METHANE

Its role in climate change and options for control

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Methaan
De rol in klimaatverandering
en opties voor emissiereducties

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SAMENVATTING

Methaan en klimaatverandering

Dit proefschrift gaat over methaan, de rol in klimaatverandering en opties voor emissie reducties. Het onderzoek omvat een analyse van toekomstige methaan emissies onder verschillende strategieën van bestrijding van de uitstoot namelijk :
1 geen bestrijding, 2 enige bestrijding en 3 maximale bestrijding. De kosten worden berekend van pakketten van opties. Inzicht wordt gegeven in de baten, namelijk minder klimaatverandering en minder stijging van de zeespiegel.

Vijf onderzoeksvragen stonden centraal :

1. Wat zijn de relevante atmosferische processen waarbij methaan betrokken is?
2. Wat zijn de mondiale methaan bronnen en afbraakprocessen?
3. Hoe kunnen officiële schattingen van de methaan uitstoot van landen worden vergeleken met een onafhankelijke schattingsmethode zoals in de Emissie Database voor Globaal Atmosferisch Onderzoek (EDGAR)?
4. Welke opties voor methaan emissie reducties zijn beschikbaar en wat zijn de kosten van elke optie?
5. Wat zijn de effecten van methaan emissie reductie pakketten op het toekomstige klimaat en wat zijn de kosten van invoering van deze pakketten?

Wat zijn de relevante atmosferische processen waarbij methaan betrokken is?

Het natuurlijke broeikaseffect is een van de redenen dat wij goed kunnen leven op aarde. Zonder de natuurlijke deken van broeikasgassen in de atmosfeer (als de atmosfeer alleen zuurstof en stikstof zou bevatten) zou de gemiddelde temperatuur op aarde minus 18^{o} Celsius zijn in plaats van de comfortabele plus 15 ^{o}C van vandaag. Het versterkte broeikaseffect wordt veroorzaakt door de toename van emissies van broeikasgassen door menselijke activiteiten, en dit veroorzaakt een toename van de gemiddelde temperatuur op aarde van 1.4 tot 5.8 ^{o}C bij een verdubbeling van de pre-industriële broeikasgas concentraties (CO_2 equivalent) in de atmosfeer. Deze opwarming zal gepaard gaan met grote verschuivingen in neerslagpatronen.

Methaan is na kooldioxide het belangrijkste broeikasgas. De gemiddelde concentratie van methaan in de atmosfeer is meer dan verdubbeld sinds 1750 (voor de industriële revolutie) namelijk van 700 parts per billion tot 1780 ppb. De gemiddelde concentratie op het noordelijk halfrond is gemiddeld nu al hoger met 1800 ppb. Boven dominante brongebieden zoals West-Europa worden uitschieters gemeten van zelfs 2500 ppb. Methaan levert een significante bijdrage aan het versterkte broeikas effect omdat het straling absorbeert bij golflengten die anders transparant zouden zijn voor de langgolvige warmte uitstraling van de aarde naar de ruimte. Methaan wordt afgebroken door OH radicalen.

De methaan concentratie neemt niet constant toe. Tussen 1960 en 1980 was er een snelle toename, daarna een stabilisatie. Er is weinig overeenstemming over de oorzaken van de gemeten lange termijn stabilisatie van de methaan concentraties in de atmosfeer tussen 1980 en 2006 en de toename van de concentratie na 2007. De concentratie groei gedurende de laatste decennia was niet constant. Dit doet een complex van factoren vermoeden, inclusief menselijke activiteiten, die de bronnen en afbraak voor methaan beïnvloeden. Grote vulkaan uitbarstingen in het verleden hebben tot afkoeling van de atmosfeer geleid door de uitstoot van zwavel en aerosol in de hogere troposfeer. Een voorbeeld is de grote Pinatubo eruptie op de Filippijnen in 1991 die een grote schommeling veroorzaakte in de groei van methaan in de atmosfeer. In de eerste maanden na de uitbarsting nam de methaan groei in de atmosfeer toe in de tropen. Dit werd toegeschreven aan de korte termijn afname van UV straling van de zon in de tropen. Dit leidde tot afname van de OH formatie snelheid in de troposfeer. Reactie van methaan met OH in de atmosfeer is de belangrijkste oorzaak voor omzetting van methaan in kooldioxide en water. Als OH afneemt neemt methaan toe in de atmosfeer. In 1992 echter werd een grote afname van de methaan groei tot bijna nul in de atmosfeer gemeten, vooral op het noordelijk halfrond. Door de afkoeling van de atmosfeer door aerosol van de Pinatubo uitbarsting waren er tenminste twee koude zomers die zorgden voor afname van methaan emissies uit de noordelijke toendra moerassen. In 1994 kwam de methaan groei weer op 8 ppb per jaar. Een grote toename van de methaan concentratie groei in 1998 en afname in 1999 werd toegeschreven aan de grote bos en veen branden in Rusland en Indonesië. De nulgroei tussen 2000 en 2006 zou het gevolg kunnen zijn geweest van de economische malaise en autonome krimp in olie en gas productie in Rusland, maar ook van succes in methaan emissie reductie maatregelen. Anderen concludeerden dat de emissie uit moerassen laag was in die jaren door hitte en droogte. Tussen 2006 en 2012 groeide de methaan concentratie weer door een toename van moeras emissies in het noorden maar ook in de tropen door warme natte condities na een periode van droogte.

Wat zijn de mondiale bronnen en afbraakprocessen voor methaan?

Bronnen

De belangrijkste bronnen voor methaan emissies zijn moerassen, olie en gas productie en gebruik, kolenmijnen, fermentatie in de voormaag van herkauwers, fermentatie van mest, rijstvelden, afvalstort, afvalwater behandeling en biomassa verbranding. Al deze bronnen zijn toegenomen met de bevolkingsgroei en de economische ontwikkeling. De natuurlijke moerassen zijn grootschalig drooggelegd voor landbouw. Natte rijstvelden zijn juist toegenomen.

Moerassen

Methaan of moerasgas wordt gevormd door methanogene bacteriën uit veen of ander organisch materiaal onder zuurstofloze omstandigheden. Dit is een natuurlijke bron van methaan maar de mens heeft wel invloed. Veel moerassen in de tropen zijn omgevormd tot natte rijstvelden bijvoorbeeld in Indonesië bij de transmigratie projecten in Borneo, Kalimantan en Nieuw Guinea. Dit leidt tot verhoogde methaan emissies. In andere landen zoals Nederland worden natuurlijke moerassen ontwaterd voor de landbouw. Dit leidt tot vermindering van methaan emissies. Natuurlijke moerassen zijn gevoelig voor klimaatverandering. Onder warme natte omstandigheden zal de methaan emissie toenemen. Onder warme droge omstandigheden zullen methaan emissies afnemen en het risico op veenbranden gaan toenemen.

Olie en gas
Methaan komt voor als geassocieerd gas in olievelden. Methaan is ook het belangrijkste bestanddeel van natuurlijk gas. Methaan ontsnapt naar de lucht door lekkages maar ook door het bewust afblazen van gas gedurende de exploratie, exploitatie, productie , transport en distributie van olie en gas. In veel gevallen wordt het gas uit olievelden afgefakkeld of afgeblazen bij afwezigheid van markten voor LPG. Vanuit gasvelden wordt aardgas getransporteerd naar compressiestations en gas behandelings faciliteiten, vandaaruit wordt het gas onder hoge druk getransporteerd naar verdeelstations. Vandaaruit wordt het gas geëxpandeerd van hoge naar lage druk en gedroogd met glycol. Daarna wordt het gedistribueerd naar de consumenten in een lage druk distributie netwerk. In olie en gas productie in Siberië en Alaska zijn de omstandigheden extreem moeilijk voor de producenten. De toplaag van de permafrost ontdooit in de lente en wordt onstabiel voor constructies. Het is moeilijk om stabiele hogedruk leidingen onder deze omstandigheden te bouwen en onderhouden. Daarom wordt verondersteld dat speciaal de Siberische gas transporten een hoog lekpercentage hebben. In Alaska wordt meer aan lek preventie gedaan en moderne technieken worden toegepast om dit probleem onder controle te houden. In grote steden is het gietijzeren distributie netwerk met jute in de verbindingen van de oude kolen vergassingsinstallaties nogal lekgevoelig. Verbeterd onderhoud en lek controle en vervanging van de buizen is urgent om deze methaan bron te reduceren.

Kolenmijnen
Methaangas is een veiligheidsrisico in mijnen. In het verleden hebben duizenden mijnwerkers hun leven verloren door mijn explosies. Daarom is een goede ventilatie van lucht in kolenmijnen nodig. Oorspronkelijk werd de mijnlucht met het verdunde gas uitgestoten naar de lucht. In Duitsland werd deze lucht al in de vijftiger jaren gebruikt bij verbrandingsmotoren. Bij een aantal mijnen in de Verenigde Staten zijn experimenten gestart om het gas te winnen door gaten te boren in de kolen lagen voordat de kolen worden gewonnen. Deze techniek kan worden toegepast in gas rijke kolen zoals in de Great Warrior Basin en de San Juan Basin. Deze ontgassingstechniek is ook in China met groot succes geïntroduceerd.

Onvolledige verbranding
Een andere belangrijke bron van methaan is onvolledige verbranding van biomassa. Vooral bij houtskool productie of smeulende houtvuren bij ontbossing ontwijkt relatief veel methaan. Deze bron is vooral belangrijk in de tropen.

Herkauwers
Door fermentatie van het voer in de voormaag (rumen) van herkauwers wordt methaan gevormd door methanogene bacteriën. Deze methaan wordt op geboerd en ontwijkt naar de lucht. Dit is een natuurlijk fenomeen, maar FAO statistieken wijzen uit dat de omvang van de veestapel tenminste is vervijfvoudigd sinds 1950. De hoogste vee dichtheid wordt gevonden in de Ganges delta, maar ook in de laaglanden van West Europa. Andere belangrijke bron gebieden voor methaan uit herkauwers zijn Rusland en Latijns- en Noord-Amerika.

Afval
Methanogene bacteriën in anaeroob afval zijn een bron van methaan emissies. In veel landen wordt afval nog steeds in gecontroleerde omstandigheden gestort in landfills. Methaan uit afvalstortplaatsen kan worden opgevangen en gebruikt voor energie

opwekking. Grote hoeveelheden industrieel en ander afvalwater heeft rivieren vervuild wereldwijd sinds 1950. In veel landen zijn afvalwater zuiverings installaties gebouwd om de vervuiling te reduceren, maar anaerobe zuivering van afvalwater is een bron van methaan. Dit methaan wordt veelal gebruikt voor energie in de zuiveringstechniek, maar een deel ontwijkt naar de lucht.

Rijst
Natte rijstvelden zijn een belangrijke bron van methaan in Azië. In sommige studies wordt methaan uit rijst beschouwd als een natuurlijke bron, omdat natuurlijke moerassen lagen op de plaats waar nu natte rijst wordt verbouwd. Maar dat is niet geheel waar, want irrigatiesystemen zijn ontwikkeld om nieuwe gebieden geschikt te maken voor natte rijst, veelal geterrasseerde hellingen. De expansie van natte rijstvelden heeft tot een toename van methaan emissies geleid. Intensieve meet studies hebben geleid tot een verbetering van de schatting van methaan uit rijst.

Hoe kunnen officiële schattingen van de methaan uitstoot van landen worden vergeleken met een onafhankelijke schattingsmethode zoals in de Emissie Database voor Globaal Atmosferisch Onderzoek (EDGAR)?

Nationale broeikasgas emissie inventarisaties

Om het rapporteren en controleren binnen het Klimaatverdrag te faciliteren zijn transparante, geloofwaardige en vergelijkbare landen data nodig. Daarom zijn Handboeken voor nationale broeikasgas emissie inventarisaties ontwikkeld door een internationale inspanning van IPCC, UNEP, WMO IEA en OESO. Deze Handboeken zijn officieel aanvaard door de partijen bij het Klimaatverdrag als de gezamenlijke methodologie voor nationale inventarisaties. Voordat ze definitief werden zijn deze Handboeken in breed verband een aantal jaren getest door experts uit vele landen teneinde overeenstemming te bereiken over de methoden. Deze consensus leidde tot de aanvaarding van de IPCC Guidelines for National Greenhouse Gas Inventories voor gebruik door de geïndustrialiseerde landen onder het Kyoto Protocol. De laatste versie van de Handboeken is verschenen als IPCC 2006 Guidelines for national greenhouse gas inventories. In deze 2006 versie is onzekerheid en kwaliteitscontrole een integraal onderdeel van de inventarisatie methoden.

Methaan inventarisaties

Voor methaan zijn de methoden momenteel in een relatief vroeg stadium van ontwikkeling, en resultaten hebben nog steeds grote onzekerheidsmarges. Een deel van het probleem hangt samen met de weerbarstigheid van het vertalen van lokale flux metingen in emissie schattingen voor een geheel jaar voor een geheel land of voor gehele continenten. Een ander deel van het probleem is de complexiteit van de processen bij biogene productie van methaan door microben in zuurstofloze omstandigheden in bodems. Emissies zijn afhankelijk van bodem type en milieu omstandigheden. Menselijk ingrijpen in de bodem beïnvloed de emissies. Bijvoorbeeld bevloeiing van een veld heeft diverse effecten op de methaan emissies, afhankelijk van de duur van bevloeiing, temperatuur en koolstofgehalte in de bodem. Het is dus moeilijk om metingen op te schalen vanwege afhankelijkheid van lokaal klimaat, bodem en management.

Onzekerheidsmarges in nationale inventarisaties zijn ongeveer 5-10% voor kooldioxide emissies uit fossiele brandstoffen, 50-100% voor kooldioxide uit landgebruiksveranderingen en 100% voor lachgas uit de bodem. Voor methaan zijn deze onzekerheidsmarges ook hoog, ongeveer 30-35% voor de meeste bronnen. Emissie inventarisaties zijn gebaseerd op statistische informatie omtrent de omvang van menselijke activiteiten en emissiefactoren. Emissiefactoren kunnen worden afgeleid van lokale veldschaal metingen en de juiste methode voor opschalen naar het nationale niveau. De IPCC heeft een grote stap gezet in de laatste decennia om gezamenlijke methoden te ontwikkelen en vast te leggen in Handboeken. Veel landen hebben meetcampagnes op touw gezet voor methaan en andere broeikasgassen om de onzekerheidsmarges te verkleinen. De onzekerheden kunnen nog verder worden gereduceerd in de komende jaren. Verbeteringen zijn mogelijk in nationale inventarisaties door betere metingen, verbeterde informatie over activiteiten en betere opschalingsmethoden. Verbeterde rapportage en documentatie kan het vertrouwen in de landenschattingen verbeteren.

In dit proefschrift is een vergelijking gemaakt tussen de officiële methaan inventarisaties van landen en een onafhankelijke betrouwbare bron namelijk de EDGAR database. De analyse toonde dat de belangrijkste verschillen gelegen waren in het gebruik van verschillende emissie factoren en verschillende statistische bronnen ten aanzien van de economische activiteiten. De vergelijking toonde eveneens een aantal gaten en omissies in de rapportages. De vergelijking was de eerste in zijn soort en heeft bijgedragen aan de validatie en verificatie van zowel EDGAR als de landenrapportages en daarmee aan de verbetering van de kwaliteit van de rapportages over emissies aan het Klimaatverdrag. De vergelijking droeg bij aan de verbetering van de methoden voor methaan emissie schattingen. Inmiddels is de vergelijking een standaard procedure bij de review van landenrapportages.

Welke opties voor methaan emissie reducties zijn beschikbaar en wat zijn de kosten van elke optie?

Klimaatcontrole

De bijdrage van methaan aan de opwarming is minder dan de bijdrage van kooldioxide. Maar methaan is heel interessant. Door zijn hoge global warming potential (GWP) van 72 keer kooldioxide over een periode van 20 jaar, en 21-25 keer kooldioxide over een periode van 100 jaar na emissie, sorteren maatregelen om methaan emissies te reduceren een groot effect. Door de korte levensduur van methaan in de atmosfeer, 12 jaar vergeleken met 50-200 jaar voor kooldioxide, zullen reducties in de antropogene methaan emissies binnen korte tijd een aanzienlijk effect sorteren op de methaan concentraties in de lucht.

Raamwerkverdrag over Klimaatverandering van de Verenigde Naties

Het klimaatverdrag (UNFCCC) getekend in Rio de Janeiro in 1992 roept op om de concentraties van broeikasgassen in de atmosfeer te stabiliseren op een zodanig niveau dat geen gevaarlijke door de mens veroorzaakte veranderingen in het klimaatsysteem optreden. Dit wordt sinds het Kyoto Protocol ingevuld door een gezamenlijk streven naar een beperking van de temperatuur stijging tot 2^{o} C tot 2050.

Dit geeft ecosystemen de tijd om zich aan te passen, zou de voedselproductie niet in gevaar brengen en zou economische ontwikkeling op duurzame wijze doen voortgaan. Als eerste opdracht werd aan de landen van de OESO gevraagd om de emissies in 2000 terug te dringen naar het niveau van 1990. Dat is niet gelukt. De meeste OESO landen hebben wel doelstellingen geformuleerd. Impliciet werd een benadering gekozen waarbij alle broeikasgassen zouden worden meegenomen op basis van hun GWP. Alle OESO landen die partij zijn bij het Klimaatverdrag hebben de verplichting hun nationale emissies en sinks en plannen om emissies terug te dringen te rapporteren in zogenaamde Nationale Communicatie Rapporten. De emissie inventarisaties worden jaarlijks ingewacht. Onafhankelijke experts reviewen deze rapporten als kwaliteitsborging.

Kyoto Protocol

Verdere reducties na 2000 werden afgesproken in Kyoto in Japan in 1997 in het Kyoto Protocol. Een gemiddelde reductie van 5% tussen 1990 en 2010 werd overeengekomen tussen de geïndustrialiseerde landen. Europa zou 8% reduceren, Japan 7% en de VS 6%. De VS bij monde van George Bush trok zich terug en liet weten dat ze alleen zouden meedoen als China, Brazilië en India commitment zouden tonen. Dat is omdat toekomstige economische groei in deze landen de broeikasgas emissies ver zou kunnen opstuwen voorbij de emissies van de OESO landen. In februari 2005 trad het Kyoto Protocol toch in werking na ratificatie door Rusland. Daarmee deed 50% van de landen met tenminste 50% van de emissies mee.

Een belangrijk struikelblok in de internationale onderhandelingen over de beste manier om broeikasgassen te reduceren is altijd geld geweest, doordat sommige economische modellen hoge implementatie kosten voorspelden voor maatregelen die in het Kyoto Protocol werden voorgesteld. Echter, waar reducties verder gaan dan alleen de kooldioxide emissies, en als alle niet-CO_2 broeikasgassen worden meegenomen, dan daalt de prijs voor reducties aanzienlijk.

Methaan opties

Opties zijn beschreven voor methaan emissie reducties. Veel opties kunnen tegen lage kosten worden ingevoerd. Veelal kan zelfs geld verdiend worden met reductie opties. De goedkope opties hangen samen met methaan opvang en gebruik in de fossiele brandstoffen industrie, vooral in kolen, olie en gas productie en transmissie. Methaan winning en gebruik uit afvalstorts in een succes in vele OESO landen. Methaan winning moet in de ontwerp fase van een stort worden meegenomen. Sommige opties kunnen later worden ingevoerd omdat ze nu nog te duur zijn. De dure opties zijn gerelateerd aan landbouw. De uitdaging is een toename in de wereldvoedsel productie met een lagere methaan uitstoot. Vooral in de melkveehouderij en in de vleesproductie is het belangrijk om de methaan emissies uit de koe en uit de mest te reduceren. Voor de overige activiteiten is het duidelijk dat er een scala van mogelijkheden bestaat voor de verbeterde bestrijding van methaan emissies in de komende jaren. De helft van de methaan emissies kan worden bestreden tegen lage kosten, slechts 0.1 % van wereld GDP.

Technologie overdracht is belangrijk. Schone technologie kan worden gestimuleerd in diverse regio's. Stortgas en mijngas winning zijn belangrijke technologieën om te exporteren.

Wat zijn de effecten van methaan emissie reductie pakketten op het toekomstige klimaat en wat zijn de kosten van invoering van deze pakketten?

Een analyse van de effecten van de methaan emissie reductie pakketten op het toekomstige klimaat is gebaseerd op model berekeningen met IMAGE (integrated model to assess the global environment). In het IMAGE model was een set van scenario's ontwikkeld voor ondersteuning van de klimaat onderhandelingen in de opmaat voor Kyoto. Het IMAGE model is gebruikt omdat het informatie bevat over belangrijke processen die de onzekerheden bepalen. Deze informatie is niet in andere modellen voorhanden. De analyse leerde dat methaan emissies tegen lage kosten konden worden gereduceerd, met tegelijkertijd een significante rol in de bestrijding van klimaatverandering en zeespiegel stijging. Tussen 2050 en 2100 met alleen methaan reducties zou de geprojecteerde temperatuur stijging een halve graad lager uitvallen. Zeespiegel zou 4 centimeter minder stijgen. Voor 2050 konden geen significante effecten van methaan reducties worden aangetoond.

Conclusie

Significante reducties in de wereldwijde methaan emissies zijn zowel technisch haalbaar als in veel gevallen zeer kosten effectief om klimaatverandering tegen te gaan. Hun brede implementatie in de komende jaren zal vooral afhangen van beleid en markt signalen uit de UNFCCC conferenties der partijen. Als niet ten volle de opties voor methaan bestrijding wereldwijd worden toegepast dan zal de kooldioxide emissie reductie alleen maar moeilijker worden. De wetenschappelijke gemeenschap kan verbeterde flux metingen leveren, onzekerheden reduceren, en ons inzicht in terugkoppelingsmechanismen verbeteren. Zoals de methaan emissies uit noordelijke moerassen toendra's en cladraten. De technologie om diepe reducties in methaan emissies te leveren in diverse sectoren is reeds beschikbaar en marktrijp. Om methaan bestrijding centraal te stellen in een robuust en geïntegreerd plan om wereldwijde klimaatverandering aan te pakken, is een verbeterde nationale en internationale samenwerking vereist om snelle technologie overdracht te bevorderen en financiele prikkels te genereren om de vele geïdentificeerde mogelijkheden wereldwijd tot bloei te laten komen. Het wordt daarom aanbevolen om markt barrières te verwijderen en om de aandacht te vergroten voor methaan bestrijdingsopties door internationale samenwerking en het leren van bewezen technieken. Een mogelijke route om de markt in methaan reductie technieken te stimuleren is internationale samenwerking tussen voorlopers en landen die willen leren. Publiek private partnerschappen kunnen worden gebruikt om internationale samenwerking te bevorderen bijvoorbeeld in het Internationaal Methaan Initiatief.

Methaan emissie kan worden gereduceerd tegen kosten lager dan 0.1% van GDP. Methaan emissie reducties leiden tot verminderde klimaatverandering in de toekomst. Deze is vooral zichtbaar tussen 2050 en 2100. Verminderde klimaatverandering voor 2050 als gevolg van uitsluitend methaan reducties kon niet worden aangetoond. Het is belangrijk om alle broeikasgas emissies tegelijkertijd te bestrijden om een maximum effect te bereiken op het toekomstige klimaat.

CONTENT

1. INTRODUCTION

1.1 Role of methane in climate change

This thesis focuses on methane (CH_4), an important greenhouse gas. CH_4's role in climate change is studied, emission inventories are described and compared, and options and costs to reduce methane emissions to the atmosphere are given.

CH_4 is a powerful greenhouse gas. It is present in the atmosphere in very low concentrations. Nevertheless, it is the third most important greenhouse gas after water vapour and carbon dioxide (CO_2). Water vapour is present in variable amounts. CO_2 contributes about 50% to the enhanced greenhouse effect, CH_4 about 15-20% and nitrous oxide (N_2O) about 6% (Wuebbles and Hayhoe, 2000).

The lifetime of CH_4 in the atmosphere is about 12 years and thus a magnitude shorter than the lifetime of CO_2 (50-200 years depending on the sources). CH_4 is broken down in the atmosphere by the hydroxyl (OH) radical, which is the most important atmospheric cleansing agent. CH_4 is converted by OH into carbon dioxide (CO_2) and water.

The global warming potential (GWP) compares the direct climate forcing of different greenhouse gases relative to that of CO_2. The GWP combines the capacity of a gas to absorb infrared radiation, its lifetime in the atmosphere, and the length of time over which the effect on the earth's climate needs to be quantified (the time horizon). In the case of CH_4 it is also adjusted to take account of indirect effects via the enhancement of tropospheric ozone, stratospheric water vapour and production of CO_2 resulting from its destruction in the atmosphere. CH_4 has a GWP of 72 over a 20-year time horizon, a GWP of 25 over a 100-year time horizon and a GWP of 7.6 over a 500-year time horizon (IPCC, 2007). So, the largest warming effect takes place within 20 years. As CH_4 has an effective climate forcing lifetime in the atmosphere of only 12 years it pays off to try and reduce methane emissions.

Since the late seventies CH_4 in the atmosphere has been measured. Measurements revealed rising concentrations between 1983 and 2000 from 1630 to 1750 ppb (parts per billion) and then a levelling off towards a steady state at 1750 ppb between 2000 and 2006 but now taking off again with growth from 1750 to 1780 ppb since 2006. Concentrations are higher in the northern hemisphere (Bousquet et al., 2006 ; Rigby et al., 2008; Dlugokencky et al., 2012; Bruhwiler et al., 2010).

There are many different sources of CH_4. Most natural emissions are from anaerobic decomposition of organic carbon in wetlands, with poorly known smaller contributions from the ocean, termites, wild animals, wildfires, and geological sources (Reay et al., 2010). The most important human sources are energy production and use, landfills, waste and waste water, and livestock production including animal manure. CH_4 from wet rice production is important because the wetland rice area has increased relatively fast since 1950. CH_4 is mainly produced under anaerobic conditions (Stams and Plugge, 2010). Keppler et al, (2006) stated that CH_4 may also be produced under aerobic conditions by living terrestrial vegetation. This finding, however, is challenged by Dueck et al. (2007) who could not find any aerobic CH_4 from plants. Rice et al. (2010) made a new discovery in this respect. According to them part of the missing source of CH_4 can be allocated to tropical wetlands where trees standing in water are siphoning CH_4 to the atmosphere, much like rice plants. A critical review of CH_4 from vegetation is given by McLeod and Keppler (2010).

