique can be in the demonstration stage by 1995. The vented air is extremely dilute, with less than 1% methane.

Oil and natural gas
Just as for coal mining, emissions of methane from oil and natural gas can be reduced in two ways: reduction of gas and oil use or prevention of the emissions. The first includes decreased energy demand and fuel shifts away from fossil fuels.

Technical options to prevent or capture emissions are numerous. Methane emissions result from the various stages in gas and oil production. Reductions are possible using new techniques, but also by improved inspection and maintenance. The following technical options are most feasible in methane reduction:

- Reduced venting and flaring. This results in a higher efficiency of the fuel use. Unused gas can also be reinjected to keep the field under pressure. Improvements can be made to reduce the losses of wells under development.
- Improved compressor operation. This can reduce the methane emission and improve the efficiency of the machines. Using gas turbines instead or diesel engines to power compressors can reduce methane emissions, as well as emissions of other pollutants, such as carbon monoxide and nitrogen oxides. Gas that is vented during shut-downs and start-ups might be captured and reused.
- Leak detection and pipeline repair. This can be intensified, especially in newly constructed areas. New corrosion-resistant materials can be used with the replacement of old systems.
- Low-emission technologies and practices can be pursued. These include low-bleed or no-bleed devices. Fugitive emissions can be reduced using automatic shut-off valves and 'smart meters' that detect sudden or abnormally high gas use. Investments using these technologies in Eastern Europe and the former Soviet Union might be especially important in reducing emissions. This can be pursued through the Energy Charter.

Ruminants
Again, methane emissions from this source can be decreased by reducing the activity level or decreasing the methane per unit of activity: in other words, either the consumption and production of animal products can be reduced, or the emission per animal.

The first option would imply discouraging the consumption of primarily dairy products and beef. In developed countries overconsumption of these products may provide a basis for such a discussion. Overproduction of dairy products has led to a milk quota in the Netherlands, which has unintentionally prevented increased methane emissions. In developing countries this will not be easy or even desirable as subsistence farmers cannot be denied the possession of one or two cows as long as no alternative production systems are within reach and dairy products and beef can provide an attractive addition to the basic diet.

Reduction of the emissions per unit of product is thus an easier and more traditional approach to control emissions from this source. Typically, from 4 to 9% of Gross Energy Intake (GEI) is lost through methane production. This methane loss can be seen as the price the ruminant pays for being able to consume fodder that otherwise cannot be utilized. The methane production in ruminants is dependent on feed quality and quantity. Higher intake and higher quality feeds are associated with increased rumen activity, and therefore a higher absolute level of methane production (kg methane per head per year). Higher intake and higher quality feeds result in better growth, productivity and reproduction. This means that relative methane production (kg methane per unit of produce) is lower. All measures that improve efficiency in production, including animal welfare and preventive health care are contributing to methane reductions per unit of produce. Some of the options, such as bio-engineering and supplemention of chemical agents can be controversial in many countries. The feasibility of such options is dependent on public and political preferences.

In developing countries similar productivity improvements have not yet been made. Strategies for reducing methane emissions from ruminants in these countries should increase productivity using local breeds, be cost effective and be consistent with local traditions and systems of production.

Recognized technical options for methane reductions in ruminant livestock are:

- Improved nutrition through mechanical and chemical feed processing.
  This option is applicable to accessible ruminant animals with limited feed resources. Assuming that feed digestibility is increased by 5%, methane emissions per unit produced may decrease by 10 to 25%, depending on management practices. Different options include alkali/ammonia treatment of low digestibility straw, and chopping of low digestibility straw and wrapped rice straw (Leng, 1991).
- Improved nutrition through strategic supplementation.
  Improved rumen function may reduce methane emissions by about 5 to 10%. Emissions per unit product may be reduced by 25 to 75% due to increases in productivity. Options include: molasses/urea blocks with or without bypass protein (short-term) and rumen bio-engineering (long-term) (Leng, 1991).
- Productivity enhancing agents.
  Agents that have been used include bovine somatotropin (BST) and anabolic steroids. BST is a naturally occurring growth hormone that with recombinant DNA techniques can now be synthesized in large quantities. BST can improve lactation by 10 to 20%. This option is not acceptable in Europe. Anabolic steroids can improve feed efficiency but were recently banned in the EC.
- Breeding programmes.
  This option includes crossbreeding in developing countries and genetic improvement in dairy cattle. Dairy countries have significant breeding programmes in place. Detailed recording systems are used to assess the genetic potential of cows and bulls. Embryo techniques can accelerate improvements.
- Improved reproduction.

Large numbers of ruminants are maintained for the purpose of producing offspring. Methane emission per unit product can be significantly reduced if the reproductive efficiency is increased. Options include reduction of time to maturity by improved feeding, twinning, artifical insemination and embryo transplantation, so that each cow becomes pregnant once a year.

Animal waste

Reduction of numbers of domestic animals obviously would reduce the associated methane emissions. Technological options include changes in livestock management and in waste handling. Waste management systems that store the manure under anaerobic conditions for long periods or in relatively warm places, such as lagoons and stables, are the major contributors to methane emissions. Emissions from animal waste can be used as an energy source. For policy development on methane prevention from manure handling there are essentially two methods. The first is to reduce emissions. The second is the opposite: fermentation can be enhanced in digesters with the aim of utilizing the biogas, thereby preventing emissions to the atmosphere and substituting part of fossil-fuel use with biogas use.

Examples of the first option are the covering of manure storage structures and appropriate design of stables. Covered silos are widespread in the Netherlands since this has become compulsory to avoid ammonia emissions. The anaerobic conditions usually result in significant methane emissions. Covering the silo and capturing methane for energy use can reduce emissions. Where there are poor stable systems, one can reduce emissions by storing the waste outside under low temperatures. Especially for pig breeding new stables can reduce emissions and improve living conditions for the animals.

Much experience has been gained to support the use of the second technical option: stimulating manure fermentation for biogas production. For instance, research has become available from NOVEM on manure digesting systems in the Netherlands (Van Nes *et al.*, 1990). These work on different levels; the farm level and a regional centralized level. Centralized manure handling systems are being developed. In Denmark there is more experience with privately owned centralized biogas plants. Evaluation of the performance of nine plants (Breinholt, 1991) has led to the following important conclusions: The slurry must be supplemented with 15% of other easily digestible organic waste to become profitable under prevailing technical and economic conditions. The biogas produced must receive a price at the level of the price paid for natural gas by ordinary consumers. Plants must be situated in areas where a reasonable amount of manure is available because transportation costs weigh heavily on operations. Plants must produce combined heat and power. Plants must receive income from organic waste treatment.

Landfills

The easiest way to prevent methane emissions from landfills is to avoid landfilling of organic waste, for example, by separately collecting and handling organic waste or by preventing the production of organic waste. Because of the problems with siting landfills and the various environmental problems associated with them, these solutions will have top priority in many countries. In some countries garden-, fruit- and kitchen waste (GFK) is collected separately. In the Netherlands the aim is to collect 1 million tons/yr by 1995. Most of this quantity will be composted, By 1995 at most 100.000 tons can be digested anaerobically. As digesters are relatively leak free, all the organic waste might be digested by 2020 and, so, reduce emissions from waste and recover the biogas. With this option fossil-fuel use can also be reduced. In many countries waste incineration is used to reduce the amount of the waste to be landfilled.

Even if part of the GFK waste is collected separately, landfills will still contain some organics

from paper and wood. After landfilling the remaining organic waste, emissions can be controlled in several ways. Methane emissions from landfills can be reduced by 50-90%. Methane recovery is practised in many countries but the methods are not yet perfect. Most methane is formed during the first years in a landfill. In this stage recovery is usually not practised. Most landfills are later on covered with permeable soil layers. Methane recovery may be practised from the early stages of the landfill. Impermeable covers can be used. New techniques can be developed or put into practise to enable recovery of the gas from the bottom of the fill from the early stages of the landfill onwards.

Waste water treatment
The best option is to recover the waste gas during the treatment proces. In some countries experience exists with recovery methods.

Rice
Research has recently revealed that methane emissions from wet rice can be decreased through multiple drainage of the fields during the growing season to keep down the reducing capacity of the soil. This option is of course only relevant in regions where enough water upstream is available to flood rice fields again after drainage. This option is more valid for Southeast Asia than for many other regions. Another option is the continuous percolation of water over the fields. This measure keeps methane emissions low as a result of methane oxidation in the water. Other options are related to soil characteristics. Methane emissions are high in peat soils and in soils where straw has been incorporated. Methane emissions can be curtailed by reducing the organic matter content of the soils. Peat soils might be used for other purposes to reduce methane emissions.

Biomass burning
Reductions of methane emissions from biomass burning can best be achieved by a reduction of burning practices. Biomass is a valuable resource. Management and control of biomass burning is needed to improve the effectiveness and efficiency. The introduction of improved cooking stoves for example can help improve the fuel efficiency of households. Another option might be to promote the development of industrial charcoal production to improve the possibility that the gaseous compounds are recovered and used. This might reduce the squandering of the forests and at the same time introduce a renewable energy source at the city level. The promotion of charcoal as a relatively clean fuel would have the extra advantage of reducing air pollution from wood burning.

4.4 Regional reduction options for methane, 1990-2025

The distribution of the methane emissions in the different regions of the world can be assessed from international studies, as summarized by IPCC; IPCC (1990; 1992). Table 4.2 gives an overview of these emissions for 1990-2100 under the IPCC scenario, 1992a. This is a 'no climate policies' scenario. The distribution of emissions over the different regions is calculated using the distribution of methane emissions from international studies as summarized by the IPCC (1992). These regional emissions have to be checked in the near future with data from country studies.

Table 4.2. Regional methane emissions under IPCC scenario 1992a (no climate policy)

CH_4 (Tg)	COAL MINING Emission					OIL & GAS Emission				
	1990	2000	2025	2050	2100	1990	2000	2025	2050	2100
World	39	44	54	64	84	37	42	52	62	82
North America	8	10	12	14	18	6	7	9	11	14
Europe	4	4	5	6	8	4	4	5	6	8
Pacific-OECD	2	2	2	3	4	0	0	1	1	1
Eastern Europe	7	8	10	12	16	13	15	18	22	29
Asia	15	17	21	25	33	6	7	8	10	13
Latin America	0	0	0	1	1	3	4	5	6	7
Africa	2	2	3	3	4	4	5	6	7	9

CH_4 (Tg)	WET RICE Emission					LIVESTOCK Emission				
	1990	2000	2025	2050	2100	1990	2000	2025	2050	2100
World	60	66	78	87	84	84	99	138	173	198
North America	1	1	1	1	1	8	9	12	16	18
Europe	0	0	0	0	0	9	11	16	19	22
Pacific-OECD	1	1	1	2	2	4	4	6	8	9
Eastern Europe	0	0	0	0	0	9	10	15	18	21
Asia	55	61	72	80	77	28	33	46	57	66
Latin America	1	1	1	1	1	16	19	26	33	38
Africa	2	2	2	3	2	11	13	18	22	25

CH_4 (Tg)	SOLID WASTE Emission				
	1990	2000	2025	2050	2100
World	38	42	63	93	109
North America	15	17	26	38	44
Europe	8	9	13	19	22
Pacific-OECD	3	3	5	7	8
Eastern Europe	4	4	6	9	11
Asia	6	6	9	14	16
Latin America	1	1	1	2	2
Africa	2	2	3	4	5

Distribution of emissions per region from calculations in the present study.

An inventory of possible reduction options per region has led to regionally specific mixes of options. Table 4.3 presents a tentative assessment of methane reduction potentials per sector per region, based on the global reduction potentials of the EPA and an assessment of a regional break-down of potential made in this study. An assumption was that large reductions are possible in either a large economic activity in a sector or large emissions per unit product. In the non-OECD countries large potentials were assumed to reduce the emissions per unit product. As these reducti-

ons have often already taken place in the OECD countries, the reduction potentials in Table 4.3 in the non-OECD countries were assessed to be higher.

Table 4.3. Tentative assessment of technically possible methane reduction potentials (% of emissions in kton/yr) per sector per region

	Oil & gas	Coal	Livestock	Landfill	Wet rice
World	20-80	30-90	25-75	50-90	10-30
North America	30	30	25	90	10
Europe	30	30	25	90	0
Pacific-OECD	30	30	50	90	10
Eastern Europe	80	80	50	70	10
Asia	80	90	50	50	30
Latin America	50	50	75	50	10
Africa	80	90	75	50	10

Sources: EPA, 1992; Lashof, 1991; present study.

4.5 Conclusions

These reduction potentials can only be achieved if appropriate policy instruments are developed and implemented. We assessed the reductions under the assumption that the potential reductions would be achieved by 2025. The results are given in Table 4.4. The total world emissions in this table are from the IPCC, 1992 (base scenario IS92a). The assumption was made that the distribution of unabated regional emissions would not change over the years until 2025. The results show that emissions can theoretically be greatly reduced: for the five source categories of Table 4.4, which cover more than 70% of the world's anthropogenic emissions, more than 50% of the projected 2025 emissions could be avoided, or the current emissions could be reduced by almost 40%.

In developed countries the potential reductions are high in the waste sector and lower in livestock and fuels. In developing countries the potential reductions are high in the fuel sector and lower in livestock and rice.

The overall emission reduction potential in both industrialized countries and developing countries is estimated to be of the same order of magnitude. This could be higher than 50% by 2025 compared to projected levels, or about 40% compared to current levels.

Table 4.4. Methane from anthropogenic sources from 1990-2025 (no climate policies) and reduction potentials under the Balanced Growth scenario (maximum climate policy)

CH4 (Tg)	COAL MINING Emission without reduction 1990	2000	2025	Reduction %	Balanced Growth 2025
World	39	44	54		18
North America	8	10	12	30	8
Europe	4	4	5	30	4
Pacific-OECD	2	2	2	30	2
Eastern Europe	7	8	10	80	2
Asia	15	17	21	90	2
Latin America	0	0	0	50	0
Africa	2	2	3	90	0

CH4 (Tg)	WET RICE Emission without reduction 1990	2000	2025	Reduction %	Balanced Growth 2025
World	60	66	78		56
North America	1	1	1	10	1
Europe	0	0	0	0	0
Pacific-OECD	1	1	1	30	1
Eastern Europe	0	0	0	10	0
Asia	55	61	72	30	50
Latin America	1	1	1	10	1
Africa	2	2	2	10	2

CH4 (Tg)	SOLID WASTE Emission without reduction 1990	2000	2025	Reduction %	Balanced Growth 2025
World	38	42	63		13
North America	15	17	26	90	3
Europe	8	9	13	90	1
Pacific-OECD	3	3	5	90	0
Eastern Europe	4	4	6	70	2
Asia	6	6	9	50	5
Latin America	1	1	1	50	1
Africa	2	2	3	50	1

Table 4.4. Continued..

CH4 (Tg)	OIL&GAS Emission without reduction 1990	2000	2025	Reduction %	Balanced Growth 2025
World	37	42	52		19
North America	6	7	9	30	6
Europe	4	4	5	30	4
Pacific-OECD	0	0	1	30	0
Eastern Europe	13	15	18	80	4
Asia	6	7	8	80	2
Latin America	3	4	5	50	2
Africa	4	5	6	80	1

CH4 (Tg)	LIVESTOCK Emission without reduction 1990	2000	2025	Reduction %	Balanced Growth 2025
World	84	99	138		54
North America	8	9	12	25	9
Europe	9	11	16	25	12
Pacific-OECD	4	4	6	50	3
Eastern Europe	9	10	15	50	7
Asia	28	33	46	75	11
Latin America	16	19	26	75	7
Africa	11	13	18	75	4

Source: IPCC, 1992, and distribution per region according to this study

Table 4.4 shows that impressive methane reductions are theoretically possible and that each continent can make its own contribution to the reduction of global warming. In coal mining the greatest methane emission reductions can be made in Eastern Europe and Asia. In wet rice production reductions can be made in Asia. In the solid waste sector the extra methane recovery can lead to a significant reduction of methane emissions in North America and Europe. In the oil and gas sector Eastern Europe can make its greatest contribution to methane emission reductions through technological improvements in the system of production, transport and distribution. In livestock the greatest methane emission reduction is possible through improved productivity in Eastern Europe, Asia, Latin America and Africa, and in reduced production and consumption of beef and dairy products in OECD countries.
In the animal waste and biomass burning sector the uncertainties are so large that at this moment no reduction potentials have been calculated.

5. IPCC PROGRAMME ON GUIDELINES FOR NATIONAL EMISSION INVENTORIES

5.1 Introduction

Working Group 1 of IPCC is currently undertaking a Programme on Guidelines for National Inventories of Greenhouse Gas Emissions and Sinks. In this programme a common basic methodology has been developed to serve as guidelines for national inventories for national and international policy evaluation. A common methodology is, for instance, needed for national estimates of greenhouse gas emissions to be used in international negotiations for a policy response to climate change. This includes the reporting necessary under the conditions of the United Nations Framework Convention on Climate Change (UN, 1992). From the scientific perspective, a bottom-up approach for methane, adding national inventories, can be compared with the 'top-down' global budget, derived from the analysis of atmospheric chemistry, to identify discrepancies and the associated gaps in knowledge. These can be used for setting research priorities.

In the field of global climate change and climate change policy, reliable data on sources and sinks of greenhouse gases are crucial. Several countries have estimated their emissions of greenhouse gases, and submitted this (preliminary) material to the IPCC National Greenhouse Gas Emission Inventories Programme. The IPCC/OECD published provisional guidelines with recommended methods based on an experts' workshop in February 1991 (OECD, 1991a). In a second IPCC/OECD workshop, the Methodology for Inventories (December 1991), the importance of intercomparison studies of existing detailed inventories was recognized as a priority (OECD, 1991). This intercomparison would contribute to the intended international agreement on the methodology, to be ready by mid-1993. In February 1-5, 1993 an expert workshop was organized in Amersfoort, The Netherlands, to further this expert agreement (Van Amstel, 1993). Data from the various countries can only be used on a global level when they have been compiled in a common framework for reporting and using a transparent methodology for calculation. However, the present version of the methodology is not perfect yet and countries have not always used the same recommended methods.

The IPCC/OECD has therefore taken the initiative for a preliminary in-depth review study involving inventories of countries selected submitted to the IPCC/OECD. The study, carried out by the OECD in cooperation with the National Institute for Public Health and Environmental Protection (RIVM) of the Netherlands and the Institute for Environmental Studies of the Free University in Amsterdam (OECD, 1992), focused on the following greenhouse gases: CO_2, CH_4 and N_2O. This chapter summarizes the aspects of the study as far as it relates to methane.

5.2 Objective

The review study concerned a selection of existing national inventories. The aim of the research was to identify differences in applied methodologies, assumptions and emission factors for estimating and reporting greenhouse gas emissions. Only those studies which reported on all of these aspects could be reviewed. The study included a simple summary report on the quality of the submitted data.

5.3 Method and scope

The focus of the review study was on the differences in the outcomes as a result of differences in methods used and emission factors applied in the national inventories. Data on activities used by countries were checked against internationally available statistics. The available country reports

were evaluated, starting with the reports containing the most extensive description of the methods (i.e. Australia, Belgium, Canada, Denmark, The Netherlands, Sri Lanka, the United Kingdom and the United States). Meanwhile, a letter was sent to other countries, who had submitted less detailed reports to the IPCC, to ask them for more background information. Contacts with the actual researchers have been established in order to clarify uncertainties and retrieve missing information. As a result some miscalculations could be rectified and other problems could be solved. Later, the reports of Norway, Poland and the former USSR (the latter not an official submission to the IPCC) could also be evaluated.

5.4 Preliminary results

Comparison of emissions
Most OECD and some other countries have so far contributed to the IPCC initiative to compile national emission inventories of greenhouse gases. Table 5.1. summarizes the totals and sources. In Table 5.2 preliminary national emission estimates of methane from these countries are compiled, along with the per capita emissions and the country's share of the global emission as a percentage. The 1988/90 total for the countries represented is 101 Tg/yr, while the estimated world total for net anthropogenic methane emission is 335 Tg/yr (excluding sewage treatment on which countries did not report) (IPCC, 1992). In this way 30% of the global total emissions are represented. The countries represented cover 25% of the Earth's land area, 20% of the world's population and about 50% of global GNP. Recently an attempt has been made to calculate methane emissions from selected source categories for most countries in the world using IPCC recommended methodology (Subak *et al.*, 1992). When comparing outcomes with the national submissions at the source-sector level large discrepancies are found. This means that the methods and assumptions used in the top-down calculations still differ from those used in the bottom-up country inventories. Preliminary evaluation of the information on the national emission inventories suggests that some countries may have underestimated their emissions from landfills and overestimated their livestock emissions. The estimates of emissions from coal, oil and gas are in reasonable accordance with other published estimates.