Observations from space have been used to reduce the uncertainty in the CH_4 sources and to estimate changing emissions from natural wetlands under changing climate (Bergamaschi et al. 2007 and 2009). Since 2003 the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) instrument on the Envisat satellite has provided global atmospheric methane column measurements over land (Frankenberg et al., 2006). Bloom et al. (2010) used this information to show a clear correlation between CH_4 from satellite data, surface temperature and water table, and to estimate global methane emissions from temperate northern latitude wetlands between 2003 and 2007. Methane from wetlands seemed to be reduced between 1980 and 2006 because of drought periods in tropical and arctic wetlands. Next to reductions in anthropogenic sources this could explain the temporary stabilization of CH_4 concentrations in the atmosphere (Christensen, 2010).

Model-based scenarios indicate that the enhanced greenhouse effect can increase the globally averaged surface temperature by 1.4 - 5.8 ^oC over the period 1990 to 2100 (IPCC, 2007). High-latitude regions are expected to warm more strongly than the tropics, which could increase the natural CH_4 emissions from tundra regions and the Arctic shelves. Warming may lead to a melting of permafrost and hydrates and may expand the wetland cover of tundra. This melting may increase CH_4 production and emissions. Such a positive feedback additionally increases the warming. CH_4 thus plays a major role in the future build-up of atmospheric greenhouse gas concentrations but its behaviour is difficult to predict. Recent observational studies now shed light on how these natural sources are changing in the changing climate. Shakova et al. (2010) for example show increasing out gassing of methane from hydrates beneath the Arctic shelf with about 10 Tg CH_4 per year from measurements between 2003 and 2008. Petrescu (2009) from detailed measurements of CH_4 from northern wetlands and using different models concluded that the average annual flux over the period 2001-2006 was estimated to be 78-157 Tg per year. The estimate was 78 Tg per year using the IPCC methods and the peatlands map from the FAO soil map of the world, 157 Tg per year following the Kaplan (2002) approach, and 89 Tg per year using the model from Prigent et al. (2007).

Why control CH_4?

There are several reasons to control methane.

First, the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, calls for reducing greenhouse gases including CH_4. Kyoto targets for greenhouse gas emission control have been agreed by the Parties to the Convention in order to reduce the expected temperature increase to 2 ^oC (Rogelj et al. 2011). An overall reduction of 5% in the period from 1990 to 2010 (with a budget period of 2008 to 2012) has been agreed for a basket of 6 greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur-hexafluoride). CH_4 emissions are thus part of the basket. Different options to reduce CH_4 emissions are available and will be described in this thesis.

Second, CH_4 is one of the most powerful greenhouse gases, as indicated above. Hansen et al.

(2000) even argue that most of the global warming in recent decades has been driven mainly by the non-CO_2 greenhouse gases, such as CH_4, nitrous oxide (N_2O) and CFC (chloro)fluorocarbons, and not, as generally believed, by the products of fossil fuel burning, like CO_2 and aerosols. They argue that the positive and negative radiative forcing of fossil fuel related CO_2 and aerosols largely cancel each other out. That is true when one excludes the CO_2 emissions from tropical deforestation and other land use change. Therefore, according to Hansen et al. (2000) in the short run emission reductions of non-CO_2 greenhouse gases would have the maximum effect on mitigating climate change. It may also be cheaper to reduce greenhouse gases other than CO_2.

Third, atmospheric CH_4 concentrations are more easily reduced than, for example CO_2 because its atmospheric lifetime is much shorter. According to DelaChesnaye and Kruger (2002) the overall emission reductions needed to stabilise atmospheric concentrations of CH_4 are only about 10-20%, while those for CO_2 are at least 80%. Additionally, because CH_4 is a more potent greenhouse gas, CH_4 emission reductions will be more effective. CH_4 emission reductions will have recognizable effects on the climate within one or two decades.

Fourth, many promising measures exist to reduce CH_4 emissions. There is scope for the reduction of radiative forcing of climate by control of CH_4 emissions that is comparable to the scope for CO_2. Thus CH_4 control is an important component in a strategic response to climate change where cheap CH_4 reduction options will be chosen first and more expensive options later. DelaChesnaye and Kruger (2002) concluded that CH_4 emission stabilisation could be achieved by 2025 based on the emission reduction potential associated with four major CH_4 sources, namely landfills, coal mines, gas and oil systems, and animal manure management systems in agriculture. Maintaining stabilisation through 2050 will necessitate extra emission reductions across a wider array of sources, particularly ruminant livestock and rice production. This will be more difficult because Winiwarter et al. (2010) concluded that methane emissions from agriculture and livestock will increase in countries like China and Brazil because of the fast growth in meat and dairy consumption.

1.2 Research aim

This thesis addresses possibilities to reduce CH_4 induced climate change by assessing possibilities to reduce emissions to the atmosphere. An integrated approach is followed to allow for balanced conclusions. In an integrated approach the causal chain is followed. Driving forces leading to increased human activities are identified first, then the pressures from methane emissions to the atmosphere are assessed, the state of the environment is measured as the concentration change over a certain period of time of CH_4 in the atmosphere. This leads to the impact of increased concentrations on climate and sea level. Finally the response of society to reduce climate change is assessed. The response in this case is an assessment of CH_4 emission reductions. An Integrated Model to Assess the Global Environment (IMAGE) is used to allow conclusions on emission reductions under two different scenario's for the future, each with three CH_4 abatement packages, while at the same time estimating the climate effect from all greenhouse gases in the atmosphere. In the IMAGE model input is used for all greenhouse gases to allow for an assessment of the climate change and sea level rise in time steps of a decade from 2010 till 2100.

The research aims at an integrated analysis of future trends in global CH_4 emissions, the associated climate change and the costs of emission control.

Different economic and integrated assessment models exist to study the integrated effect of greenhouse gas emissions on climate (Alcamo et al., 1998; Pepper et al., 1998; Sankovski et al., 2000; Mori, 2000; Morita and Lee, 2000; Winiwarter et al., 2010). In this thesis IMAGE is used for the analysis (Alcamo et al., 1998; IMAGE team, 2001; Bouwman et al., 2006). An integrated assessment takes into account natural processes determining the CH_4 sources and sinks, the human activities leading to CH_4 emissions, atmospheric processes that control concentrations, which alter radiative forcing and cause climate change, and options to reduce the emissions through policy measures. In the following chapters we will analyse a number of these issues including an assessment of the quality of emission inventories and options for CH_4 emission reductions. The integrated analysis presented in the last section of this thesis focuses on CH_4, but takes into account other greenhouse gases as well for reasons of comparison.

Five research questions are formulated and these will be covered in the following chapters:

1. What are relevant atmospheric processes that involve CH_4? (chapter 2).

2. What are the global CH_4 emissions and sinks? (chapter 3).

3. How do estimates from an comprehensive global emissions database for atmospheric research (i.e. EDGAR) compare to aggregated national emission estimates? (chapter 4).

4. Which options are available to reduce CH_4 emissions and what are the costs of each option? (chapter 5).

5. What are the effects of CH_4 emission reduction packages on future climate change and what are the associated costs of these packages? (chapter 6).

1.3 Outline of the thesis.

This thesis aims at an analysis of mitigation options and costs for methane emissions reductions. Global atmospheric processes are described in chapter 2. The global emissions database for atmospheric research EDGAR is used as input for the IMAGE model. In chapter 3 a description is given of inverse modelling to improve "a priori" estimates of methane emissions. Top-down and bottom-up comparison of EDGAR and national emission inventories is described in chapter 4. It is used as a tool to improve the methodology to estimate methane emissions. This exercise contributed to the improved IPCC 2006 Guidelines for National Emission Inventories (IPCC, 2006). Options and costs are described in chapter 5 and scenario exercises with IMAGE are treated in chapter 6. Finally in chapter 7 conclusions are drawn and a synthesis is given.

Methane in the atmosphere (chapter 2)

Chapter 2 provides a background on atmospheric processes based on the literature. After CH_4 is emitted into the atmosphere from natural and anthropogenic sources, CH_4 is broken down by atmospheric chemical processes. The natural sink for CH_4 in the atmosphere is the hydroxyl radical (OH), the natural cleansing agent of the troposphere. Chemical processes determine the CH_4 budget.

Global emission and sink estimates (chapters 3)

Chapter 3 provides an overview of global CH_4 emissions and sinks, and an assessment of the global emissions of CH_4 for the years 1980 to 2010. A critical reflection will be given on the CH_4 budget, and on methods to estimate emissions. Such methods include those developed for the IPCC Guidelines for National Greenhouse Gas Inventories (Van Amstel, 1993a; IPCC/OECD/IEA, 1997; IPCC, 2000; IPCC 2002; IPCC, 2006). In the IMAGE model, future emissions using scenario assumptions on future developments in population, energy use, agriculture, land use and the economy are estimated based on these standardized IPCC methodologies. A description of the IMAGE model is given in Bouwman et al. (2006).

Quality of emission inventories (chapter 4)

Chapter 4 investigates the quality of emission inventories as input for the integrated assessment model IMAGE presented in later chapters. Emission inventories typically include estimates based on measurements, emission factors and activity data. In this chapter, different CH_4 emission inventories are compared. This gives an indication of the uncertainties involved.

The uncertainty of emission estimates is a combination of the uncertainty in the measurements, the uncertainty in the upscaling to an emission factor, the uncertainty in time of the emission and the uncertainty in space introduced by extrapolation over countries or continents. IPCC developed 'Good Practice Guidance for national greenhouse gas inventories and an updated 2006 Guideline (IPCC, 2000, IPCC, 2002, IPCC 2006). Uncertainty management is part of the guidelines. Van Aardenne (2002) and Olivier (2002) developed frameworks for uncertainty analysis. Comparison with other inventories is a powerful tool to check the accuracy of national inventories according to Van Aardenne (2002) and Olivier (2002). Therefore, I choose to compare official national emission estimates with an independent Emissions Database for Global Atmospheric Research (EDGAR) (Olivier et al., 1996, 1999; Olivier, 2002; Olivier, 2009). Both estimates are uncertain, a comparison is used to find the gaps, large differences and particular weak points.

EDGAR 3.2 data are compared with the official national estimates that are available for most OECD and Eastern European countries. For some countries short time series are available from 1990. The EDGAR database with emission estimates on a grid of 1^{o} x 1^{o} is developed at the Dutch National Institute for Public Health and the Environment (RIVM) (Olivier et al., 1996, 1999, 2009). The EDGAR database is used as input for emissions from 1970 to 2000 in the IMAGE model. The methodology is then also used to estimate future emissions for 2010 to 2100 using scenario assumptions. Since 2008 EDGAR 3.2 is updated to EDGAR 4.0 to include more recent information. It is adopted by the European Commission. It is managed at the European Joint Research Centre in Ispra, Italy. It was not possible in this thesis to compare more recent information from national inventories with the EDGAR 4.0 database. EDGAR 4.0 is updated to include data on emissions from 2000 to 2010 mainly on fluorinated substances which are not part of this thesis.

Control options for CH_4 (chapter 5)

CH_4 emissions can be abated with technical measures. The next step in this thesis is to describe these technical options to control methane emissions and their costs. This step in the study is executed to give an overview of the options and their costs. What options are available for CH_4 reductions and what are their technical and economic potentials? Various authors describe options for emission reductions. Pilot studies have given insight in the magnitude of reductions that are attainable and the investment and maintenance costs per ton of avoided CH_4 emissions. Some options are especially profitable because captured CH_4 can be used for energy. Most options are ready for the market, they can be implemented but the investments will not be returned within a short period of time. Pay back times adopted in the costing methodology are the lifetimes of the installed equipment. Some options are expensive and investments will not be profitable now, but maybe in the future. In most situations research and development will make these options cheaper over time. An overview of options is given in this thesis together with cost estimates. The IMAGE model is used to assess the abatement potential in two scenarios with three CH_4 reduction packages each.

Scenarios to reduce CH_4 emissions (chapter 6)

The final step in the methodology in this thesis is to assess the effects on the future climate of CH_4 emission reduction strategies and the total costs of these CH_4 reductions. The IMAGE model is used for the scenario analysis (Leemans et al., 1998; Alcamo et al., 1994; Alcamo et al., 1998; and De Vries et al., 1998; De Vries et al., 2000; Bouwman, 2006). Two scenarios and six CH_4 reduction strategies will be presented. The global warming will be calculated for the two scenarios and six CH_4 reduction strategies in order to assess the relevance of CH_4 control.

The following steps in the scenario analysis will be taken for a global assessment:

1. Baseline development: Two scenarios will be used without CH_4 abatement. These baseline scenarios describe the growth in emissions expected as a result of economic growth, population developments, and wealth indicators, assuming no climate policies are adopted.
2. Identification and characterisation of three alternative CH_4 abatement packages (no methane control, moderate methane control and maximum methane control). This includes a ranking of options identified in chapter 5. The ranking will be based on the costs.
3. Development of six CH_4 reduction strategies: A reduction strategy is a scenario with a CH_4 abatement package.
4. Estimation of incremental costs of CH_4 abatement: These are the differences between the baselines and the alternative strategies.
5. Assessment of the climatic impacts of alternative reduction strategies.
6. A critical reflection on the analysis will be made as a last step.

2. METHANE AS A GREENHOUSE GAS

Updated from Van Amstel, A.R., L.H.J.M. Janssen, J.G.J. Olivier, 2000: Greenhouse Gas Emission Accounting. In: J. van Ham, A.P.M. Baede, L.A. Meyer and R. Ybema editors: Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation. P 461-468. Kluwer Academic Publishers.
and
Dave Reay, Pete Smith and André van Amstel, 2010: Methane and Climate Change. Earthscan Publishers London, Washington DC.

2.1 Introduction

The sun was 20 to 30% dimmer in its early youth. Under the faint young sun our planet should have been frozen over for much of its early history (Sagan and Mullen, 1972). Over the entire history of the Earth of 4 billion years the surface environment as recorded in geologic formations however appears to have been maintained within a relatively narrow range in which liquid water was stable. Levels of atmospheric oxygen were low before 2.4 billion years ago. A high concentration of methane in the early atmosphere together with a lower reflection of the sun's energy by the earth helped to maintain the friendly environment over the eons (Kasting, 2010 and Rosing et al., 2010). So methane has been and still is one of the important trace gases in the atmosphere. Methane and other volatile organic compounds react with nitrogen oxides to form tropospheric ozone. It is important to understand these atmospheric processes. Therefore in this chapter research question 1 will be answered:

What are relevant atmospheric processes that involve methane?

Atmospheric methane is a strong greenhouse gas and it affects background air quality through atmospheric chemistry. Methane is an ozone precursor. Methane reacts with nitrogen oxides to form tropospheric ozone. Tropospheric ozone is an oxidant that damages agriculture, ecosystems, materials and lung tissue reducing human health. Methane is the primary anthropogenic VOC in the global troposphere. Because methane reacts slowly it affects global background concentrations of ozone. Because this background concentration underlies the ozone formation in urban areas, methane mitigation reduces the ozone concentrations by roughly the same amount in polluted regions as well as in rural regions (West et al., 2006). Methane and ozone are both greenhouse gases and consequently abatement of methane emissions reduces surface pollution and slows warming.

The methane growth in the atmosphere leads to extra warming. At the same time the methane concentration growth is influenced by multiple processes in the atmosphere. The build up of methane in the atmosphere is balanced by the most important sink processes, which are the breakdown through hydroxyl (OH) radicals, the stratospheric breakdown and the oxidation of methane in soils.

The following processes will be covered in this chapter: the concentration increase, the influence of methane on the radiation balance, the interaction of methane with hydroxyl radicals, the masking of the warming by volcanic eruptions, the influence of methane on its own lifetime, the warming that leads to a positive feedback by releasing methane in northern latitudes from melting permafrost and hydrates and the uncertainty in the combined outcome.

2.2 Methane in the atmosphere

The global atmosphere is a mixture of gases. It consists mainly of oxygen (21%) and nitrogen (78%) and a mixture of trace gases (1%). Water vapour is present in highly variable amounts (0 to 3%), mainly in the lower troposphere. Even in highly polluted areas the combined concentration of the more reactive trace gas species in the lower atmosphere seldom exceeds 0.001%. The average composition of clean and dry air in the lower troposphere around 2010 is given in Table 2.1.

Methane concentration increase and budget

The annual increase in atmospheric methane has slowed down between 1998 and 2006. This has been attributed to decreasing wetland emissions (Bruhwiler and Dlugokencky, 2009; Fuu Ming Kai et al. 2011) and reduced anthropogenic emissions from fossil fuels (Aydin et al., 2011), but is thought to be only a temporary pause (Bousquet et al., 2006). Indeed the atmospheric methane concentration increased again since 2007 with 7.5 ppb per year (Dlugokencky et al., 2012; Schneising et al., 2011).

Records of atmospheric methane in the distant past obtained from air bubbles trapped in glacial ice (from the EPICA Dome C ice core from the south pole) suggest that methane varied between 350 and 800 ppb over the past 800000 years during glacial and interglacial periods. Methane at that time seems to be related to the millennial scale variations in temperature during the ice ages (Loulergue et al., 2008). In modern times methane rose throughout the industrial revolution from 500 ppb until it reached values of about 1780 ppb, which is 2-4 times the preindustrial value. This was interpreted earlier by Steele et al. (1992) as approaching a new steady state. One of the possible explanations of the slowing down of the increase was a reduction of methane emissions from fossil sources by the economic collapse of the Eastern European states in the early 1990s. The present increase is interpreted as the increase of methane emissions from the warming of northern wetlands in 2007 and 2008 and an increase in methane from tropical wetlands because of extremely wet conditions.

The present day concentrations are measured world wide through the NOAA/ESRL/GMD cooperative air sampling network, spanning nearly 3 decades (Dlugokencky et al., 2003; Dlugokencky et al., 2009 and 2012). Between 1980 and 1998 the concentration of methane in the atmosphere was rising fast from 1630 to 1750 ppb. Between 1998 and 2006 the global burden of atmospheric methane remained nearly constant. Since 2007 atmospheric methane increased globally with 7.5 ppb per year (Schneiding et al., 2011).The period from 1998 to 2006 growth of methane is steady or even declining but is characterized by abrupt changes in growth rates. These changes are probably caused by variations in temperature and moisture over wetlands with smaller contributions from biomass burning (Dlugokencky et al., 2012). According to these authors 2007 was an extremely warm and moist year over parts of the Arctic, and increases in methane growth rate are likely from increased emissions from Northern wetlands. The growth rate of methane in the Arctic decreased in 2008, but increased in the tropics, where above average precipitation fell over tropical wetlands (Dlugokencky et al., 2012). The increase was also observed in the southwest Pacific region (Lassey et al., 2010). The New Zealand mixing ratio data from Baring Head and Lauder generally confirm the trends since late 2006 described by Rigby et al. (2008), but suggest a shorter period of enhanced growth rate of 10 ppb/year. Lassey et al. (2010) conclude that a weakening of the chlorine sink may have been the cause in New Zealand. This term is often overlooked in quantitative assessments of the global methane budget. Houweling (2000, 2008) studied the methane concentrations over Asia. They are increasing because of increasing methane sources from rice farming.

The concentration over the mid Northern Hemisphere is slightly higher with 1800 ppbv on average, and even higher in North-West Europe. Atmospheric concentrations over three monitoring sites in the Netherlands are 2000 ppbv on average based on measurements in the period 1990 to 1994 in Arnhem, Kollumerwaard and Delft (Hollander and Vosbeek, 1996). Over important source areas like Western Europe, the methane concentration is occasionally increasing to 2500 ppbv because of point source releases (Berdowski et al., 1998; Janssen et al., 1999; Vermeulen et al., 1999; Eisma, 2000). The most important methane sources in the Netherlands and Western Europe are oil and gas production and distribution, including the production on the continental shelf in the North Sea; cattle and manure management in the dairy farm regions of Western Europe; waste dumped in landfills; and waste water treatment plants near the larger cities.

Table 2.1: Composition of dry air at ground level in remote continental areas in 2010. (Source: own compilation, WMO, 2010 and IPCC, 2007).

Component	Symbol	Concentration (%)
Nitrogen	N_2	78.10
Oxygen	O_2	20.90
Argon	Ar	0.93
Carbon dioxide	CO_2	0.0390
Neon	Ne	0.0018
Helium	He	0.0005
Krypton	Kr	0.00011
Methane	CH_4	0.00018
Hydrogen	H_2	0.00005
Nitrous oxide	N_2O	0.0000314
Ozone	O_3	0.000001-0.000004

Methane is present in the atmosphere in tiny amounts, but it is the most abundant reactive hydrocarbon in the atmosphere. The globally averaged atmospheric surface abundance in 2010 was 1780 ppbv, corresponding to a total burden in the atmosphere of about 4850 Tg methane. The uncertainty in the burden is small ($\pm$5%) because the spatial and temporal distributions of tropospheric and stratospheric methane have been determined by extensive high-precision measurements and the tropospheric variability is relatively small (IPCC, 2007). The other terms in the budget are more uncertain. The reaction with hydroxyl (OH) radicals is the main sink term for methane in the troposphere. The lifetime of the hydroxyl radical (OH) is so small that measuring the OH concentration is done indirectly through the measurements of methyl chloroform (Krol and Lelieveld, 2003). The reaction speed of methane with OH is poorly known. By tropospheric OH each year an estimated 500 (405-575) Teragram methane is removed (IPCC, 2007). Methane that reaches the stratosphere is photo dissociated by exited oxygen atoms (O^1D). Part is lost through reaction with chlorine. This stratospheric loss accounts for 40 (32-48) Tg CH_4 per year. Some methane is oxidised in soils: 30 (15-45) Tg CH_4 per year. So the total estimated sink is 560 $\pm$ 100 Tg CH_4/yr. The implied atmospheric increase, that is sources minus sinks, is about 45 Tg methane per year. The methane budget is still under discussion especially since methane was increasing again in the atmosphere since 2006. In the next chapter the uncertainty will be discussed through a comparison with other budgets.

Radiative properties of methane

The climate effect of the methane concentration increase is dependent on the radiative properties of methane and on the rate of saturation of the absorption bands in the spectrum. Because there is so much water vapour in the atmosphere, water vapour already absorbs much infrared radiation that is radiated from the earth. CO_2 is also present in sufficient quantities to saturate the main absorption bands. Extra CO_2 only has an effect on the weaker absorption bands. But extra CH_4 has a significant effect because it absorbs strongly at wavelengths, which are otherwise transparent to the earth's outgoing radiation. This strong absorption band is at 7.66 μm. The lifetime of methane in the atmosphere is about 8.4/12.2 years (IPCC, 2007). The contribution of carbon dioxide to global warming is 1.56 W/m^2 in 1990 and 1.46 W/m^2 in 2000. The contribution of CH_4 to global warming is about 0.47 W/m^2 in 1990 and about 0.5 W/m^2 in 2010. In table 2.2. some properties of methane are compared with other important greenhouse gases. These properties of methane will be described in the next sections.

Table 2.2: Some properties of greenhouse gases affected by human activities (IPCC, 2007).

	CO_2	CH_4	N_2O	CFC-11	HCFC-22	HFC-23	CF_4
Pre-industrial concentration in 1750	280 ppm	700 ppb	275 ppb	Zero	Zero	Zero	40 ppt
Concentration in 2010	380 ppm	1800 ppb	314 ppb	268 pptv	132 pptv	14 pptv	80 ppt
Rate of concentration change in 90s	1.5ppm/yr	7 ppb/yr	0.8 ppb/yr	-1.4 pptv/yr[1)]	5 pptv/yr	0.55 pptv/yr	1.0 ppt/yr
Rate of change	0.4 %/yr	0.6 %/yr	0.25 %/yr	0[1)]	5 %/yr		2 %/yr
Atmospheric lifetime [2)]	50-200 yr	8.4/12.2 $\pm$3 yr	120 yr	45yr	12 yr	260 yr	> 50000 yr
Radiative forcing	1.46 W/m^2	0.50 W/m^2	0.15 W/m^2	0.06 W/m^2	0.02 W/m^2	0.16 W/m^2	0.007 W/m^2
Global Warming Potential 100yr	1	25	296	4600	1700	12000	5700

Ppm = parts per million Ppb = parts per billion Ppt = parts per tera

1) Halocarbon growth rates are based on measurements in the nineties.

2) No Single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes.

For CH_4, the global mean atmospheric lifetime is 8.4 years and the perturbation lifetime is 12.2 years. This is the adjustment time, which takes into account the indirect effect of methane on its own lifetime.

2.3 Global warming potential

The global warming potential is a simple measure for the relative radiative effects of a pulse of greenhouse gas emission integrated over time. The global warming potential is defined as the cumulative radiative forcing between the present and some chosen time horizon (e.g. 20, 100 or 500 years as given in IPCC tables) caused by a unit mass of gas emitted now, relative to that for CO_2. The GWP of CO_2 is 1 by definition. Methane has a global warming potential of 72 when calculated over 20 years and 25 (CO_2=1), when calculated for a 100 years time horizon. This includes an indirect effect resulting from reaction with OH and the formation of tropospheric ozone (O_3).

2.4 Rate of concentration change of methane

Atmospheric methane concentrations have been measured on a regular basis since the nineteen seventies in a number of monitoring programs (ALE-GAGE, CMDL, NOAA/ESRL/GMD) (Dlugokencky et al., 2009 and 2012). Methane is measured at several remote locations on earth (see NOAA website). In addition, satellites provide geographic explicit information on the methane content of the lower atmosphere (Frankenberg et al., 2006). Ice cores provide information on atmospheric methane concentrations in the past, before actual measurements in the atmosphere started (Loulerge et al., 2008).

Atmospheric monitoring networks indicate that the methane concentration growth in the atmosphere was high during the nineteen seventies. During the eighties and nineties of the last century a slowing down of the increase of methane in the atmosphere has been observed. The yearly increase was 20 ppbv in 1978 (1.3% per year), in 1989 it was 10 ppbv (0.6% per year) (Steele *et al.*, 1992). In the nineties it was about 7 ppbv per year (Dlugokencky et al., 1998). Following the Pinatubo eruption in June 1991, the methane growth rate first increased sharply over a period of 6 months at tropical latitudes. This has been attributed to short-term decreases in solar UV radiation in the tropics immediately following the eruption that decreased the OH formation rates in the troposphere (Dlugokencky et al., 1996). A large decrease in growth was observed in the northern hemisphere in 1992. This has been attributed in part to decreased northern wetland emission rates resulting from unusually low surface temperatures (Hogan and Harriss, 1994), and in part to stratospheric ozone depletion that increased tropospheric OH (Bekki et al., 1994). Growth rates dropped abruptly to almost zero in 1992 and 1993. In 1995, global methane growth rates recovered back to about 7 ppbv per year. Later the growth rate increased again to 15 ppbv per year in 1998 and was reduced to almost zero in 2000 to 2006 (IPCC, 2007). More recently, since 2007 the growth rate increased again with 7.5 ppbv per year (Dlugokencky et al. 2009 and 2012). Bloom et al. (2010) isolated the wetland and rice paddy contributions to spaceborne methane measurements over 2003-2005 using satellite observations of gravity anomalies, a proxy for water table depth, and surface temperature analysis. Their work suggests that tropical wetlands contribute 52-58% of global emissions, with the remainder from extra tropical regions, of which 2% is from arctic latitudes. They estimate a 7% rise in wetland methane emissions over 2003-2007, due to warming of the mid-latitude and Arctic wetland regions.

The reason of the overall slowing down of the methane growth rate since 1992 in the atmosphere is not clear. Both modelling studies and isotopic analysis conclude that several mechanisms may have combined to produce the observed drop in growth rates. Estimated changes in individual sources or sinks, with moderate assumptions of their sensitivity to the changed chemistry and temperature as a consequence of the Pinatubo eruption in June 1991, are insufficient to account for the entire decrease (Lelieveld et al., 1998). Since the early nineties the source strength of methane from coal, oil and gas in the former Soviet Union has been decreasing because of the economic recession and the related reduction in production (Aydin et al. 2011). Other sources like cattle in Eastern Europe have been decreasing as well. The zero growth rate might thus be partly attributed to the reduction of the sources and through methane mitigating measures in the early 1990's. The recent increase of methane is attributed to wetland emissions.

2.5 Atmospheric lifetime of methane

The atmospheric lifetime of gases other than CO_2 are determined predominantly by chemical reactions with the hydroxyl radical (OH), the most important cleansing agent of the troposphere. It is formed by dissociation of water through lightning. Methane together with other non-methane hydrocarbons NMHC and CO in the troposphere react with OH to form tropospheric ozone, which is a greenhouse gas. This is a positive feedback. CO competes with CH_4 for the OH radicals. Therefore these constituents influence each other's lifetime and the OH concentration. The lifetimes of all those gases that react primarily with tropospheric OH were revised downward by about 11% in the mid nineties. For CH_4 from 14.5 $\pm$ 2.5 to 12.2 $\pm$ 3 year (Schimel et al. in IPCC, 1996; IPCC, 2001). This is based on an upward revision of the mean global OH concentration, which in turn is based on a revision of the budget of methyl chloroform, which serves as a reference to estimate mean global OH concentrations (Prinn et al. 1995). The loss of methane through reaction with the tropospheric hydroxyl radical OH is 11% faster, or 37 Tg more per year, than recommended in IPCC 1994. The new recommendation for the CH_4 turnover time of 8.4 yr (including troposheric OH, stratospheric loss and uptake by soils) results in an inferred global loss of 560 $\pm$ 100 Tg CH_4/yr (IPCC, 2001 and IPCC, 2007).

2.6 Feedback of climate change on methane concentrations and emissions

Methane in the past

In Greenland ice records clear indications are found of rapid climatic changes at the end of the last ice age, the Pleistocene. During deglaciation the so-called Bolling-Allerod-Younger Dryas oscillation (Dansgaard and Oeschger, 1988), which is reasonably well dated in the Dye 3 ice core, depicts a mean temperature increase in Greenland of about 7 ^oC over a time period on the order of only 40 years, around 10720 year before present (BP). The accumulation rate of snow increased approximately 60% judging from the rapid increase in annual layer thickness. This was caused by increasing cloud cover and increasing precipitation under a higher air temperature over ice. Concentrations of chemical components in the ice changed drastically, including CO_2 and CH_4 concentrations. This type of rapid climatic change illustrated by the Bolling-Allerod-Younger Dryas oscillation is not unique. It appears to be the last of a series of events observed throughout the glaciation. During periods around 30 and 40 thousand years BP., $\delta^{18}O$ varied up to about 4‰ in the Greenland ice records, corresponding to temperature changes of about 5-6 ^oC within about a century or less. A detailed plot of the $\delta^{18}O$ peaks from the Dye 3 record reveals a saw-tooth shape with more abrupt changes from cold to mild conditions than vice-versa. It is the time of the sand and dust storms in the northern tundras. Over these time intervals the temperature changes are in phase with dust concentration in the ice, with higher values during cold conditions. Measurements (Stauffer et al., 1988; Blunier et al., 1995; Chappellaz et al., 1997; Petit et al., 1999; Loulerge et al., 2008) show that CH_4 concentrations follow similar patterns as CO_2 with an increase from about 350 ppbv near the end of the last ice age to Holocene values of about 650 ppbv.

Release of one major burst of 10^{15} g of one of the larger pools in the past could have doubled global CH_4 for several decades. Very widespread pockmarks in the sediments are evidence of Bolling-Allerod and Younger Dryas bursts in the Arctic shelf, off Northern Europe, in the North Sea, West Siberia, and North-western Canada. Murton et al. (2010) recently found evidence of the melting Laurentide Ice Sheet from Lake Agassiz to the Arctic Ocean and possible abrupt climate change as a result of this methane outburst. At the termination that marked the ends of the Older and Younger Dryas periods, at the close of the last major glaciation, atmospheric methane levels rose sharply. Biological sources may have played a part in this increase, but it is unlikely that they could have accounted for the suddenness of the rise in methane production. Some fossil methane stores, such as marine and continental hydrates, may have become unstable at the end of the Pleistocene, and there is much geological evidence, like pockmarks at the sea floor, that many catastrophic releases of methane occurred. It is possible that part of the increase in global atmospheric methane may have been the result of these releases, which may also have played a part in recharging the total carbon load in the atmosphere-biosphere system. The Younger Dryas cooling may represent a transient response to a reduction in greenhouse forcing when the CH_4 mixing ratio in the atmosphere dropped again. This transient response would have been more marked in the Northern Hemisphere than in the Southern. The termination of the Younger Dryas may have occurred after a further catastrophic release of fossil methane (Nisbet, 1992; Blunier et al., 1995; Ganopolski and Rahmsdorf, 2001).

Methane in the future

Shakova et al. (2010) in East Siberia and Westbrook et al. (2009) in West Spitsbergen continental margin now document large areas of the Arctic Shelf waters with super saturation of methane from decomposing hydrates. In some places methane concentrations are more than 100 times higher than expected in equilibrium with ambient atmosphere. Based on their dataset, the authors estimate an annual outgassing to the atmosphere of 10 Tg methane indicating melting hydrate outgassing. With an increasing warming of the Northern Arctic permafrost and shelf areas, a new catastrophic hydrate release is possible. The exact circumstances of hydrate destabilisation are under research. In strata above major hydrocarbon fields, such as northern West Siberia, Alberta, Alaska and the North Sea, during normal interglacial time, gas seeps steadily to the surface. During glaciation a layer of permafrost clathrate builds up, in which gas accumulates. Gas is then stored in enormous quantities both in the hydrate and also as pools of free gas trapped beneath the permafrost layer. Modern giant Arctic gas fields are residual remnants of much more extensive fields that existed at the last glacial maximum. The mass of gas trapped today is immense, with perhaps 5.4 x 10^{17} g of carbon in CH_4 remaining today in the Arctic hydrate zone (Kvenvolden, 1988, 1998 and 2006; Davaasuren et al. 2010).

With high levels of warming, methane stored in methane hydrates under permafrost and in sea beds could become destabilised, releasing large amounts of methane into the atmosphere and increasing climate forcing. Through positive feedback processes this may even trigger a runaway greenhouse effect (Harvey and Huang, 1995).

2.7 Conclusions

Radiation balance

Methane has a distinctive effect on the radiation balance. Methane is the second important greenhouse gas after carbon dioxide. The contribution of carbon dioxide to global warming in 1990 is 1.56 W/m^2. The contribution of CH_4 to global warming in 1990 is about 0.47 W/m^2 and in 2012 is about 0.5 W/m^2. During the last decades the relative contribution of methane to global warming was an estimated 15-20%. The relative contribution has been growing over the years. Due to its relatively short atmospheric lifetime of about 12 years, reductions in the anthropogenic emissions are measurable in the atmospheric concentrations within 10 or 20 years time.

Methane in the atmosphere

Methane concentration in the atmosphere is 1780 ppbv. It has been growing although the growth rate has been variable between zero and 17 ppbv per year. The annual growth rate of methane in the atmosphere has increased from about 5 ppbv per year in 1940 to 17 ppbv per year in 1980. Growth rates dropped abruptly to almost zero in 1992 and 1993. In 1995, global methane growth rates recovered back to about 7 ppbv per year. Later the growth rate rose again to 15 ppbv per year in 1998 and was reduced to almost zero in 2000 to 2006. Methane concentrations are on the increase again since 2007 with 7.5 ppb per year. The slowing down of the atmospheric growth rate during the eighties and nineties is attributed to a diminishing of anthropogenic sources and an increase in the atmospheric OH sink. The reduction of methane sources over the last decades is likely for coal, oil and gas because of the economic recession and improved leakage control. The recent increase is attributed to increasing wetland sources.

Radiative properties

The climate effect of methane concentration increase is dependent on the radiative properties of methane and on the rate of saturation of the absorption bands in the spectrum. Extra methane has a significant effect because it absorbs strongly at wavelengths which are other wise transparent to the earths outgoing radiation. This strong absorption band or atmospheric window is at 7.66 micrometer.

Global warming potential

The cumulative radiative forcing over a hundred year period caused by a unit mass of methane emitted now is 25 times as large as carbon dioxide. The GWP over a shorter time period is 72 times as large as carbon dioxide. Thus a reduction of methane emissions is expected to result in reduced global warming.

Feed back of methane

In ice core records clear indications are found of rapid climatic change at the end of the last ice age. Methane concentrations follow similar patterns as carbon dioxide with an increase from about 350 ppbv near the end of the last ice age to Holocene values of about 650 ppbv. The end of the Pleistocene may have occurred after catastrophic releases of fossil methane from hydrates. In the future positive feedbacks in the climate can result in a run-away greenhouse effect if more of these methane hydrates are released by warming from the northern permafrost areas and tundra's.

Uncertainty

The growth rate of methane in the atmosphere is the resultant of a small imbalance between sources and sinks. Both are poorly characterised which makes the prediction of future concentrations problematic. Although the main sources and sinks have been identified most of them are uncertain quantitatively because both fossil and biogenic sources have highly variable emission rates and the sinks are variable because of complicated atmospheric processes. Both fossil and natural emissions and sinks can be influenced substantially by climate change.

Concluding remarks

Methane affects the radiation balance through its absorptive properties. Radiation reflected by the earth surface is mainly absorbed at 7.66 micrometer. Through the growth of methane the global warming from methane has increased between 1750 and 1980. Aydin concluded that the methane concentration growth between 1980 and 2007 decreased because of decreased emissions from fossil sources (Murat Aydin et al. 2011). The growth rate has slowed down to zero by 2006, indicating a possible success in global methane mitigation in oil and gas or reductions of emissions from wetlands. Since 2007 methane concentrations are rising again but the reasons are unclear. One research group concluded that the methane concentration in the air increased since 2007 because of increased wetland emissions (Fuu Ming Kai et al. 2011). Methane is very important as a greenhouse gas because it has a strong absorption band for outgoing radiation. Over a 100 years time horizon it is 25 times as powerful as carbon dioxide in global warming. Because of its short atmospheric lifetime a reduction of sources is noticeable in the concentrations within one or two decades. Methane reduction since 1990 already has reduced global warming but this has been masked by other more powerful changes like cooling from large volcanic eruptions. Future warming is very dangerous as methane hydrates in higher latitudes can become destabilized. This can result in future methane bursts into the atmosphere with a risk of starting a run away greenhouse effect. Monitoring is therefore very important at all levels.

3. GLOBAL METHANE BUDGETS

Updated from Van Amstel, A.R., L.H.J.M. Janssen, J.G.J. Olivier, 2000: Greenhouse Gas Emission Accounting. In: J. van Ham, A.P.M. Baede, L.A. Meyer and R. Ybema editors: Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation. Pp 461-468. Kluwer Academic Publishers.

3.1 Introduction

Methane is the third most important greenhouse gas after water vapour and carbon dioxide. Energy production and use, landfills and waste, cattle and milk production, rice agriculture and biomass burning are considered important human sources (Reay et al., 2010). Natural sources include wetlands, termites, oceans, hydrates, geological sources, wild animals and wildfires (See Table 3.1). In this chapter global methane budgets will be reviewed. Global budgets are overviews of sources and sinks for methane. In chapter 3.2 the global source estimates will be described. In chapter 3.3 it will be described how this information is used in global atmospheric chemistry and transport models to derive global methane concentration fields and geographic detail on the methane sources. Global networks of methane measurement instruments have improved our knowledge on methane concentrations in the atmosphere. These measured methane concentration fields are used to improve the methane source estimates for countries and regions. Global methane budgets are quantified overviews of sources and sinks. They are derived from "a priori" emission estimates and long-term measurements of methane concentrations at background stations (e.g. the National Oceanic and Atmospheric Administration - Earth System Research Laboratory (NOAA ESRL) global air sampling network, using simulations of global atmospheric chemistry and transport models. Satellite information from instruments on board ENVISAT on methane concentrations can be used to validate these model simulations and develop global maps of emissions. Inverse modelling is used to improve the "a priori" emission estimates. Methane emission estimates from tropical wetlands and remote areas were improved through inverse modelling exercises (Houweling, 2000; Bergamaschi et al., 2005, 2007 and 2009; Schneising et al., 2011), using satellite data and the TM5 model (Krol et al. 2005). In this chapter the literature on global methane budgets will be reviewed.

In this chapter research question 2 will be answered:

What are the global CH_4 emissions and sinks?

The global methane budget remains ill-quantified, despite several decades of research (Lassey and Ragnauth, 2010). According to the Fourth Assessment Report of the IPCC (Denman et al., 2007) the global sinks that remove tropospheric methane are uncertain to about 20%. This infers a similar uncertainty in the global top-down estimate of world methane emissions from the different sources. The emission sources themselves are in general poorly determined, leading to a poorly defined source distribution. This has enabled significant new source categories to be postulated or discovered, while the total source strength is still consistent with the top-down aggregate of methane. For example, a claim for a large new source, aerobic methane from plants, estimated at 236 Tg per year was put forward by Keppler et al. (2006). This is more than the total wetland source and is about 40% of the global total source of 600 Tg. This estimate has been questioned by others and the upper limit revised downwards significantly by Kirschbaum et al. (2006) and Parsons et al. (2006). A detailed description of the methane source from vegetation is given by McLeod and Keppler (2010). Another new source is methane from geological resources. This is estimated at 9 Tg per year (Etiope, 2010).

In this chapter methane budgets are derived from top-down versus bottom-up comparisons for methane. Two definitions are used in the literature:

1. Comparison of a priori methane emission estimates in space and time with measured concentrations in the atmosphere.
2. Comparison of national estimates of emissions with independent sources like the EDGAR database.

The first comparison is called "inverse modelling". With this kind of comparison "a priori" emission estimates from EDGAR are improved by using all available information from measurements of methane concentrations in the atmosphere. The results are improved or "a posteriori" emission estimates. Improved emissions from Bergamaschi et al. (2007) are given in Table 3.5.

The second definition is the comparison of global top-down methane emission estimates of EDGAR with the bottom-up methane emission estimates based on experimental research and official country reports to the UN Framework Convention on Climate Change (UNFCCC). Results for such a comparison are given in chapter 4 in this thesis.

The global CH_4 budget comprises a wide range of sources balanced by a much smaller number of sinks. Here the consensus budget is given from Denman et al. (2007) (see Table 3.1). Any imbalance in these sources and sinks result in a change in the atmospheric concentration. There are three main sinks for CH_4 emitted into the atmosphere, with the destruction of CH_4 by hydroxyl (OH) radicals in the troposphere being the dominant one. This process also contributes to the production of peroxy radicals, and it is this process that can subsequently lead to the formation of ozone and so induce a further indirect climate forcing effect of CH_4 in the atmosphere. In addition this reaction with OH radicals reduces the overall oxidizing capacity of atmosphere – extending the atmospheric lifetime of other CH_4 molecules – and produces CO_2 and water vapour. Each year an estimated 428–507 Tg (teragram; 1 Tg = 10^{15} gram or 1 million tonnes) of CH_4 are removed from the atmosphere in this way.

The other sinks are much smaller, with a 39 Tg CH_4 removed each year by reaction in the stratosphere, and 30 Tg CH_4 removed by CH_4 oxidizing bacteria (methanotrophs) in soils that use the CH_4 as a source of carbon and energy. A relatively small amount of CH_4 is also removed from the atmosphere through chemical oxidation by chlorine in the air and in the surface waters of our seas. Detailed reviews of the key CH_4 sinks and their role globally can be found in Cicerone and Oremland (1988), Crutzen (1991) and Reay et al. (2007 and 2010).

Table 3.1 Global estimates of methane sources and sinks

Natural sources	*Methane flux (Tg CH_4 yr^{-1})*[a]	*Range*[b]
Wetlands	174	100–231
Termites	22	20–29
Oceans	10	4–15
Hydrates	5	4–5
Geological	9	4–14
Wild animals	15	15
Wild fires	3	2–5
Total (natural)	**238**	**149–319**
Anthropogenic sources		
Coal mining	36	30–46
Gas, oil, industry	61	52–68
Landfills and waste	54	35–69
Ruminants	84	76–92
Rice agriculture	54	31–83
Biomass burning	47	14–88
Total, anthropogenic	336	238–446
Total, all sources (AR4)[c]	**574 (582)**	**387–765**
Sinks		
Soils	-30	26–34
Tropospheric OH	-467	428–507
Stratospheric loss	-39	30–45
Total sinks (AR4)	**536 (581)**	**484–-586**
Imbalance (AR4)	**38 (1)**	**-199–281**

Note: [a] Values represent mean of those provided in Denman (2007) rounded to the nearest whole number. They draw on eight separate studies, with base years spanning the period 1983–2001. [b] Range is derived from values given in Denman (2007). Values from Chen and Prinn (2006) for anthropogenic sources are not included due to overlaps between source sectors. [C] Values in parentheses denote those provided in the IPCC Fourth Assessment Report (AR4) as the 'best estimates' for the period 2000–2004.

Of the many significant global sources of CH_4, both natural and anthropogenic, the bulk have a common basis – that of microbial methanogenesis. This involves the breakdown of organic matter under anaerobic conditions (Stams and Plugge, 2010). Though CH_4 from biomass burning, vegetation and geological or fossil fuel sources may be largely non-microbial in nature, understanding the processes that underpin microbially-mediated CH_4 fluxes is central to quantifying, and potentially, reducing emissions from all other major sources.

A number of authors have used inverse modelling as an approach to reduce the uncertainties in the global budgets for methane (e.g. Hein and Heimann, 1994; The and Beck, 1995; Hein et al., 1997; Lelieveld et al., 1998; Houweling, 1999 and 2000; Bergamaschi et al., 2005, 2007 and 2009; Schneising et al., 2011). With inverse modelling “a priori” emission estimates are improved by using global atmospheric transport and chemistry models in the inverse mode. Global concentration fields are used as input to estimate the sources and sinks. Results of inverse modelling are called “a posteriori” or improved estimates.

Results from inverse modelling are regional emissions (on isoline maps or grids) derived from global atmospheric concentration fields. These can be compared with bottom-up estimates on the same spatial scale.

Because comparison can be performed at different scales: global average emission, emission per period per zonal band or emission per period per grid cell, results are not easily interpreted. Periods can be anything between one hour and one year. Daily, weekly and/or monthly averages for wind fields and hydroxyl are often used in these global models.

Inverse modelling can be an independent check on emission inventories if no “a priori” emission estimates are used in the chemistry and transport models, however many more background measurement stations than the existing ones would then be needed to eliminate the uncertainty. In practice ‘a priori’ emission profiles through the year are used for each source of emissions to reduce the uncertainty.

Improved ‘a posteriori’ atmospheric methane budgets can be derived from these atmospheric models in the inverse mode and measurements from remote clean air locations. Inverse modelling results are treated further in paragraph 3.3. Now the bottom up inventories are treated in paragraph 3.2.

3.2 Global bottom-up inventories of methane sources

3.2.1 Introduction

In this section an overview is given of bottom-up global methane emission estimates from human activities. Bottom-up estimates are based on the extrapolation of measurement results from experimental research. Estimates are often based on emission factors x activity levels. For example the methane emissions per ton of coal produced per country.

3.2.2 Methane from coal mining

Coal mining is an important source of atmospheric methane. Methane formed during coalification of peat or wood is trapped in coal seams and in surrounding strata. It is released with mining. The methane content of coal seams is highly variable and is a function of coal rank, age and depth of seams. As a rule higher rank coal and deeper seams have higher methane content. But if erosion took place at any time in geological history after coal formation, or if overlaying strata are porous, part of the methane may have migrated or disappeared (Williams et al., 1993). Different coal basins in the world differ in overall methane content. Methane is a safety hazard. Thousands of miners have lost their lives in mine explosions caused by methane explosions. Methane is vented from the mines to get rid of the gas as soon as possible. As methane is diluted in the process of venting from mine shafts it is difficult to use for energy. Pre-mining degasification via boreholes is practised since World War II in Europe and more recently in the United States.

Methane emissions from underground mines are in the range of 10 to 25 $m^3 tonne^{-1}$ coal compared to values of 0.3 to 2.0 $m^3 tonne^{-1}$ for surface mines (1 m^3 CH_4 = 0.68 kg). Only a few percent of the potential methane from coalmines is captured for use as a fossil fuel. In the near future pre-mining degasification will increase coal-bed methane capture and use. Many authors have estimated the total emissions from coal mining. Olivier et al. (1996) estimated a total of 38 Tg CH4 in 1990. This estimate is based on an overview of mines in the world, coal production figures and country specific methane emission factors. This estimate is within the range given by IPCC in 2007 (see table 3.1). Globally this source is estimated to be between 30 and 46 Tg CH_4 each year (Denman et al., 2007). Williams et al. (1996) made another estimate of methane emissions based on country specific emission factors. They estimated only 20.3 Tg CH_4 using 1993 coal production figures (1 m^3 CH_4 = 0.68 kg). This estimate is below the IPCC range in Table 3.1. Coal use is expected to increase in the future, especially in India and China because of huge coal reserves and the economic growth in these regions. Methane emissions are therefore expected to increase unless modern techniques for gas capture and use are applied in the near future. Williams et al. (1996) expected an increase of capture and utilisation from 5% in 1993 to 10% in 2010 and 15% in 2020. Williams (1999) expected to capture and use extra methane from coal mines by injection of the coal seams with CO_2. Mattus (2010) described new developments in coal mining ventilation air use. It is estimated that around 97% of all methane emissions from coal mines can be avoided with new catalytic oxidizer technology.

3.2.3 Methane from the oil and gas industry

Methane leaks during exploration of fields, operation of vents and flares, production of oil and gas, compression of gas for transport, oil tanker loading and transport. It is practically impossible to prevent methane from leaking all together from different parts in the oil and natural gas systems, but methane leakage should be reduced to the minimum. Transmission in high pressure pipes shows less leakage. Glycol use for the drying of gas and glycol regeneration leads to high losses. Gas distribution to the consumers in low pressure pipes is especially leaky if old town gas distribution pipes are still used. In many countries in the Middle East, Latin America, Asia and Africa unused associated gas from oil wells is vented to the atmosphere. This is a mere waste of a valuable energy resource. Absence of local markets for the gas is the reason for venting this gas to the atmosphere. In Nigeria, where about 216 Gigagram is vented to the atmosphere each year (Obioh et al. 1996), Shell invests in techniques to capture the gas to liquidize and transport it as LPG to the European markets. Investment costs are high. In the Western world leaking is reduced by applying modern techniques and regular leak control. Old distribution networks for town gas, which were notoriously leaky systems are replaced by PVC pipes in most Western European towns. Regional emission factors have been developed by Ebert et al. (1993). World total emissions are estimated at 15 Tg of methane in the oil industry and 40 Tg of methane in the natural gas industry of which 20 Tg in Russia and Siberia. De Jager et al. (1997) used specific emission factors for different regions in the world and for each step in the production chain. They estimated a total emission of 47 Tg in oil and gas of which 25 Tg in the former USSR. We used the EDGAR estimate of 15 Tg in the oil industry and 40 Tg in the gas industry for the integrated assessment in chapter 6. See table 3.6. Denman et al. (2007) estimated 61 Tg with a range of 52-68 Tg including the industry emissions.

Russia and Siberia

The leaking of gas from the Russian and Siberian oil and gas industry is estimated to be high because of low maintenance and permafrost problems which instabilizes the pipelines. Rabchuk et al. (1991) estimated that 10% of production was lost to the atmosphere. Bordiugov (1995) estimated a loss of only 1.2% of 1990 gas production of 770 billion cubic meters and 1.4% of 1994 gas production of 570.7 billion cubic meters. This is 9.2 billion cub, or 5.3 Tg in 1990 and 8.12 billion cub, or 4.7 Tg in 1994 (1 cubic meter of natural gas with 80% methane is 0.58 kg). The high figure of Rabchuk included methane used in the process of transporting the gas from Siberia to the consumers. Using inverse modeling techniques Hein and Heimann (1994) have estimated the Russian and Siberian source to be at least double the IPCC estimate of 20 Tg. They estimated a loss of 45 (34-56) Tg methane. This is clearly contradictory to Russian estimates. The inverse modelling exercise of Bergamaschi et al. (2007) resulted in only 16.4$\pm$3.6 Tg from oil and gas for North Asia including the Asian part of Russia.