The national totals of some of the countries in the tables presented have not yet been evaluated, so these might not be totally comparable due to differences in sector definitions, methods applied and assumptions. Some countries provided background information on activity levels, emission factors, methods and assumptions. For these countries the national totals could be differentiated in emissions per comparable sector. The results are given in Table 5.3.

Table 5.1. National net anthropogenic methane emissions (Tg/yr) from OECD countries and a few others

Country	Year	Methane	Source
Australia	1988	5.426	Australia, 1991
Belgium	1990	0.362	Van Rensbergen and Debruyn, 1991
Canada	1990	2.942	Jaques, 1992
Denmark	1989	0.645	Fenger *et al.*, 1990
Finland	1988	0.250	Boström *et al.*, 1992
Germany	1989	3.100	Weber, 1991
Italy	1989	2.500	ENEA, 1991
Japan*	1988	0.540	Japan, 1990
Netherlands	88-90	0.831	Van den Born *et al.*, 1991
New Zealand	1988	1.700	Von Dadelszen, 1991
Norway	1989	0.322	Rypdal, 1992
Poland	1988	1.543	Cofala and Klimond, 1991
Sweden	1990	0.460	Swedish, 1991
Switzerland	1988	0.240	Switzerland, 1991
Thailand*	1988	0.616	Sungsuwan and Buranasajja, 1990
United Kingdom	1988	3.433	Munday, 1990
United States	1988	33.000	United States
Former USSR*	1988	43.000	Andronova and Karol, 1992

* Not an official government submission to IPCC/OECD, result of independent research.

Table 5.2. Methane emissions from selected countries

Country	Year	Emission Tg/yr	Population (million)	Per cap. em. (kg)	Land area (km2)	Emission (kg/km2)	GNP $US (million)	Emission (kg/mio $US)	Share: world emission (%)
Australia	87-88	5.426	16.87	322	7617930	712	242131	22409	1.6
Belgium	1990	0.362	9.85	37	30250	11967	162026	2234	0.1
Canada	1990	2.942	26.52	111	9220970	319	500337	5880	0.9
Denmark	1989	0.645	5.14	125	42370	15223	105263	6128	0.2
Finland	1988	0.250	4.98	50	304610	821	109705	2279	0.1
Germany	1989	3.100	77.57	40	349470	8871	1432459	2164	0.9
Italy	1989	2.500	57.06	44	294060	8502	871955	2867	0.7
Japan	1988	0.540	123.46	4	376520	1434	2920310	185	0.2
Netherlands	88-90	0.831	14.95	56	33920	24499	237415	3500	0.2
New Zealand	1988	1.700	3.39	501	267990	6344	39437	43107	0.5
Norway	1990	0.322	4.21	76	306830	1049	72028	4470	0.1
Poland	1988	1.543	38.42	40	304450	5068	66974	23039	0.5
Sweden	1990	0.460	8.44	55	411620	1118	184230	2497	0.1
Switzerland	1988	0.240	6.61	36	39770	6035	197984	1212	0.1
Thailand	1988	0.616	55.70	11	510890	1206	64437	9560	0.2
United Kingdom	1988	3.433	57.24	60	241600	14209	834166	4115	1.0
United States	1988	33.000	249.22	132	9166600	3600	5237707	6300	9.9
Russia	1988	43.000	288.60	149	22272000	1931	2659500	16168	12.8
Total represented countries		100.910	1048.23	96	51791850	1948	15938064	6331	30.1
World total	1990	335.000	5292.20	63	131288410	2552			100.0

Source: National inventories and calculations from this study

Table 5.3. Methane emissions per sector from selected countries

Methane kton/yr	Australia 1988	Belgium 1990	Canada 1990	Denm. 1989	Neth. 1988/90	Norway 1989	Poland 1988	Sri Lanka 1988/89	UK 1988	USA 1988	F. USSR 1988	Total repr.	World 1990	Share: (%)
Energy combustion	263	5	7	42	12		34					364		
Production gas and oil		39	288	9	153	23	128		564	1991	19000	22194	50000	44
Production of coal	577	15	143	16		6	968		992	7456	12000	22172	50000	44
Transport	94	16	23	7	8		8	1	21	216		394		
Enteric fermentation	2793	169	648	136	378	70		193	1140	6238	12000	23764	80000	30
Animal waste	522	115	330	125	15	70		9		3930		5116	25000	20
Flooded rice fields	20							407		781		1208	60000	2
Landfills	666	2	1406	310	260	153	405	122	716	1150		5189	30000	17
Land use change								16				16		
Biomass burning	492		80					12				584	40000	1
Industrial processes		2			4							6		
Total methane emission	5426	362	2924	645	831	322	1543	759	3433	21761	43000	81006	335000	24
Population (millions)	17	10	27	5	15	4	38	17	57	249	289	728	5292	14
Emission (kg CH4 per capita)	322	37	110	126	56	77	40	44	60	87	149	111	63	176

Source: National inventories and OECD (1993)

From table 5.3 it is clear that not all sectors have been reported on by the different countries. Furthermore, some large emission factor differences were found that have to be discussed in expert groups.

However, from comparison with other published data, like that of the World Resources Institute (1992) and the data from Subak *et al.* (1992) some conclusions can be drawn. The preliminary data represent 30% of the world anthropogenic emissions, 20% of the world population, 25% of the global land cover and about 50% of the world GNP. The mean per capita emission for these countries is 96 kg/yr, while the world per capita emission is estimated at 63 kg/yr. The per capita emissions in the countries respresented ranges from 37 kg per capita (Belgium) to 501 kg per capita (New Zealand). The mean per unit area emission in the countries represented is 1948 kg/km^2, while the world average is 2552 kg/km^2. Densely populated countries have the highest per unit area emissions. The mean emission per unit GNP for the countries represented is 6331 kg/million $US. The sparsely populated and poorer countries have the highest per unit GNP emissions. This might be due to hight soil emissions and burning emissions.

The submissions, which should improve in the near future, will cover all relevant source categories, and calculation methods will become more comparable. As more countries make official submissions to the IPCC a more thorough comparison with top-down calculations will become possible.

Comparison of emission factors
In Table 5.4. the emission factors from the submissions of the countries reviewed are given.
This table shows that emission factors differ per source category. In oil and gas production the differences are explained by the fact that few measurements have been made on venting and leaking in this sector. The few measurement results have led to different estimates. In enteric fermentation emission factors are comparable and can be traced back to the work of Crutzen *et al.* (1986). No agreement has yet been reached on emission factors for methane from animal waste because of the many variables involved. These include methane production potential, waste management, temperature and period of storage. In flooded rice cultivation, methane emission factors are dependent on rice ecologies like length of growing season, length of period that fields are flooded, etc. Country and region-specific emission factors will evolve from measurement studies that are now under way. In landfills methane emission factors differ as a result of different assumptions with respect to the methane potential. Another problem is that yearly methane emission factors are difficult to calculate and depend on the point in time that waste is landfilled. If time-dependent dissimilation of organic carbon is assumed, a time series of emissions results. Combustion is a minor source of methane emissions. Rather detailed emission estimates have been made. Variables are fuel type, combustion technology and temperature. Emission factors as yet vary widely.

5.5 Conclusions and recommendations

1. The reporting format should be standardized for transparency.

From the in-depth review of studies from selected countries it was concluded that comparable, consistent and complete national inventories can only be made if a standardized reporting format and a common set of source categories is agreed upon and used. Comparability and transparency will be enhanced if standard summary tables are provided per country to give an overview of the completeness and the precise results of each submission to IPCC. This summary would contain total emissions for each main source category for each of the greenhouse gases estimated. Harmonization of EC country submissions to the CORINAIR database with the submissions to the IPCC

should be enhanced. A hierarchical source sector division will solve part of the problem. Coordination is already taking place with the EC Task Force On Emissions. Common units and time intervals are recommended to facilitate rapid data handling and international comparison.

2. Minimum standards should be set for documentation of inventories.

Preparing greenhouse gas emission inventories constitutes an important task for national administrations. In some cases, however, the absence of documentation on constructing inventories has hindered the evaluation of the submitted emission inventories. Therefore it is recommended that each emission inventory would be accompanied by a textual description and references sufficient to allow a third party to reconstruct the emission figures.

An inventory can be reproduced if all assumptions are documented in the submission. These include emission factors, data on activities and other related but secondary variables. Secondary variables are, for example, the methane content of landfill gas, or the amount oxidized in the soil cover. Examples of well-documented submissions have been identified in this in-depth review and can serve as models for those countries preparing material for the first time.

3. Verification procedures should be established.

Verification checks should be a routine part of the centralized reporting function of the General Convention on Climate Change. Active follow-up with countries should be initiated if errors or major differences from international activity data are identified. Verification should include: 1) source category definition checks, 2) checks on activity data used with international data available, 3) cross-country comparison of emission factors and related assumptions, and 4) comparing emission estimates with independent, internationally estimated emissions. While the verification remains a major undertaking, future attempts can be simplified if countries follow the recommendations on reporting standards. Verification has proven to be essential for arriving at comparable estimates.

4. Reference emission factors should be developed.

Differences in emission factors make sense if regional differences are expressed, for example, in rice cultivation. Differences have been found, however, in emission factors for the same technology and circumstances. A full set of default values should therefore be prepared by the IPCC. This may then be used as a reference guide for emission factors.

In the following chapters emission estimates per sector will be presented for the Netherlands. Test calculations with the IPCC/OECD recommended methodology (OECD, 1991) are compared with earlier estimates for the Netherlands.

In this report in the following chapters, we focus on anthropogenic sources. For some source categories, the definition of "anthropogenic" can be subject to debate. For example, natural emissions that would have occurred if wetlands would not have been drained, or if wetland rice would not have been produced, could be subtracted from national anthropogenic emissions. This has not been taken into account in this report.

Table 5.4 Methane emission factors used by selected countries (only those countries with detailed reports could be analysed)

Source categories	Australia 1988	Belgium 1990	Canada 1990	Denmark 1989	Neth. 1988/90	Norway 1989	Poland 1988	Sri Lanka 1989/90	UK 1988
Oil and gas production									
Porduction/central proc		0.1 g/m3	1.8 g/m3	0.65 g/m3	0.87 g/m3	0.04 kg/ton			
Transm. and storage			0.2 g/m3	0.07 g/m3		0.1 kg/ton			
Distribution		3.5 g/m3	0.18 g/m3	6.1 g/m3	0.6 g/m3				
Oil loading offshore						0.1 kg/ton			
Oil loading onshore						0.1 kg/ton			
Coal mining (kg/ton)									
Coal mining surface			1.2	1.5					
Coal mining underground		14	16.5			18			
Enteric fermentation (kg/hd/yr)									
Cattle total			50	57	74	55		57.7	
Cattle beef	60.5								65
Cattle diary	92.2								95
Sheep	9		8	11	8	8		25.4	8
Goats	8.7				5	8		34.2	
Buffaloes	55.1							71.6	
Deer	10.7								
Reindeer						15			
Horses	18		18	19	18	18			18
Mules/Asses									
Pigs	1.5		2	0.8	1.5	1.5			1.5
Camels									
Animal waste (kg/hd/yr)									
Cattle beef	5.11					4		2.3	
Cattle diary	27.1							7.9	
Pigs	87				1.75	1		1.4	
Poultry	0.25					0.03		0.1	
Goats	0.62							0.8	
Buffaloes								2.3	
Sheep	0.62								
Horses	19.9								
Mules/Asses									
Rice (g/m2/day)	0.12							0.19-0.69	
Biomass burning									
Agric. waste burning cereal	5.3 kg/ha								
Agric. waste burning sugar cane	32 kg/ha								
Savanna burning	5.3 kg/ha								
Prescribed burning			0.3-1.2 ton/ha						
Forest clearing								0.49 ton/ha	
Landfills (kg/ton)	64	2	66	75		76.2		385	
Energy combustion (ton/PJ)									
Electr. and heat gen.									
Solid		0.6			2		0.6		
Liquid		0.7			1		0.7		
Natural gas		0.3			6		0.7		
Blast furnace		1							
Coke oven		1							
Biomass									
Petroleum refining (evaporative)		5 g/ton		5 g/ton					
Cokes production		400 g/ton			1				
Industry									
Solid		2.4			1				
Liquid		2.9			3			2	
Gas		1.4			4				
Biomass					15			15	
Space heating									
Solid		10			1	0.3 kg/ton	10		
Liquid		3				0.05 kg/ton	1.6		
Gas		1.2			30	0.1 kg/ton	1.2	1.2	
Biomass		150				9.02 kg/ton		74	
Transport (ton/PJ)									
Air jet fuel				11.4	2	0.1 kg/ton	2		
Road gasoline cars				97.4	39	1.7 kg/ton	31.4	31.4	
Road gasoline motorcycles								130	
Road diesel				5-7.2	6	0.3 kg/ton	10	10	
Road gas				45.8	26				
Railways diesel				8.3	14	0.3 kg/ton	6	6	
Navigation diesel				8.3	21	0.9 kg/ton	6		
Navigation fuel oil				8.3		1.9 kg/ton	6		
Industrial processes					41 ton/PJ				
Silicon carbide production						10 kg/ton			

Sources: National inventories and OECD (1993).

6. NATIONAL ESTIMATES OF METHANE EMISSIONS: AN UPDATE

6.1 Introduction

Van den Born *et al.* (1991) estimated the methane emissions in the Netherlands for 1988/1989. Their findings are summarized in Table 6.1. Since the publication of their report new information from experimental research on methane emissions, notably on landfills has become available. Also, the IPCC has published a report on Guidelines for the Inventory of Greenhouse Gas Emissions (OECD, 1991). The methods followed by Van den Born are not always the same as those recommended by the IPCC. The IPCC requested countries to test the methodology in order to improve the Guidelines and also to submit the most recent emission estimates on Greenhouse Gases. This chapter therefore records the most recent data. The IPCC methodology is followed and a comparison is made with the earlier estimates. For all source sectors the IPCC recommended method is first followed; than a comparison is made with the estimate of Van den Born *et al.* The differences between the two approaches will be discussed. Since the national emissions of methane in the Netherlands are dominated by a small number of sources, notably oil and gas, landfills, ruminants, animal waste and wetlands, the chapter is limited to these sources only. Minor sources that have been suggested by Van den Born *et al.* (1991), including composting and drinking water production, are not covered in this report. We refer to Van den Born *et al.* (1991) for information about these minor sources.

Table 6.1. Estimated emissions of methane in the Netherlands in 1988/1989: Earlier estimate.

Sources (kton CH_4/yr)	1988/89 Low	1988/89 Medium	1988/89 High
Gas production	40	55	70
Gas transportation	2	7	12
Gas distribution	60	70	80
Oil production	0	18	35
Power plants/refinery	2	2	2
Residential	8	8	8
Transportation	8	8	8
Industry	5	5	5
Commercial	4	4	4
Wetlands	40	70	120
Inland and coastal waters	24	35	60
Small water bodies	11	17	23
Ruminants/pseudo rum.	295	379	462
Animal waste	10	15	20
Landfills	190	255	320
Sewage treatment	3	3	3
Water production	2	2	2
TOTAL	704	953	1235

Source: Van den Born et al. 1991

6.2. Oil and gas

Gas production
For the Netherlands an emission estimate for 1989 was made by Nielen (1991). In the Netherlands 71.8 billion m^3 (st) or 2272 PJ of natural gas was produced and processed in 1989. On the basis of estimates and the recorded quantities of flared/vented natural gas, it is estimated that emissions lie between 37 and 76 kton CH_4/yr in natural gas production (see Table 6.3). The emissions for 1990 and 1991 are calculated using the same emission factors (see Table 6.2). Off-shore emissions are 80% of total. This is because off-shore most non-used gas is vented.

Oil production
In the Netherlands there are two concessions onshore, i.e. Rijswijk and Schoonebeek and four concessions on the continental shelf. Total production was 3.83 million m^3 (st) or 145 PJ in 1989. This is 13% less than in 1988 because the companies are over their production top. Nielen estimated methane emissions between 0.7 and 35 kton/yr in petroleum production in 1989. This estimate is confirmed by estimates given by the NAM. The production and emissions for 1990 and 1991 are practically the same (see Table 6.2 and 6.3).

Transport of natural gas
The high pressure transport of natural gas and sales to consumers is undertaken by the Netherlands Gasunie (the national gas authority). The Gasunie has two transport systems, one main national system operating at a pressure of 65 bar, and a regional system operating at a 40-bar maximum pressure. The national network has a length of 4600 km. The regional network is 6200 km long. Eight compressor stations keep the systems under pressure. Start-up after maintenance leads to emissions from these stations. In 1988 an estimated 2.1 million m^3 (st) natural gas or 1.2 kton methane per year was thus emitted. At 1098 stations receiving gas pressure reduction takes place and the gas is sold to industry and energy distributors. This gas is distributed in the local networks. The amount transported yearly is more-or-less constant at 75 billion m^3 (st). Methane emissions occur in the transportation phase due to adjustments and maintenance works of the pipe system and compressor stations. The emissions have a fixed and a variable part. The fixed part, related to the regular maintenance, is estimated at 5 million m^3/yr (st) of natural gas. The variable part is related to irregular problems with the system. It was estimated at 6 million m^3/yr (st) of natural gas in 1989, a normal year. The total is strongly dependent on weather conditions: total is high at a high throughput in cold winter spells. Methane emissions from transport of gas in 1989 and 1990 came to 6 kton CH_4 and in 1991, 7 kton. This represents 0.015% on the basis of the throughput (see Table 6.2).

Distribution of natural gas
The total length of the regional and local distribution network was 93,000 km in 1987. An extra 42,000 km is pipes from the network to the consumers. The length of pipes designed for dry gas is 84,880 km, the length of old pipes designed for town gas was 11,210 km in 1987. The old cast iron network for town gas in some places is more than 100 years old. Methane emissions during distribution are due in particular to leaks in this town network. The lead/oakum joints in this network were designed for relatively wet town gas. At present 11% of the distribution network still consists of these grey cast iron pipes. At the moment 2-3 leaks per km are found in this network, compared to 1 leak per 10 km in the polyethene network. Two methods are possible for the measurement of leakage from pipes.

1: A comparison of the received and delivered amounts. This method led to the discovery in 1974 that more gas seemed to be sold than the gas distribution companies bought from the Gasunie. A study in 1987 proved that the difference was due to temperature differences at

the downward end of the networks at the consumer level. In general this method is very difficult to apply because of calibration errors and other uncertainties.

2: The direct measurement of leaks. The second method has not yet been used because of problems in finding representative networks.

The Gasunie estimated a loss of 120-150 million m^3 natural gas or 65-79 kton methane, assuming 10% oxidation in the soil covering the pipes (Nielen, 1991). This amounts to about 0.6% of the throughput, the highest losses are from the old network. Using this emission factor the loss was 72 kton in 1990 and 84 kton in 1991.

IPCC method

The IPCC recommended methods are the same as used here. Usually losses are expressed as percentages of throughput. The IPCC/OECD working group of experts in 1991, recommended presenting emission factors based on the number of wells per country, the level of production of oil and gas and the length of pipelines for the different transmission types (high pressure, low pressure, wet gas, dry gas) (OECD, 1991). It proved to be difficult to calculate the emission per well and per km of pipeline. In Table 6.2 the data on activities and emission factors are given as used in the calculations.

Table 6.2 Activity data and emission factors for oil and gas in the Netherlands

	Activity data			Emission factors	
	1989	1990	1991	Low	High
	10^9m^3	10^9m^3	10^9m^3	Vol %	Vol %
Production	71.8	72.4	82.4	0.09	0.16
Transport	71.8	72.4	82.4	0.015	0.015
Distribution	20.6	20.8	24.0	0.6	0.6
Oil production	0.0038	0.004	0.0037	0.005	0.16
End-use gas	41.3	40.1	44.8	0.06	0.12

Table 6.3. shows the current emissions in the Netherlands according to the IPCC method as compared to the earlier estimates by Nielen (1991) and van den Born *et al.* (1991). The newly estimated emissions from oil and gas are practically the same in all reports. The differences are explained by differences in emission factor use and activity levels.