3.2.4 Methane from combustion of fossil fuels

Incomplete combustion of fossil fuels is a small source of methane. Berdowski et al. (1993) have developed emission factors for this source and Olivier et al. (1996) based on these factors, have given an estimate of 4.8 Tg/yr of CH_4. High emissions are only expected in the smouldering phase of a wood fire. This typically occurs in biomass burning, not with fossil fuel use.

3.2.5 Methane from biomass burning

Joel Levine (2010) gives an overview of methane from biomass burning. Biomass burning is a significant source of atmospheric trace gases like carbon monoxide and methane. Anthropogenic biomass burning is more important now than natural fires because of forest destruction (Delmas, 1993 and 1994; Hao, 1999; Page et al., 2002). Simpson (2006) found that biomass burning had a significant influence on the large global CH_4 pulses observed in 1998 and 2003. Simpson (2006) attributed the large global increase of methane to the massive forest and peat fires in Indonesia in 1997 and in the boreal forests of Russia in 1998 and again in 2003. This resulted in emissions of carbon dioxide and methane to the tune of the national emissions of the UK in one year. The products of complete combustion of biomass are carbon dioxide and water vapour. The combustion process however is never complete and this prevents some carbon from being oxidised. This generates several carbonaceous products of incomplete combustion, some gaseous and some particulate. Every biomass fire has four phases of combustion: flaming, pyrolysis, smouldering and glowing. The magnitude and duration of each of these processes depend on the kind of biomass and the conditions during the fire. Flaming dominates the start of a fire. The heat initiates pyrolysis that provides the fuel gases, including methane that sustain the visible flaming process. In the smouldering process charcoal is produced. Gaseous products can escape oxidation during this phase. During the glowing of the charcoal no appreciable emissions of volatile compounds occur. Each process has different amounts of resulting products. Methane is released in large quantities especially during the smouldering phase, with emission factors 2-3 times greater than during the flaming phase. Delmas (1993) estimates the total methane emission from biomass burning in the world at 34 (range 22-46) Tg/yr. Three sources dominate this budget: fuel wood burning and tropical forest and savannah fires. Another estimate is from Ahuja (1993). His estimate is 48 Tg/yr. It is based on a careful re-evaluation of information and the IPCC methodology. This is about the same as the IPCC estimate of 47 (range 14-88) Tg/yr (Denman et al., 2007). According to Ahuja (1993) biofuels emit 21 Tg/yr, shifting cultivation 10 Tg/yr, deforestation 8.5 Tg/yr, savanna burning 6 Tg/yr, charcoal production 2.5 Tg/yr and agricultural residues 1 Tg/yr. In Chapter 6 the EDGAR estimate is used of 10 Tg/yr for deforestation, 10 Tg/yr in biofuel burning, 3 Tg/yr in agricultural waste burning and 15 Tg/yr for savanna burning (Olivier et al., 1996 and 2009). See also Table 3.6.

3.2.6 Methane from agriculture

Enteric fermentation in ruminants

Methane is formed in the rumen of cattle by methanogenic bacteria under anaerobic conditions. This process enables ruminants to utilise the energy in low-quality feeds like grass and fodder with high cellulose content. Pseudo-ruminants like e.g. pigs and horses also produce methane but in much smaller quantities. Methane production by fermentation in insects, e.g. termites is now seen as significant on a global scale (Denman et al., 2007). Ritzman and Benedict (1938) published early data on methane yields by cows, sheep, goats, horses and elephants. They found that methane emissions are 4-7% of gross energy intake for ruminants fed at maintenance level. Blaxter and Clapperton (1965) found that methane emissions depended on feeding level and digestibility. The relation they found is used to calculate emissions at a detailed level. In developing countries a large proportion of the feed consists of low-quality straw and fodder. Krishna *et al.* (1978) estimated 9% methane yields in Indian cattle fed at maintenance level with low-quality feeds.

Crutzen *et al.* (1986) estimated the methane emissions from wild and domesticated animals, and humans. They found 80 (range 65-100) Tg CH_4/yr. World herds of domesticated animals have increased since 1950. Crutzen found an increase of methane emissions from domesticated animals of 0.6 Tg/yr or 0.75 % per year between 1966 and 1986. Lerner *et al.* (1988) made a global database of methane emissions from livestock per gridcell of $1x1^o$. They found emissions of more than 5000 kg per km^2 per year in small regions such as the Netherlands and Belgium, Bangladesh, parts of northern India and New Zealand. They also found that half the global emissions are from only five countries: India, the former Soviet Union, Brazil, the USA and China. Gibbs and Johnson (1993) made an estimate for 1990 based on detailed calculations of feed intake and energy requirements for work and lactation. They found a total global emission of 58 Tg/yr, with 30 Tg/yr coming from six countries: the former Soviet Union: 7.5 Tg/yr; Brazil: 7.0 Tg/yr; India: 5.6 Tg/yr; United States: 5.3 Tg/yr; China: 3.4 Tg/yr and Australia: 1.2

Tg/yr. Methane emissions from ruminants are increasing because of increasing numbers and increasing milk production. Steinfeld et al. (2006) based on IPCC methodology estimated a global total of 84 Tg methane per year from ruminants for the year 2005. An overview of methane from ruminants is given by Kelliher and Clark (2010). They estimated an emission of about 100 Tg per year from ruminants for 2010, of which 14 Tg from China, 12 Tg from Brazil, 11 Tg from India, 5.5 Tg from the USA, 3 Tg from Australia, 3 Tg from Pakistan, 3 Tg from Argentina, 2.5 Tg from Russia, 2.3 Tg from Mexico and 2 Tg from Ethiopia.

Animal waste

Methane from animal manure is formed in anaerobic conditions when stored in lagoons or in manure tanks. Manure production in the world is large and because manure is primarily composed of organic material, the potential for methane emissions is great. However, only a small part of the potential is realised because when the manure is kept in contact with oxygen, e.g. daily spread on the fields, methane production is minimal. Therefore the manure management system used in each country strongly influences the methane production and emission. Gibbs and Woodbury (1993) made an estimate of emissions based on animal numbers, manure production and the manure management system in each country. Their estimate is 13.9 Tg CH_4 per year in 1990, with the highest emissions in liquid or slurry manure storage in Europe and Asia, and in anaerobic lagoons in North America. Woodbury and Hashimoto (1993) estimated a total emission of 14 Tg/yr from animal waste, using assumptions about the share of different manure treatment systems per country. Zeeman (1994) reports on methane emissions from animal manure in the Netherlands. She found that temperature, storage time and amount of inoculation from waste that remains in the system after emptying influence methane emissions. Van Eekert et al (2010) published an overview of methane from wastewater and manure. They treated anaerobic digestion as a technology to enhance and recover the methane for energy.

Rice

Methane is formed in the growing season in paddy soils during flooding by methanogenic bacteria. Methane escapes through bubbling and diffusion but also through the rice stems. Therefore rice variety and soil type is important. Draining of the fields stops methane formation because of aeration. Methane formation is reduced in the presence of sulphate and gypsum. Therefore methane emissions from rice are dependent on the period that the paddies are flooded, the climate, the soil type, the management and the type, amount and application method of fertilisers. Minami (1994) reports that emissions increase in all fields with rice straw application. 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. The rainfed and irrigated rice fields have significant emissions. The other types less so. The IRRI (1988) has information on the area of wetland rice. About 80 million ha harvested wetland rice are a potential sources of methane. On the basis of this information and experimental results, Neue *et al.* (1990) assumed average emissions of 200-500 mg/m^2 during an average growing season of 130 days. They estimated a global emission of only 25-60 Tg/yr compared to 40-160 Tg/yr as estimated by Matthews and Fung in 1987. Sass (1994) in a review of measurement studies concluded a smaller methane emission of 25-54 Tg/yr from a total rice area of 147.5 million ha. Sass concluded that China is the most important region with 13-17 Tg from 32.2 million ha. Olivier et al. (1996), based on a single IPCC default emission factor of 45.5 g methane per m^2 per growing season of 130 days (0.350 g per day), estimated a total of 60 Tg/yr with the largest share of 25 Tg in India and 20 Tg in China. Denier van der Gon (1996) described more factors that influence emissions like salinity, alkalinity, organic matter content, drainage situation and methane transport. Integration of emission measurements over a whole growing season has lowered the estimates of methane from rice from about 80 Tg/yr to about 40 Tg/yr (Denier van der Gon, 1996; Sass et al., 1999; Denier van der Gon, 2000; Van Bodegom, 2000). The total emission estimate is rather low compared to the IPCC estimate of 54 Tg methane per year (Denman et al., 2007). Conen (2010) estimated methane from rice between 25 and 50 Tg per year.

3.2.7 Methane from solid waste disposal and landfills

Methane is formed in anaerobic solid waste disposal or landfills. Because of highly variable composition and irregular structure it is difficult to predict the methane potential. Municipal solid waste with a high content of readily degradable organic material like vegetable and garden waste has the highest potential. The emission of methane starts after a timelag in which fatty acids are formed. The timelag is unpredictable and dependent on the initial water content of the waste. Bingemer and Crutzen (1987) estimated emissions from landfills. They calculated emissions per country from the amount of waste generated per capita, the fraction landfilled, the fraction degradable organic carbon, the fraction dissimilated degradable organic carbon, the fraction methane in the waste gas and the amount recovered. Their estimate was 50 (30-70) Tg/yr. Thorneloe (1993) estimated methane from landfills using a regression model developed from refuse and actual gas recovery data of US landfills. She estimated a world emission of 21 (range 11-32) Tg/yr. Meadows et al. (1996) have re-evaluated the data and made an estimate of 29 Tg/yr. First order decay functions or time dependent models are used in some countries to predict methane potentials for methane recovery projects. These models can also be applied at the country level. When outcomes are compared for one country significant differences are found. This is related to the growth of waste to landfills. Due to scarcity of data world estimates have not been made using time dependent methods. In our integrated assessment with IMAGE we used an estimate of 36 Tg/yr for 1990 and 46 Tg/yr for 2000 based on the growth of waste to landfills (see table 3.6). The IPCC estimate is 54 Tg from landfills including wastewater based on Denman et al. (2007).

3.2.8 Methane from waste water treatment

Methane is emitted from different kinds of waste water: from anaerobically treated human and industrial liquid wastes mainly from the agribusiness (like wine, beer, palmoil, olive oil, sugar, meat processing etc. The potential amount of methane formed in different waste types and the actual amount of methane emitted from different treatment systems depend on the waste characteristics like the COD and BOD (chemical and biological oxygen demand in the degradation), and the storage time and temperature. Methane emissions from sewage treatment systems are estimated by Thorneloe (1993) using the BOD_5 values of the waste water and an emission factor of 0.22 kg CH_4/kg BOD_5. Her global estimate ranges from 30 to 40 Tg per year. Industrial waste water treatment is the major contributor. Doorn (1999) described good practice guidelines for methane emission estimation for the IPCC. Doorn (2000) estimated methane emissions from domestic waste water at 29 Tg per year using an emission factor of 0.2 to 0.4 g methane per gram COD. In our assessment in IMAGE in chapter 6 we used an estimate of 26 Tg/yr for 1990 and 30 Tg/yr for 2000 based on the growth of sewage treatment. Denman (2007) did not treat methane from waste water separately.

3.2.9 Methane from natural sources

Wetlands

In wetlands methane is formed under anaerobic conditions by microbial decomposition of organic matter. This occurs in natural wetlands and in wet rice fields. Methane is formed by methanogenic organisms. Aselmann and Crutzen (1989) calculated that 2 to 7% of the net primary productivity in wetlands is emitted as methane. Whiting (1991) found a 5% emission from their measurements. Bloom (2010) based a global estimate of wetlands and rice emissions on spaceborne CH_4 measurements over 2003-2005 using satellite observations of gravity anomalies, a proxy for water table depth and surface temperature analyses. Bloom suggests that that tropical wetlands contribute 50-60% of global emissions, with the remainder coming from the extra-tropics, 2% of which is from the Arctic wetland regions. Bloom (2010) estimates a 7% rise in wetland CH_4 emissions over 2003-2007, due to warming of mid-latitude and Arctic wetland regions, which is consistent with recent changes in atmospheric CH_4.

Anaerobic conditions can be found at different places on earth: in wet soils, in shallow lakes, in peat areas, on the continental shelves. Above the zone of strict anaeroby, an aerobic zone is found. Methane that diffuses upwards is partly oxidised by methanotrophic microbes in this zone. If methane diffuses upwards through a water column, most of it is oxidised. The net budget between methanogenesis and methanotrophy determines whether the site acts as a source or a sink for atmospheric methane. In addition to diffusive processes, methane can escape by bubbling up through the water, or by transport through the stems of reed and other waterplants in marshes, lakes, and shallow lagoons. In swamps most of the net emissions are from bubbles or stem flow (up to 90% of emissions). In salty sediments and in the presence of sulphate, practically no methane is formed. After drainage of wetlands for agriculture oxidation starts. From a source for methane, drained wetlands turn into sinks. Different authors have made global estimates of emissions. Aselmann and Crutzen (1989) used average values for wetland methane fluxes in the range of 15-300 mg/m^2 per day and calculated a global emission of 40-160 Tg/yr. Matthews and Fung (1987) used values in the range of 30-200 mg/m^2 per day and found a total of about 110 Tg/yr. For our integrated analysis in chapter 6 we used an estimate of 105 Tg/yr for the period 1990 to 2100.

Hydrates

Hydrates of methane or clathrates are cubic ice crystals with methane locked in. One cubic meter of hydrate can contain up to 170 cubic meter of methane. Methane hydrates are found under specific temperature and pressure conditions under permafrost soils and at certain depths under the continental shelves (Maslin, 2010). Hydrates of methane are potential sources for natural gas, but no method for exploitation has been found yet. It is expected that this source will be economically exploited after conventional fields have been exhausted. It is unknown how much methane from hydrates is leaking and how much ends up in the atmosphere when it escapes oxidation in the overlaying soil or water column. The estimate is about 0 to 5 Tg per year. Recent research indicates that the emissions are increasing at an alarming rate. Shakova et al (2010) estimated 10 Tg methane per year from melting of hydrates in the eastern Siberian Arctic shelf.

3.2.10 Soils as a sink for methane.

Methanotrophic bacteria in the aerated parts of the soils take up methane. Different authors estimated the total actual sink for methane in oxidative soils (Crill, 1991; Steudler *et al.,* 1989; Striegl *et al.*1992; Whalen and Reeburgh, 1990; Whalen *et al.* 1992; Whalen *et al.* 1991; Mosier *et al.*, 1991). The IPCC estimated a total soil sink for methane of 30 Tg CH_4 (IPCC, 2007). Steudler *et al.* (1989) calculated a global total consumption of methane by temperate and boreal forests of 12.4 Tg CH_4 per year. They also found that the uptake rates were significantly decreased by nitrogen additions, implying that acid deposition and nitrogen fertilisation may reduce the sink capacity of soils. Striegl *et al.* (1992) estimated the global sink for methane by desert soils at about 7 Tg CH_4 per year.

3.3 Budgets of methane

3.3.1 Introduction

In paragraph 3.2 bottom-up estimates of methane emissions from various sources and sinks are described. These “a priori” methane emission estimates are used to feed into atmospheric chemistry and transport models for forward calculations of methane concentration fields. The concentration fields are then compared with measured concentrations on a number of background stations. Inverse modelling is used to calculate “a posteriori” or improved global emission estimates from measured methane concentrations in the atmosphere. It is done to improve “a priori” emission estimates using known concentrations. It is an “ill defined problem” to deduce top-down methane budgets from methane concentration fields because one particular concentration field gives not enough information about the individual methane sources. Therefore methane isotopic information is used as extra fingerprint information on the methane sources in a particular air mass to distinguish fossil and other biogenic methane sources.

In the following section I review the various attempts to use the methane concentrations to estimate the “a posteriori” or “improved” top-down methane emission estimates around the world.

3.3.2 The global budgets

Fung et al. (1991), Lelieveld and Crutzen (1993), Hein and Heimann (1994), The and Beck (1995), Hein et al. (1997), Lelieveld et al. (1998), Houweling (1999 and 2000), and Bergamaschi et al. (2005 and 2007), have published analyses of the CH_4 budget based on measurements and model calculations. IPCC has summarised them in the Second, Third and Fourth Assessment reports (IPCC, 1995; IPCC, 2001; IPCC, 2007). Bottom-up estimates are made in EDGAR (Olivier et al., 1999; Olivier, 2002; Olivier et al., 2005; Olivier et al., 2009) and in National Communications. In this thesis bottom-up budgets are presented for 1990 and 2000. See Table 3.6 for a summary and overview.

Important differences between the published (inverse) modelling studies of methane are the type of model and the definition of the fluxes that are estimated. Fung used a global Eulerian 3-D model with 9 layers in the vertical and 4-hourly winds to estimate the methane concentration resulting from different methane annual fluxes in the period 1984-1987 (Fung et al., 1991). Lelieveld and Crutzen (1993) used the Moguntia 3-D model with monthly averaged wind and OH to estimate the methane concentration from fluxes in the 1980s. Hein and Heimann (1994) used a 3-D model with 9 layers in the vertical and 12-hourly averaged winds to estimate the methane concentrations from annual fluxes in 1987. The and Beck (1995) used Global Moguntia with 10 layers in the vertical and monthly wind fields for 1987 to estimate the methane concentration from annual fluxes in 1987. Hein (1997) used a 3-D model and updated the annual methane flux per process, like oil and gas and ruminants or rice paddies, keeping their spatial and temporal distributions fixed. Lelieveld (1998) used the Global Moguntia model with 10 layers in the vertical and monthly wind fields from 1963 to 1973 to estimate the methane concentration from annual fluxes for 1992. Houweling (1999 and 2000) used the TM3 model with 19 layers and 6-hourly average meteorological fields of wind, pressure, temperature and humidity from the European Centre on Medium Term Weather Forecasting to resolve the methane concentrations from annual fluxes for 1993. Bergamaschi (2007) used the two-way nested atmospheric zoom model TM5 (Krol et al., 2005). The TM5 model used 25 vertical layers in the troposphere. This TM5 version is extensively validated and compared with other transport models (Bergamaschi et al., 2005 and 2007). See Table 3.3 for an overview of model characteristics.

Table 3.3: Overview of 3-D models used in this chapter

Model type	Spatial resolution/Model name	Temporal resolution	Period	Reference and Method
Eulerian 3-D	Global 4^0x5^0 and 9 layers	4-hourly winds	1 year in 1984-1987	Fung (1991) Best fit
3-D	Moguntia	Monthly	1980s	Lelieveld and Crutzen (1993)
3-D	8^0x10^0 9 layers	12-hourly winds	1987	Hein and Heimann (1994)
Eulerian 3-D	Global Moguntia 10^0x10^0 and 10 layers	Monthly 1987 wind fields	1987	The and Beck (1995) Best fit
Eulerian 3-D	Global 8^ox 10^o and 9 layers	12-hourly winds 1986 and 1987	1983/89 1991/93	Hein (1997) Baysian inversion
Eulerian 3-D	Global Moguntia 10^ox 10^o and 10 layers	Monthly wind fields 1963-1973	1992	Lelieveld (1998)
3-D	TM3: 5^ox3.8^o 19 vertical levels	6 Hourly mean meteorological fields, including wind, pressure, temperature and humidity (ECMWF)	1993	Houweling (1999)
4D-VAR	TM5 25 vertical layers	6 Hourly mean meteorological fields, including wind, pressure, temperature and humidity (ECMWF)	2003	Bergamaschi (2007)

Fung constructed seven possible budgets to test their ability to reproduce the observed geographic observations. To reduce the degrees of freedom several constraints were formulated:

1. The rate of atmospheric increase is 40 Tg
2. In budgets 1-4 chemical destruction is 500 Tg in budgets 5-7 chemical destruction is 450 Tg
3. The soil sink was varied from 0 to 60 Tg to optimise the fit between observed and modelled distribution.
4. The fossil source of 27%, 20% and 16% was tested in the different budgets
5. The global annual average $\delta^{13}C$ is –47.2 promille
6. The animal source was fixed at 80 Tg
7. The ability of the budget to match observed geographic and temporal features in the atmosphere
8. The ability of the budget to match the annual north south gradient of atmospheric methane concentrations from the NOAA ESRI network.
9. The ability to match the methane seasonal cycle at each of the observing stations.

On the basis of these constraints Fung concluded that budget 7 was the preferred budget. Budgets 1-6 were eliminated as likely budgets by comparing with the measured fluxes. She further concluded that the OH oxidation is the largest single term in the global methane budget. Narrowing the uncertainties in the magnitude and distribution of this term must be of prime importance.

Table 3.4 Budget of methane according to Hein and Heimann (1994).

Source	A priori		A posteriori		A posteriori	
		Uncertainty	Reference scenario	Uncertainty	Based on CH_4 data only	Uncertainty
Domestic animals	80	$\pm$18	68	$\pm$16	70	$\pm$16
Rice paddies	60	$\pm$40	65	$\pm$19	67	$\pm$19
Bogs	40	$\pm$20	27	$\pm$8	22	$\pm$9
Swamps	80	$\pm$40	65	$\pm$17	67	$\pm$18
Waste treatment	80	$\pm$20	64	$\pm$17	66	$\pm$16
Biomass burning	40	$\pm$30	52	$\pm$12	48	$\pm$13
Coal	50	$\pm$20	46	$\pm$17	43	$\pm$18
Gas	15	$\pm$10	12	$\pm$9	13	$\pm$9
Oil	15	$\pm$10	14	$\pm$10	14	$\pm$10
Gas Siberia	20	$\pm$20	43	$\pm$11	45	$\pm$11
OH oxidation	-376		-375		-375	
Stratospheric loss	-16		-16		-16	
Uptake by soils	-29		-29		-29	

Hein and Heimann (1994) have made an evaluation of the global budget of methane using an inverse modelling technique. Their conclusion is that a doubling of the estimated Siberian source is needed to explain the high methane mixing ratios measured there.

The and Beck (1995) compared existing budgets with the outcomes of the Moguntia 3-dimensional atmospheric chemistry model, originally developed at the Max Planck Institute for Chemistry in Mainz, Germany. Initial CH_4 emissions estimates were adjusted to fit the 1990 data, matching a globally averaged concentration of about 1712 ppbv at surface level and a 0.7% annual net increase of the global burden. The latter corresponds to an atmospheric increase of 12 ppbv per year at surface level. The adjustment was obtained by scaling all methane sources proportionally. The and Beck show in their report a comparison between the measured 1990 concentrations and the initial zonally averaged modelled concentrations. The 1990 concentration levels for methane could be reproduced by assuming a global emission of 540 Tg/yr. Using this initialisation The and Beck calculated a methane lifetime of 8.9 years and a tropospheric burden of 4515 Tg methane for 1990. The resulting budget is compared with other budgets in Table 3.6.

Houweling (2000) described an inverse modelling exercise to improve the budget of methane. The inversion was performed at a relatively high spatial and temporal resolution per grid and per month over the continents using an adjoint version of the global transport model by Kaminski et al. (1999). Estimates of the sources and sinks of methane were used as a first guess input, including minor sources. The inversion resulted in an improvement of the net global surface source of methane from 528 Tg to 505 Tg for the target period of 1993-1995. Houweling improved the chemical sink estimate for the troposphere from 485 to 451 Tg per year and for the stratosphere from 40 to 37 Tg. Houweling estimated a methane increase of 18 Tg per year in the atmosphere. Inverse modelling helps to reduce the uncertainty in the budgets. The uncertainty reductions are however strongly related to scale. Small reductions of less then 1 percent are computed on a grid scale. At the scale of hemispheres, uncertainty reductions can be as large as 75%. Houweling obtained an uncertainty reduction from $\pm$80 Tg a priori to $\pm$20 Tg a posteriori for the Northern Hemisphere. He concluded that at the grid scale the fluxes are not resolved by the measurements. This means that the density of measurement stations over the globe is still too small for the type of atmospheric models that are in use.

Recently the methane concentrations measured from space in 2003 were used to improve the global estimates. Bergamaschi et al. (2007) used a global CH_4 dataset from SCIAMACHY from the European Environment satellite (Envisat) for a detailed comparison with inverse TM5 model simulations that were optimized versus high accuracy CH_4 surface measurements from the NOAA ESRL (formerly CMDL) global cooperative air sampling network at background stations. The resulting estimates of emissions per region are given in Table 3.5

Table 3.5: Methane emissions a priori and a posteriori and their uncertainties in Tg per year Source: Bergamaschi et al. (2007)

Source	Region	A priori	Uncertainty	Posteriori	Uncertainty	Region
Coal	NHemisphere 1	3.7	+1.5	5.1	+1.4	America Canada
	NHemisphere 2	5.1	+2.1	6.3	+1.9	Europe Africa
	NHemisphere 3	11.1	+4.6	19.4	+3.3	Asia
	SHemisphere	6.8	+2.8	4.7	+1.8	South of Equator
	Global	**26.6**	**+6.0**	**35.5**	**+4.4**	
Oil and Gas	NH1	3.4	+1.4	5.3	+1.2	America Canada
	NH2	27.8	+11.5	16.1	+5.2	Europe Africa
	NH3	16.1	+6.7	16.4	+3.6	Asia
	SH	3.3	+1.4	4.3	+1.3	South of Equator
	Global	**50.6**	**+13.5**	**42.0**	**+5.5**	
Ruminants	NH1	15.3	+3.8	19.8	+3.2	America Canada
	NH2	25.9	+6.4	28.1	+5.2	Europe Africa
	NH3	37.5	+9.3	10.2	+6.3	Asia
	SH	20.8	+5.2	27.0	+3.5	South of Equator
	Global	**99.6**	**+13.0**	**85.2**	**+9.6**	
Rice	NH1	1.1	+0.2	1.1	+0.2	America Canada
	NH2	1.9	+0.4	1.9	+0.4	Europe Africa
	NH3	49.6	+8.8	37.7	+4.9	Asia
	SH	7.3	+1.3	8.0	+1.2	South of Equator
	Global	**59.7**	**+8.9**	**48.7**	**+5.1**	
Biomass	EX NHem	1.1	+0.4	1.3	+0.4	America Canada
Burning	Trop Reg 1	8.7	+2.6	9.9	+1.8	Mid and South Amer
	TR2	9.7	+2.5	7.7	+1.8	Africa
	TR3	3.8	+1.1	3.2	+1.0	SE Asia and Austr
	EX SHem	0.2	+0.1	0.2	+0.1	South of 32 ^{o}
	Global	**23.6**	**+3.8**	**22.2**	**+2.6**	
Waste	NH1	10.8	+4.5	12.3	+3.4	America Canada
	NH2	17.3	+7.2	18.7	+5.6	Europe Africa
	NH3	33.7	+14.0	27.8	+8.3	Asia
	SH	7.9	+3.3	13.5	+3.1	South of Equator
	Global	**69.7**	**+16.7**	**72.3**	**+10.7**	
Wetlands	EXNH1	32.5	+9.1	23.3	+2.1	America Canada
	EXNH2	8.9	+2.3	3.4	+1.2	Europe
	EXNH3	18.5	+5.7	19.0	+2.1	Russia North Asia
	TR1	49.9	+12.5	69.4	+3.5	Mid and South Amer
	TR2	24.4	+5.8	48.4	+3.0	Africa
	TR3	38.6	+9.2	50.6	+4.2	SE Asia and Austr
	EXSH	1.8	+0.5	1.8	+0.4	South of 32 ^{o}
	Global	**174.6**	**+19.6**	**215.8**	**+7.6**	
Wild animals	Global	5.0	+2.1	7.0	+2.0	
Termites	Global	19.2	+8.0	46.0	+6.7	
Soil	Global	-37.8	+6.4	-18.8	+5.8	
Ocean	Global	17.0	+7.0	-1.3	+2.9	
Total	**Global**	**507.7**	**+36.0**	**554.4**	**+3.7**	

Table 3.6: Global CH_4 budgets of various authors (in Tg CH_4/yr).