Table 6.3. Current emissions in the Netherlands according to the IPCC method as compared to the earlier estimates by van den Born *et al.* (1991)

	Van den Born et al. 1991		This report IPCC		This report IPCC		This report IPCC	
	1988/89 Low	1988/89 High	1989 Low	1989 High	1990 Low	1990 High	1991 Low	1991 High
Production	40	70	37	67	38	67	43	76
Transport	2	12	6	6	6	6	7	7
Distribution	60	80	72	72	72	72	84	84
Oil production	0	35	1	35	1	37	1	34
Total oil and gas	102	197	117	180	118	183	135	201
End-use combustion	27	27	14	29	14	28	16	31

6.3 Ruminants

In the method followed, as recommended by the IPCC (OECD, 1991), the quantity of methane emission is calculated as a function of energy intake and energy demand of the animals. The emission of methane according to this method is calculated for dairy cattle, beef cattle, sheep and goats. For pigs and horses IPCC recommends a simple approach, with the use of emission factors. Cattle is kept inside during the winter period in the Netherlands. In the summer period some of the dairy cattle are kept inside. The feeding level is high with a good digestibility of the fodder.

Energy utilization and methane production in animals
Methane is produced during the digestion in the rumen. With the help of methanogenic bacteria food is pre-digested. This process enables ruminants to utilize nutrients from low-quality food. As food is digested and taken up by the organism, the energy content is partly lost in faeces, urine and fermentation gases. The remainder is used to regulate the body temperature, perform work, build new body tissue and offspring or produce milk. The energy losses depend on the kind of animal and the kind and quality of the feedstuff. Measures of the feed quality are **digestibility** and **metabolizability**. These are the fractions of the gross energy intake that are converted to digestible and metabolizable energy. This can be illustrated in the following flow diagram:

Food energy------> Digestible energy------> Metabolizable energy--------> Net energy.

Losses in the respective steps are:
1. Energy in faeces.
2. Energy in methane and urine.
3. Heat and evaporation loss, basal metabolic processes.
Net energy is available for work, growth, production of milk etc.

In adult homeotherms (warm blooded animals) **basal metabolism** is the minimum energy demand under conditions of thermoneutrality and total rest. The daily basal metabolism in megajoules (MJ) is roughly proportional to body weight (BW) in kg raised to the power of 0.75:

Basal metabolism (MJ) = $0.293\ BW^{0.75}$

with an uncertainty of 14% (Menke and Huss, 1975). The energy demand for preventing the breakdown of body tissue is higher and often expressed as energy intake at maintenance level (MEm) (Maynard and Loosli, 1962). This quantity depends on utilization and kind of livestock. The amount of energy lost by methane production depends on quality and quantity of the food and the performance of individuals. Methane is a by-product of microbial breakdown of otherwise non-digestible carbohydrates (mainly cellulose) in the rumen. Very high losses of methane are reported in ruminants with large populations of bacteria and protozoans in their rumens. Methane yield can be expressed as a fraction of the gross energy intake (GEi). In the literature methane losses of 4 to 9% GEi are frequently mentioned as the range of potential emissions (e.g. Crutzen *et al.*, 1986). Food quantities can be converted to gross energy intake by using an average conversion factor of 18.41 MJ/kg dry matter (or 19.2 MJ/kg dry matter for northern America and Western Europe) to account for the higher energy content of silage and oil compounds in the feed (McDonald *et al.*, 1988). Crutzen *et al.* (1986) used a conversion factor of 17.5 MJ/kg dry matter given by Lieth (1975). The energy content of methane is equal to 55.65 MJ/kg (Crutzen *et al.*, 1986).

IPCC method

Methane production of grazers according to the IPCC preliminary guidelines.

The IPCC recommended methodology has three steps:

- Calculating the percentage of feed energy that is converted to CH_4 by the animal (Ym).
- Estimating the total feed energy intake of the animal.
- Multiplying the conversion percentage by the feed intake.

For the calculation of methane emissions, the formula from Blaxter and Clapperton (1965) is recommended by the IPCC.

Ym (MJ CH_4/100 MJ feed) = 1.30 + 0.112DMD + FL(2.37 - 0.050DMD)

where:

Ym = the methane yield in MJ per 100 MJ of gross feed intake.

DMD = percent of feed digestibility at the maintainance level of feeding, expressed in %, not as a fraction. DMD is estimated by averaging digestibilities of commonly used feedstuffs.

FL = feeding level, expressed as a multiple of the maintenance level. FL is high in the Netherlands. Calculated FL ranges from 2 to 4, depending on age class and differences between beef and dairy cattle.

Methane megajoules are converted to Tg and multiplied by 365 and by the number of animals in each class to arrive at the annual methane production. Methane production per animal is also expressed in kg CH_4/yr per head. FL was calculated by dividing metabolizable energy intake (MEi) by metabolizable energy for maintainance (MEm):

FL = MEi/MEm.

See annex 3 for further details.

Results

The estimate for the Netherlands is based on a differentiation of animal categories. Values for feeding level were calculated. Default values for net energy use at maintenance level are used for the Dutch situation. Methane emissions are calculated for the Dutch herd for the years 1986-1992. In table 6.4. the results are summarized. Table 6.5 summarizes the assumptions used for the different animal categories. The mean data are given. An uncertainty range of 15% is assumed for these estimates. In the chosen period methane emissions from dairy cattle are decreasing because of decreasing animal numbers. Beef cattle is increasing. These trends reflect the results of government policies to reduce the milk surplus.

Table 6.4. Numbers of animals and methane emissions from (pseudo) ruminants in the Netherlands

NUMBERS		Realized								
TYPE		SUBTYPE	1980 ('000)	1985	1986	1987	1988	1989	1990	1991	1992
Cattle	dairy	young <1	870	796	747	690	721	772	806	820	776
Cattle	dairy	young female >1	1038	1014	918	856	803	830	880	908	897
Cattle	dairy	female	2356	2367	2288	2100	1971	1913	1878	1852	1776
Cattle	dairy	male >1	54	45	44	39	40	40	43	48	49
Cattle	beef	calves	582	638	690	700	619	597	602	622	632
Cattle	beef	young	292	342	390	444	484	537	598	674	646
Cattle	beef	female >2	44	46	46	66	72	83	120	139	146
Sheep		male	9	9	11	13	11	16	28	28	27
Sheep		female	368	358	389	442	534	649	790	857	874
Sheep		fattened lamb	481	447	468	529	624	740	884	993	1047
Goats		male					15	18	23	26	25
Goats		female					19	24	38	43	38
Pigs			10138	12383	13481	14349	13934	13729	13915	13217	14147
Horses				62	63	64	65	67	70	77	86

Methane emissions Tg CH4/yr		Realized	1980	1985	1986	1987	1988	1989	1990	1991	1992
Cattle	dairy	young <1	0.043	0.039	0.037	0.034	0.036	0.038	0.040	0.040	0.038
Cattle	dairy	young female >1	0.065	0.064	0.058	0.054	0.050	0.052	0.055	0.057	0.056
Cattle	dairy	female	0.241	0.242	0.234	0.214	0.201	0.195	0.192	0.189	0.181
Cattle	dairy	male >1	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005
Cattle	beef	calves	0.010	0.011	0.012	0.012	0.011	0.011	0.011	0.011	0.011
Cattle	beef	young	0.025	0.030	0.034	0.039	0.042	0.047	0.052	0.059	0.056
Cattle	beef	female >2	0.004	0.005	0.005	0.007	0.007	0.008	0.012	0.014	0.015
Sheep		male	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Sheep		female	0.006	0.006	0.006	0.007	0.009	0.010	0.013	0.014	0.014
Sheep		fattened lamb	0.006	0.006	0.006	0.007	0.008	0.009	0.011	0.012	0.013
Goats		male	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001
Goats		female	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001
Pigs			0.015	0.019	0.020	0.022	0.021	0.021	0.021	0.020	0.021
Horses			0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002
Total			0.421	0.426	0.417	0.400	0.391	0.398	0.414	0.424	0.415

Table 6.5 Assumptions for the calculation of methane emissions from (pseudo) ruminants in the Netherlands

TYPE		SUBTYPE	WEIGHT kg	DMi kg/day	FL	Ym MJ/100MJ	CH4 kg/yr/head
Cattle	dairy	young <1	212.50	6.00	2.31	6.52	49.25
Cattle	dairy	young female >1	282.00	7.90	2.45	6.31	62.80
Cattle	dairy	female	500.00	14.00	2.83	3.90	102.13
Cattle	dairy	male >1	648.00	10.00	1.67	5.54	93.22
Cattle	beef	calves	172.00	14.00	6.30	1.00	17.65
Cattle	beef	young	500.00	10.00	2.02	4.65	87.01
Cattle	beef	female >2	500.00	14.00	2.83	3.90	102.13
Sheep							8.00
Goats							8.00
Pigs							1.5
Horses							18

Comparison with earlier national estimates

The above results using IPCC methods are within the range of Van den Born *et al.* (1991), who used less sophisticated data for the Netherlands. In the simplified approach for the Netherlands Van den Born *et al.* (1991) used emission factors per head per year from different literature sources.

For Germany, Crutzen calculated that dairy cows produce about 94 kg CH_4/yr. Heifers and steers produce about 65 kg/yr and animals between 6 and 24 months produce about 51 kg methane. Calves younger than six months do not produce considerable amounts of methane, because of the highly digestible feed they consume (Crutzen *et al.*, 1986). Goossensen and Meeuwissen (1990) used a range of 91 to 143 kg CH_4/yr for dairy cows and a proportional factor for the other cattle types (0.7 for steers; 0.5 for heifers older than 1 year and 0.3 for heifers younger than 1 year). The Institute for Livestock Feeding and Nutrition Research in the Netherlands (IVVO) used 128 kg CH_4/yr for dairy cattle, 55 kg CH_4/yr for steers/bulls and 53 kg CH_4/yr for young cattle (Van der Honing and Vuuren, 1991).

For sheep Van den Born *et al.* (1991) used 8 kg/yr, for goats 5 kg/yr, for pigs 1.5 kg/yr and for horses 18 kg/yr. Goossensen and Meeuwissen (1990) used 0.1 GVE (35 to 50 l/d) for sheep. No calculations have been made by Goossensen en Meeuwissen for other animals. The methane emission factors used in the calculations of Van den Born *et al.* are summarized in Table 6.6.

Table 6.6. Emission factors for methane from ruminants and pseudoruminants as used in earlier estimates

	Crutzen 1986	Goossensen and Meeuwissen 1990	Van der Honing and Van Vuuren 1991
	kg CH_4/head/yr	kg CH_4/head/yr	kg CH_4/head/yr
Dairy cows	94	91-143	128
Heifers	65	46-72	-
Steers	65	63-100	55
Young cows <2 yr	51	27-43	53
Horses	18	-	-
Sheep	8	-	-
Goats	5	-	-
Pigs	1.5	-	-
Mules/Asses/Llamas	10	-	-

Source: Van den Born *et al.* 1991.
- = no emission factor used.

The results of Van den Born *et al.*, 1991 and the results using the IPCC method for the different categories are summarized in Table 6.7. The total production of methane in the Netherlands from ruminants, pseudoruminants, other animals and humans in 1989 ranges from about 295 to 462 kton CH_4/yr. This includes 270 to 430 kton for ruminants only and about 25 to 32 kton for other animals and humans. The average emission for ruminants using Crutzen and Goossensen emission factors is 320 kton and 360 kton CH_4/yr, respectively. The total of 360 kton CH_4/yr calculated by the Dutch Institute for Livestock Feeding and Nutrition Research (IVVO), Van der Honing and Vuuren (1991) is just within this range. Van den Born *et al.* (1991), following Goossensen, assumed a range of 270 to 430 kton CH_4/yr for ruminants and an average of 350 kton CH_4/yr. For other animals and humans a range of 25 to 30 kton CH_4/yr was estimated. This amount is at the lower end of the range calculated by Van der Honing and Vuuren (1991). For more detailed information see Van den Born *et al.*, 1991. In conclusion, the IPCC methodology used in this report and the simple approach by Van den Born *et al.* (1991) give similar results.

Table 6.7. Comparison with earlier estimates of methane emissions from (pseudo) ruminants and humans in the Netherlands in 1989 using different emission factors

	Crutzen		Goossensen		IVVO	This report
1989	kton CH_4/yr low	kton CH_4/yr high	kton CH_4/yr low	kton CH_4/yr high	kton CH_4/yr	kton CH_4/yr
Cattle	270	360	270	430	360	355
Sheep/Goats	5	6	6	10	-	20
Pigs	18	24	-	-	-	20
Horses	1	1	-	-	-	1
Humans	1	1	-	-	-	1

Source: Van den Born *et al.* 1991 and this report
- = no estimate given.

Conclusion
The IPCC methodology and the national approach are leading to comparable results, with the more detailed IPCC methodology being preferred for reasons of international comparison and better scientific support. For sheep, goats, horses and pigs the simple emission factor approach is appropriate.

6.4 Animal waste

National estimate: the IPCC methodology
The IPCC recommends using the method of Casada and Safley (1990) for the estimate of methane emissions from animal waste. This method consists of the following steps:

- Defining the different waste categories and waste handling systems.
- Estimating the potential methane emission per unit of waste (Bo).
- Estimating the fraction of the potential emission that is actually emitted for each waste management type (MCF).
- Estimating the amount of waste and the volatile solids (VS) content in each category.
- Estimating the actual methane emissions by multiplying the actual emission rate by the amount of waste in each category.

Potential methane emission is primarily a function of the quantity and quality of the degradable organic material content, or VS content, of the waste. Because the digestion processes of animals differ, the VS content is generally a function of animal type and feeding quality. So the methane emission can be estimated as follows:

$TM = (VS \times Bo \times MCF \times 365 \times Density)/10^9$ (minus methane recovered from waste gas)

where:
TM = total methane in Tg/yr

VS = volatile solids in the waste
Bo = the methane emission potential
MCF = methane conversion factor
density = 0.662 kg/m^3 methane

The methane recovered from waste digesters should be subtracted from the methane emissions thus calculated.

Casada and Safley collected information on 10 different animal types and eight major waste management systems. In annex 4 an overview is given of predicted methane production rates in different management systems and of waste characteristics and potential emissions in different parts of the world. The extent to which these potential emissions are realized depends on how the waste is managed. Casada and Safley estimated the fraction of the potential methane emission for each waste management system. This is called the 'methane conversion factor'. The Amersfoort meeting of methane experts in the Netherlands in February 1993 suggested MCF's for three different temperature regimes (Van Amstel, 1993). These have been used in this report.

The following waste management systems and MCF's were suggested by Casada and Safley and methane experts in Amersfoort:

1. Pasture and range: Animals grazing on pasture or range are not on any true waste handling system. Manure is allowed to lie on the fields and dry out. Only a minimum amount of methane can be expected. MCF is 2% at 30°C, 1.5% at 20°C and 1% at 10°C.

2. Liquid/slurry storage: Water is frequently added to the manure for liquid systems. Its total solid concentration is reduced to less than 12%. Slurry systems do not necessarily require the addition of water. When the manure is kept in a silo anaerobic conditions will lead to methane production. Deep storage facilities lead to totally anaerobic conditions, thereby maximizing the methane production potential of the manure over time. MCF is 65% at 30°C, 35% at 20°C and 10% at 10°C. If the storage is less then 30 days the MCF is 33% at 30°C, 18% at 20°C and 5% at 10°C.

3. Solid storage: The manure is collected in solid form and stored in piles without treatment. This manure does not have a high methane producing potential. MCF is 2% at 30°C, 1.5% at 20°C and 1% at 10°C.

4. Anaerobic lagoon: Manure in liquid form is put into a pit deeper than six feet and specifically designed to create anaerobic conditions as a means of treating the waste. It is possible to cover these lagoons and collect methane gas. MCF is 90% at all temperature regimes.

5. Drylot: In dry climates manure from feedlot animals is left on unpaved areas. The potential for methane formation is low. MCF is 5% at 30°C, 1.5% at 20°C and 1% at 10°C.

6. Burned for fuel: In some regions with subsistence agriculture and a wood shortage, manure is collected and dried for fuel use. MCF is 5 to 10% under all temperature regimes.

7. Daily spread: The manure is collected in solid form and spread regularly on the fields. The spreading increases the drying process, so that the methane potential is even lower than manure on pasture. MCF is 1% at 30°C, 0.5% at 20°C and 0.1% at 10°C.

8. Paddocks: Horses are frequently kept in paddocks where they are confined to a limited area. This manure will be essentially the same as on pasture, with a limited methane production

potential. The same can be said about the manure from the stalls. MCF is the same as with pasture and range.

9. Deep pit: Manure from caged layers is allowed to collect in solid form in deep pits. This manure may be removed only once a year. The methane production potential is low. MCF is 5% under all temperature regimes.

10. Litter: Broilers and young turkeys may be raised on beds of litter. The mixture is removed periodically. It will not be as dry as in deep pits. This manure has low methane producing potential. MCF is 10% under all temperature regimes.

11. Anaerobic digester: The liquid or slurry is placed in an anaerobic digester for treatment. Depending on the retention time, most of the methane production potential will be used. Theoretically, all methane will be used (burned); in practice, digesters in developing countries are having various problems. One of these is leaking. Chinese digesters have caused at least 14% production loss through leakage. MCF is 14%. Indian digesters have a floating cover with less leaking; here less of production is lost. MCF: 5%.

The following waste management systems are relevant to the Netherlands.

1. Pasture (most regions)
2. Slurry storage (>1 month)
3. Solid storage
4. Litter
5. Anaerobic digester

For the Dutch situation Casada and Safley's original MCFs were scaled down as suggested by the methane experts in the Netherlands because earlier research indicated lower methane formation in all systems amongst others because of low average temperatures in the Netherlands (Zeeman and Hamelers, 1992).

The following methane conversion factors (%) are assumed for the Netherlands:

1. Pasture:	0
2. Slurry storage (>1month)	10
3. Solid storage	5
4. Litter	10
5. Anaerobic digester	80

Manure slurry in the Netherlands is increasingly stored in silos outside the stable. Statistics are available on the total number and total volume. No distinction can be made between silos for cow manure or pig manure. So an overall emission factor has to be applied.

Manure statistics do not allow a detailed estimate for all systems, as only total production data per animal type are available. Slurry storage under the stable in a piggery, for example, is widespread but methane emission estimates cannot yet be made. Therefore a rough estimate has been made for a selection of systems. The manure production in the Netherlands according to CBS (1992) is summarized in Table 6.8. Table 6.9 summarizes the emission factors as used in the Netherlands.

Table 6.8. Manure production (10^6 ton slurry) in the Netherlands

Manure (million tons of slurry)	1970	1975	1980	1984	1986	1988	1990
Cattle	56.1	64.3	67.2	78.6	69.5	59.9	60.9
o.w. in stable	28.1	32.2	33.7	35.6	32.8	27.5	27.9
o.w. in meadow	28	32.1	33.5	43	36.7	32.4	33
Fattening steers						2.3	2.7
Fattening calves	1	1	1.3	1.8	2.2	2	1.9
Sheep and Goats						1.3	1.9
Pigs	8.9	12.2	14.6	15.9	19.1	19.2	19.8
o.w. breeding pigs						7.2	7.9
Poultry dry	1.1	1.3	1.7	0.6	0.7	0.9	0.9
Poultry slurry				1.6	1.7	1.5	1.5

Source: Hoogervorst, 1991; CBS, 1992

Table 6.9. Emission factors used in the Netherlands for estimating methane from animal waste

	Volatile solids fraction	Emission pot: Bo m3/kgVS	MCF fraction of Bo
Cattle			
o.w. in stable	0.124	0.17	0.05
o.w. in meadow	0.116	0.24	0
Fattening steers	0.116	0.33	0.1
Fattening calves	0.116	0.33	0.1
Sheep and Goats	0.25	0.18	0.1
Pigs	0.101	0.45	0.1
o.w. breeding pigs	0.101	0.45	0.1
Poultry dry	0.194	0.32	0.1
Poultry slurry	0.194	0.32	0.1

Emission factor assumptions

As no information is available on the quantity of waste and the storage time in the silos, an overall assumption was made that pig slurry is stored outside for more than 1 month (MCF: 10%) and that most of the cow manure is kept either in drylot or in slurry storage for less than a month (MCF: 5%). Slurry from beef steers and calves was assumed to be stored for about six months (MCF: 10%). It was assumed that cow manure in the meadow period does not emit methane (MCF: 0%). For sheep, goats and poultry waste an MCF of 10% was assumed.