Reference:	Fung et al (1991)	Lelieveld and Crutzen (1993)	Hein and Heimann (1994)	The and Beck (1995)	IPCC (1996) SAR	Hein, et al. (1997)	Lelieveld et al. (1998)	Houweling (1999)	Olivier et al. (1996)	Bergamaschi (2007)	IPCC (2007) AR4	Van Amstel This thesis
Base year:	1980s	1980s	1980s	1990	1980s	1990	1992	1993	1990	2003	2000	2010
Lifetime methane	10.1			8.2/10	8.6±1.6	8.3	7.9					
Type of estimates	Top down	Top down	Top down	Top down	Top down	Top down	Top down	Top down	Bottom-up	Top down	Top-down	Bottom up
Natural sources												
Wetlands	115	125	90	150	115 (55-150)	237±20	115-175	145	125		174	105
Bogs/tundra	35	-	22±9	-	-	44 ± 7	-	54±15	-		-	-
Tropical swamps	80	-	67±18	-	-	192 ± 19	-	91±26	-		-	-
Total wetlands	**115**	**125**	**90**	**150**	**115**	**237 ± 20**	**115-175**	**145**	**125**	**215.8±7.6**	**174**	**105**
Termites	20	30	-	-	20 (10-50)	Small	0-40	20±20	-	46+6.7	22	5
Hydrates	5	10	-	-	5 (0-5)	Small	5-15	-	-	-	5	10
Oceans	10	10	-	10	10 (5-50)	Small	0-30	15±10	-	-	10	10
Fresh water	-	-	-	-	5	-	-	-	-	-	15	5
Other	-	-	-	-	5	-	-	20±16	-	**7±2**	9	5
Total other natural	**35**	**50**	**-**	**10**	**45**	**-**	**-**	**55**	**-**	**53±6.7**	**64**	**35**
Total natural	**150**	**175**	**90**	**160**	**110-210**	**237±20**	**120-260**	**200**	**125**	**268.8**	**238**	**140**
Anthropogenic sources												
Ruminants	80	80	70±16	85	85 (65-100)	90 ± 20	115	93±35	80	85.2±9.6	84	74
Animal waste	-	-	-	-	-	-	25	-	13	-	-	15
Rice	100	70	67±19	75	60 (20-100)	88 ± 20	In wetl.	80±50	60	48.7±5.1	54	29
Total agriculture	**180**	**150**	**137**	**160**	**145**	**178±20**	**140**	**173**	**153**	**134**	**138**	**118**
Sewage water	-	-	-	-	-	-	-	-	-		-	30
Landfills	40	40	66±16	75	40 (20-70)	35 ± 15	40	48±20	36		54	46
Total waste	**40**	**40**	**66**	**75**	**40**	**35±15**	**40**	**48**	**36**	**72.3±10.7**	**54**	**76**
Oil vents	10	15	14±10	65	15 (5-30)	-	-		15	-	-	15
Gas leaks	30	30	13±9		40 (25-50)	46 ± 23	-	51±30	40	42.0±5.5	61	45

Reference:	Fung et al (1991)	Lelieveld and Crutzen (1993)	Hein and Heimann (1994)	The and Beck (1995)	IPCC (1996) SAR	Hein, et al. (1997)	Lelieveld et al. (1998)	Houweling (1999)	Olivier et al. (1996)	Bergamaschi (2007)	IPCC (2007) AR4	Van Amstel (2010) This thesis
Base year:	1980s	1980s	1980s	1990	1980s	1990	1992	1993	1990	2003	2000	2000
Siberian gas	-	-	45±11	-	-	17 ± 14	-	-	-	16.4±3.6	-	-
Coal mining	35	35	43±18	15	30 (15-45)	35 ± 10	-	38±15	38	35.5±4.4	36	40
Total energy	**75**	**80**	**115**	**80**	**70**	**97 ± 15**	**110**	**89**	**93**	**75.5±9.9**	**97**	**100**
Biomass burning	55	30	48±13	60	40 (20-80)	40 ± 12	40	40±30	32	22.2±2.6	47	35
Anthropogenic	**350**	**300**	**366**	**375**	**375 (300-450)**	**350**	**400**	**480**	**315**	**312**	**336**	**400**
Total Source	**500**	**475**	**456**	**550**	**535 (410-660)**	**587**	**600**	**528**	**440**	**527.8**	**574**	**470**
OH sink	450	455	375	460-485	490 (405-575)	489	510			500	467	450
Soil sink	10	30	29	30	30 (15-45)	-	30	30±15		18.8±5.8	30	10
Stratospheric sink	-	-	16		40 (32-48)	46	40			40	39	40
Total Sinks	**460**	**485**	**420**	**500**	**560 (460-660)**	**535**	**580**			**560**	**536**	**500**
Atm. Increase	**40**		**36**	**50**	**37 (35-40)**	**52**	**20**			**-5**	**38**	**-30**
Implied total	**500**		**456**	**550**	**597 (495-700)**	**587**	**600**			**554.4±3.7**	**574**	**470**

3.4 Conclusions

The estimates for the different anthropogenic sources tend to be lower than the top-down estimates from inverse modelling. Bottom-up estimates are based on emission factors and activity levels. More information has become available since the SCIAMACHY instrument on board the Envisat has become operational. Since 2003 vertical column measurements of methane concentrations in the atmosphere are available. Based on this information a new global budget based on inverse modelling has become available with new uncertainty ranges (Bergamaschi 2007). The estimates from anthropogenic methane emissions come closer together. On the other hand the estimate from natural sources has increased recently. The most pronounced difference with earlier budgets and with the consensus budget from the fourth assessment of IPCC is the increased methane emission estimate from wetlands. The methane emissions estimate from wetlands in Denman (2007) is 174 (range 100-231) Tg and the methane emissions estimate from wetlands in Bergamaschi (2007) is to 216 (range 208-224) Tg. More satellite data and a more dense network of continuous methane concentration measurements are needed to narrow these ranges of uncertainty even further.

Wetlands
A comparison of budgets shows that since the estimate for wetlands by Fung in 1991 of 115 Tg per year a lot has changed. The inversion technique together with satellite measurements has improved our understanding of the remote tropical wetland regions. The estimate for wetlands by Hein (1997) is 237 Tg (range 217-257). The estimate of Bergamaschi (2007) for wetlands is 216 Tg (range 208-224).

Total other natural
Total other natural emissions are estimated at 35 Tg by Fung, lower than the estimate of 53 Tg (range 46-60) by Bergamaschi et al. (2007).

Agriculture
The estimate of methane emission from agriculture in this thesis is 118 Tg for 2000. This is much lower than earlier estimates of 180 Tg by Fung and others in 1991 and lower than the estimate of Bergamaschi (2007) of 153 Tg. This is related to a much lower estimate of methane from rice by Bergamaschi in 2007 of 50 Tg instead of 100 Tg by Fung. Ruminants with 85 Tg and animal waste with 25 Tg are slightly lower than earlier estimates.

Landfills and Waste
The estimate of methane from landfills and waste is 54 Tg according to Denman in 2007. This is higher than the original estimate by Fung of 40 Tg. Since the publication by Fung sewage treatment is added as a source in the Guidelines by IPCC (2007).

Coal, oil and gas
The total estimate is 80 Tg according to Bergamaschi in 2007. This estimate is only slightly higher than the 75 Tg from Fung.

"A priori" methane emission estimates have been analysed as a starting point for atmospheric modelling of the methane concentration fields around the earth. With the increasing amount of actual methane concentration measurements at stations at different continents and satellite information from SCIAMACHY with inverse modelling the "a priori" methane emission estimates have been improved by Bergamaschi (2007) at hemispheric and regional scales. The reduction of uncertainty at the grid scale is very low according to Houweling (2000), often only 1% or lower. Especially the tropical swamp emission estimate has increased from about 80 Tg to 192 Tg max. Using inverse modelling the estimate of methane emissions from tropical swamps was increased by Hein et al. (1997) to 192 Tg, by Houweling (1999) to 91 Tg and by Bergamaschi (2007) to 150 Tg. Methane emissions from oil and gas systems in Siberia are estimated by Hein in 1997 and Bergamaschi in 2007. These are only 16 $\pm$ 4 Tg, contrary to earlier estimates of 45 Tg or more.

In Table 3.6 the bottom up budget is given and compared with budgets from various authors to illustrate the problem that from measurements and model results still different budgets can be constructed. This is related to the uncertainties in all terms of the budgets. Hein (1997) claims that they have reduced the overall uncertainty in the budget with 10%. Houweling reduced the northern hemispheric uncertainty from $\pm$80 to $\pm$20 Tg. The estimate of methane emissions from wetlands has increased from 115 in Fungs budget to 216 Tg in the budget of Bergamaschi. Compared to the earlier budgets a higher total source but lower anthropogenic source is estimated. The anthropogenic source estimated by Fung is 350 Tg and Bergamaschi estimates 312 Tg mainly because of a lower estimate from biomass burning.

When the budget of Fung (1991) for the eighties is compared with Lelieveld (1998) for the nineties, anthropogenic emissions have increased. When we compare Lelieveld (1998) however with this study the estimate of anthropogenic emissions has decreased.

The top-down estimates of the overall total of sources and sinks tend to increase over time (e.g. Lelieveld et al., 1998; Bergamaschi et al., 2007). The results from bottom-up estimates based on recent experimental field research however, tend to decrease and are lower than the top-down inverse model results.

Concluding remark

The sources of methane have been described and quantified. It is shown that "a priori" estimates can be improved by inverse modelling. Still, uncertainties are not completely resolved. From a particular methane concentration field and information on the isotopic content of the methane still different budgets can be constructed. To further improve the methane emission estimates careful bottom-up research and upscaling to country or regional totals is necessary. The reporting obligations under the Climate Convention and the Kyoto Protocol have been very beneficial in this respect. Satellite data on methane concentration fields and profiles in the troposphere have helped to further resolve the uncertainties in the budgets, see e.g. Bergamaschi (2007).

4. NATIONAL METHANE EMISSION INVENTORIES

Updated from Van Amstel, A.R., J.G.J. Olivier, L.H.J.M. Janssen, 1999: Analysis of differences between national inventories and an Emissions Database for Global Atmospheric Research (EDGAR). Environmental Science & Policy 2: 275-293.

4.1 Introduction

In this chapter a comparison is made of methane estimates from official national inventories based on IPCC guidelines with estimates from EDGAR. A comparison with EDGAR was needed to find gaps in the data and differences with official national emission inventories. The results of the comparison were needed to improve the IPCC Guidelines and to learn about uncertainty (IPCC, 2006). Based on this information many countries improved their emission factors and formal uncertainty analysis. We present 20 years old emissions because at the time it was the first comparison of its kind. Later, the method has been used by others to make comparisons of more recent national inventory information of industrialized countries with EDGAR (Olivier et al. 2005; Winiwarter et al, 2010). This iterative process is further developed as an official review tool for the national emission inventories.

Industrialised countries (listed in Annex 1 to the UN Framework Convention on Climate Change, UNFCCC) are obliged to annually report their national emissions and sinks of greenhouse gases to the UNFCCC Secretariat and to report progress in curbing greenhouse gases in National Communications. As such a body of experience has developed over the last decades on building emission inventories that are transparent, complete, comparable, credible and accurate. Developing countries have no reduction targets yet but also report emissions and sinks to the Secretariat. They all should use the IPCC default methodology (IPCC, 2006). In some cases developing countries like India started experimental research and measurements to develop their own country specific methodology and emission factors (e.g. Mitra et al., 2004, IPCC, 2006). It is vital to follow these developments closely. For example, criteria for good practice should be implemented so that the measurement or estimation results can be selected for inclusion in an IPCC emissions factor database. Developing the IPCC Guidelines has brought together experts from different countries to develop Good Practice Guidance (IPCC, 2000; IPCC, 2003; IPCC, 2006). In different panel meetings (energy/industry, agriculture/waste and forestry) all greenhouse gas sources and sinks have been covered for the exchange of experience in developing emission inventories. This comparison study was used as one of the inputs in the discussions for the IPCC good practice guidelines and the IPCC updated Guidelines for National Greenhouse Gas Inventories in 2006.

Transparent, complete, comparable, credible and accurate national emission inventories are needed in the international negotiating process for emission reductions under the UNFCCC (UN, 1992) and its Kyoto Protocol . Emissions of individual countries are estimated using the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC/OECD/IEA, 1997), the Good Practice Guidance (IPCC, 2000; IPCC, 2002) and the updated 2006 Guidelines (IPCC, 2006). A review process has been developed by the Climate Secretariat. During a review gaps, inconsistencies and uncertainties in inventories could be traced through comparison with other countries and with independent authoritative sources. The Emissions Database for Global

Atmospheric Research (EDGAR) (Olivier et al., 1999; Olivier, 2002; Van Aardenne et al., 2005; Olivier et al., 2005) is selected as such an independent authoritative source.

EDGAR, developed at the National Institute for Health and the Environment in the Netherlands, and since 2005 hosted at the Joint Research Centre in Ispra, Italy, is the most complete global database on emissions of pollutants and greenhouse gas emissions with geographic detail in each source sector. EDGAR can make graphics per sector and substance. EDGAR can provide grid output and zonal averages for use in global models. EDGAR is compared with the national inventories to analyse the uncertainties and is a good proxy for the official inventories. The differences with the country data are small. An additional advantage of EDGAR is that it closes some apparent gaps, as it has data on countries that have no official obligation yet to report emissions to the Climate Convention. This is one of the reasons to use EDGAR as input for the IMAGE model (Bouwman et al, 2007), one of the models that is used in developing the IPCC scenarios and that also will be applied later in this thesis.

In this chapter research question 3 will be answered: **How do estimates from a comprehensive global emissions database for atmospheric research (i.e. EDGAR) compare to aggregated national emission estimates?**

In section 4.2 the methodologies are described of national inventories and EDGAR. In 4.3 a comparison of total emissions of countries will be made. In section 4.4 the national emission estimates per country will be compared with EDGAR. In section 4.5 conclusions are drawn.

National estimates based on IPCC methodology were taken from a database of first and second National Communications at the Climate Secretariat in Bonn and from the US country studies programme for capacity building in developing countries (Braatz et al., 1996). EDGAR results were taken from a scientific database of emission estimates made at the National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands (Olivier et al., 1996 and 1999; Olivier, 2002; Van Aardenne et al. 2005).

4.2 Methodology of national greenhouse gas inventories

4.2.1 Introduction

The mapping of one database onto the other gives information on gaps in reporting, large differences and omissions. For this kind of detailed evaluation to be successful, the documentation of the inventories must be complete and transparent (Van Amstel, 1993; Van Amstel, 1999). The data must be detailed enough to reconstruct the inventory. Original calculation sheets and background reports to the National Inventory must be available and data must be referenced. A first evaluation or in-depth review on draft inventories was carried out by IPCC/OECD/IEA in 1993 to evaluate the IPCC methodology. Since then the Climate Secretariat and review teams have regularly carried out other in-depth comparisons. National reports have improved throughout the years because of these reviews.

4.2.2 Uncertainties

In national inventories three sources of uncertainty can be defined: 1. Uncertainties in the national and international statistics; 2. Uncertainties in the emission factors calculated from experimental research; 3. Uncertainty in the accuracy of the extrapolation methods for the upscaling of measurement results from the field level to the national level (Olivier, 2002; Van Aardenne, 2002). The precision of both IPCC and EDGAR estimation methods for methane is dependent on the underlying field research and the methods for upscaling to derive emission factors per unit of product or area. This will not be analysed here. Details can be found in Hensen (2011), the IPCC Guidelines and in the Good Practice Guidance (IPCC, 1997; IPCC, 2000; IPCC, 2007), in Bouwman (1998) and in the EDGAR documentation (Olivier, 2002; Van Aardenne 2002, Van Aardenne et al., 2005). Here comparisons will be made of methane emissions per source.

4.2.3 Methodology for estimating CH_4 emissions according to IPCC and EDGAR

Based on 'a priori' global estimates (at a reconnaissance level) a more detailed methodology for national emission inventories was developed by the IPCC during the years in the preparation of the Climate Convention. This methodology is based on a combination of measurement results and extrapolation to the level of a whole country, continent or even the globe. The emissions per unit product or per unit of area per year are estimated on the basis of experimental research. The result is called the emission factor. This emission factor is multiplied by the total production or the total area over a particular year to estimate the total national emissions.

For example, the methane emissions from natural gas production in any particular year can be calculated from the amount of methane that leaks from all steps in the production, transmission and distribution of natural gas. The amount of methane from leaks per kilometre of pipeline can be measured. By multiplying this amount of methane with the total length of pipelines in the country provides an estimate of the total leakage in that country. Another example is the emission of methane from ruminants. This can be estimated from measured amounts per head of cattle per year. The number of cattle in a country in a particular year multiplied by the emission per head gives the total emission. Of course the methodology can be very detailed but this requires the availability of extra information. In agriculture it is possible to distinguish for example between different age classes and types of animals and different feeding types (rations) to estimate the emission per unit of life weight. But as the methodology is intended for all parties (i.e. nations) to the UNFCCC, also the least developed countries, the methodology must also be applicable in situations with poor statistics.

The inventories suffer from a fair amount of uncertainty. First of all the measurement results have uncertainties due to the measurement instruments or due to the restricted length of the period of measuring. Extrapolation is difficult. A workshop on scaling of measurements of trace gas fluxes gives more information (Bouwman, 1999). Results from one particular spot or animal may not be representative for the country as a whole. The problem of variation over time of methane emissions has to be tackled. In soils there is a diurnal and seasonal variation. In oil and gas there is the variation in production. Production is highest in times of high demand, for example in wintertime for heating. In methane emissions serious investigations into the uncertainties have yet to be made. In many countries lack of measurement results make emission estimation very tricky. Default emission factors were developed by IPCC for use in these situations, but the error introduced by the application of an emission factor in tropical countries that was originally developed for OECD countries has not been estimated yet. More research will be needed to extend the existing information.

Even before the Earth Summit in Rio de Janeiro in 1992, experts were working together to develop a common methodology for national inventories of sources and sinks of greenhouse gases. A draft methodology was published by the OECD (1991) for extensive testing by national experts in industrialised and non-industrialised countries. The IPCC, UNEP, IEA and OECD co-operated in the organisation of regional workshops to exchange views on the methodology, and to test the methodology in different regions. Regional workshops were held in Latin America, Eastern Europe, Africa, and the Far East. In a regional workshop in Europe all the testing experience resulted in recommendations to improve national inventories for methane and nitrous oxide. This information was published in the Amersfoort Proceedings (Van Amstel editor. 1993), one of the important building blocks for the final consensus methodology (IPCC/OECD/IEA Guidelines in three Volumes, 1995). The methodology was approved and adopted as the common methodology in March 1995 during the Conference of the Parties to the Climate Convention. Revised Guidelines were published (IPCC/OECD/IEA, 1997), based on experience gathered during a second round of regional workshops organised by UNEP and UNDP through the United States Country Studies Programme (Marland et al. eds. 1995; Braatz et al. eds. 1996). The Revised 1996 Guidelines were adopted as common methodology during the Kyoto Conference in 1997. Industrialised countries in their Second National Communications used these revised Guidelines. Since then many countries have used the IPCC Guidelines. Based on their experience a three Tier methodology was recommended with the simple Tier 1 methodology to be used by countries with less developed statistical information, Tier 2 methodology for countries with more advanced statistical information and Tier 3 methodology for countries who wanted to develop advanced country specific methods and models. Based on this recommendation the most recent update of the IPCC Guidelines was developed (IPCC, 2006).

Countries are free to use their own emission factors if they think these are better than the default IPCC emission factors published in the Guidelines provided they publish their research in peer reviewed journals. The methodology is based on a tiered approach with simpler Tier 1 methodology that can be used in situations with scarce statistical information in developing countries and Tier 2 methods for countries with more advanced statistics. Results are available for most OECD countries and Eastern Europe for 1990 to 1998. This information can be compared with EDGAR to analyse differences and uncertainties.

4.3 Comparison of global methane emissions

Total anthropogenic methane emissions are 320 Tg according to EDGAR (see Table 4.1). The total anthropogenic methane emissions according to the National Inventories and US country studies are 170 Tg. Clearly, not all countries have reported yet, which explaines the big gap. The global total according to the IPCC assessments (2001 and 2005) is 375 Tg. In Table 4.2 the difference between EDGAR and National Inventories is given for twelve world regions. The total difference can be explained mainly because developing countries have not yet reported to the Climate Secretariat because they have no reporting obligation. The figures for the fifteen countries of the European Union (EU15) for EDGAR and national inventories are comparable. Reporting in the EU15 is clearly complete.

Table 4.1 Methane emissions according to EDGAR. (Source: Olivier et al., 1999).

	Tg methane per year
Industry	0.4
Power	0.1
Other transformation	0.4
Residential	3.1
Road transport	0.7
Non-road land transport	0.0
Air transport	0.1
International shipping	0.0
Fossil fuel combustion total	**4.8**
Coal production	37.8
Oil production	7.6
Oil handling	0.2
Gas production	17.6
Gas distribution	26.1
Fossil fuel production total	**89.3**
Industry	0.1
Residential	13.9
Biofuel	**14.1**
Iron and steel	0.8
Chemicals	0.0
Industrial processes total	**0.8**
Rice	59.8
Enteric fermentation	78.6
Animal manure	14.0
Biomass burning	11.5
Landfills	35.7
Agricultural waste burning	11.9
Agriculture/waste total	**211.4**
Total world	**320.2**

4.4 Comparison of national methane emissions

For methane, differences of more than 10% between EDGAR and National data will be looked into in more detail. The differences between EDGAR and National Communications in total national methane emissions were more than 10% in many countries (see Table 4.2).

Table 4.2: Total methane emissions in 1990 in OECD and Eastern European countries. Comparison of EDGAR data and the official National Communications. (Source: Van Amstel et al., 1997 and 1999). (Unit: Million kg CH_4 per year)

Country[1]	Total Official	Total EDGAR	Absolute difference	Relative difference
Australia	6243	4476	-1770	-28%
Austria	603	452	-153	-25%
Belgium	NA	599		
Bulgaria	1370	515	-856	-63%
Canada	3088	3851	+763	+25%
Czech Republic	942	1654		
Slovak Republic	347	NA		
Czechoslovakia	1289	1654	+365	+28%
Denmark	407	423	+16	+4%
Estonia	323	NA		
Finland	252	264	+12	+5%
France	2896	3757	+861	+30%
Federal Republic Germany	NA	4809		
Former DDR	NA	1327		
Germany	5682	6136	+454	+8%
Greece	343	426	+83	+24%
Hungary	545	708	+163	+30%
Iceland	23	19	-4	-19%
Ireland	796	657	-139	-17%
Italy	3901	2388	-1513	-39%
Japan	1382	3336	+1954	+141%
Latvia	159	NA		
Liechtenstein	1	1	0	0%
Luxembourg	24	NA		
Monaco	NA	0,5		
Netherlands	1060	1002	-58	-5%
New Zealand	1986	1032	-954	-48%
Norway	290	265	-25	-8%
Poland	6100	4619	-1481	-24%
Portugal	226	421	+195	+86%
Romania	1954	2202	+248	+13%
Russian Federation	27000	47092 [2)]	+20092	+74%
Spain	2151	2027	-124	-6%
Sweden	329	364	+35	+11%
Switzerland	332	313	-19	-6%
United Kingdom	4531	3868	-663	-15%
United States of America	27000	41512	+14512	+54%

1) Because of large uncertainty in activity level of biofuel use, this source is excluded here.
2) Total for former USSR.
NA = not available

National methods used by industrialised countries are generally IPCC TIER 2 or even more detailed. This is one of the reasons for differences between EDGAR and country estimates. Another reason is the use of different emission factors. Differences in methane inventories will be explained later for each methane source.

Table 4.3 gives the methane emissions per region and per source according to the official National Communications and the US country studies programme. In Table 4.4 the same is given according to EDGAR. In Table 4.5 a comparison is made between these two, i.e. the official data and EDGAR.

The database of developing country inventories is not complete. In Table 4.3 this can be seen from the ratio of total of countries and total of world (ratio <1). Part of the developing countries have not reported because they have no reporting obligation under the Climate Convention. The total of countries is smaller than the total of the world according to IPCC. The ratio shows that reporting by countries could be improved considerably with the exception of the methane from fugitive oil and gas, which is more than covered by the country estimates (ratio >1).

Table 4.4 shows in the totals that the EDGAR estimates are close to the IPCC estimates with the exception of methane from biofuels and methane from manure. EDGAR estimates from biofuels and manure are incomplete. EDGAR estimates are larger than the IPCC estimates in the case of fugitive methane from coal because of higher estimates from hard coal. EDGAR is higher in methane from waste because of new higher estimates for waste generation per capita.