In Tables 6.10 and 6.11 some information is given on manure silos in the Netherlands.

Table 6.10. Surface area ($m^{2)}$ of manure silos outside stables in 1988, according to type of farm

Manure silos, surface realized in 1988	m^2 covered	m^2 uncovered
Arable land	30,600	45,400
Cattle	834,100	1,024,900
Pigs and poultry	173,800	101,100
Mixed animal farms	74,800	56,000
Mixed farms	41,500	39,000
Total	1,156,800	1,266,400

Table 6.11. Number of newly constructed manure silos and their total volume (x 1000 m^3).

	1987	1988	1989	1990
Silos	1387	1259	505	395
Volume	905	1003	408	-

No correction for the amount of covered silos could as yet be made. More information is needed about the actual emissions.

Methane emissions can be calculated from total manure production using the Casada and Safley method with different methane conversion factors. Table 6.12 summarizes the results.

Comparison with earlier estimates

Assumptions made by Van den Born *et al.* (1991) were: methane is emitted if manure is stored in anaerobic environments like silos or basins and if the temperature is higher than 15 °C. A potential of 4.8-7.2 kg of methane from a ton of pig manure stored in the cellar of the pigsty and 3.6 kg of methane from a ton of cattle manure, as long as it is in the stable, was calculated, with a total calculated potential methane emission of 180 kton CH_4/yr. Actual emission was only estimated to be 10-20 kton/yr because of relatively cold storage systems.

Table 6.12. Methane emissions from animal waste in the Netherlands

	(kton/yr) 1970	1975	1980	1984	1986	1988	1990	1991
Cattle								
o.w. in stable	20	22	24	25	23	19	19	16
o.w. in meadow	0	0	0	0	0	0	0	0
Fattening steers	0	0	0	0	0	6	7	8
Fattening calves	3	3	3	5	6	5	5	5
Sheep and Goats	0	0	0	0	0	4	6	6
Pigs	27	37	44	48	57	58	60	65
o.w. breeding pigs	0	0	0	0	0	22	24	30
Poultry dry	5	5	7	2	3	4	4	3
Poultry slurry	0	0	0	7	7	6	6	7
Total	53	67	78	86	96	102	106	109

The emission figures calculated with IPCC methods are considerably higher than the results of Van den Born *et al.* (1991): 102 kton CH_4/yr in 1988 using the IPCC method with adapted MCF rates according to the Amersfoort expert meeting, versus 10 - 20 kton CH_4/yr estimated by Van den Born *et al.* (1991). More research is needed to confirm the estimates in practical situations

Conclusions

In Table 6.13 the results are compared. In many cases data do not exist to confirm methane emission estimates from animal waste. The need to make assumptions adds to the uncertainty in the estimates. A comprehensive field measurement programme is needed to improve the basis for the MCF estimates. Even the new IPCC emission factors have led to results much higher than earlier estimates in the Netherlands.

Table 6.13. Comparison of methane emissions (kton CH_4/yr) from manure in the Netherlands

	Van den Born *et al.*	This report with IPCC methods		
	1988/89	1986	1988	1990
Cattle		29	30	31
Sheep/Goats		0	4	6
Pigs	10-20	57	58	60
Poultry		10	10	10

6.5. Landfills

National estimate: the IPCC methodology

The availability of sufficient data allows for the application of the second, detailed methodology of IPCC for the Netherlands: a first-order kinetic model is applied to the whole country (OECD, 1991). Detailed information on landfilling is available for some years (SVA, 1973; CBS, 1988; CBS, 1989; Nagelhout *et al.*, 1989). It is assumed that during the Second World War not much waste was dumped and that the dumping of waste started after 1945. Data for the remaining years were obtained via inter- or extrapolation. With respect to waste composition a degradable organic matter fraction of 18% before 1986, and 17% between 1986 and 1995 is assumed. After 1995 the fraction decreases. This is based on two developments. Firstly, organic fractions like paper and wood waste are recycled increasingly. Secondly, the separate collection of fruit and garden waste is assumed to result in an additional decrease of organic carbon content of landfills. A decrease by 5% per year from 1995 is assumed. The government is aiming at a zero organic matter content in landfills. In practice, a maximum content of degradable organic material of 5% for all landfilled fractions by 2000 is expected (Beker, pers. comm.). The emissions have been calculated using the formula for specific gas production.

$$\alpha = 0.8\ k\ P_O\ e^{-kt}$$

α	= production in m^3 waste gas (ton/yr)
P_O	= concentration of degradable organic matter in kg/ton refuse
k	= degradation rate coefficient (0.1 per year)
t	= time after landfilling (year)

Source: Hoeks ,1983; Hoeks and Oosthoek, 1981]

Current production potential of waste gas from material dumped in the past is accounted for by integrating the production potential over time. So far, waste gas potential is considered and not methane emission.

TNO measured actual methane emissions at three landfill sites (Verschut *et al.*, 1991). They calculated a mean degradation coëfficient *k* based on their measurements of 0.1/yr. This means that half of the organic matter is degraded in seven years. This is about twice the rate of Van den Born *et al.* (1991), and more in accordance with other literature about biogas formation (Scheepers, 1991). Based on this information a mean *k* factor of 0.1/yr for the years 1945 to 1995 is used.

Furthermore, to estimate the current emission an oxidation percentage in the soil cover of 20% and a methane concentration of 50% waste gas is assumed. An uncertainty range of 50% around the mean must be expected because of the variability in circumstances in individual landfills. The actual government policy is aimed at reducing the amount of waste landfilled. According to the National Environmental Outlook 2 in the year 2000, 6 million tons of waste will still be landfilled (Nagelhout and Lohuizen, 1992). By then this waste will contain practically no degradable organic carbon because of recycling organic wastes (paper and wood) and separate collection of garden, fruit and kitchen (GFK) waste. In our model the degradable organic carbon content (Po) therefore decreases to about 5% between 1995 and 2000.

Government policy is also aimed at cost-effective landfill gas recovery. The action programme of NOVEM, which coordinates landfill gas recovery investments in the Netherlands, wants in its action programme to recover 185 million m^3 landfill gas in 1995 (NOVEM, 1991). This equals 67 kton CH_4 in 1995, or about 25% of the potential gas production. The NOVEM aim is 25%; this is

assumed to be attainable with existing policies. In 1991 74 million m^3 of landfill gas was recovered (Oonk, 1993). Additional policies, with some extra cost-effective measures, are considered necessary to attain a 50% recovery; 90% of landfill gas may be recoverable after 2000 if the law ('Stortbesluit') asks for impermeable top-lining systems and if new technology is applied. In practise less then 90% may be recovered in each landfill because of system problems and late starts of projects.

Waste-gas recovery is a cost-effective measure to mitigate methane emissions. More gas is formed in a shorter period of time compared to earlier estimates of Van den Born et al. 1991. Investments in waste gas recovery are therefore especially relevant in the period up to 2000. An advisory centre for waste-gas recovery has therefore been set up under the NOVEM programme to stimulate investments in recovery techniques (NOVEM, 1991). To date, waste-gas recovery projects have started after covering (part of) the landfill with a soil layer. The new 'Stortbesluit' in which gas recovery or flares are made obligatory after closure of the landfill may need reconsideration. Landfill gas recovery obviously has to start from the very beginning in a compartment that is still unstable, settling and open. New techniques, like temporary covers and gas recovery at the base of a landfill or landfill compartment, may be needed.

As organic fractions are increasingly recycled or collected separately landfill gas may be a diminishing source, leading to consideration of alternatives like fermenting of organic waste.

Comparison with earlier estimates
The emission in 1990 is, on the basis of our model, 377 kton methane per year (range 178-576) with 25% recovery. In table 6.14 a summary is given of the comparison with an earlier estimate of Van den Born *et al.* (1991) Then the same methodology was used, but it was assumed that half of the degradable organic carbon was fermented in 20 years instead of 7 years (k factor = 0.0365/yr). On the basis of that model, the emission estimate without recovery for 1988/89 was 300 kton methane (range 230-360). A landfill gas recovery of 40 kton was assumed. So a net emission of 260 kton (range 190-320) was calculated. From table 6.14 it can be seen that the maximum methane emission estimated in this report is considerably higher and earlier in time compared to the earlier estimate of Van den Born *et al.* (1991). On the basis of our model the emission estimate of Van den Born *et al.* for 1990 has to be revised from 260 to 377 kton CH_4/yr (range 178-576). The difference is mainly due to the revised estimate of the degradation rate. Due to the more rapid breakdown of organic material, however, the emissions will also decrease more rapidly after the maximum has been reached.

Conclusions
The IPCC methodology was followed both in this and in the earlier estimate. The difference in outcome between the two estimates is due to a different assumption with respect to the breakdown time of organic material. Methane emissions from landfills are now believed to be higher and earlier in time than originally thought. Landfill gas recovery, an important option for reducing methane emissions, will be pursued in due course; this is because landfill gas formation after 2000 will diminish rapidly because of the increase in recycling and separate collection of GFK waste.

6.6. Wetlands

IPCC methodology

No IPCC method exists for estimating methane emissions from wetlands. In the framework of the guidelines for national inventories, the IPCC is interested in the net anthropogenic emissions. The IPCC is therefore interested in the change in methane emissions over the years as a result of anthropogenic water management. This national estimate of methane emissions from changes in wetland areas is based on the surface area of different ecosystems and groundwater classes and emission factors based on Aselmann and Crutzen (1989) and Moore and Knowles (1989). A summary for the situation in 1990 is given in Table 6.14.

Table 6.14. Summary of emission factors and emissions from wetlands in the Netherlands

Type	Emission factors mg $CH_4/m^2/day$	Emission kton CH_4/yr
Organic soils with high water table	80-200	
Organic soils, drained	10-200	42-116
Inland and coastal waters	20-50	24-60
Small water bodies	80-200	8-24
Total		74-200

Source: Bouwman and Van der Hoek, 1991

There is a great variability in emissions from different aquatic systems and throughout the season. Many authors in different countries have measured methane emissions. A summary of these measurement results and resulting emission factors are given in Table 6.15. Not many measurements have been carried out in the Netherlands, so it is uncertain to what extent the emission factors apply to the country. Still they have been used as the best available factors.

Table 6.15. Summary of measurement results and emission factors for wetlands

Type	Measured emission range $g/m^2/yr$	Mean emission factor assumption $mg/m^2/day$
Bogs	0.3-106	15-80
Fens	4-126	80-200
Marshes	44-590	130-400
Wooded marsh	4-192	10-200
Lakes	5-350	20-50
Rivers	0.4-145	20-50

Sources: Franken, 1991; Bouwman and Van der Hoek, 1991

The variation of methane emissions in time and space is responsible for the large uncertainty ranges as reported in the literature. For good extrapolations it is suggested to develop process-oriented models for the yearly flux as a function of factors such as temperature, growing season, flooded period and amount of organic material in the profile. Yearly fluxes from different ecosystems with uncertainty ranges might be calculated from these models. This way the seasonal and spatial variations can be separated more explicitly. Another very important fact as mentioned by Franken (1991), is that the ebullition of methane, a rather important emission source, has often not been measured.

Trend in methane from drainage between 1950 and 1990

No IPCC method exists for the methane trend calculation from drainage. A rough estimate is possible using estimates of drained surface area and the emission factors as mentioned before. In the Netherlands different calculations have been made of the actual surface area of wetland soils. Data are available on ecosystem areas, soil types and areal extent of water-table classes. To begin with the last, water-table classes are defined according to the range in distance the water table is below the surface area during winter time (high) and summertime (low). Table 6.16 gives the classes, ranges and surface area in 1990. Potential significant methane sources are soils with water-table classes 0 and 1. High water tables are usually found in the peat soils of undrained low-lying fens in the western and northern part of the country.

Table 6.16. Water-table classes of terrestrial soils in the Netherlands

Class	Winter, cm below surface	Summer, cm below surface	Area (km^2)
0	flooded	0	240
1	0	<50	373
2	0	50-80	3345
2*	>25	50-80	
3	<40	80-120	
3*	25-40	80-120	
5	<40	>120	
5*	25-40	>120	total (2*-5*)15,690
4	>40	>120	
6	40-80	>120	total (4 and 6) 8950
7	80-140	>120	
7*	>140	>140	total (7 and 7*)562

Source: Klijn *et al.*, 1992

Supplementary information on surface water areas is from the Nature Values Map of the Netherlands (Bakker *et al.*, 1989). According to this map wetlands and surface water in the Netherlands occupy surface areas presented in Table 6.17.

Table 6.17 Wetland and surface water area (km^2) in the Netherlands in 1988

INLAND	km^2
Reservoirs	12.8
Ditches and small waters	1018
Water (>6 m wide)	1498.4
IJssel Lake	1656.6
Wet natural areas	538.5
SEA AND ESTUARIES	
Mud flats and salt marshes	120 (brackish)
Wadden Sea, Eems, Dollard	4209.8
East and West Scheldt	7048.1
North Sea (Dutch part)	6112.6

Source: Bakker *et al.*, 1989

Overlapping categories are wet natural areas, and mud flats and salt marshes. According to this source only a quarter of the wetlands in 1988 consist of undrained natural semi-aquatic inland systems. The surface area of the natural part of the wetlands is given in Table 6.18. The flood-plains of large rivers are wet only part of the year. If subtracted the total of Table 6.18 is comparable to the total of water-table class 0 and 1 of Table 6.16.

Table 6.18. Area (km^2) of natural undrained semi-aquatic inland systems in 1988

Flood plains of larger rivers	380
Marsh	210
Peat in low-lying fens	98
Peat in high-lying fens	90
Wet nutrient-poor soils	82
Forested marsh	71
Total	931

Source: Bakker *et al.*, 1989

An estimate of the methane trend from 1950 to 1990 can be made on the basis of these data and the following assumptions. The surface area of the natural non-salty, non-brackish undrained semi-aquatic inland systems with a high water table (less than 50 cm) in the Netherlands around 1950 was around 2000 km^2 (Van Amstel *et al.*, 1989; COLN, 1958). The total area of high water table in 1990, with summer levels less than 50 cm below the surface (class 1) is 373 km^2 (Klijn *et al.*1992. Thus we assume an areal extent of class 1 in 1950 of about 2000 km^2 and in 1990 of 373 km^2. An emission estimate of 80-200 mg is used by Van den Born *et al.* (1991) for high water tables. If this emission factor is used and in a productive period of 360 days, as in Van den Born (1991), 58-216 kton CH_4/yr was emitted from wet areas with a high water table in 1950 and 10-27

kton in 1990. We assume some emissions from drained organic soils, as given by Van den Born. We assume the areal extent of surface water to be constant. In Table 6.19 a summary is given for the resulting trend between 1950 and 1990. Less methane is emitted from wetlands in the Netherlands in 1990 compared to 1950. The difference is about 15-100 kton methane per year.

Table 6.19 Methane emissions change in the Netherlands from drainage of wetlands between 1950 and in 1990

Type	Emission rates (mg $CH_4/m^2/day$)		Emissions (kton CH_4/yr)	
	1950	1990	1950	1990
Wet organic soils	80-200	80-200	58-216	10-27
Drained organic soils	10-200	10-200	0	32-89
Inland and coastal waters	20-50	20-50	24-60	24-60
Small water bodies	80-200	80-200	8-24	8-24
Total			90-300	74-200

The change in methane emissions resulting from an increased surface water pollution between 1950 and 1990 is not taken into account.

Comparison with earlier estimates
Van den Born *et al.* (1991) estimated emissions from wetlands to be 122 kton/yr (range 75-203); 70 kton/yr (range: 40-120) from wet soils, 35 kton/yr (range: 24-60) from inland and coastal waters and 17 kton/yr (range: 11-23) from small water bodies, leading to a total of 122 kton/yr (range: 75-203). This is the same as the 1990 data in this report.

Conclusion
As no IPCC method exists for wetland emissions or an emission change from wetland drainage, no comparison could be made. As a result of drainage about 15-100 kton less methane is emitted in 1990 compared to 1950. The emissions from this source quoted in this report are the same as previously estimated. This source is not likely to be intentionally managed to control methane emissions. Expansion of natural wetland areas in the Netherlands may reverse the decreasing trend of this source.

6.7 Methane uptake in forest soils

National estimate of methane uptake and change in the Netherlands
No IPCC method exists to estimate the forest sink for methane. A very rough estimate of methane uptake through the years can be made using the methane uptake factor of Crill (1991), from literature from temperate forests. The CBS (1989) has provided data on the extent of the forest over the period 1940 to 1983. The forest area has grown slightly in the Netherlands since 1900. In table 6.20 the results are summarized.

Table 6.20 Methane uptake in forest soils in the Netherlands

Forest extent	Methane uptake factor (10^4 mg/ha/yr)	Methane uptake (kton/yr)
1938-1942: 250,000 ha	578-616	1.4-1.5
1952-1963: 260,000 ha	578-616	1.5-1.6
1964-1968: 299,000 ha	578-616	1.7-1.8
1980-1983: 334,000 ha	578-616	1.9-2.1

Conclusion
The sink capacity of the forest in the Netherlands is very small as compared to the strength of the sources.

6.8 Conclusions

Comparison of results of Van den Born et al. 1991 with this report leads to the following conclusion: The emission estimates from landfills and animal waste have to be revised upwards. The other estimates are in agreement. New estimates are given for wetland drainage since 1950 and for forest soils as sinks for methane. In table 6.21 the results are summarized.

Table 6.21 Summary of estimates and comparison with Van den Born et al.

	Vd Born 1988/89			This report 1990			This report 1991		
	Low	Med.	High	Low	Med.	High	Low	Med.	High
Gas production	40	55	70	38	52	67	43	60	76
Gas transport	2	7	12	2	6	12	2	7	12
Gas distribution	60	70	80	61	72	83	71	84	97
Oil production	0	18	35	1	19	37	1	17	34
Combustion	22	27	32	14	21	28	16	23	31
Wetlands	40	70	120	40	70	120	40	70	120
Inland and coastal waters	24	35	60	24	35	60	24	35	60
Small water bodies	11	17	23	8	16	24	8	16	24
Animals	295	379	462	290	414	538	297	424	551
Animal waste	10	15	20	74	106	138	76	109	142
Landfills	190	255	320	178	377	576	178	377	576
Sewage treatment	3	3	3	3	3	3	3	3	3
Water production	2	2	2	2	2	2	2	2	2

7. SCENARIOS AND QUANTIFICATION OF EMISSION REDUCTIONS IN THE NETHERLANDS, 1988-2015

7.1 Introduction

This chapter assesses how the emissions of methane may develop in the Netherlands over the period 1988-2015. The RIVM's National Environmental Outlook 3 forms the basis of this assessment for the various relevant sectors. Assumptions will be made on the emission controls indirectly achieved through existing environmental policies in relevant areas such as manure disposal, acidification and waste management.

The Netherlands open economy is, by nature, very much linked to the international economy. Recently, the Central Planning Bureau (CPB) initiated a long-term scenario study on the world economy: Scanning the Future (CPB, 1992). In this study four scenarios are developed for various paths of economic growth in the world. To study the effects of these different growth paths for the Netherlands, the scenarios are further elaborated for Dutch socio-economic developments ('Nederland in Drievoud'). Different institutes have made contributions to this study on different issues, including The National Energy Outlook, 1990-2015 of the Netherlands Energy Research Foundation (ECN) (Boonekamp *et al.*, 1992), and the National Environmental Outlook 2 (RIVM, 1991; Wieringa and Maas, 1992). Some features of the four scenarios (i.e. Global shift, European renaissance, Global crisis and Balanced growth) will be given here.

The CPB scenarios will form the basis for the RIVM's third National Environmental Outlook, which is due for publication in 1993. After a short description of the scenarios, methane emissions per sector will be assessed for a reference scenario (no additional climate policies) and for an additional policies scenario over the period 1988-2015.

Global shift (GS)
In this scenario the core of the world's economic activity shifts to the Asia-Pacific region. Europe loses terrain in important industrial sectors and stagnation is a result. Only after 2000 a gradual improvement takes place. Migration from Africa and Eastern Europe to Western Europe takes place as a result of the failure to financially support development of these regions. Environmental policies fail to halt pollution. In Western Europe and the Asian-Pacific region only local problems are addressed. In Africa and Eastern Europe negative trends continue. Total CO_2 emissions in 2015 are 60% above the 1990 level despite the development of extra nuclear energy sources and new energy-saving techniques.