Table 4.5 gives the comparison of methane emission estimates per source per region. It shows a general agreement for the estimates per source for the EU, China and OECD-North America. For the other regions the differences in the sources are larger although the totals match more closely. In the next figures the differences will be illustrated per region. Differences in methane emissions per source per country over 10% between EDGAR and country estimate will be looked into. In the next sections some of the reasons for these differences will be discussed.

Table 4.3 Methane emissions per source (Gg CH_4/yr) according to First National Communications and US Country Studies Program.

Methane emissions according to National Communications and US country studies

	Fossil Fuels	Biomass Burning	Fugitive Coal	Fugitive Oil & Gas	Industry	Solvents	Enteric	Manure	Rice	Soils	Agr.Waste. Burning	Savanna Burning	Land.Use Change	Waste	Total (incl. Biomass for energy excl. Int. Bunkers)	
IPCC code	1A1-5	1A6	1B1	1B2	2	3	4A	4B	4C	4D	4E	4F	5	6		
EU15	734	86	2854	1499	23	0	6732	2626	102	299	0	146	14	8052	23169	EU15
OECD Europe	22	3	5	23	1	0	224	93	0	25	0	0	0	247	643	Other OECD-Eur.
E-Eur+Russia	102	23	6495	21686	6	0	6278	350	186	0	0	3	8	4572	39709	E-Eur+Russia
OECD-N.Am.	655	772	4491	4472	0	0	6460	2520	429	0	0	79	38	10945	30861	OECD-NA
OECD-Pacific	59	2	854	296	25	0	4768	271	271	0	370	22	379	2294	9611	OECD-Pacific
Latin-Am.	260	75	73	2820	0	0	3523	109	267	0	238	16	921	908	9210	Latin-Am.
Africa	594	1374	1440	217	0	0	3275	301	854	0	1822	349	221	2562	13009	Africa
India Plus	0	0	0	6	0	0	453	0	439	0	0	0	0	76	974	India Plus
China Plus	73	2686	10656	387	0	0	5850	2850	11800	0	0	0	0	14	34316	China Plus
E-Asia	12	240	7	1	0	0	732	109	6657	0	0	48	223	0	8029	E-Asia
Total of countries	2511	5261	26875	31407	56	0	38295	9228	21005	323	2430	663	1805	29670	169530	Total of countries
Total of world		40000	55000	30000			80000	25000	60000					55000	375000	Total of world
Ratio		0,13	0,49	1.13			0,48	0,37	0,35					0,54	0,45	Ratio

Note: Part of the developing countries have not reported, therefore the ratio: world total/total of countries, is small in most source sectors.

Table 4.4 Methane emissions per source (Gg CH_4 /year full molecular) according to EDGAR. (all countries in the World)

METHANE EMISSIONS 1990 EDGAR																
			Fugitives				Agriculture									
	Fossil fuels	Biofuels	Coal	Oil gas	Industry	Solvents	Enteric	Manure	Rice	Soils	Agr. waste	Savanna burning	Land use	Waste	Total (incl. biofuels, excl. Int.Bunkers)	
IPCC source code	1A1-5	1A6	1B1	1B2	2	3	4A	4B	4C	4D	4E	4F	5	6		
EU15	620	55	3586	1138	151	0	6996	3069	169	0	0	969	0	6101	22854	EU15
Other OECD Europe	60	129	100	95	32	0	939	174	21	0	0	383	0	724	2655	Rest OECD Europe
East Eur + former USSR	1283	36	8924	27402	218	0	11420	2540	311	0	0	1376	0	4573	58083	Eastern Eur. +fUSSR
OECD North America	555	395	12217	10804	65	0	6353	2289	520	0	0	1230	0	11053	45482	OECD North America
Pacific	137	25	1123	765	130	0	3159	773	997	0	0	172	0	1754	9034	Pacific
Latin America	126	1077	417	2279	38	0	17537	858	2398	0	1384	1022	2617	2683	32436	Latin America
Africa	81	3769	1324	1590	7	0	9014	393	1409	0	4293	1090	1728	1724	26422	Africa
Middle East	63	177	39	4309	0	0	1203	147	391	0	0	521	1	1388	8238	Middle East
India Plus	68	4021	865	479	17	0	13547	1100	24627	0	23	2821	403	1966	49938	India Plus
China Plus	1552	2776	9176	644	106	0	7125	2099	18922	0	48	1461	252	2571	46732	China Plus
East Asia	188	1600	194	2091	28	0	1288	564	10037	0	55	780	570	1144	18540	East Asia
Total Rest of World	6	10	0	7	0	0	6	1	3	0	0	0	0	13	46	Rest of World
Total World EDGAR	4739	14070	37965	51604	791	0	78586	14006	59805	0	5803	11826	5571	35694	320462	World EDGAR
Total World IPCC		40000	30000	50000			80000	25000	60000					30000	375000	World IPCC
Share EDGAR		0,35	1,26	1,03			0,98	0,56	1,00					1,19	0,85	Share EDGAR

Note: Because in principle all countries are reported in EDGAR the share gives us information on the accuracy of the Total World estimates from IPCC compared to EDGAR.

Table 4.5 Methane emissions (Gg CH_4/yr for 1990) per region compared: First row: NatComm = National Communications. Second row: Emissions Database for Global Atmospheric Research (EDGAR).

		Fossil Fuels	Biomass Burning	Fugitive Coal	Fugitive Oil & Gas	Industry	Solvents	Enteric	Manure	Rice	Soils	Agr.Waste .Burning	Savannah Burning	Land.Use Change	Waste	Total (incl. Biomass for energy, excl. Int.Bunk)	
IPCC source code		1A1-5	1A6	1B1	1B2	2	3	4A	4B	4C	4D	4E	4F	5	6		
NatComm	1 EU15	734	86	2854	1499	23	0	6732	2626	102	299	0	146	14	8052	23169	EU15
EDGAR	1 EU15	620	55	3586	1139	151	0	6996	3070	169	0	0	967	0	6101	22854	EU15
NatComm	2 OECD-Eur.	22	3	5	23	1	0	224	93	0	25	0	0	0	247	643	OECD-Eur.
EDGAR	2 OECD-Eur	60	129	100	95	32	0	936	172	21	0	0	383	0	714	2641	OECD-Eur.
NatComm	4 E-Eur+fUSSR	102	23	6495	21686	6	0	6278	350	186	0	0	3	8	4572	39709	E-Eur+fUSSR
EDGAR	4 E-Eur+fUSSR	1281	35	8924	27394	218	0	11357	2527	310	0	0	1373	0	4534	57952	E-Eur+fUSSR
NatComm	5 OECD-NA	655	772	4491	4472	0	0	6460	2520	429	0	0	79	38	10945	30861	OECD-NA
EDGAR	5 OECD-NA	555	395	12217	10804	65	0	6353	2289	520	0	0	1230	0	11053	45482	OECD-NA
NatComm	6 OECD-Pacific	59	2	854	296	25	0	4768	271	271	0	370	22	379	2294	9611	OECD-Pacific
EDGAR	6 OECD-Pacific	136	15	1123	765	130	0	3132	759	991	0	0	172	0	1653	8875	OECD-Pacific
NatComm	7 Latin-Am.	260	75	73	2820	0	0	3523	109	267	0	238	16	921	908	9210	Latin-Am.
EDGAR	7 Latin-Am.	59	354	151	1518	4	0	3239	215	225	0	135	236	794	840	7770	Latin-Am.
NatComm	8 Africa	594	1374	1440	217	0	0	3275	301	854	0	1822	349	221	2562	13009	Africa
EDGAR	8 Africa	64	2062	1316	853	7	0	4239	178	567	0	1267	645	671	924	12794	Africa
NatComm	10 India Plus	0	0	0	6	0	0	453	0	439	0	0	0	0	76	974	India Plus
EDGAR	10 India Plus	1	312	0	50	0	0	806	76	4131	0		121	6	194	5696	India Plus
NatComm	11 China Plus	73	2686	10656	387	0	0	5850	2850	11800	0	0	0	0	14	34316	China Plus
EDGAR	11 China Plus	1531	2398	9057	635	100	0	6529	1986	14869	0	11	1291	67	2351	40824	China Plus
NatComm	12 E-Asia	12	240	7	1	0	0	732	109	6657	0	0	48	223	0	8029	E-Asia
EDGAR	12 E-Asia	16	321	11	71	2	0	609	195	5134	0	12	397	172	364	7306	E-Asia

Note: First row is aggregate of national communications of that region, the second row is aggregate of EDGAR database for that region etc. Only the countries with information from National Communications or US Country Studies Program (Braatz et al., 1996) are aggregated in the regional totals and compared with the same countries in EDGAR. So these regional totals are not the final estimates because more countries in the future will report their emissions estimates.

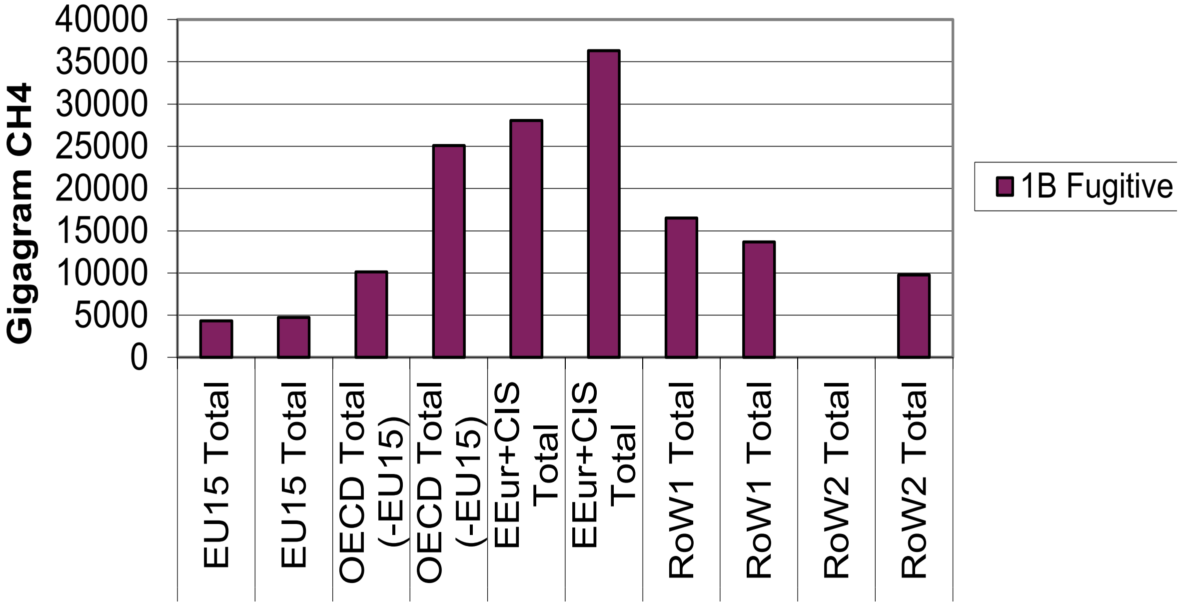

Figure 4.1: Methane emissions from coal, oil and gas. Comparison of National Communications (NC) with EDGAR data for regions in the World.

Columns: European Union 15 from official national communications (NC), European Union 15 from EDGAR, OECD countries minus EU15 from NC and from EDGAR, Eastern Europe and former Soviet Union from NC and from EDGAR, Rest of the World (RoW) 1 for which US country studies were available. (First bar of RoW1 is country studies aggregate and second bar is EDGAR aggregate) and Rest of the World 2 where only EDGAR data were available. 1B Fugitive = IPCC category for methane from coal, oil and gas.

In Figure 4.1 methane emissions from coal, oil and gas (fugitives) are compared. This figure shows that the regional official total for the EU-15 is about the same as the EDGAR data. The difference in the rest of OECD is large. The difference in Eastern Europe is large as well. For the rest of the World, differences are not large. National inventories from many developing countries are still missing (i.e. rest of the World 2).

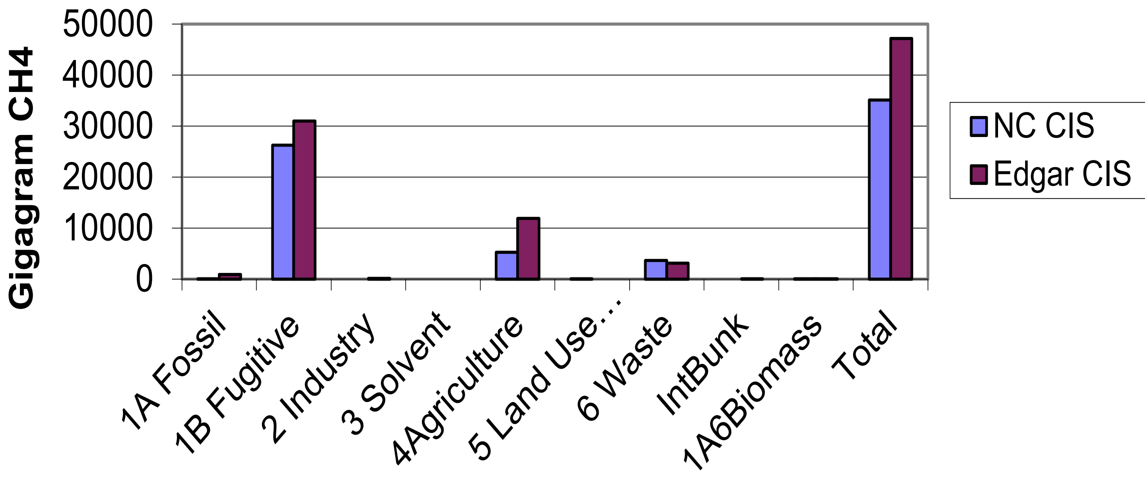

Figure 4.2: Methane from Russia. Comparison of National Inventory data with EDGAR data for the Commonwealth of Independent States (CIS).

For the former Soviet States in general EDGAR estimated the methane emissions from fugitive and agriculture higher than the aggregated national inventory data (see figure 4.2). Explanation of the differences per source (IPCC sector codes are used) is given below.

Methane from fossil fuel combustion (IPCC sector 1A1-5)
No differences are found over 10% between EDGAR and national data, with the exception of Algeria and Botswana. In Algeria methane from fossil fuel burning seems to be reported incorrectly. It is the same amount as fugitive emissions in EDGAR so maybe it should have been reported under fugitive emissions. Methane from biomass burning (IPCC code 1A6) shows some large differences in Bangladesh, Botswana and Nigeria, but in absolute terms the quantities are small.

Fugitive Methane emissions (IPCC sector 1B)
Differences between EDGAR and national estimates are over 10% in the following regions: Eastern Europe + former Soviet Union and in the OECD (excluding EU15) (See figure 4.1). The following countries show differences of more than 20%: Hungary, Spain, Japan, Norway, United States, Algeria, and Venezuela. The most important differences are in the Russian Federation where the EDGAR estimate is 13% higher, in the USA where the EDGAR estimate is 50% higher, and in Germany where the EDGAR estimate in 13% higher. (See Figures 4.5 and 4.6).

Reasons for the differences are:
1. EDGAR overestimates leaks from the distribution network by using gross gas consumption. In reality part of this gas is distributed directly to the industry and to power plants by high-pressure transport mains that are less leaky than the low-pressure distribution network.
2. EDGAR uses its own detailed methodology for methane from coal mines, based on basin specific methane emission factors.

Methane from agriculture (IPCC sector 4)
Methane from agriculture is emitted by different sub sectors. Methane from animals and from manure are the larger contributors. Methane from agricultural waste burning is more important in the tropics. A difference between national inventories and EDGAR data of more than 20% was found in the following countries in Europe: Finland, France, Greece, Portugal (see Figures 4.3 and 4.4). In the rest of the OECD differences more than 20% were found in: Japan, New Zealand; and in the rest of the world: Bangladesh, Botswana, Cameroon, Ethiopia, Gambia, Ghana, Mongolia, Peru, Philippines, Senegal, Thailand, Uganda, Zimbabwe (See Figure 4.7). EDGAR estimates are higher than national estimates with the exception of Ireland, Italy, Australia, New Zealand, Switzerland, Peru, Thailand and Uganda. The differences are primarily a consequence of the more detailed calculations used in national estimates. The animal statistics used by countries may differ somewhat from the FAO statistics used in EDGAR. Another possible explanation is that in EDGAR estimates were used for the amount of agricultural residues burned from Hall et al. (1994). These are different from country statistics.

Methane from land use change and forestry (IPCC sector 5)
Methane from land use and forestry is a minor source with only 5.6 Tg according to EDGAR.

Methane from waste (IPCC sector 6)
Differences are high and primarily the result of more detailed estimates used in national inventories. When looking at totals per region, differences are below 10%, so it seems that EDGAR comes closer to regional totals. For the following countries differences of more than 20% were found between EDGAR and national data: Bulgaria, Austria, Finland, Portugal, United Kingdom, Iceland, Norway, Algeria, Botswana, Cote d'Ivoire, Gambia, Mongolia and Senegal (See Figures 4.3, 4.4 and 4.7).

Reasons for differences are:
1. In EDGAR an estimate is made using per capita waste generation and the methane potential from landfilled waste, whereas in countries more detailed statistics are used on the amounts produced and landfilled.
2. In some countries a more detailed time dependent first order decay method is used to calculate methane from landfills. This is the case in the Netherlands and the United Kingdom. Differences are about 20%.
3. In national estimates methane from liquid waste is included.

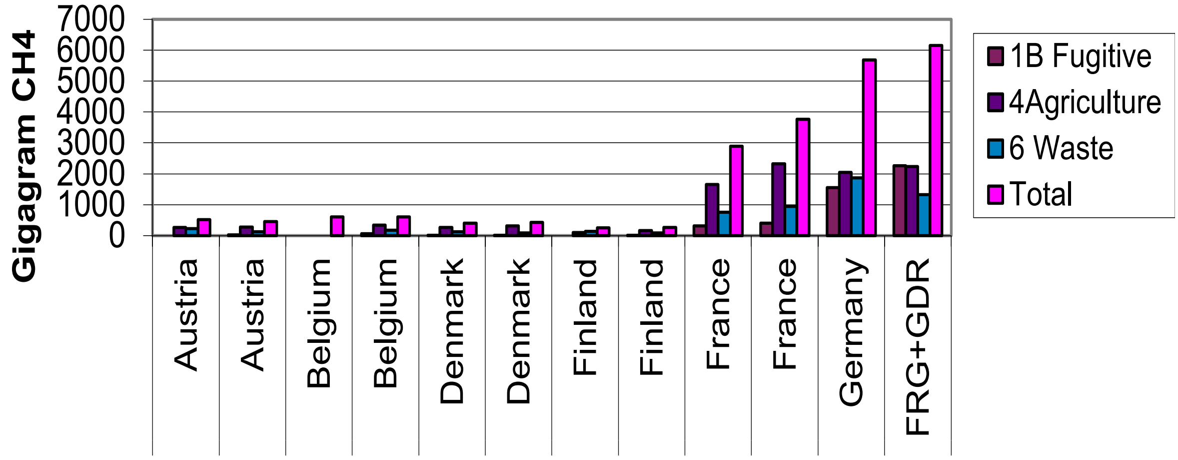

Figure 4.3: Methane emissions. Comparison of national inventories with EDGAR data for European countries (EU15).

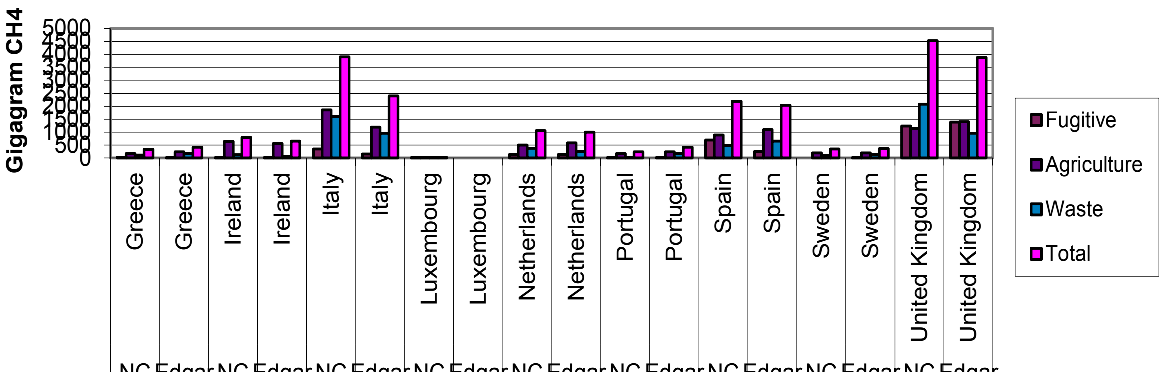

Figure 4.4: Methane emissions. Comparison of national inventories with EDGAR data for European countries (EU15).

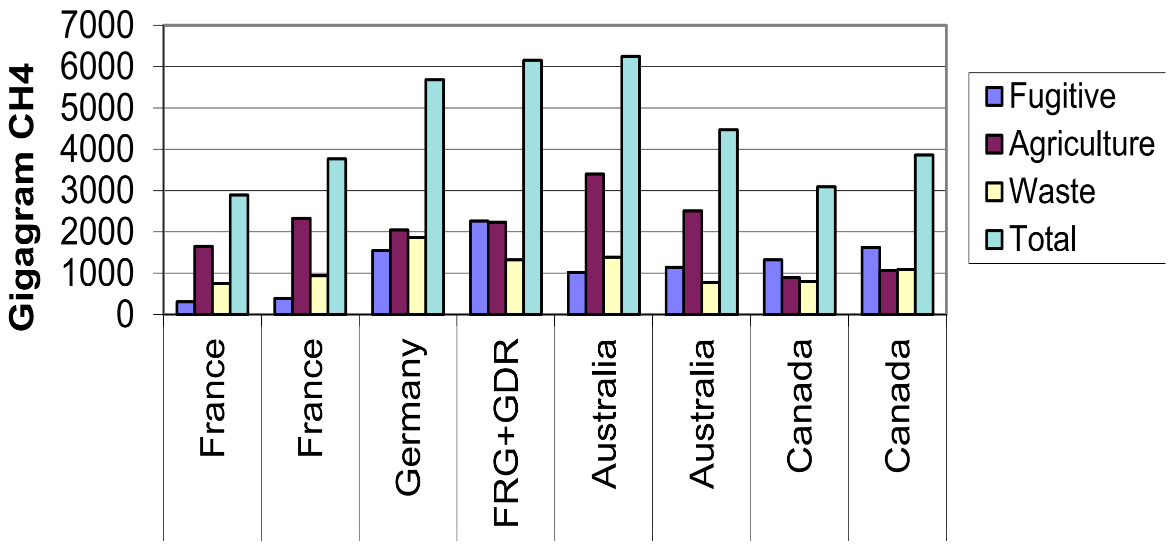

Figure 4.5: Methane emissions. Comparison of national communications with EDGAR data in some of the larger EU and OECD countries in the World.

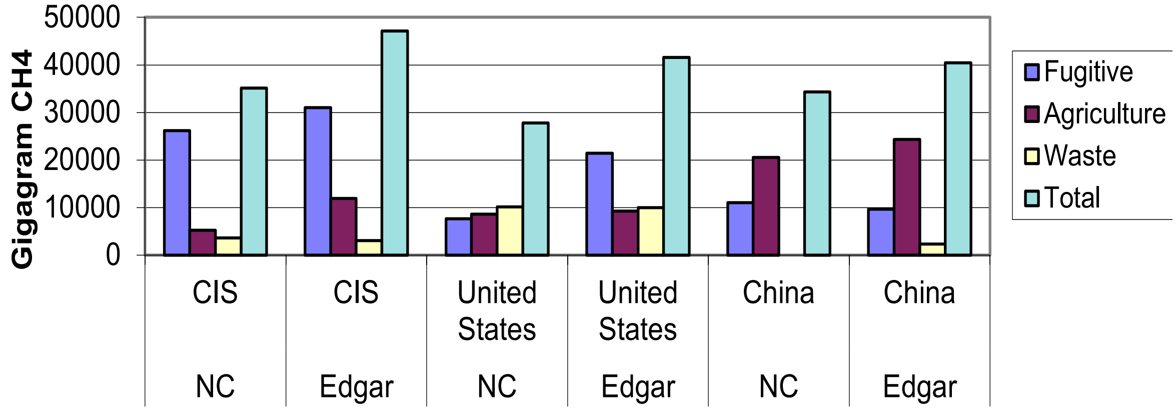

Figure 4.6: Methane emissions. Comparison of national communications NC with EDGAR data in some of the larger countries in the World.

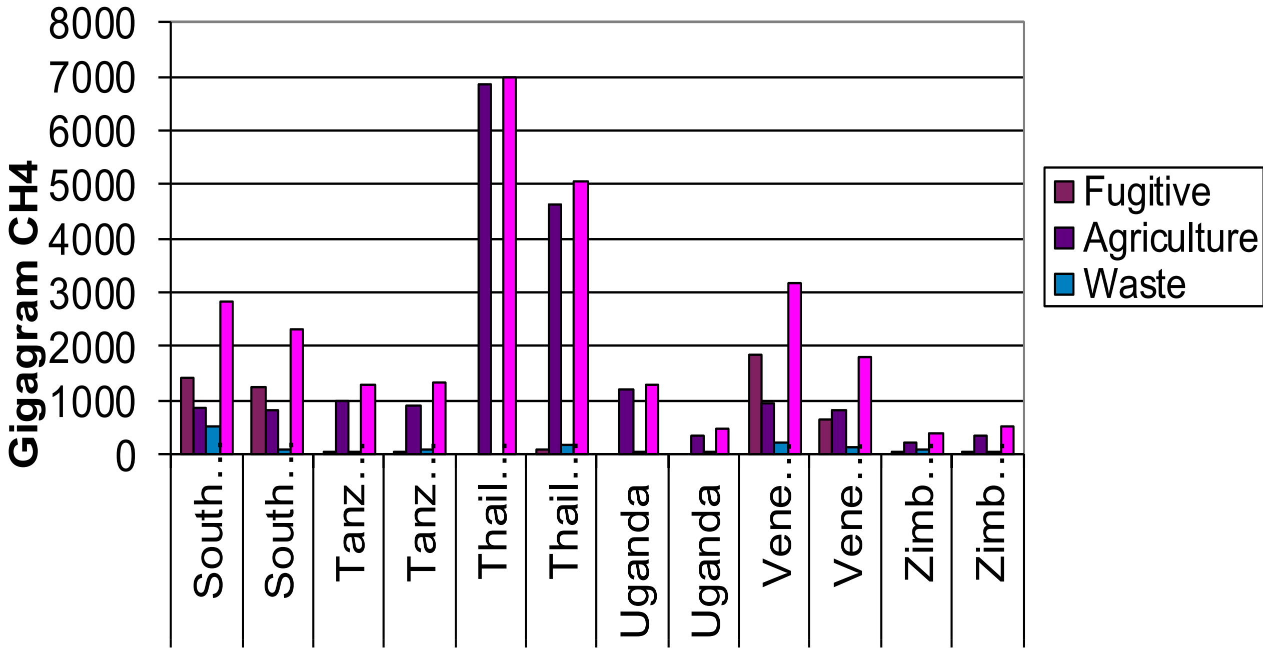

Figure 4.7: Methane emissions. Comparison of national inventories (NC) with EDGAR for some developing countries in the World.