European renaissance (ER)
Western Europe develops prosperously in this scenario. The European integration is a success. The European Monetary Union will be completed before the end of the century, when the American economy will be faced with a recession resulting in further unemployment and poverty. The central European states will be assisted by the European Community's financial and technical support. The former Soviet Union is faced with stagnation, but some republics, especially those near Western Europe, will recover quickly. The European Energy Charter will play an important role in this respect. Energy savings take place in these countries. Increased earnings from the exports of energy, especially gas, will be used for investments in infrastructure and capital goods.

A strong improvement sets in in the USA around the first half of the next decade. At that time international cooperation increases. In Europe a moderate CO_2-tax is realized and will continue to 2005, but has no effects of global significance. Carbon dioxide emissions in 2015 are 40% above the 1990 level.

Global crisis (GC)
In this scenario the negative trends of the eighties in the USA will continue. In Western Europe cooperation is not what it should be. Slow growth and increasing unemployment are the result. In Japan growth will continue as in the eighties. The world economy slows down. No progress can be seen in the international cooperation on energy and environment issues. Hunger, deforestation, floods and disease take their increasing toll. A food crisis is expected in 2000 in this scenario. The crisis is seen as an 'ecoshock'. Carbon dioxide emissions in 2015 will rise to 50% above 1990 levels. A late response to all these problems is responsible for the slow recovery after 2010.

Balanced growth (BG)
The need for sustainable economic development and a brisk technological momentum dominate in this scenario. The powerful elements of the free market economy are combined with national cooperation. In the nineties the USA reduce the deficit on the balance of payments and improve the quality of education and infrastructure. Western Europe stimulates competition, improves the financial stimuli and cuts back on regulations. Japan opens up to the world economy. Economic reform processes take place in regions like Latin America, the former Soviet Union, India and China. In response, a strong worldwide economic growth takes place in the second half of the nineties. The GATT agrees on a drastic liberalization of agriculture. A CO_2-tax is agreed as insurance against the possible negative effects of global warming. The revenues from this tax are used to lower other taxes. This stimulates energy saving and switches to gas and sustainable energy sources for fuel take place. The energy intensity of production is reduced by 50% as a result, with only minor negative effects on the growth of the world economy. In 2015 the CO_2 emissions from energy use are 5 to 10% above 1990 levels, while production of energy is increased worldwide to 145%. The phase-out of deforestation and increasing reforestation even result in CO_2 emissions 25% below 1990 levels.

7.2 Oil and gas

Emissions of methane from the oil and gas systems are a function of the energy demand, production, energy efficiency and emission per unit product. Emissions can be reduced either by reducing the demand for oil and gas, or by reducing the emission per unit product. The future demand for oil and gas and the technical options available to reduce leaking will determine the future emissions and reduction potentials.

Development of gas consumption

In all four scenarios Boonekamp *et al.* (1992) expect a constant natural gas production, export and import until 2010. Boonekamp *et al.* (1992) expect that export volumes will begin to decrease after 2010 because of long-term export contracts. The volumes as given by Gasunie (1992) are taken as a 'no additional policies scenario' for the period up to 2015.

The Gasunie expects a domestic demand of between 40 and 45 x 10^9 m^3/yr, depending on economic developments and weather conditions during winter, for the coming 25 years. It also expects an increase of exports to a level of about 40 x 10^9 m^3/yr up to 2015 (Gasunie, 1992). Exports were 28, 33 and 38.6 x 10^9 m^3 in 1988, 1989 and 1991, respectively (CBS, 1991; Gasunie, 1992). Domestic demand has been between 40 and 45 x 10^9 m^3 in the years since 1980 (CBS, 1991).

Emissions
The emission calculations for the period 1980-2015 are based on the above assumptions and

assuming that no extra technical measures are taken as a response to climate change. Total emissions from the natural gas sector, excluding end use, are estimated between 110 and 170 kt/yr in 2000 and in 2015 under this current policy scenario.

Additional technical reduction measures

The emission of methane in natural gas production is important in the Netherlands due to the large gas production activities. Off-shore natural gas production is responsible for the larger part of these emissions. Off-shore fields only produce 25% of the total natural gas production in the Netherlands, but are responsible for 80% of emissions. The reason is that onshore flaring is practiced and off-shore excess natural gas is mainly vented. In the distribution system leak repair can reduce the emissions. Modernization of old cast-iron systems is an expensive measure. This measure may be less expensive if only leak repair is intensified.

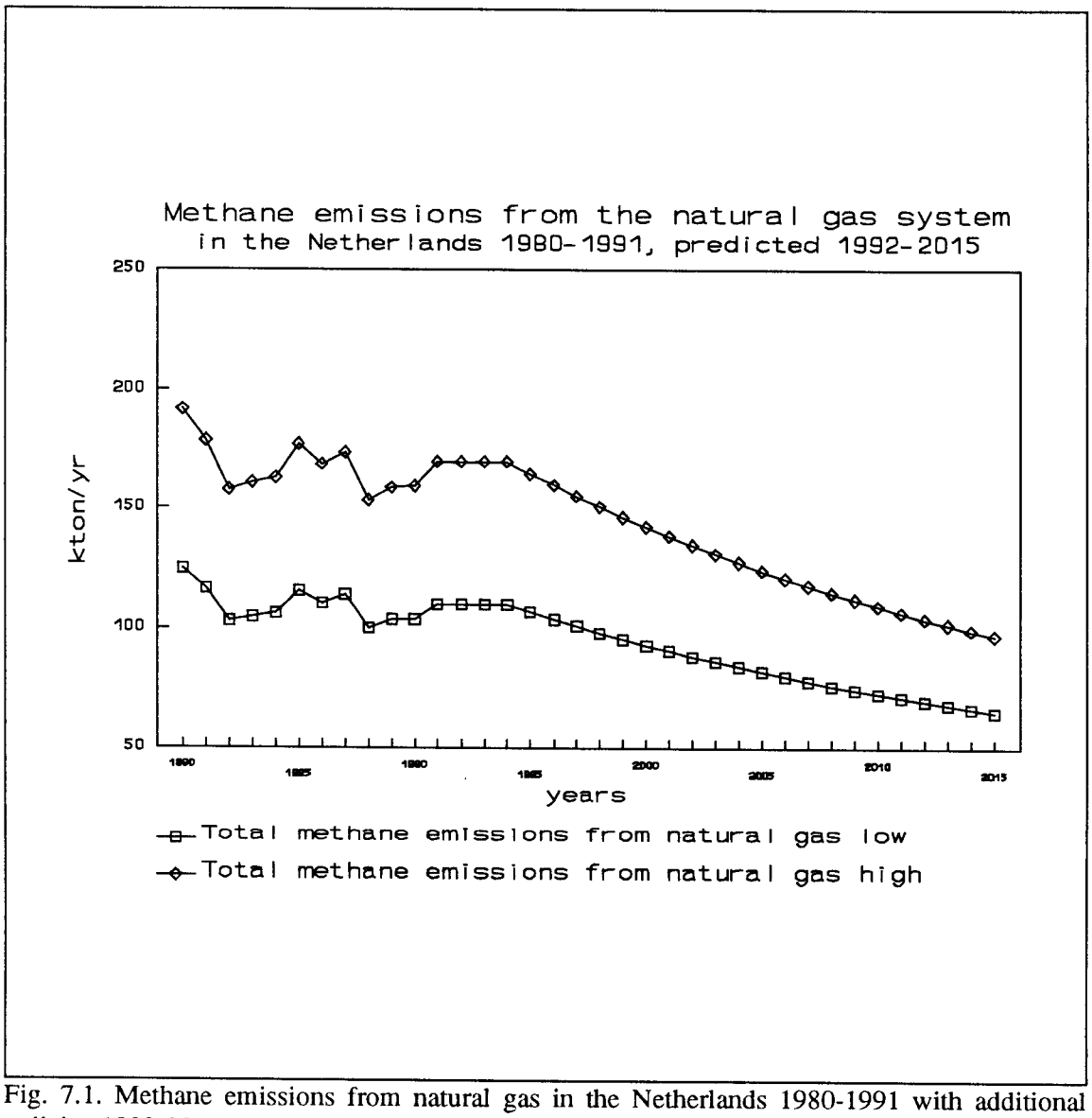


Fig. 7.1. Methane emissions from natural gas in the Netherlands 1980-1991 with additional policies 1992-2015.

Possible additional measures taken between 1990 and 2015 can result in the following reductions of methane emissions from the gas systems:

1. Increased gas use on platforms off-shore and reduced flaring during production can result in ca. 80% reduction of methane emissions from this source in 2015. This is from 40-70 kton in 1988 to 8-14 kton in 2015.
2. Increased recapture of gas during maintenance operations in transport and handling of gas can result in a 50% reduction of methane emissions from this source. This brings the estimated emission of 6.4 kt/yr in 1988 down to 3.2 kt in 2015.
3. Replacement and an increased leak repair of the old cast iron network can result in a 15% reduction in leaks from the distribution of gas. This will lead to 55-67 kton in 2015 from an estimated 65-79 kton in 1988.

Total reductions in the gas sector can be from 110-170 kton in 1988 to 78-110 kton in 2015. This is about 30%. The result of this additional policies scenario is given in Figure 7.1.

7.3 Ruminants

Emissions of methane from enteric fermentation are a function of the demand for meat and milk, the efficiency of the production and the emissions per unit product. Emissions can be reduced by decreasing the number of cattle, (e.g. to address the surplus in meat and milk or to tackle the Dutch manure problem). Emissions can also be reduced by an increase in the efficiency of the production; this means a reduction of emissions per unit of product.

Demand

In the European Community a surplus of milk, meat and other products exists. In 1991 the European Commission developed a plan to revise the Common Agricultural Policy of the EC. This plan is known as the MacSharry plan. The MacSharry plan will result in drastic reductions of price guarantees for wheat and feeding grains. Feeding costs for grain animals will consequently drop. It is expected that more European grain will replace the cheaper imported feeds from outside the European Community. The plan proposes to reduce price guarantees for milk and meat. Compensation will only be paid to farmers who use predominantly roughage to feed their herds. This will probably increase the methane emission per animal.

Existing policies have already affected animal numbers during the past years. The milk-quota instrument proved to be very effective in reducing the milk surplus and dairy cattle numbers. This trend is shown in the Dutch herd statistics up to 1992. A slight compensating effect is also noticeable in the growing beef cattle numbers. It is expected that the increase of beef cattle and suckler cows will accelerate. Ewe premiums have resulted in growing numbers of sheep in the Netherlands during the past years. This will level off in the near future as these premiums are restricted to a limited number of ewes.

The balance of all these trends as it is foreseen is a reduction in ruminant numbers and a slight increase in methane emissions per animal.

Emissions

Three institutes in the Netherlands, the CPB, the LEI and the SOW, have assessed the longer term effects of the MacSharry plan on agriculture in the Netherlands. The resulting animal numbers have been used to estimate methane emissions. Methane emissions under a 'no additional policies scenario' have been calculated using the National Environmental Outlook 3. Table 7.1 and Figure 7.2 present the resulting methane emissions.

Table 7.1. Methane emissions of ruminants under the National Environmental Outlook 3 agriculture scenario

NUMBERS							
TYPE		SUBTYPE	1995 ('000)	2000	2005	2010	2015
Cattle	dairy	young <1	687	633	618	571	540
Cattle	dairy	young female >1	739	681	664	614	581
Cattle	dairy	female	1703	1569	1530	1416	1339
Cattle	dairy	male >1	36	33	32	30	28
Cattle	beef	calves	496	496	496	496	496
Cattle	beef	young	677	661	687	677	671
Cattle	beef	female >2	135	259	349	435	525
Sheep		male	15	13	12	10	8
Sheep		female	617	539	493	402	331
Sheep		fattened lamb	703	614	562	459	377
Goats		male	26	26	26	26	26
Goats		female	35	35	35	35	35
Pigs			14004	14004	14004	14004	14004
Horses			101	101	101	101	101

Methane emissions Tg CH4/yr			1995	2000	2005	2010	2015
Cattle	dairy	young <1	0.034	0.031	0.030	0.028	0.027
Cattle	dairy	young female >1	0.046	0.043	0.042	0.039	0.036
Cattle	dairy	female	0.174	0.160	0.156	0.145	0.137
Cattle	dairy	male >1	0.003	0.003	0.003	0.003	0.003
Cattle	beef	calves	0.009	0.009	0.009	0.009	0.009
Cattle	beef	young	0.059	0.057	0.060	0.059	0.058
Cattle	beef	female >2	0.014	0.026	0.036	0.044	0.054
Sheep		male	0.000	0.000	0.000	0.000	0.000
Sheep		female	0.010	0.009	0.008	0.006	0.005
Sheep		fattened lamb	0.009	0.008	0.007	0.006	0.005
Goats		male	0.001	0.001	0.001	0.001	0.001
Goats		female	0.001	0.001	0.001	0.001	0.001
Pigs			0.021	0.021	0.021	0.021	0.021
Horses			0.002	0.002	0.002	0.002	0.002
Total			0.382	0.371	0.375	0.363	0.358

Additional policies

An increase in production efficiency can result in lower methane emissions per unit of product. The most important increase in production efficiency can be expected from breeding programmes to increase the meat and milk production per animal. Future increases are expected. Production-enhancing agents can effectively reduce methane emission per unit product. However, the absolute methane emission reductions will be low. Moreover, technical measures to reduce emissions are more difficult to apply as we are dealing with animals, and the necessity to reduce emissions has to be weighted against animal welfare.

It is very difficult to quantify the effect of additional policies on methane emissions, as potential policies directed to methane have not yet been formulated. There is an important side effect of

manure, milk and beef policies on methane emissions however, and additional environmental policies might result in further herd size reductions. If additional environmental policies are deemed necessary to reduce manure and overproduction of milk and beef an extra reduction of methane emissions from additional policies can be expected by 2015. In Figure 7.2 10% extra reduction is assumed.

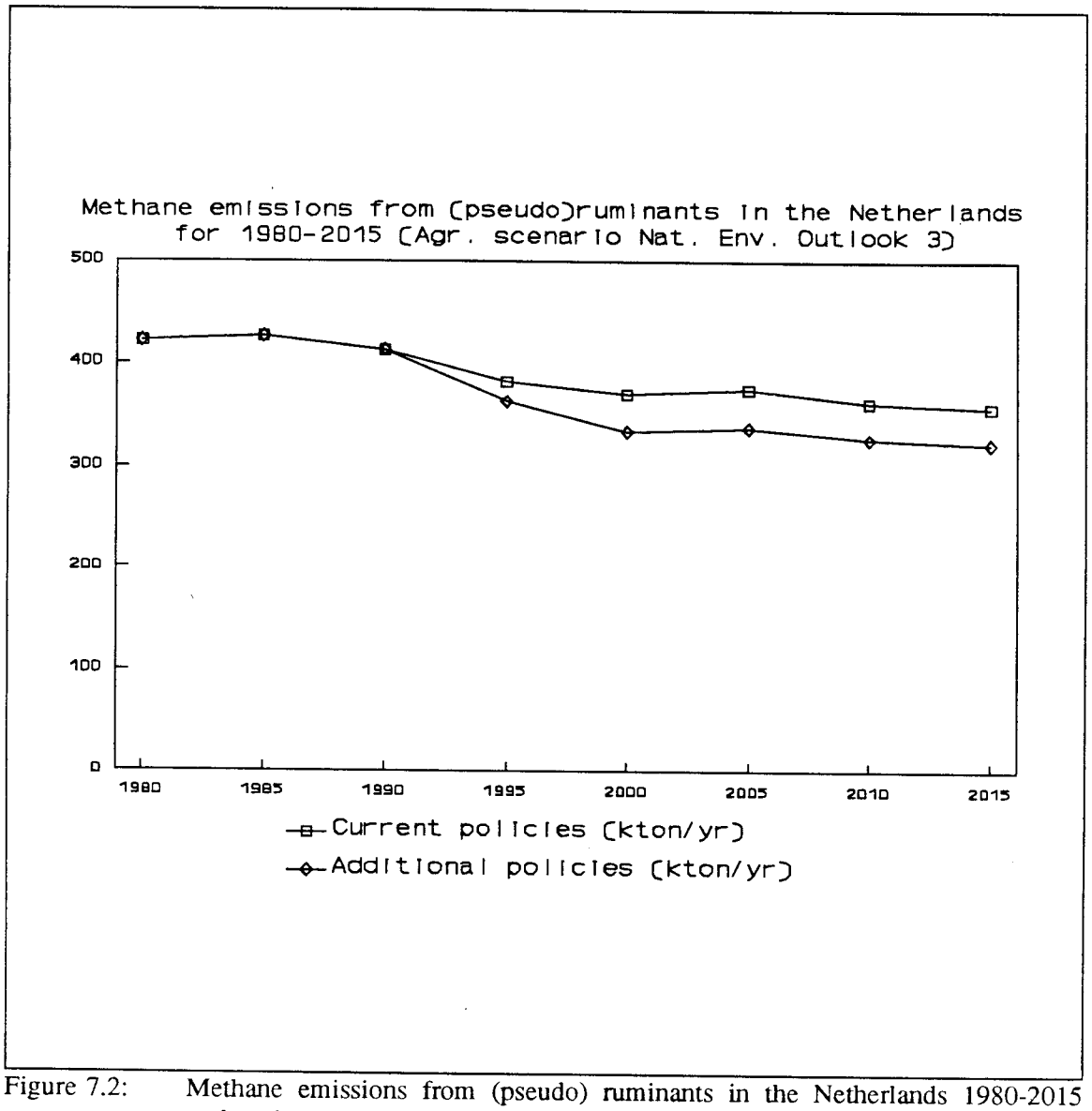


Figure 7.2: Methane emissions from (pseudo) ruminants in the Netherlands 1980-2015 under the Agriculture scenario of the National Environmental Outlook 3 (ER/GS), current and additional policies.

7.4 Emissions from animal manure

Emission of methane from manure is a function of animal numbers, manure production per animal, composition of the manure, emissions per manure handling system, storage capacity per system and technical measures to utilize the biogas from small and large-scale digesters. Methane emissions from manure will decrease as manure is stored in silos outside the stable or collected in advanced digesters.

Manure production

The manure production in the Netherlands is summarized in Table 7.2. The calculations are based on animal numbers and production of manure per animal. The Agriculture scenario of the National Environmental Outlook 3 (ER/GS) is used.

Table 7.2. Manure production (10^6 ton slurry) in the Netherlands

Manure (million tons of slurry)	1994	1995	2000	2010	2015
Cattle	49.1	48.9	44.2	40.7	40.7
o.w. in stable	19.64	19.56	17.68	16.28	16.28
o.w. in meadow	29.46	29.34	26.52	24.42	24.42
Fattening steers	3	3	3	3	3
Fattening calves	1.8	1.7	1.7	1.7	1.7
Sheep and Goats	2	2	2	2	2
Pigs	16.6	16.2	13.7	14.2	14.2
o.w. breeding pigs	7.7	7.5	6.7	6.9	6.9
Poultry dry	0.7	0.8	0.9	0.9	0.9
Poultry slurry	1.4	1	0.4	0.3	0.3

Source: Hoogervorst, 1991; CBS, 1992

Future methane emissions are calculated from production data and storage assumptions using the method of Casada and Safley (1991), but with lower emission factors, as discussed in Chapter 6. The results are summarized in Table 7.3 and Figure 7.3.