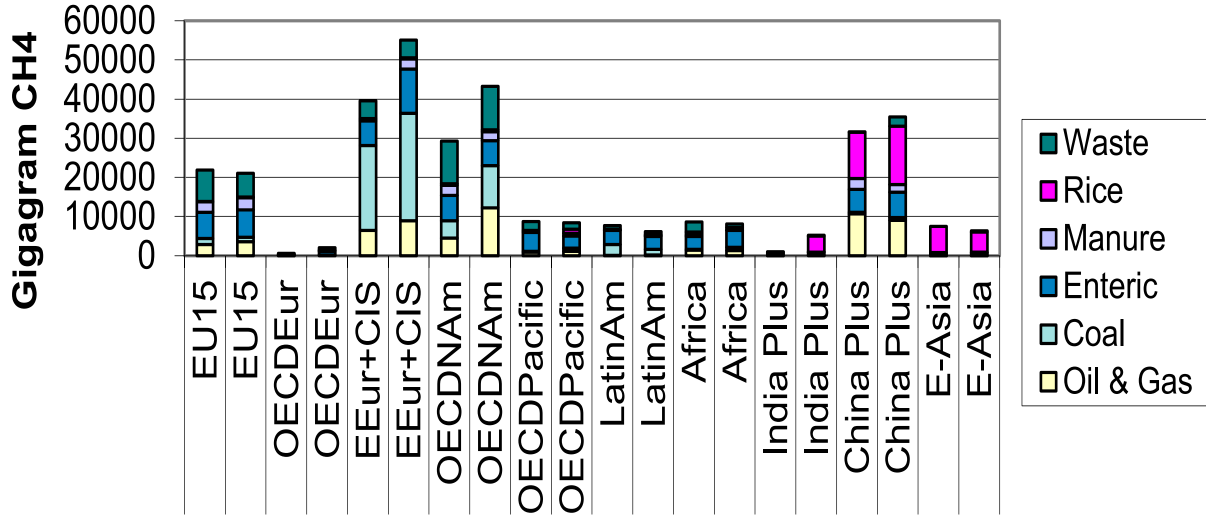

Figure 4.8: Methane emissions. Comparison of National Communications (NC) with EDGAR emissions database (ED) for the aggregate for different regions in the World.

(In the above graph the first bar is the sum of national inventories (NC) and US country studies (CS). The second bar is the sum of EDGAR data for the same countries. Countries are compared only if National Communications (NC) and Country Study (CS) and EDGAR data were available).

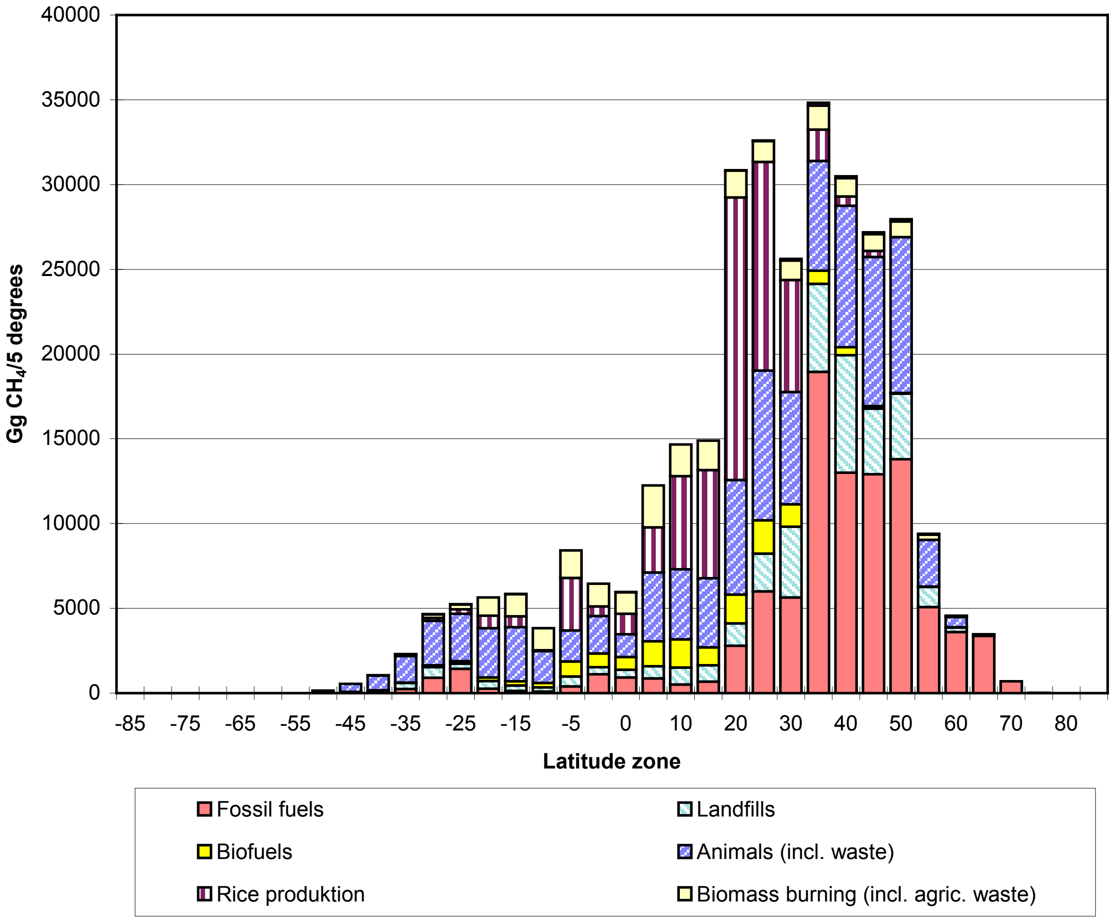

Figure 4.9: Latitudinal distribution of anthropogenic methane emissions in 1990 according to EDGAR 2. (over 5 degree bands, 90 = N)

In Figure 4.9 the latitudinal distribution of methane emissions in 1990 according to EDGAR 2.0 is given over zonal bands of 5 degrees. From this graph it is clear that the emissions of methane originate mainly from the industrialized countries between 20 to 50 degrees north of the equator, mainly from fossil fuels, animals and landfills. The methane emissions from rice are mainly between 0 and 30 degrees north.

4.5 Conclusions.

The comparison as presented here was the first of its kind. The methodology was developed to improve the quality of national emissions inventories. Based on the outcomes many countries re-evaluated their time series. The quality of national emission inventories improved a lot from these comparisons. IPCC adopted this method in the IPCC 2006 Guidelines as one of the methods to improve the quality of national emission inventories.

When comparing national inventories and EDGAR data for 1990, the net large differences are 29 Tg. This is about 30% and may be interpreted as the uncertainty of the methane emission inventories. The world total methane emission estimated from national data, US country studies and EDGAR, fall short of the best estimate of the IPCC budget. The aggregated world total compares with the low end of the range as published by IPCC. This means that IPCC default emission factors and emission factors used in national communications are generally at the low end of the range.

Coal

The large differences that were encountered in methane from coal between national inventories and EDGAR were mainly the result of the use of different emission factors. A careful reanalysis of emission factors based on available inventories is recommended. It is suggested that criteria are developed for quality of measurement programs, before emission factors are based on these. It is recommended that experts bring the two sets used by EDGAR and IPCC in line. Further it is recommended to evaluate the possibility to incorporate a coal basin approach as used in EDGAR into the IPCC methodology. It is recommended to combine efforts with experiments on methane emission reductions. In different industrialised countries experiments have started for enhanced methane recovery from deep coal beds using CO_2 e.g. flooding of coal strata. Measurements could give more information on the methane content of coal strata, and the possibilities to capture and use this methane.

Oil and gas

The large differences between EDGAR and the national inventories for some countries were caused by the use of different emission factors. Some countries re-examined the use of their emission factors based on this comparison. It is recommended that experts bring the two sets of emission factors used by EDGAR and IPCC in line. More measurements are needed in the regions with suspected high emissions. A methodology for up-scaling of measurement results to a national level must be developed before the start of a measurement program, to be sure that the results can be used for developing updated emission factors. It is recommended to evaluate the recent history of emissions in Russia. The economic reform in Russia resulted in lower oil and gas production in the nineties (1989-2000), but it has not been evaluated in terms of emission inventories.

Combustion

The reporting on methane emissions from fossil fuel and traditional biofuel combustion is not complete for many countries. The differences are often caused by gaps in reporting. It is recommended to improve on biofuel statistics within the countries. Seeing the large differences, the default IPCC emission factors need evaluation by experts. Some industrialised countries underestimated the use of traditional fuelwood in the energy mix. Statistics of fuel wood could therefore be improved in industrialised countries as well.

Agriculture: Enteric fermentation and animal manure
The differences between the national estimates and EDGAR are a consequence of the detail of reporting in each source, it is not so much related to a difference in methodology. The detailed reporting as used in country reports is recommended in this sector. If FAO statistics are available on this level of detail, these can be used for verification. It is recommended to develop a global set of emission factors using information on weight of cattle and amount and quality of food intake in each country for representative cattle types. It is recommended to evaluate the effect of increasing milk production and related changes in diets on emissions. Most countries used one set of emission factors throughout 1990-2005. This means that no effects of autonomous developments in milk production were taken into account. The trend over the years is merely a trend in cattle numbers. The effects of changing diets and increasing milk production could be taken into account. The emission factors over time could be calculated using the IPCC Tier 2 method each year.

Rice
The differences between the national estimates and EDGAR are a consequence of the rather weak international databases on rice area and the aggregated methane emission factors used in EDGAR. It is recommended to develop a database of rice area based on a climate database with information on growing period and soil moisture. Information on major soil types, using remotely sensed information and soil maps could be used for further detail. Especially rice on peat soils emit much methane. An example of rice expansion on peat is the “Transmigratie” project of Indonesia, where large numbers of people from Java were encouraged to migrate to newly developed agricultural areas in other islands, mostly on peat soils. It is recommended to review the methane emission factors used by countries for each soil type and rice variety and make a more detailed emissions factor database. Criteria for good practice could be developed for incorporation of emission factors from measurement programs into this database. It is recommended to develop a database on fertiliser and organic application in the different rice areas.

Agricultural waste burning
The reporting in this sector is irregular. Statistics are weak on agricultural waste burning. The emission factor used in the Tier 1 approach of 1% of carbon combusted is emitted as methane, needs evaluation in the light of newly reported values.

Savanna burning
The reporting in this sector is not complete for all countries. Bush fires in Australia are reported here. The emission factors need re-evaluation in the light of new information that has become available through country studies.

Soils
It is very important that a clear definition is drawn up for anthropogenic methane emissions from soils. The largest source is managed wet peat soils. Originally these were natural emissions. But, if these peat soils are reclaimed and have become farmland, these emissions have become anthropogenic because these soils are managed. In some countries draining of

peat soils have resulted in slightly lowered methane emissions. A reduction realised after 1990 could be subtracted from total emissions.

Waste
Differences between national estimates and EDGAR estimates are a consequence of the weak methodology used in both country estimates and EDGAR estimates. It is recommended to start an extensive programme for methane recovery from landfills and at the same time measuring the potential and actual emissions. It is recommended to make an effort to apply the time dependent method (as used in the Netherlands and the UK) on countries with large landfills near the largest cities in the world. An international database on waste in place and potential methane emissions should be developed.

Land use change
A comparison between country estimates and EDGAR was not possible because of the scattered reporting on carbon dioxide, methane and nitrous oxide emissions and/or sinks from land use change and deforestation. It is recommended to develop global databases on forests, carbon stocks per hectare and deforestation, reforestation, reafforestation from all information available.

Overall concluding remark

Independent authoritative sources (like the EDGAR database on emissions) are needed to review official country submissions to the United Nations Framework Convention on Climate Change. Quantitative quality control is needed to prevent mistakes and improve the inventory methodology. Based on this first comparison of country studies and EDGAR the quality control was formalised in the 2006 IPCC Guidelines for national greenhouse gas inventories.

5. OPTIONS FOR METHANE CONTROL

Published as edited chapter Andre van Amstel, 2010: Options for methane control. Chapter 13 in Dave Reay et al.(editors) 2010: Methane and Climate Change. Earthscan, London, Washington DC pp 211-241.

5.1 Introduction

Emissions of greenhouse gases other than carbon dioxide are responsible for about 50 per cent of radiative forcing, the determinant of global warming (IPCC, 2007). This means that emission reductions of such gases, like CH_4 and nitrous oxide, are important and should be taken into account when developing policy strategies for reducing the risk of global warming.

Emission reductions of CH_4 can be very effective in reducing climate forcing compared to CO_2, because each unit of CH_4 is 25 times more powerful than CO_2 over a 100-year time horizon. Given the fact that CH_4 can often be recovered and used for energy generation, many options can be cost effective because of the benefits of the energy sold. In this chapter cost estimates of technical reduction measures will be given that will be used in the integrated assessment in the next chapter 6 to estimate the overall reduction costs for different CH_4 reduction strategies.

Therefore in this chapter research question 4 will be answered:

Which options are available to reduce CH_4 emissions and what are the costs of these options?

Various authors have made estimates of the costs of measures per ton of CH_4 emission reduction. With some technical measures, CH_4 emissions can be significantly reduced And experience of these measures has been developed in actual CH_4 reduction projects. A body of literature is available on measures to reduce CH_4 (for example AEAT, 1998; IEA, 1999; Hendriks and De Jager, 2000; DelaChesnaye and Kruger, 2002; Graus et al., 2003; Gallaher et al., 2005; Delhotal et al., 2005; Harmelink et al., 2005). Measures are considered cheap if they are below \$20 per ton. Some measures even generate money and can be implemented for \$-200 to \$0 per ton of reduced CH_4. These are called “no-regret” measures. Most measures, however, are more expensive and can only be implemented at \$20-500 per ton of CH_4 reduced. Very expensive options are available at \$500 per ton or more. Van Amstel (2005) made a first global estimate of costs.

IPCC (2007) showed that climate is already changing and that these changes will likely accelerate in the next 50 years as a result of human activities. To limit these changes, greenhouse gas emissions should be reduced rapidly worldwide. The UNFCCC has a stated objective to stabilize atmospheric concentrations of greenhouse gases at a level that will avoid dangerous climate change. The science, technology and know how is potentially available to meet this goal. Proposals to limit atmospheric CO_2 concentrations to prevent the most damaging effects have often focussed stabilization targets of 550 parts per million (ppm), almost a doubling of the preindustrial average concentration of 280 ppm. The current CO_2 concentration is 390 ppm, with a growth rate of 2 ppm per yr.

Greenhouse gas emissions are reported to the Climate Convention and the Kyoto Protocol. IPCC (2006) developed guidelines for national inventories of emissions. In general, greenhouse gas emissions from fossil fuels can be controlled by energy efficiency measures, energy conservation and decarbonization of the economy, which includes fuel switching to renewables. Short term options are carbon capture and storage, fuel switching from coal to gas (i.e. from a high to a lower carbon-density fuel) or from fossil to biomass fuels (biomass is a carbon-dense fuel but emitted CO_2 is taken up by the vegetation in a closed short-term cycle) (Leemans et al., 1998; Pacala and Socolow, 2004). Medium term options are switching to hydrogen and other renewables like solar and wind. Some even advocate a large increase in nuclear power generation around the world, but the problems of nuclear waste storage and security remain unresolved in many areas.

Pacala and Socolow (2004) have suggested that the policy gap between a business as usual (BAU) scenario and a stabilization scenario could be tackled stepwise through stabilization wedges, using current technologies. In a BAU scenario, carbon emissions are increasing by 1.5 to 2 per cent per year. In their view, every wedge contains a package of measures that reduces the emissions substantially. Wedges can be achieved from, for example, energy efficiency, the decarbonization of the supply of electricity and fuels by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy. With energy conservation and efficiency improvements large reductions in carbon dioxide emissions have already been achieved in some sectors and regions. In industrialized countries, the autonomous energy efficiency improvement (AEEI) of the total economy was 2 per cent per year over the last four decades, with a levelling off during the last 20 years (Schipper, 1998).

Van Amstel (2009) developed scenarios for 2100, and estimated climate change with CH_4 reduction measures. Every possible measure to reduce the other greenhouse gases, including CH_4, should be added to the greenhouse gas technology portfolio. Methane emitted to the atmosphere is 21 to 25 times more powerful than CO_2 and it can often be captured and used for energy generation. For CH_4, this means tracking down and removing all leaks in the exploration, mining and supply sectors of the fossil fuel industry. It means abandoning wasteful venting and flaring in the oil and gas industry and capturing coal mine ventilation air CH_4.

Pre-mining degasification in “gassy” coalmines could be promoted to increase safety and to capture and use the CH_4 for energy generation. A market for ventilation air CH_4 use and oxidation is emerging in many of the world’s coal producing countries with an equipment sales market of more than $8.4 billion (EPA, 2003; Gunning, 2005; Mattus, 2010). Harvesting biogenic CH_4 from landfills, manure fermentation and waste water treatment plants, for example (IEA, 2003; Maione et al., 2005; Ugalde et al., 2005), could be also promoted wherever possible.

Below, I discuss different options that are already being deployed at an industrial scale and that could be scaled up further. Methane can also be seen as the perfect carrier for hydrogen in the hydrogen economy (it is much cheaper than metal hydrates). This chapter then continues with a conceptual section focussed on the way to determine the costs of emission reductions and a technical section in which the reduction measures are described.

5.2 On the determination of characteristics and costs of emission reduction options.

In this section, a number of issues important for the assessment of greenhouse gas emission reduction options will be considered. I start with some definitions and then discuss the possibilities to estimate the costs of reduction technologies. The options can be evaluated using supply curves.

Two types of measures can be distinguished that reduce (with respect to a given baseline development) the emissions of greenhouse gases: efficiency improvements and volume measures. Efficiency improvement is defined as decreasing the specific emissions. Volume measures are a reduction of the human activity itself.

Specific emissions are defined as the emission per unit of human activity, such as emissions per amount of coal produced, or emissions per unit of meat or milk produced. Emissions are calculated with the general formula: volume of activity * emission per unit of activity * abatement per unit of emission. Total costs in the target year are calculated from the reduction of emissions compared to a baseline development without reduction measures. In general the activity indicator is a physical measure relevant for the economic value of a human activity. Examples are the amount of fossil fuels produced, the size of the livestock herd or the amount of meat or milk produced, or the amount of municipal waste produced. The choice of the activity indicator is not unambiguous: sometimes a simple indicator must be chosen because of a lack of statistics. Here only efficiency improvements are described. These are often described as technological options, however this does not always mean that technologies are applied. Also good housekeeping can be considered an efficiency improvement (Harmelink et al., 2005).

Several types of emission reduction potentials can be distinguished.

- The technological potential is the amount by which it is possible to reduce greenhouse gas emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated. The emission reduction is calculated with respect to a baseline scenario development.
- The economic potential is the portion of technological potential for greenhouse gas emission reductions or energy efficiency improvements that could be achieved cost-effectively through the creation of markets, reduction of market failures, increased financial and technological transfers. The achievement of economic potential requires additional policies and measures to breakdown market barriers. Measures are cost-effective when the benefits of the measures are larger than the costs (including interest and depreciation)
- The market potential is the portion of the economic potential for greenhouse gas emission reductions or energy efficiency improvements that could be achieved under forecast market conditions, assuming no new policies and measures.

An assessment of emission reduction technologies within a certain sector in general consists of the following steps:

- Breakdown of the sectoral emissions into categories and/or processes
- Inventory of possible emission reduction options per category and process

- Determination of characteristics of the various emission reduction options
- Evaluation of the set of emission reduction options (for instance by construction of a supply curve or evaluation against baseline scenarios with the help of an integrated model)

Balanced cost estimates are based on real projects where CH_4 emissions have been reduced by technical measures. These estimates take into account all costs of a project, including investment, operation and maintenance, labour and the depreciation of capital. It is important that cost estimates are comparable between countries and regions, so methods between research groups should be comparable. There are different ways to estimate the costs of abatement measures. Marginal abatement cost curves are estimated by Gallaher et al (2005), in which the reduction of costs over time have been taken into account. Here a static approach has been chosen as first adopted by Blok and De Jager (1994), and applied in the Netherlands by Harmelink et al (2005). The Energy Modelling Forum 21 (EMF21) also applied static marginal abatement curves for non-CO_2 greenhouse gases for worlwide abatement (Delhotal et al., 2005). The data used in the EMF21 study are country or region-specific marginal abatement cost curves based on country or region specific labour rates, energy system infrastructure, and the latest emission data.

A static analysis has limitations. First, the static approach to the abatement cost assessment does not account for technological change over time, which would reduce the cost of abatement and increase the efficiency of the abatement options. Second, the static EMF21 approach used only limited regional data. Difficulties arise with the cost estimates when multipurpose projects are developed. Then it is difficult to attribute the investment costs to CH_4 reduction because the investment was done also for other purposes. For example, wastewater and sewage treatment plants are developed to improve the health and living conditions of the people. Anaerobic digesters can be flared or the CH_4 used for cogeneration to reduce CH_4 emissions from biomass or liquid effluents with high organic content. Because most centralized systems automatically either flare or capture and use CH_4 for safety reasons, add-on abatement technology for existing wastewater treatment plants does not exist. As a result potential emission reductions depend on large-scale structural changes in wastewater management. For this reason the cost of CH_4 reduction in sewage treatment is difficult to estimate. Overriding economic and social factors influence wastewater treatment practices throughout the world. The benefits of installing wastewater systems in developing countries for the purpose of disease reduction greatly outweigh potential benefits associated with CH_4 reduction. It would be misleading to imply that carbon taxes would be the driving force behind investment decisions that influence CH_4 emissions from wastewater. So cost estimates must be treated with caution.

Here the method as described by Blok and De Jager (1994) for specific costs is used. In this method the costs per ton of reduction of CH_4 (or other greenhouse gas) per sub-sector are calculated with the following formula:

$$C_{spec} = (a.I + OM - B)/ER$$

in which: C_{spec} = the specific emission reduction costs (in $\$_{1990}$ per ton of avoided CH_4); a=an annuity factor depending on interest (or discount) rate r and depreciation period n; $a = r/(1-(1+r)^{-n})$; I=the (additional) initial investment required for the measure in \$; a.I=the annualized capital costs in \$ per year; OM = the (additional) annual operation and maintenance costs associated with the measure in \$ per year; B = benefits associated with the measure in \$ per year (for example avoided energy costs); ER = emission reduction associated with the measure in ton of avoided CH_4 per year. Also:

Paybacktime = I/(B-OM)

Costs of measures are expressed in constant $\$_{1990}$ per ton of emission reduction for CH_4. The specific costs can be negative if the benefits associated with the measure are sufficiently large. Thus money can be earned by implementing beneficial measures. The costs calculated this way are meant to be the life-cycle costs, i.e. the total costs taking into account the technical life span of the equipment required for the measure. Thus the depreciation period is taken equal to the technical life span of equipment. The prices are market prices. The real interest rate is taken, i.e. the market interest rate corrected for inflation. This interest is 3 to 6 per cent generally. The sum of the emission reductions with negative net costs is called the economic potential. The specific costs can be used as a selection criterion for the set of measures chosen in a certain scenario. Total costs calculated for a selected set of measures give a first approximation of the national economic costs of the measures on the gross national product (assuming perfect competition). However the discount rate r that should be chosen is still a matter of discussion, and might be higher than the real interest rate. In public policy decision-making the social discount rate is sometimes chosen higher (at 10 per cent) because it should reflect the rate of return that could be realised through private spending on consumption and investment, assuming the same level of risk (Callan and Thomas, 2000). Also the technical lifetime as the period of depreciation might be too long. In reality measures are taken if payback times are five years or even shorter. However the method by Blok and De Jager (1994) is adopted here because it is widely accepted. Below, the available technical measures and reduction potential and costs for CH_4 will be described in the next section for the different important CH_4 sources.

5.3 Technical reduction potential for methane

Sources of methane emissions from natural gas and oil infrastructure

Natural gas and oil infrastructure accounts for over 20 per cent of global anthropogenic CH_4 emissions. Methane gas emissions occur in all sectors of the natural gas and oil industries, from drilling and production, through processing and transmission, to distribution and even end-use as a fuel. The natural gas infrastructure is composed of five major segments: production, processing, transmission, storage and distribution. The oil industry CH_4 emissions occur primarily from field production operations, such as venting gas from oil wells, oil storage tanks and production-related equipment. Table 5.1 provides a summary of country specific CH_4 emissions from oil and gas for 1990 and 2000 and expected emissions for 2010 for some of the largest producers.

Table 5.1: Country reported CH_4 emissions from oil and gas for 1990 and 2000 and a scenario for 2010. (Source: Van Amstel 2009)

Methane emissions Country	Gg CO_2-equivalent 1990	Gg CO_2-equivalent 2000	Gg CO_2-equivalent 2010
Russia	335,3	252,9	273,5
United States	121,2	116,4	138,7
Ukraine	71,6	60,2	39,4
Venezuela	40,2	52,2	68,0
Uzbekistan	27,2	33,7	42,9
India	12,9	24,4	54,9
Canada	17,1	23,3	23,8
Mexico	11,1	15,4	22,1
Argentina	8,0	13,7	30,5
Thailand	2,9	8,6	15,9
China	0,9	1,5	4,9

Methane emission reductions from oil

During the production of oil, associated gas is pumped up. In many producing countries this gas is either flared or vented. In these cases it is a wasted resource and it is more cost-effective to capture this gas for marketing or for energy at the production site. This valuable resource is vented and flared in large quantities in Nigeria and several production sites in the Middle East. Investments are needed to produce liquefied petroleum gas (LPG) for the local market or more distant markets.