Table 7.3. Methane emissions from animal waste in the Netherlands

(kton/yr)	1994	1995	2000	2010	2015
Cattle					
o.w. in stable	14	14	12	11	11
o.w. in meadow	0	0	0	0	0
Fattening steers	8	8	8	8	8
Fattening calves	5	4	4	4	4
Sheep and Goats	6	6	6	6	6
Pigs	50	49	41	43	43
o.w. breeding pigs	23	23	20	21	21
Poultry dry	3	3	4	4	4
Poultry slurry	6	4	2	1	1
Total	90	88	77	77	77

The emissions are much higher than calculated by Van den Born *et al.* (1991), although we adopted some of the assumptions from that study:

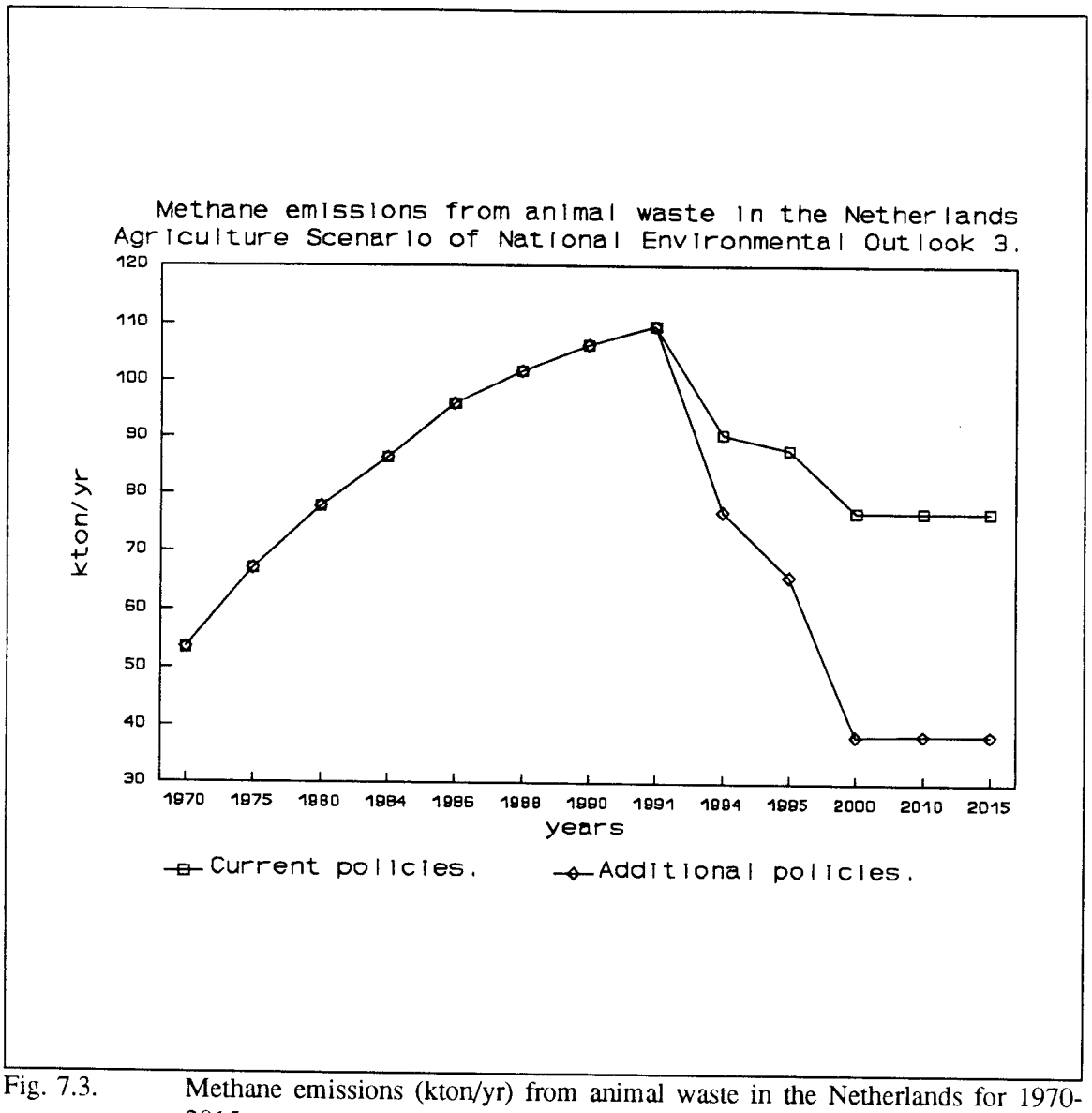


Fig. 7.3. Methane emissions (kton/yr) from animal waste in the Netherlands for 1970-2015.

- Methane emissions from cattle manure in the meadow are zero;
- Emissions from cold storage (below 15°C) are 1/6 of stable emissions.

The calculated emissions are provisional and considered maximum values until more measurements of actual emissions are carried out.

Additional policies

For a further reduction of methane emissions from animal waste different options can be formulated:

- Reduction of livestock numbers, notably pigs.
- New stable systems with prevention of fermentation in the stables.
- Increased manure storage outside the stables.
- Controlled fermentation in advanced digesters.
- Fermentation inhibitors.

It is assumed that a further reduction of 50% emissions is possible with a combination of these measures. The exact contribution of each of these measures cannot yet be calculated because of the high uncertainties in the estimates.

7.5 Emissions from landfills

In the Netherlands National Environmental Policy Plan the main aims are waste prevention, improvement of the waste disposal structure and stimulation of recycling. Landfilling should be kept to a minimum. Emissions of methane from landfills are a function of the amount of waste landfilled, the composition of the waste, the actual processes in the landfills and the age of the waste tips. All of these are changing as more waste is collected separately and treated differently. Because of prevention and recycling being stimulated now, less waste will be landfilled in the near future. The garden, fruit and kitchen (GFK) waste will be collected separately and composted or fermented with biogas recovery.

To evaluate the effects of different waste prevention programmes on methane emissions from landfills we formulated scenarios of landfilling up to 2050. Nagelhout and Lohuizen (1992) have made a prognosis for waste disposal in the Netherlands for the National Environmental Outlook 3 for the period 1990-2015. They expect that after prevention and recycling, and the incineration of unusable products a total of 6 million tons will be left to be landfilled in 2000. When the degradable organic carbon content of this waste was assessed, it was found that this waste still contained about 5% degradable organic carbon, mainly from paper and wood waste. To calculate the methane emissions from landfills, the k factor in our model was set at 0.1 for the period 1945-1995 and was at 0.365 from 1995 to 2050 to account for the residual enrichment in the waste of paper and wood with a mean degradation time of 20 years (half of the material degraded in 20 years).

No additional policies scenario

The first scenario is without additional policies. The National Environmental Outlook 3 scenario is taken for the development of the amount of waste. We assumed a 10% per year decrease of landfilling from 1990. We assumed a 5% decrease per year of degradable organic carbon in the landfilled waste because of separate collection of GFK waste (interpretation of data from Nagelhout and Lohuizen, 1992). A waste gas recovery of 25% of the potential production is assumed. The results of this scenario are given in Figure 7.4.

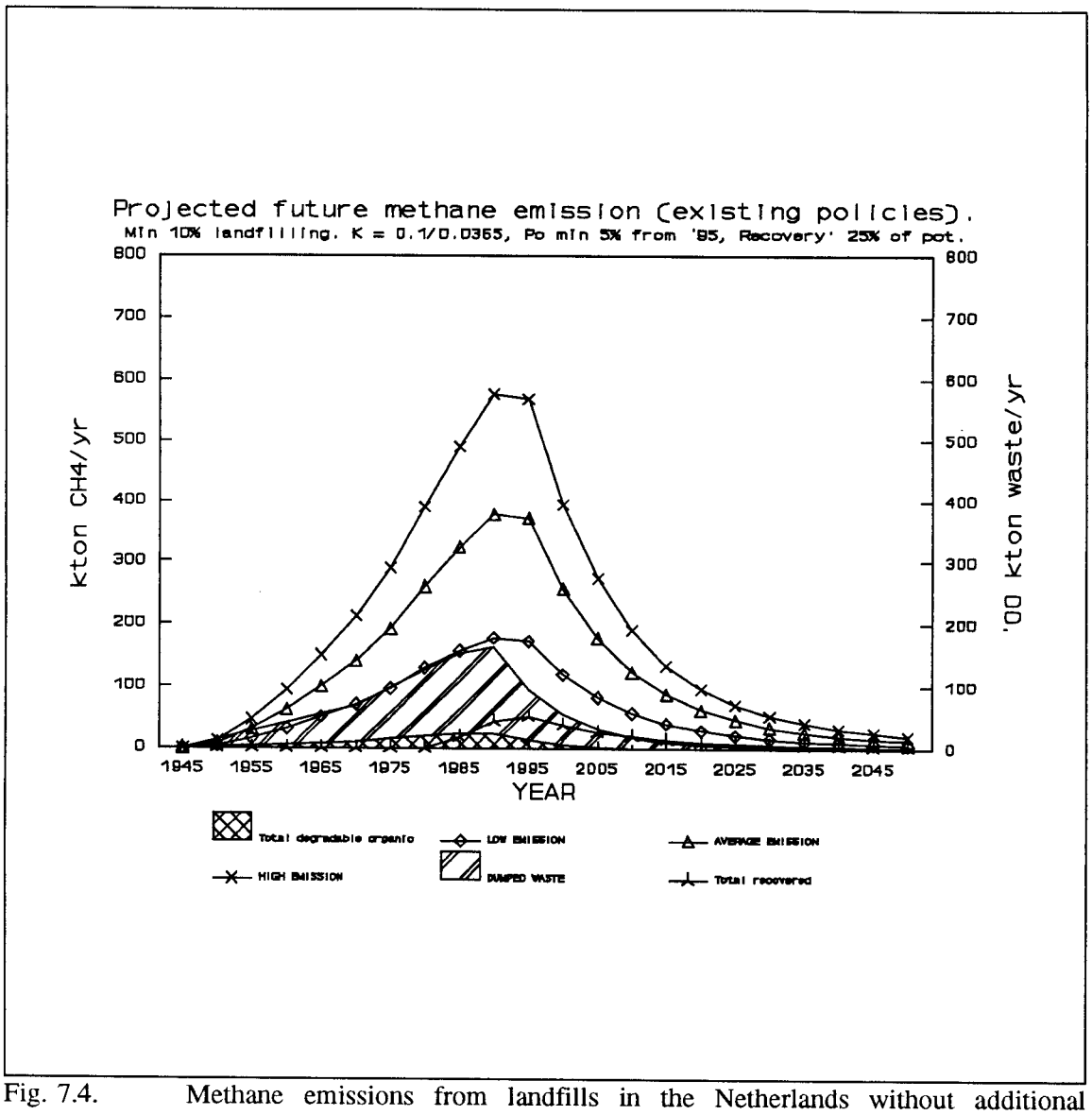


Fig. 7.4. Methane emissions from landfills in the Netherlands without additional policies. Scenario from the National Environmental Outlook 3.

This figure and tables in Annex 5 show that the average methane emissions decrease from 377 kton in 1990 to 257 kton in 2000 and 87 kton in 2015.

Pessimistic scenario

A more pessimistic scenario has a 2% decrease per year of landfilling from 1990, and a 2% instead of 5% decrease per year of degradable organic carbon, in the waste tips to account for potential problems in realizing waste incineration capacity and problems with separate collection of organic waste. Again, a waste-gas recovery of 25% of potential production is assumed. The result is given in the Figure 7.5.

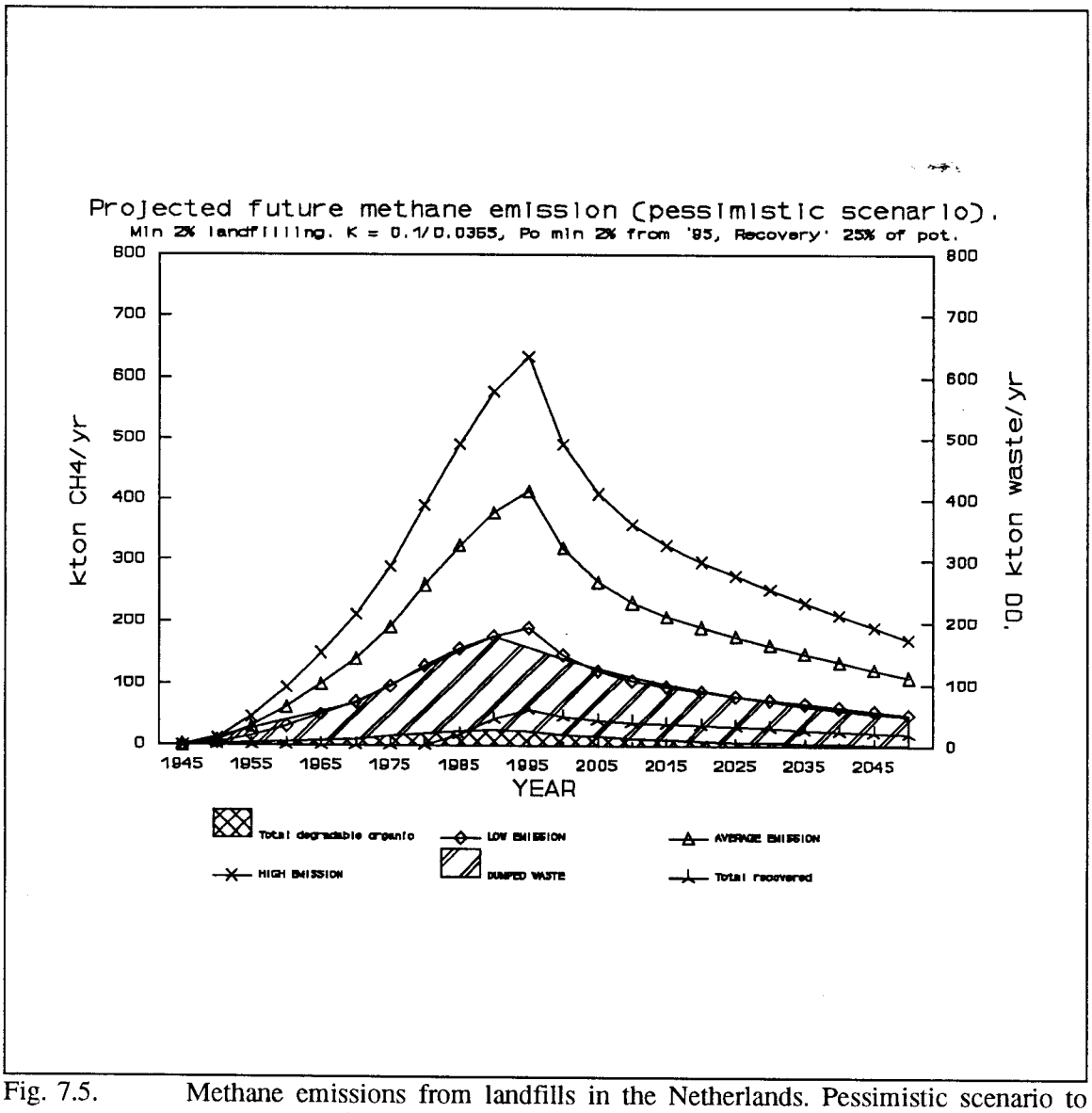


Fig. 7.5. Methane emissions from landfills in the Netherlands. Pessimistic scenario to account for a delay in the growth of incineration capacity and not such a successful separate collection of organic waste.

From this figure and tables in Annex 5 it can be seen that, in this scenario, average methane emissions are increasing from 377 kton in 1990 to 412 kton in 1995. In 2000: 319 kton are emitted and in 2015: 210 kton. It is obvious that extra investments in waste gas recovery can reduce possible problems with methane emissions in this pessimistic scenario.

Additional policies scenario

In the former scenarios, emissions of methane are either stable or increase up to 1995. The most cost-effective method of abatement is waste-gas recovery. NOVEM made a waste-gas recovery plan for the time up to 1995. In 1990 only 70 million m^3 waste gas was recovered. NOVEM is expecting a potential production of 540-840 million m^3/yr between 1992 and 2000. They expect that 50% of this amount is recoverable. This will be 270-420 million m^3/yr. In 1995 the NOVEM expects to recover 185 million m^3 waste gas per year. This equals 140 Mm^3 natural gas equivalents. These are still minor amounts of total gas. In Figure 7.6 the result of the additional

policies scenario with 50% of the potential waste-gas production recovered is presented. Assumptions are from the NOVEM action programme.

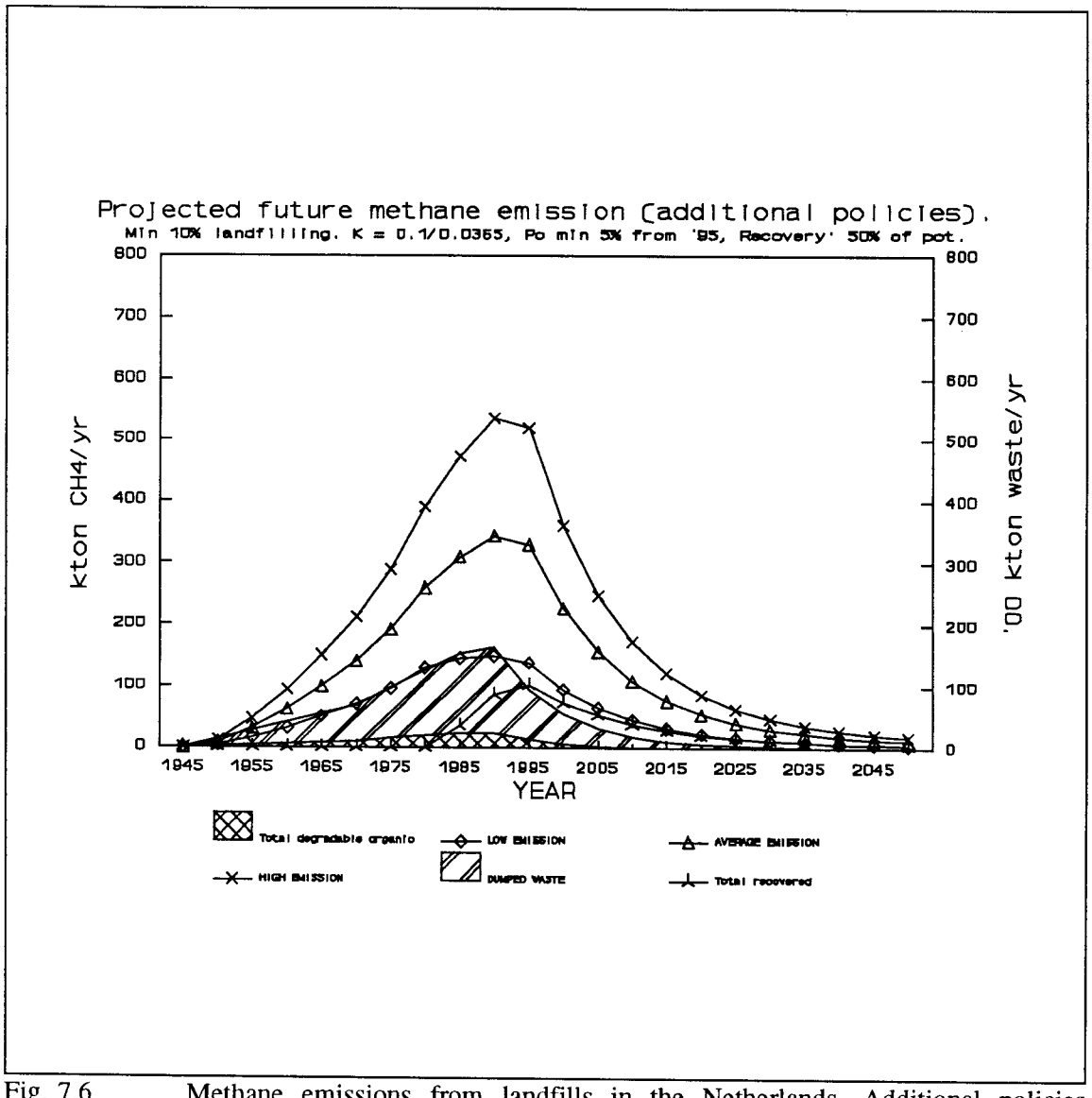


Fig. 7.6. Methane emissions from landfills in the Netherlands. Additional policies scenario: 50% of waste gas production is recovered.

This figure shows that emissions are decreasing from 377 kton in 1990 to 227 kton in 2000 and 77 kton in 2015.

Methane recovery would have to be developed with sophisticated technical means to be able to fully recover the methane potential in the waste. This implies a temporary impermeable cover of the waste and methane recovery from the early stages of the dumping. If this can be realized, a waste-gas recovery up to 2020, with a growth from 185 to 500 Mm^3/yr of waste gas would result.

Old landfills

Old, already closed landfills are also still emitting methane. Additional effort could be devoted to recovering methane from these sites. To evaluate the potential waste-gas production an extra run with the model is done, assuming no waste dumping after 1986. This gives the emissions from old landfills. The result is presented in Figure 7.7, which gives a partial picture of old landfills. All the landfills are represented in the previous figures.

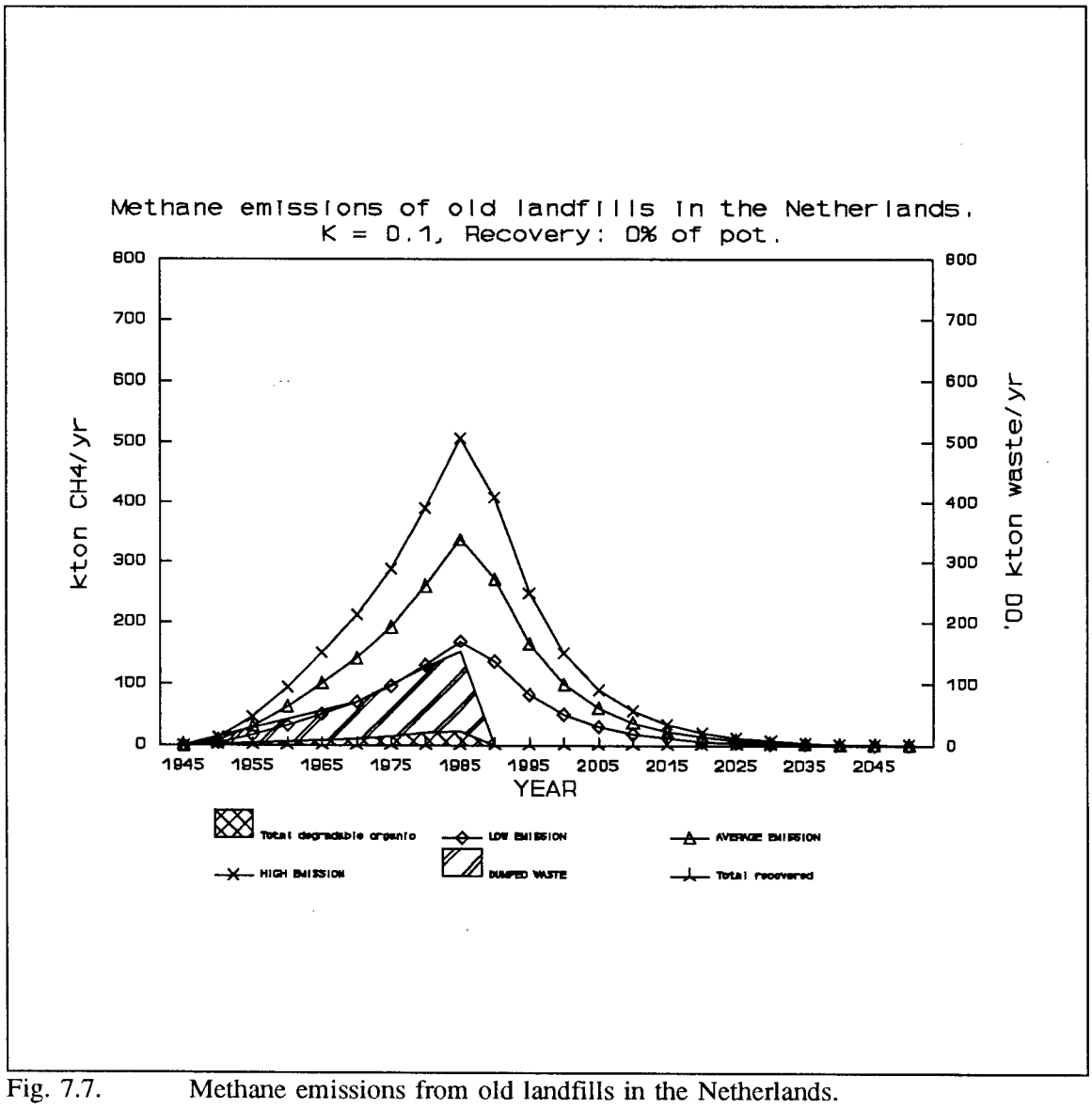


Fig. 7.7. Methane emissions from old landfills in the Netherlands.

As can be seen from this figure, it may be profitable to invest in some installations to recover the waste gas from some old landfills.
In all scenarios GFK waste is collected separately. It is assumed that eventually most of this waste can be fermented in a controlled way to make best use of the biogas potential. Possibly more organic waste categories could be fermented. This way the paper and wood fraction could also be utilized for gas production.

7.6 Conclusions

Methane emission reductions are expected of ca. 200 kton between 1990 and 2000, and of another 200 kton between 2000 and 2015 with no extra climate policies. This is expected as a result of policies to reduce acid deposition and a manure surplus. With additional policies especially developed for methane reductions an extra 132 kton/yr can be mitigated in 2000 and another extra 143 kton/yr in 2015. If other policies fail, methane reductions are not expected to be large.
In table 7.4 the results of the current policies and the additional policies scenario are summarized. Background natural emissions from wetlands and (small) water bodies are not considered here.

Table 7.4 Methane emissions in the National Environmental Outlook 3 scenario, with and without additional policies

Methane emissions kton/yr	National Environmental Outlook 3 scenario			Additional policies scenario		
	1990	2000	2015	1990	2000	2015
Gas production	52	52	52	52	35	11
Gas transportation	6	6	6	6	5	3
Gas distribution	72	72	72	72	65	60
Oil production	19	0	0	19	0	0
Animals	414	371	358	414	334	322
Animal waste	106	77	77	106	38	38
Landfills	377	257	87	377	227	77
(Sewage) water treatment	5	5	5	5	4	3
Combustion	28	26	24	28	26	24
TOTAL	1079	866	681	1079	734	538

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

In 1991 an initial national inventory of greenhouse gas emissions, based on 1988 and 1989, was published for the Netherlands by the RIVM (Van den Born *et al.*, 1991). A summary of this report was submitted to the IPCC as the official National Inventory of the Netherlands. While all direct and indirect greenhouse gases were covered in this document, the focus was on methane and nitrous oxide, the gases about which the uncertainties were the greatest and for which no policies yet existed. Production and distribution of natural gas, ruminants, landfills and wetlands were identified as the most important sources of methane. Primarily because of current policies on waste management and livestock, national emissions, without specific methane policies, were estimated to decrease by about 10% between 1990 and 2000. To confirm the likely impacts of these policies the Dutch government has consequently formulated an emission target for methane: i.e. a 10% reduction of 1990 levels by 2000 (VROM, 1991). During and after the development of the Van den Born *et al.* (1991) report new information became available, including:

- the development of draft Guidelines for National Inventories of Greenhouse Gases by the IPCC, coordinated by the OECD Environment Directorate;
- preliminary results of experimental research projects of the National Research Programme on Global Air Pollution and Climate Change, notably on methane emissions from landfills;
- new scenarios, developed for the global and national economy and energy systems by the Central Planning Bureau and the Energy Study Centre of the Netherlands Energy Research Foundation;
- new scientific information about current and future emissions of methane and its radiative effect, a.o. published by the IPCC in its 1992 Supplement;
- new insights into the effectiveness of related national policies.

RIVM has therefore prepared this Background Document on Methane to test the IPCC methodology on 1990 data, to further refine the emission estimates, to assess the effects of current policies and to assess the needs of additional policies in reaching a methane reduction of 10%. The report summarizes new findings on background information on the sources of the atmospheric chemistry of methane and new insights into potential technological emissions and control options. The analysis presented largely confirms the findings of the Van den Born *et al.* (1991) report. However, some important issues have been identified which deserve further attention .

As a follow-up to this report regular updates of national methane emissions and evaluation of national policies will be part of RIVM's planned annual "Environmental Balance" reports (Milieubalans) and its four-yearly "Environmental Outlooks" (Milieuverkenningen). This report will be followed by a similar document on nitrous oxide, which will be published in early 1994.

A companying document has been made on the costs of technical measures for methane reductions by De Jager and Blok of ECOFYS.

Taking the new information on methane into account, we have drawn the following conclusions (see also Figure 8.1 and Table 8.1).

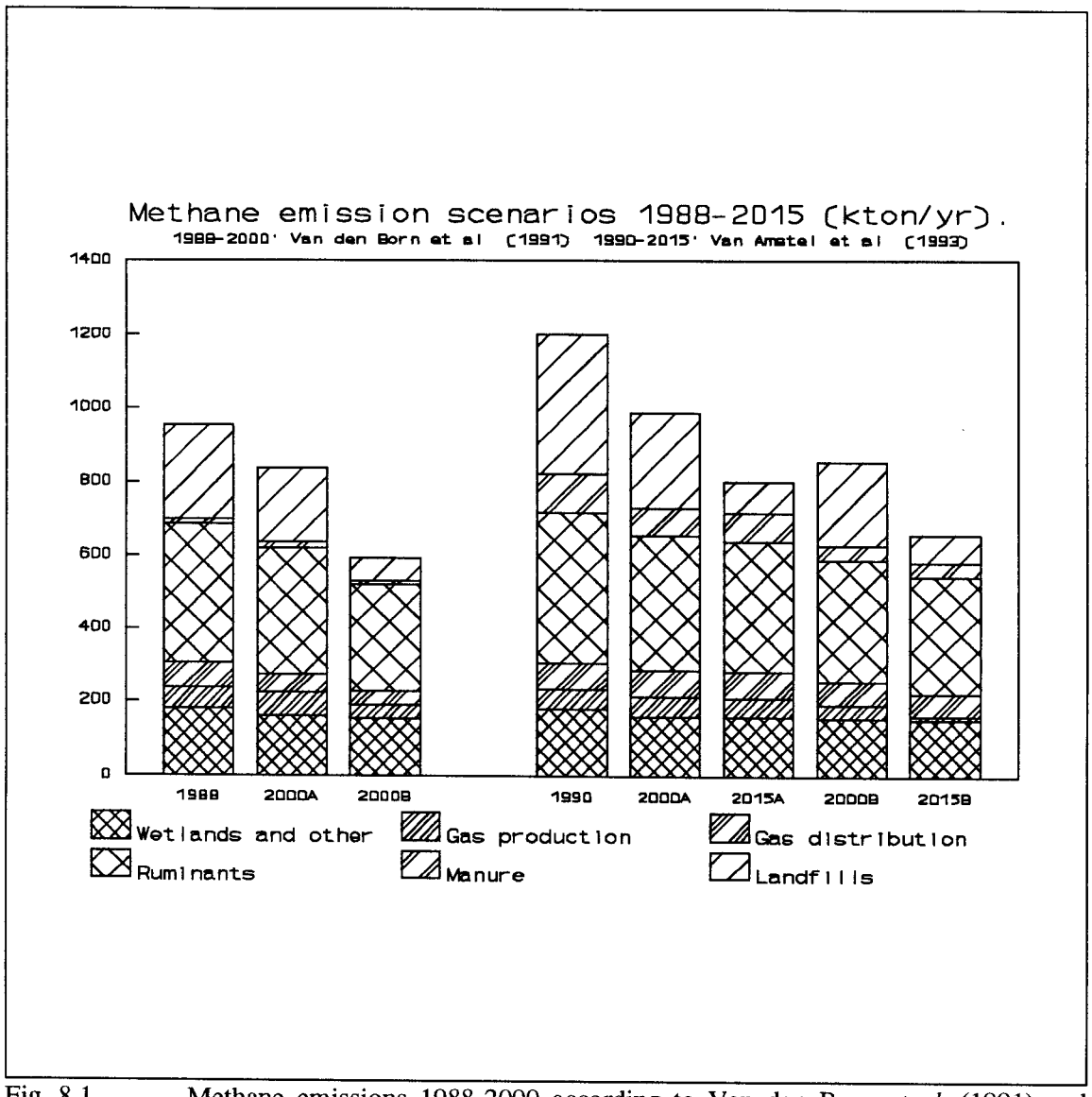


Fig. 8.1. Methane emissions 1988-2000 according to Van den Born *et al.* (1991) and 1990-2015 according to Van Amstel *et al.* (1993). A=current policies, B=additional policies.

Table 8.1. Comparison of emission data of Van de Born *et al.* and this report. A=current policies, B=additional policies.

Methane kton/yr	Van den Born et al. 1991 1988	Additional policies 2000A	Additional policies 2000B	This report 1990	2000A	2015A	Additional policies 2000B	2015B
Gas production	55	61	35	52	52	52	35	11
Gas transportation	7	7	7	6	6	6	5	3
Gas distribution	70	50	37	72	72	72	65	60
Oil production	18	0	0	19	0	0	0	0
Enteric fermentation	379	349	295	414	371	358	334	322
Manure	15	15	11	106	77	77	38	38
Landfills	255	200	60	377	257	87	227	77
Water treatment	5	5	0	5	5	5	4	3
Combustion	28	26	24	28	26	24	26	24
Wetlands and water	122	122	122	121	121	121	121	121
TOTAL anthropogenic	832	713	469	1079	866	681	734	538

Sources: Van den Born et al., 1991
This report

8.2 Findings with respect to the science of the budget, atmospheric behaviour and radiative effects of methane

1. The global warming potential of methane is reassessed in the IPCC Supplement (IPCC, 1992). The direct radiative effect is now 35 times the CO_2 effect when calculated on a 20-yr time horizon, 11 times calculated on a 100-yr time horizon and 4 times calculated on a 500-yr time horizon. The indirect effect is "positive" but to an unknown extent.

2. The actual measured background concentration of methane is 1.72 ppmv. The lifetime is 10.5 years. The measured atmospheric increase slowed down from 20 ppbv/yr in the late seventies to 10 ppbv in 1990. This slowing down is attributed to an increase, at least regionally, of OH radicals in the atmosphere.

3. Future methane concentrations have been calculated by different atmospheric models. IPCC scenario A of methane concentrations in the atmosphere over the period 1990-2100 shows a gradual increase from 1700 ppbv in 1990 to 4000 ppbv in 2100, with a difference between model outcomes of about 1000 ppbv or 25% around the mean. Scenario B peaks at 2400 ppbv in 2050 and is then constant up to 2100, with a difference between model outcomes of about 500 ppbv or 20%. Scenario C peaks at 2000 ppbv in 2050 with a return to original concentrations in 2100 and a difference between model outcomes of about 500 ppbv or 20%. Scenario D shows a gradual decrease of concentrations from 1700 ppbv in 2020 to 1500 ppbv in 2100, with a difference between model outcomes of 500 ppbv or 25%.

4. The global budget is reassessed in the IPCC Supplement because the reaction rate of methane with OH radicals was shown to be overestimated by 25%. It is now thought that the reaction with OH radicals removes 470 Tg methane from the atmosphere per year, with a range of 420-520 Tg. The total annual emission is about 515 Tg, of which about 360 Tg is anthropogenic and 155 Tg is natural. Of the anthropogenic emissions 100 Tg is from fossil-fuel production and use.

5. There is sufficient scientific information to postulate that global emission reductions of 10-20% are sufficient to stabilize atmospheric concentrations of methane at 1990 levels, depending on similar controls for other reactive gases, such as carbon monoxide, non-methane hydrocarbons and nitrogen compounds. Positive temperature feedbacks on wetland methane emissions caused by climate changes may interfere with this assessment. Finally, in addition to directly addressing the sources of methane, we can influence its atmospheric sink by controlling the emissions of different pollutants, thus enhancing the oxidizing capacity of the atmosphere.

8.3 Findings with respect to the IPCC Guidelines for National Emission Inventories

6. Even for the Netherlands the application of the draft IPCC Guidelines for estimating the emissions from the production of oil and gas have appeared difficult. This is primarily due to the absence of sufficient information about the number of wells in operation and the composition of the oil/gas mixture. The national method, which makes use of emission factors expressed as volume percentage of the quantities produced, processed and distributed, is recommended. However in the future a distinction between onshore and off-shore emission factors is necessary. In distribution a distinction between emission factors for old and new networks are necessary.

7. The draft IPCC Guidelines for the estimation of methane emissions from animals has appeared to be very complicated. As the results do not differ very much from the earlier national estimates in which Crutzen's emission factors were applied, this simple method should be recommended. The emissions from ruminants calculated with the IPCC method and the national method were both about 380 kton CH_4/yr in 1989.

8. Applying the draft IPCC Guidelines for National Emissions Inventories to animal waste revealed an important difference from the method applied in the Dutch inventory. Emissions from animal manure were much higher in the IPCC method (106 kton CH_4/yr) compared to the national result (kton CH_4/yr). The difference was partly a result of IPCC relying heavily on experimental results from the USA; European or national emission factors based on European and/or national experimental results have to be established.

9. Emissions from landfills were calculated with a first-order decay model. The results were higher than the original national result (377 compared to 255 kton CH_4/yr). Here however, the difference was explained by a change in scientific knowledge, not in the difference between the IPCC method and this one. Compared to the earlier national estimate a faster degradation of organic material and hence an earlier peak in the emission of 1990 was found.

10. The uncertainties on the estimated current emissions of methane - notably those from solid and animal wastes - and its radiative effects are even larger than assessed in 1991 by Van den Born et al. (1991). The uncertainty in landfill emissions is about 50%. The uncertainty in animal waste emissions is about 30%.

11. A transparency study, performed on the request of the IPCC, in which the National Inventories of OECD countries and some developing countries have been compared, revealed that the IPCC reporting format, methods, assumptions, definitions and emission factors still have to be refined. This is to allow them to serve as common or minimally required format and methodology to report emissions within the framework of the Climate Convention. Methane estimates are not yet comparable in all the countries (OECD, 1992.

8.4 Findings with respect to the future methane emissions in the Netherlands as a function of policies

12. Potentials to reduce methane emissions are large, at least 30% for most of the sources. The most cost effective solutions are in preventing the spills of natural gas in production and the extra recovery of landfill gas.

13. Emissions from oil and gas production sites, and gas distribution systems can probably be reduced considerably through obligatory flaring of waste gas (also on platforms offshore), increased use of associated gas and early replacement of old distribution pipes; cooperation with industry is necessary to confirm this assessment and to evaluate the technical and economic feasibility of these options.

14. By means of a programme to collect and handle garden, fruit and kitchen (GFK) waste separately, and to enhance gas recovery from landfills and from separately collected GFK waste, additional reductions can be achieved, with the additional benefits of saving fossil fuel and limiting related carbon dioxide emissions.

15. Because the assessment of methane releases over time has changed and expectations for the results of solid waste policies in 2000 are different, methane emissions from landfills are now expected to decrease somewhat later than originally estimated. In 2000 some organic waste will still be landfilled.

16. Emission decreases as a result of a decreasing dairy cattle herd size are expected as a consequence of fixed milk quota. Decreases in dairy cattle herd size are expected to be partially compensated by increases in beef cattle herd size. The McSharry plan will also have an effect on the animal rations. Increases of roughage, which tends to increase the emissions per animal, are expected and breeding will increase the mean milk production per animal. As these animals need more food the methane emission per animal will increase. The net effect of all these trends however is a decreasing methane emission.

17. The analysis in this report suggests that the targeted 10% reduction of national methane emissions by 2000 can only be achieved with full and successful implementation of current policies in the gas sector, the waste sector and the livestock sector. However, while the estimated total of current emissions in absolute terms has increased (according to this report) the emissions expected by 2000 are now estimated to be approximately equal to the those in 1990, conforming to earlier estimates.

18. To avoid partial failure or delay of existing policies, additional measures can be introduced e.g. limitations on venting of natural gas during (off-shore) production of gas and oil (specific costs: minus DFL 160/ton prevented CH_4 emission), increased recovery of landfill gas (specific costs: minus DFL 95/ton prevented CH_4 emissions), and fermentation of (animal) waste (specific costs: DFL 1300/ton prevented methane emissions). Information from De Jager and Blok (1993).

19. The additional measures identified could deliver an extra 132 kton reduction or 13% of emissions by the year 2000.

20. The findings in this report suggest a need for additional research into methane emissions in the Netherlands or a change in emphasis of current research programmes. This particularly relates to emissions from animal manure under Dutch circumstances, the feasibility of options to control emissions from the oil and gas industry, the feasibility of centralized systems of organic waste collection and landfill gas recovery, and the global possibilities of cost-effective methane control programmes.

Annex 1

UNITS AND CONVERSION FACTORS

General

peta = P = 10^{15}
tera = T = 10^{12}
giga = G = 10^{9}
mega = M = 10^{6}
kilo = k = 10^{3}

pptv = parts per trillion (10^{12}) by volume
ppbv = parts per billion (10^{9}) by volume
ppmv = parts per million (10^{6}) by volume

ton = metric ton = 1000 kg
kton = 1000 ton = 10^{9} g
Mton = 10^{12} g = 1 Tg
1000 kton = 1 Tg

CATTLE

1 kg Methane = 55.65 MJ
1 kg dry matter of feed = 18.41 MJ (average)
1 kg dry matter of feed = 19.20 MJ (Europe, USA and Canada)

1 mol carbon = 12 g
1 mol methane = 16 g
1 mol methane = 22.4 lr
1 lr methane = 31650 J
1 lr benzine = 32.6 MJ

If emission per cow = 8.8 g/hr
it emits 77.1 kg/yr
= 4818 mol/yr
= 107923 lr/yr
= 3415769280 J/yr
= 3416 MJ/yr
= equivalent to 105 lr of benzine
or 1572 km/yr by car (at 15 km to the litre)

GAS.

Natural gas and oil reserves are stated in terms of metre cubic (m^3) at a pressure of 1.01325 bar and 15^0 C. This cubic metre is the standard according to ISO; it is usually abbreviated to m^3 (st).
Dutch natural gas contains on average 81.3 vol % methane (Assumption of Nielen, 1991.)
Density of natural gas = 0.717
So, 1 m^3 (st) natural gas then contains 0.58 kg methane.

The energy content of natural gas is also reported in terms of the Groningen Natural Gas

equivalent, which has a gross caloric value of 35.17 MJ/m^3 at 0^0C and 1.01325 bar absolute.
For calculated energy content the volume of natural gas from the various fields producing different qualities of gas are restated in terms of combustion heat as the notional volumes which would be measured if each field were to produce gas of the same quality as that from the Groningen reservoir.
The Groningen natural gas equivalent is used, for example, by the N.V. Nederlandse Gasunie. Figures stated as the Groningen equivalent can be converted in a simple way into equivalents for other fuels, such as Ton of Oil Equivalent (TOE) and Coal Equivalent (CE). The conversion factors are as follows:

1 ton of oil equivalent =
41.868 x 10^9 joule = 1191 m^3 of natural gas
(0^0C; 35.17 MJ).

10^9 m^3 natural gas =
0.84 million tons oil equivalent, usually abbreviated to 0.84 MTOE.

1 ton of coal equivalent =
2.93 x 10^{10} joule = 833 m^3 natural gas
(0^0C; 35.17 MJ)

10^9 m^3 natural gas =
1.20 million tons coal equivalent.

1 Joule = 1 J = 1 $kg.m^2.s^{-2}$
1 Megajoule = 1 MJ = 10^6 $kg.m^2.s^{-2}$

Source: Ministry of Economic Affairs 1989: Oil and gas in the Netherlands 1989

ENERGY CARRIERS.

Caloric value in TJ per unit indicated based on the "lower heating value".

Coal and Coal products		
	Coal and Brown coal	Variable
	Cokes	28.5 TJ/10^6 kg
	Cokesovengas	31.65 TJ/10^6 m^3 (st)
	Hoogovengas	31.65 TJ/10^6 m^3 (st)
	Other coalderivatives	Variable
Oil		
	Crude oil	42.7 TJ/10^6 kg
	Natural gas condensate	44.0 TJ/10^6 kg
	Other oil	42.7 TJ/10^6 kg
Other energy carriers		
	Natural gas	31.65 TJ/10^6 m^3
	Electricity	3.6 TJ/10^6 kWh
	Steam and/or warm water	2.67 TJ/10^6 kg N steam
	Fermentation gas	31.55 TJ/10^6 m^3 (st)

Source: CBS 1992: The Dutch Energybalance 1991-2.

1 PJ = 23.4 mln kg crude oil
= 31.6 mln m^3 natural gas
= 277.8 mln kWh electricity

Source: CBS 1991: Milieufacetten 1991

LANDFILLS

landfill gas = 50% methane 50% carbon dioxide (average)
Landfill gas = 31.65 $TJ/10^6$ m^3 (st)

ANIMAL WASTE.
1 m^3 methane = 0.662 kg methane (Casada and Safley, 1990)

Annex 2

OIL AND GAS

NATURAL GAS	Production in the Netherlands. in millions of cubic meter (st)		
Year	Territory	Offshore	Total
up to 1969	55113.1	0.0	55113.1
1970	33417.8	7.9	33425.7
71	46248.3	2.4	46250.7
72	61661.1	1.4	61662.5
73	74765.9	7.8	74773.7
74	88358.7	14.6	88373.3
1975	93924.0	963.3	94887.3
76	98307.4	3092.7	101400.1
77	95603.2	5479.6	101082.8
78	86475.0	6298.5	92773.5
79	85861.9	10925.5	96787.4
1980	78208.9	12102.0	90310.9
81	70928.3	11798.3	82726.6
82	60004.3	11073.3	71077.6
83	61533.0	13172.2	74705.2
84	59351.6	15787.3	75138.9
1985	64573.4	16070.9	80644.3
86	58479.5	15549.0	74028.5
87	58088.8	17271.4	75360.2
88	49092.4	17591.2	66683.6
89	52569.6	19300.0	71869.6
1990	54585.4	17856.0	72441.4
91	63724.1	18686.3	82410.4
Total	1550875.7	213051.6	1763927.3

Source: Dutch Ministry of Economic Affairs, 1992.

OIL PRODUCTION IN THE NETHERLANDS
in 1000 cubic meters (st)

Year	Concession Schoonebeek	Concession Rijswijk	Continental Shelf	Total
up to 1969	21662.8	15587.2	0.0	37250.0
1970	976.0	1112.2	0.0	2088.2
71	940.7	926.8	0.0	1867.5
72	856.3	883.1	0.0	1739.4
73	838.2	787.4	0.0	1625.6
74	878.0	715.5	0.0	1593.5
1975	877.0	671.5	0.0	1548.5
76	891.9	605.2	0.0	1497.1
77	890.8	617.8	0.0	1508.6
78	862.3	667.8	0.0	1530.1
79	820.4	615.6	0.0	1436.0
1980	778.9	617.7	0.0	1396.6
81	839.2	596.5	0.0	1435.7
82	987.9	625.3	159.7	1772.9
83	960.0	655.6	1209.1	2824.7
84	846.9	615.6	1921.7	3384.2
1985	734.5	602.8	2825.4	4162.7
86	658.9	688.8	3889.7	5237.4
87	556.4	692.5	3607.8	4856.7
88	536.0	844.9	3032.9	4413.8
89	464.3	731.6	2634.5	3830.4
1990	463.0	784.9	2744.5	3992.4
91	366.0	777.3	2527.9	3671.2
Total	38686.4	31423.6	24553.2	94663.2

Source: Dutch Ministry of Economic Affairs, 1992.

Annex 3

METHANE EMISSIONS FROM RUMINANTS AND PSEUDORUMINANTS.

A complex method is based on the work of Blaxter and Clapperton (1965).

This method takes place in three overall steps:

Step 1: Calculate the percentage of the feed energy Ym that is converted to methane by the animal.
Step 2: Estimate the total gross feed energy intake of the animal GEi.
Step 3: Multiply the conversion percentage Ym by the total gross feed intake per animal and animal category.

Step 1. The formula of Blaxter and Clapperton is used to estimate the methane yield:

$$\mathbf{Ym = 1.3 + 0.112\ DMD + FL(2.37 - 0.05\ DMD)}$$

where:
Ym = the methane yield in MJ CH_4/100 MJ of gross feed intake.
DMD = Dry matter digestibility at maintenance level, expressed in %. (DMD in the Netherlands is assumed 75%.)
FL = Feeding level expressed as a multiple of the maintenance level. FL ranges from 1 to 4.

Step 2. To estimate the total feed energy intake of the animal the following equation can be used:

$$\mathbf{FL = (NEm + NEg + NEl)/0.322W^{0.75}}$$

where
FL = Feeding level
NEm = Net energy use at maintenance level (MJ/day).
NEg = Net energy use for growth (MJ/day).
NEl = Net energy use for lactation (MJ/day).
W = weight of the animal (kg).

$NEm = 0.322W^{0.75}$x activity factor

Defaults for the activity factor are:
1.00 for confined animals that are stall fed.
1.17 for animals grazing on good quality pasture.
1.35 for animals grazing over large areas (rangeland).

$NEg = 4.18 \times (0.035W^{0.75} \times WG^{1.119} + WG)$

WG = Daily weight gain in kg.

NEl = 3.1 x milk production in kg per day.

Translating net energy into gross energy for use in Ym:

GEi (MJ/day) = [{(NEm + NEl + WE)/0.492} + (NEg + 0.328)]/(digestibility)

where
GEi = gross energy intake
WE = work energy per day
digestibility is expressed as a fraction here (for example 0.65 for 65% digestibility).

To check for the reasonableness of this value, one can assume that 1 kg of feed is about 18.4 MJ of energy. Then the daily dry matter intake in kg is given as:

DMi = GEi/18.4

which should be 2-3% of the weight of the animal.

Step 3. Finally the annual methane emission from the representative animal can be estimated as:

E = GEi x Ym/100 x 365 x 0.018

where
E = methane emission in kg per animal per year
0.018 = coversion of MJ to kg of methane
1 kg Methane = 55.65 MJ

Total methane emission is estimated by multiplying with total number of animals in the categories, and then summing across categories.

In a worksheet these three main steps can be broken down in thirteen substeps:

Step 1: Determine the number of animals in each category.
Step 2. Determine the average life weight in each category.
Step 3. Determine the average daily weight gain in each category.
Step 4. Calculate the Net energy required for maintenance.
Step 5. Calculate the Net energy required for growth.
Step 6. Calculate the Net energy required for lactation.
Step 7. Calculate the Feeding level.
Step 8. Determine the Dry matter digestibility in each category.
Step 9. Determine the work energy delivered per day in each category.
Step 10. Calculate the Gross energy intake.
Step 11. Calculate the methane yield per unit of feed.
Step 12. Calculate the methane emission per animal per year.
Step 13. Multiply with number of animals and sum across categories, to arrive at the total methane emission per year from ruminants.

Annex 4

ANIMAL WASTE

Developed countries

Animal type	Waste production kg/d/1000kg	Volatile solids %	Emission potential: Bo m3/kg VS
Feed cattle	86	11.6	0.33
Grazing cattle	58	12.4	0.17
Dairy cattle	86	11.6	0.24
Swine	84	10.1	0.45
Sheep	40	23	0.19
Goats	41	26.6	0.17
Chickens/Duck	85	19.4	0.32
Turkeys	47	19.4	0.3
Horses,Mules	51	19.6	0.33
Camels	na	na	na
Donkeys	51	19.6	0.33

Developing countries

Animal type	Waste production kg/d/TAM	Volatile solids %	Emission potential: Bo m3/kg VS
Feed cattle	na	15	0.1
Grazing cattle	12.5	15	0.1
Dairy cattle	15.6	15	0.14
Swine	4.1	10	0.29
Sheep	1.6	23	0.13
Goats	1.8	27	0.13
Chickens/Duck	0.12	19	0.26
Turkeys	0.26	19	0.26
Horses,Mules	18.4	20	0.26
Camels	184	16	0.21
Donkeys	12.2	20	0.26

Remarks:
Waste production in kg per day per 1000 kg of live weight or typical animal mass (TAM)
m3/kg VS = methane production in m3 per kg of volatile solids
na = not applicable
Grazing cattle includes buffalo in developing contries

Source: Casada and Safley, 1990

Annex 5

LANDFILLS

SUMMARIES OF RUNS

RUN 1: Methane emission from landfills (additional policies for recovery, 50% of potential)
Emission overview in kton CH4/yr for timesteps of five years.

CODE OPTION:	2 Decline after 1990
PERCENTAGE DECLINE	-10 %
K-factor 1995-	0.1 (KEUZE 0.2-0.03)
K-factor 1995+	0.0365 (KEUZE 0.2-0.03)
% OXIDATION	20 (KEUZE 10-30)
METHANE CONTENT %	50 (KEUZE 50-60)
Po FROM 1995	0.05 (KEUZE fractie 0.0-0.1)
WASTEGAS RECOVERY	50 (KEUZE 0-100)

YEAR	TOTAL WASTE 100 kton mean/yr	Total Po = Degradable organic carbon kton	Emissiontable		Production kton CH4 Low	kton CH4 Mean	kton CH4 High	Recovery kton CH4 Low	kton CH4 Mean	kton CH4 High	Emission kton CH4 Low	kton CH4 Mean	kton CH4 High
1945	0	0		1945	0	0	0	0	0	0	0	0	0
1950	12	2		1950	4	8	12	0	0	0	4	8	12
1955	23	4		1955	15	31	46	0	0	0	15	31	46
1960	35	6		1960	31	63	94	0	0	0	31	63	94
1965	47	8		1965	50	100	150	0	0	0	50	100	150
1970	59	11		1970	71	141	212	0	0	0	71	141	212
1975	83	15		1975	96	192	288	0	0	0	96	192	288
1980	106	19		1980	130	260	390	0	0	0	130	260	390
1985	130	23		1985	172	345	517	27	36	45	145	309	472
1990	139	24		1990	214	429	643	65	87	108	150	342	535
1995	82	13		1995	216	432	648	77	103	129	139	329	519
2000	48	6		2000	150	301	451	55	74	92	95	227	359
2005	29	3		2005	105	209	314	39	53	66	65	156	248
2010	17	1		2010	73	146	220	28	38	47	45	109	172
2015	10	1		2015	52	104	156	20	27	34	31	77	122
2020	6	0		2020	37	75	112	15	20	25	22	55	87
2025	3	0		2025	28	55	83	11	15	19	16	40	64
2030	2	0		2030	21	41	62	9	11	14	12	30	48
2035	1	0		2035	15	32	48	7	9	11	9	23	36
2040	1	0		2040	12	25	37	5	7	9	7	18	28
2045	0	0		2045	10	20	29	4	6	7	6	14	22
2050	0	0		2050	8	16	23	3	5	6	4	11	18

RUN 2: Methane emission from landfills (existing policies for recovery, 25% of potential).
Emission overview in kton CH4/yr for timesteps of five years.

CODE OPTION:	2 Decline after 1995
PERCENTAGE DECLINE	-10 %
K-factor 1995-	0.1 (KEUZE 0.2-0.03)
K-factor 1995+	0.0365 (KEUZE 0.2-0.03)
% OXIDATION	20 (KEUZE 10-30)
METHANE CONTENT %	50 (KEUZE 50-60)
Po FROM 1995	0.05 (KEUZE fractie 0.0-0.1)
WASTEGAS RECOVERY	25 (KEUZE 0-100)

YEAR	TOTAL WASTE 100 kton mean/yr	Total Po = Degradable organic carbon kton	Emissiontable		Production kton CH4 Low	kton CH4 Mean	kton CH4 High	Recovery kton CH4 Low	kton CH4 Mean	kton CH4 High	Emission kton CH4 Low	kton CH4 Mean	kton CH4 High
1945	0	0		1945	0	0	0	0	0	0	0	0	0
1950	12	2		1950	4	8	12	0	0	0	4	8	12
1955	23	4		1955	15	31	46	0	0	0	15	31	46
1960	35	6		1960	31	63	94	0	0	0	31	63	94
1965	47	8		1965	50	100	150	0	0	0	50	100	150
1970	59	11		1970	71	141	212	0	0	0	71	141	212
1975	83	15		1975	96	192	288	0	0	0	96	192	288
1980	106	19		1980	130	260	390	0	0	0	130	260	390
1985	130	23		1985	170	341	511	14	18	23	157	323	489
1990	139	24		1990	210	420	630	32	43	54	178	377	576
1995	82	13		1995	211	422	632	39	51	64	172	370	568
2000	48	6		2000	147	293	440	28	37	46	119	257	394
2005	29	3		2005	102	204	306	20	26	33	82	178	273
2010	17	1		2010	71	143	214	14	19	24	57	124	190
2015	10	1		2015	51	101	152	10	14	17	40	87	135
2020	6	0		2020	36	73	109	8	10	13	29	63	97
2025	3	0		2025	27	54	81	6	8	9	21	46	71
2030	2	0		2030	20	40	60	4	6	7	16	35	53
2035	1	0		2035	15	31	46	3	4	6	12	26	41
2040	1	0		2040	12	24	36	3	4	4	9	21	32
2045	0	0		2045	9	19	28	2	3	3	7	16	25
2050	0	0		2050	8	15	23	2	2	3	6	13	20

RUN 3: Methane emissions from landfills (pessimistic scenario for waste disposal).
Emission overview in kton CH4/yr for timesteps of five years.

CODE OPTION:	2 decline after 1995
PERCENTAGE DECLINE	-2 %
K-factor 1995-	0.1 (KEUZE 0.2-0.03)
K-factor 1995+	0.0365 (KEUZE 0.2-0.03)
% OXIDATION	20 (KEUZE 10-30)
METHANE CONTENT %	50 (KEUZE 50-60)
Po FROM 1995	0.02 (KEUZE fractie 0.0-0.1)
WASTEGAS RECOVERY	25 (KEUZE 0-100)

YEAR	TOTAL WASTE 100 kton mean/yr	Total Po = Degradable organic carbon kton	Emissiontable		Production kton CH4			Recovery kton CH4			Emission kton CH4		
					kton CH4 Low	kton CH4 Mean	kton CH4 High	kton CH4 Low	kton CH4 Mean	kton CH4 High	kton CH4 Low	kton CH4 Mean	kton CH4 High
1945	0	0		1945	0	0	0	0	0	0	0	0	0
1950	12	2		1950	4	8	12	0	0	0	4	8	12
1955	23	4		1955	15	31	46	0	0	0	15	31	46
1960	35	6		1960	31	63	94	0	0	0	31	63	94
1965	47	8		1965	50	100	150	0	0	0	50	100	150
1970	59	11		1970	71	141	212	0	0	0	71	141	212
1975	83	15		1975	96	192	288	0	0	0	96	192	288
1980	106	19		1980	130	260	390	0	0	0	130	260	390
1985	130	23		1985	170	341	511	14	18	23	157	323	489
1990	151	26		1990	210	420	630	32	43	54	178	377	576
1995	136	23		1995	236	471	707	44	59	74	191	412	633
2000	123	19		2000	183	367	550	36	48	60	147	319	490
2005	112	15		2005	153	307	460	31	42	52	122	265	408
2010	101	12		2010	135	270	405	29	38	48	107	232	358
2015	91	10		2015	123	245	368	27	36	44	96	210	324
2020	82	8		2020	113	226	339	25	33	42	88	193	298
2025	74	7		2025	105	209	314	23	31	39	81	178	275
2030	67	6		2030	96	193	289	22	29	36	75	164	253
2035	61	5		2035	89	177	266	20	27	33	69	151	232
2040	55	4		2040	81	162	243	18	24	30	63	137	212
2045	50	3		2045	73	147	220	17	22	28	57	125	192
2050	46	3		2050	66	132	198	15	20	25	51	112	173

RUN 4: Methane emission from old landfills in the Netherlands.
Emission overview in kton CH4/yr for timesteps of five years.

CODE OPTION:	2 Stable, growth or decline after 1995
PERCENTAGE DECLINE	0 %
K-factor 1995-	0.1 (KEUZE 0.2-0.03)
K-factor 1995+	0.0365 (KEUZE 0.2-0.03)
% OXIDATION	20 (KEUZE 10-30)
METHANE CONTENT %	50 (KEUZE 50-60)
Po FROM 1995	0 (KEUZE fractie 0.0-0.1)
WASTEGAS RECOVERY	0 (KEUZE 0-100)

YEAR	TOTAL WASTE 100 kton mean/yr	Total Po = Degradable organic carbon kton	Emissiontable		Emission (no recovery) kton CH4 Low	kton CH4 Mean	kton CH4 High
1945	0	0		1945	0	0	0
1950	12	2		1950	4	8	12
1955	23	4		1955	15	31	46
1960	35	6		1960	31	63	94
1965	47	8		1965	50	100	150
1970	59	11		1970	71	141	212
1975	83	15		1975	96	192	288
1980	106	19		1980	130	260	390
1985	130	23		1985	169	337	506
1990	0	0		1990	136	271	407
1995	0	0		1995	82	165	247
2000	0	0		2000	50	100	150
2005	0	0		2005	30	61	91
2010	0	0		2010	18	37	55
2015	0	0		2015	11	22	33
2020	0	0		2020	7	14	20
2025	0	0		2025	4	8	12
2030	0	0		2030	2	5	7
2035	0	0		2035	2	3	5
2040	0	0		2040	1	2	3
2045	0	0		2045	1	1	2
2050	0	0		2050	0	1	1

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