Methane emission reductions from gas

Methane emissions from explorations could potentially be increasing in the near future. While looking for unconventional fossil fuel resources CH_4 hydrates have recently attracted increased attention. As each cubic meter of CH4 hydrate contains up to 170m^3 of CH_4 gas, the CH_4 hydrate resource potential in some regions is huge. Methane hydrate is found under the bottom of oceans and under permafrost regions. It is frozen with CH_4 locked into the ice cristals. At the moment characterization of the regional resource potentials is taking place (Maslin, 2010). Technology to bring this resource to the surface is, however, still lacking. Therefore it is important to develop methods that are absolutely “leak-free” to prevent hydrate CH_4 from substantially adding to global CH_4 emissions should these deposits be exploited.

During the production of natural gas the main CH_4 emission sources are:
- Natural gas treatment operations, like drying of the gas with glycol and removal of H_2S or CO_2 with amine solutions.
- Separation of natural gas condensate and measurement of its volume.
- Safety systems with CH_4 purge streams in order to prevent air infiltration into the system.

The mainstream gas is dehydrated with glycol. During decompression of glycol gas is released and either vented or flared especially on offshore platforms). During maintenance works, or through safety valves, gas is also released and again vented or flared. Flaring was only recently introduced at "flare tips" away from the platforms because of security reasons. It is presumed that, on newly built platforms, measures will be taken to reduce flaring and venting to a minimum. On platforms that are in use, measures can be taken at little costs to increase the on-site use of this "waste" gas. Achieving CH_4 emissions of below 10 g/GJ are feasible, as proven by some offshore operations in Norway (OLF, 1994). To reduce CH_4 losses from such fossil fuel systems the following options are available (see also table 5.4):

Option 1. Increased inspection and maintenance.
Before repair or maintenance, emissions occur when parts of the system are depressurized. These gases may be recompressed and rerouted to the system. This might be done using a transportable compressor unit. Recompression is economically attractive when the amounts recompressed are over 65000m^3. Onshore recompression is often economically viable with specific costs of –200 $\$_{1990}$/ton of avoided CH_4 per year. Offshore, this is harder to achieve since all equipment has to be flown in by helicopter (De Jager et al., 1996).

Option 2. Increased on site use of otherwise vented CH_4 at oil and gas production sites.
Reduction of CH_4 emissions can be achieved by the increased on-site use or marketing of "waste" gas during production of oil and gas. Increased on-site use in production is a relatively cheap measure with net costs of \$10 per tonne CH_4 emission reduction. Increased marketing by liquefaction and transport to distant markets is even less expensive with \$ -100 per tonne of reduced CH_4 emission. In theory, a ~50 per cent reduction of emissions can take place between 1990 and 2025, with 60 per cent in the former Soviet states and the Middle East (De Jager et al., 1996).

Option 3. Increased flaring instead of venting.
During production of oil and gas venting and flaring takes place from the safety system at the production site. During "flaring", gas is burned and CO_2 emission takes place, while during "venting" gas is emitted unburned. Because CH_4 has 21-25 times the global warming potential of CO_2 on a mass basis, venting can result in greater climate forcing than flaring. Thus, increased flaring instead of venting reduces this problem. Costs are low if flares are installed in the development phase or during the start of operations (De Jager et al, 1996). If flares have to be installed the costs are \$400 per ton of avoided CH_4. Increased flaring, instead of venting, can in theory reduce net emissions by 10 to 30 per cent between 1990 and 2025 in OECD (Organisation for Economic Co-operation and Development) countries, and 50 per cent in oil and gas producing regions such as the former Soviet states, the Middle East and Eastern Europe.

Option 4. Accelerated pipeline modernization.
Leaking of CH_4 is higher in old pipeline systems or in permafrost regions with low levels of maintenance. Accelerated pipeline modernisation is expensive if pipes are underground. In the former Soviet states and Middle East, by 2025 90 per cent of leakages can be controlled by modernisation of pipes. In the other regions by 2025, a reduction of 20-40 per cent of leakages can be attained. Estimated costs are \$1000 per tonne of CH_4 reduction if underground, and \$500 if above-ground pipes are replaced (De Jager et al., 1996).

Option 5. Improved leak control and repair.
In OECD countries, about three to five leaks are found per km of mains gas supply. In older

systems this number could be much higher. Improved control and repair can radically reduce leakages by 2025, with reductions of up to 90 per cent in Eastern Europe, Russia, Middle East, India and China, and with 40 per cent in the other regions. This measure has medium costs, with around \$200 per tonne of CH_4 reduction (De Jager et al., 1996).

Methane emission reduction from coal mining

In deep underground mines CH_4 is trapped in the coal beds and the surrounding rock strata. High pressure of the overlying strata prevents this CH_4 from being released. Once mining starts, this CH_4 can escape and fill the excavated space. Coal mine CH_4 is a safety hazard and therefore mine shafts are ventilated. It is emitted into the atmosphere through ventilation air containing on average about 1 per cent of CH_4. After mining, a small but not negligible part of the CH_4 is released from the coal by post mining activities such as breaking, crushing and drying. Global emission factors for deep mining are between 10 to 25m^3 per ton coal, not including post mine activities. Global emission factors for surface mines are between 0.3 to 2.0m^3 per ton, not including post mine activities. Emissions from post mining activities are 4 to 20m^3 per ton (Kruger, 1993). Emissions can be mitigated before, during and after mining.

Before mining, CH_4 can be captured by drilling from the surface into the coal strata and capture the CH_4 before mining starts. This can be done from half a year to several years before mining starts. During mining, ventilation air can be used as combustion air. After mining, CH_4 emissions can be reduced by recovering CH_4 from the areas of fractured coal and rock that is left behind, for example by using “gob-wells”.

There are two main methods of underground mining: “room and pillar” and “longwall mining”. In the “room and pillar” approach, coal deposits are mined by cutting a network of rooms into the coal seam and leaving behind pillars of coal to support the roof of the mine. “Longwall mining” means cutting successive strips of coal from a face, typically 100-250m in length. Roadways are driven into each side of the panel of coal to access the face and the roof strata are allowed to collapse behind the face. Usually the face is established as the remote end of the panel and is retreated back towards the main trunk roadways (AEAT, 1998).

Current European CH_4 mine draining practice is to drill inclined holes into the strata above the seam being mined. These are drilled from the panel roadways in advance of the face. Gas emission starts as the face approaches and passes beneath the holes. In the case of retreat mining, the holes then pass into the caved area behind the face, where access is no longer possible. In this way, a considerable amount of air is drawn in and mixed with the CH_4. This means that the gas, when it reaches the surface contains 50 per cent or less of CH_4. This has cost implications, in that the system must be designed to handle a higher total flow. It may also cause problems at the utilization stage.

Another method, used in the US, is to drill vertical holes from the surface into the target seam and drain off gas prior to mining. This is a way of obtaining gas independently of any mining operation. Coal bed methane (CBM), as it is called, is extracted in large quantities from the Black Warrior and San Juan Basins in the US. Because there is minimal opportunity for dilution, the gas is near-pure CH_4 and needs only minimal treatment. This system is only practical in “gassy” mines with high coal permeability. The potential for de-gassing European coals is very limited, as European coals have a high rank and very low permeability. Another approach developed in Germany is to drive in a "super adjacent heading". This is a special roadway some distance above the face and parallel to its run, which then acts as a collection point. Overall, the following mitigation options can be described:

Option 6. Pre-mining degasification
This measure can be taken for safety reasons. It recovers CH_4 before the coal is mined. It is an emission reduction option if CH_4 is then used for energy generation. Wells can be drilled in advance of mining, within the mine or from the surface. In typical mining regions such as China, Eastern Europe and Russia, a 90 per cent reduction in venting losses can be achieved by 2025, and in the US a 70 per cent reduction is possible, at an estimated cost of $40 per tonne of CH_4 emission reduction. In other regions a reduction of 30-50 per cent can be achieved by 2025 using this strategy (IEA, 1999).

Option 7. Enhanced gob-well recovery.
This measure can be taken to reduce CH_4 emissions from the "gob" of the coal mine. This is the place where the roof has collapsed after mining and it may require additional drilling. Methane can be used for energy generation. By the year 2025 about 50 per cent of CH_4 emissions from used coalmines can be recovered this way at around $10 per tonne of CH_4 reduction (IEA, 1999).

Option 8. Ventilation air utilization.
Ventilation is necessary in underground mines for safety reasons and large fans are used to blow air through the mines. The CH_4 content of the air must be below 5 per cent, and is frequently below 0.5 percent to comply with relevant regulations. Ventilation air can be used as combustion air in turbines or boilers. Technical and economic feasibility has been demonstrated in Germany, Australia and in the UK. If introduced in other countries CH_4 emissions can be reduced by up to 80 per cent in typical mining regions, and by 10 to 20 per cent in the other regions. Estimated costs are $10 per tonne CH_4 reduction (IEA, 1999). All the major coal producers have some recovery and utilisation of mine CH_4. For Germany the overall utilization rate in 1995 was 36 per cent. For the UK the recovery rate is estimated to be 11 per cent. In Spain recovery rates are below 5 per cent (AEAT, 1998).

Methane emission reduction from enteric fermentation in livestock

Cattle, sheep, goats (ruminants) and horses and pigs (pseudo-ruminants) produce CH_4 as part of their normal digestive process. In cattle it is estimated that about 4 to 7 per cent of gross energy intake is lost as CH_4 (Van Amstel et al., 1993). Animals in modern intensive livestock feedlots with high protein supplements emit 4 percent of gross energy intake, animals in range systems without supplements emit up to 7 percent of gross energy intake. The worldwide spectacular growth of herds since the 1950s is responsible for the increase of this CH_4 source (Steinfeld et al, 2006). Reductions per unit of meat or milk can be expected with increasing productivity improvements, especially in developing regions. Absolute reductions in the future are expected to be small. The following reduction options can be described.

Option 9. Improved production efficiency.
Methane is produced as part of the normal digestion process in ruminant animals. Methane

emissions per unit of milk or beef can be reduced if breeding programmes result in animals with high milk or meat production and good reproduction. Production efficiency is already very high in the US, Canada, OECD Europe and Japan, no reduction is expected here. In the other regions this can be improved. In those regions a CH_4 reduction of 20 per cent is expected without extra costs (Blok and De Jager, 1994).

Option 10. Improved feeding.
In many regions feeding of livestock can be improved. An increase in protein rich feed and increasing digestibility of roughage reduces CH_4 per unit of product. No reductions are expected in the OECD countries. A reduction of about 10 per cent is expected in the other regions. Costs are low, with \$5 per tonne of CH_4 reduction, but availability of high quality feed is a problem in those regions (EPA, 1998).

Option 11. Production enhancing agents.
These agents have proved to improve production in the US, but are not generally accepted by the public in Europe. Examples are hormones such as bovine somatotropin bST and anabolic steroids. In the European Union these hormones are banned. If used in other regions a ~5 per cent reduction of emissions may take place. This option is expensive with an estimated \$400 per ton of avoided CH_4 (AEAT, 1998).

Option 12. Reducing animal numbers.
In some regions in the world animal density is so high that environmental problems are a consequence. Examples are manure surpluses, ammonia emissions and acid deposition on natural areas, forests and surface water, also leading to groundwater pollution. Reducing animal numbers could be the solution. It is not a technical measure but a volume measure and may result autonomously if environmental regulations are too costly for farmers. In the European Union, dairy animal numbers were reduced after milk quotas were introduced. Reductions in CH_4 emissions of 20 to 30 per cent may be achieved in OECD countries as a result of economic circumstances and as a result of these quota systems. Costs of reducing animal numbers are taken as zero.

Option 13. Increase rumen efficiency.
Rumen fermentation is controlled by rumen acidity and turnover rate. These are controlled by diet and other nutritional characteristics, such as level of intake, feeding strategies, forage length and quality and the ratio between forage and concentrates. Although significant advances in the knowledge of effects of various combinations of factors on microbial growth have been made in recent years, there is still insufficient information available to identify and control the interactions in the rumen that will result in optimal rumen fermentation.

Feeding ruminants on diets containing high levels of readily fermented non-structural carbohydrate has been shown to minimise CH_4 production by reducing protozoal population and lowering rumen acidity. This, however, may lead to depressed rumen fermentation, which may then lower the feed energy conversion into animal product and may effect the animal's health. Using diets without much forage is therefore not considered a sustainable method to control CH_4 emissions from ruminants. A number of possible but costly options have been identified for rumen manipulation with additives: hexose partitioning, propionate precursors, direct fed microbials that oxidise CH_4, genetic engineering, immunogenic approach. In the next table an overview is given of technical reduction potentials in the European Union and costs of the rumen manipulation (AEAT, 1998). Costs are high with \$3000-6000 per ton of avoided CH_4 (AEAT, 1998).

Table 5.2. Reduction and costs in the European Union of increased rumen efficiency (Source: AEAT, 1998).

Measure	Reduction Per head	Kton reduction in 2020 in EU			Costs $/t CH_4		Available from year
		Dairy	Non-dairy	Total	Dairy	Non-dairy	
Propionate precursors	25 per cent	69	270	339	2729	5686	2005
Hexose partitioning	15 per cent	41	162	203	?	?	2010
Methane oxidisers	8 per cent	22	86	108	?	?	2010
Probiotics	8 per cent	21	81	102	5440	11332	Now
High genetic merit	20 per cent	364		364	0	0	Now

Methane from manure

If manure is kept in liquid or slurry storage, at temperatures higher than about 15°C and storage periods longer than 100 days, methanogenic bacteria will produce CH_4 in significant amounts (Zeeman, 1994). While, if manure is kept in liquid or slurry storage, at temperatures of 10°C or less and storage periods less than 100 days, CH_4 will not be produced in significant quantities (Zeeman, 1994). The amount of CH_4 produced is dependent on the manure composition and manure management systems. Methane emission reduction measures can be directed at preventing conditions where fermentation starts, or at stimulation of controlled fermentation with CH_4 recovery for energy generation. Small-scale manure digesters are widespread in China and India. Large-scale systems can be found in Denmark. The following reduction options can be described.

Option 14. Dry storage.
Methane is produced during anaerobic decay of the organic material in livestock manure. It is emitted from manure if fermentation takes place over longer periods in anaerobic liquid or slurry storage. The optimum temperature is 15-35°C. Manure can also be stored dry and cool, to prevent fermentation. Manure management varies in different regions in the world. Therefore a reduction is only expected in regions with high animal densities where liquid/slurry storage is practised. A reduction of about 10 per cent can be achieved in those regions, with a cost of \$200 per ton of avoided CH_4 (AEAT, 1998).

Option 15. Daily spreading.
When daily spreading of manure on the land, anaerobic degradation can be minimised by avoiding anaerobic soil conditions. Ammonia and N_2O loss should be taken into account with this option. Up to 90 per cent of ammonia is lost to the atmosphere within 12 hours of spreading, therefore it is important to incorporate the manure into the soil to minimize this loss. Switching to daily spreading of manure can reduce related CH_4 emissions by 10-35 per cent in Europe. However it is a labour intensive and therefore costly measure, costing ~\$2000 per ton of avoided CH_4 emission (AEAT, 1998).

Option 16. Large scale digestion and biogas recovery.
Advanced farm-scale and village-scale digesters are in use in some European countries with

high intensity livestock farming, for example Denmark and Germany. Manure is transported from the farms to the farm-scale or village-scale digester. The technology is proven and the economic performance is acceptable. If introduced in all OECD countries and China, a 10 per cent reduction would be expected in CH_4 emissions from manure in these regions. Costs are ~\$1000 per ton CH_4 for large scale digesters (AEAT, 1998).

Option 17. Small scale digestion and biogas recovery.
Small-scale digesters are found in temperate and tropical regions to enhance the anaerobic decomposition of the manure and to maximize CH_4 production and recovery. In OECD countries they are not used. Fermented manure is a high quality fertilizer and an important product in resource-constrained regions. A reduction of 10 per cent of manure-related CH_4 emissions is expected in these regions, if introduced widely in India, China, East Asia and Latin America. Costs are ~\$500 per ton of avoided CH_4 emission for small-scale digesters. Benefits are the waste reduction and small-scale energy production for households and farms. A more detailed cost estimate of these options is given in Table 5.3.

Table 5.3. Costs of measures to reduce CH_4 emissions from animal manure in Europe in \$/t CH_4 (Source AEAT, 1998)

Measure	Cool climate			Temperate climate		
	Pigs	Dairy	Beef	Pigs	Dairy	Beef
Daily spreading	2264	4124	5505	645	1183	1579
Large scale digestion UK	450	828	1106	75	138	184
Large scale digestion Denmark	2287	4211	7878	500	921	1723
Small scale Germany (heat and power)	286	526	703	48	88	117
Small scale Germany (heat only)	95	175	234	16	29	39
Italy (CHP)	181	334	446	30	56	74

Methane emission reductions from wastewater and sewage treatment

Emissions from wastewater systems are still highly uncertain. The OECD countries have invested in wastewater treatment plants with CH_4 recovery. The problem is mainly concentrated in regions without this technology. At present for the wastewater sector, industrial wastewater in developing regions is considered to be the main CH_4 source (Thorneloe, 1993; Doorn and Liles, 2000). Two possible routes for reduction of CH_4 emissions can be followed. Aerobic treatment technologies can be selected, which prevents the formation of CH_4. Alternatively, anaerobic treatment technologies can be used, with CH_4 recovery for energy generation (Lexmond and Zeeman, 1995). Anaerobic treatment is commercially available. Fuel can be produced from the CH_4 for about \$1 per GJ (Lettinga and Van Den Haandel, 1993). This emission reduction option is summarized below.

Option 18. Increased on-site use of biogas.
Sewage treatment can result in CH_4 emissions if stored and treated under anaerobic conditions and if the CH_4 is released instead of recovered for energy generation. In the OECD countries, CH_4 is often already recovered in closed systems and only a 10 per cent reduction in emissions is expected through increased on-site biogas use. In other regions, larger reductions - of up to 80 per cent - are expected if these closed systems are introduced. The costs are variable between,

being between \$50 and \$500 per ton of CH_4 reduction (Byfield et al., 1997).

Methane from landfills

Methane is formed in landfills by methanogenic microorganisms (methanogens). The CH_4 generation is higher with a high organic matter content. The CH_4 is formed over a shorter time period where there is a higher content of easily degradable material, such as fruit and vegetable waste. The CH_4 emission shows a time lag after the the point at which waste is landfilled. The CH_4 emission in time can be estimated by a simple first order decay function. Research in The Netherlands, in which measured amounts are compared with estimates, shows that the uncertainty of the first order decay function is 22 per cent. It also shows that the accuracy of the estimate is not improved if more detailed estimation functions are applied. About $1.87m^3$ landfill gas (with 57 per cent CH_4) is formed per kg of organic carbon (Oonk et al., 1994). The most important mitigation strategies are to reduce, reuse and recycle waste. Those are volume related measures and not covered in this context. Three technical options can be formulated for CH_4 emission reductions from landfills. The first is to optimize waste gas formation and to recover as much as possible for energy use. This is one of the most promising and profitable options worldwide for CH_4 reductions. The waste gas is recovered from boreholes or gas trenches. To optimize waste gas recovery an impermeable clay layer cover is needed. The second option is to separately collect organic waste to be fermented in closed systems with CH_4 recovery for energy generation. The third option is controlled gasification of organic waste and wood. Small-scale combined heat and power (CHP) systems can be fuelled with organic waste and wood from gardens and village parks. The following reduction options can be described:

Option 19. Landfill gas recovery and use for heat.
Methane is formed in landfills during anaerobic decomposition of the organic material in the waste. Gas can be recovered by drilling holes in the landfill and collecting the gas. It can be used directly at the site or distributed to off-site buildings and industries. This option is beneficial with \$–50 per ton of avoided CH_4 (Meadows et al., 1996).

Option 20. Landfill gas recovery and upgrading.
Landfill gas can also be upgraded to natural gas quality for use in a gas grid. This option is profitable with a “cost” of \$–200 per ton of avoided CH_4. If not enough gas is available for use it can be flared. These options are a success in the OECD countries. A 50 per cent reduction in CH_4 emissions from landfill is possible in these regions using this strategy. Power generation costs ~\$23 per ton CH_4. Flaring costs ~\$44 per ton reduced CH_4. Improved capping of landfills at \$600 per ton reduced CH_4, though expensive, is important for an early start of landfill gas recovery.

Option 21. Controlled gasification of waste.
Gasification of waste is a proven technology. It seems to be the option with the highest profit, at about \$-350 per tonne of CH_4 reduction. Introduced in the OECD regions, expected reductions are some 80 per cent of CH_4 from landfills (De Jager et al., 1997)

Option 22. Reduction of biodegradable waste to landfill
Waste to landfill can be reduced by recycling, open composting, closed composting or incineration. Paper recycling is the most profitable option with a “cost” of \$–2200 per ton

reduced CH_4.

Option 23. Reduction of biodegradable waste to landfill by composting or incineration.
Open composting is expensive with a cost of ~\$1000 per ton reduced CH_4. Incineration of waste costs ~\$1423 per ton reduced CH_4, and "closed composting" costs as much as \$1800 per ton reduced CH_4.

Option 24. Fermentation of organic waste.
Instead of landfilling organic waste, it can be separately collected and fermented in closed systems. This option is in study in Europe and the US. At the moment it is more expensive than landfill gas recovery. If introduced, a 50 per cent reduction is expected of CH_4 emissions from landfills in OECD Europe and North America, at a cost of \$500 per tonne of CH_4 reduction. AEAT (1998) estimated the cost of this option in Europe at ~\$1860 per ton reduced CH_4.

Methane from wetland rice

Methane emissions from wetland rice have increased since the 1950s, with increasing cultivation area. Reduction strategies have to be found that do not interfere with yields. Denier van der Gon (2000) has suggested some strategies. These options have to be further explored. Intermittent draining is suggested, but this can only be applied in area with abundant water.

Option 25. Intermittent draining and other cultivation practices.
Methane is formed during the growing season in the flooded soils of rice fields. Present knowledge indicates that various cultivation practices could potentially achieve significant reductions. These include cultivar selection, water management, and nutrient application and soil management. Potentially a reduction of 30 per cent in CH_4 emissions from typical rice regions can be achieved with low costs. In other regions, a 5 per cent reduction may be possible by 2025. The costs are low if water is abundant with a cost of \$5 per ton of avoided CH_4 (Byfield et al., 1997).

Trace gases from biomass burning

Biomass burning is a source for various trace gases such as CO, CH_4, NO_x and VOCs (volatile organic carbons). Especially high concentrations are measured during the smouldering of biomass (Delmas, 1994). One option to reduce CH_4 emissions is therefore to increase the burning efficiency of biomass.

Option 26. Improved burning of traditional fuelwood.
Emissions of trace gases like CH_4, non-CH_4 volatile organic carbons (or NMVOCs), carbon monoxide (CO) and nitrogen oxides (NO_x) in traditional biomass burning are relatively high because of the burning conditions (for example the slow smouldering of moist biomass). Modern technology for biomass burning leads to lower emissions. One such promising technology is biomass integrated gasifier/intercooled steam-injected gas turbine (BIG/ISTIG) technology. If introduced, trace gas emissions from traditional fuelwood could be reduced by 90 per cent in all regions at low costs. A profit of \$100 per ton of avoided CH_4 was estimated in Byfield et al. (1997).

Option 27. Reduced deforestation.
Reduced biomass burning often also leads to lower rates of deforestation. It is estimated that this measure costs ~\$200 per ton of avoided CH_4 emission (Byfield et al., 1997).

Option 28. Reduced agricultural waste and savanna burning.
In most European countries, agricultural waste burning has been abandoned or is prohibited. However, in tropical countries it still occurs and can lead to both air pollution and CH_4 emission problems. Alternative handling of agricultural waste for example storage and application can reduce burning rates. This costs ~\$150 per ton of avoided CH_4 according to Byfield et al. (1997).

In table 5.5 and 5.6 an overview is given of the options and the costs of measures. These costs per option are needed to calculate the total costs of six CH_4 reduction strategies that have been formulated and assessed in the next chapter.

Most cost estimates originated from studies in industrialized countries. Costs of measures taken in other world regions represent a real gap in current knowledge. In the integrated analysis in the next chapter two scenarios are formulated. Measures are taken to reduce CH_4 emissions in all world regions. Three CH_4 emission reduction packages are formulated for each scenario. Six resulting CH_4 reduction strategies are analysed. Here the costs of reductions are calculated off-line.

5.4 Methane emission control costs

5.4.1 Introduction

I have chosen a cost-effectiveness analysis because it is difficult to estimate the benefits of reduced climate change. It is a sector-level analysis in combination with the detailed bottom-up cost effectiveness estimation methodology. A baseline without climate policies is needed in such an analysis. The baseline by definition gives the emissions of greenhouse gases in the absence of climate change interventions. The baseline is critical to the assessment of the costs of climate change mitigation because it determines the potential for future greenhouse gas reduction as well as the costs of implementing these reduction policies. The baseline also has a number of important implicit assumptions about future economic policies at the macroeconomic and sectoral levels, including sectoral structure, resource intensity, prices and technology choice. In my analysis, the “P1 and Q1” scenarios, as described in detail below, are considered the baselines against which the costs will be analysed.

Scenarios

Two contrasting scenarios and three methane emission reduction packages are developed. Each scenario is for the long run (2000–2100). The scenarios depict different possible futures and the reduction packages show different ways of combining methane abatement options. An existing integrated assessment model (IMAGE) is used to analyse the consequences of six emission reduction strategies for future air temperature. A reduction strategy is taken here as a scenario plus a methane abatement package.

The scenarios P and Q are in general agreement with scenarios as described in the IPCC *Special Report on Emission Scenarios* A1B-IMAGE and B1-IMAGE (Table 5.4) (IPCC, 2000). For the respective scenarios (P and Q), P1 and Q1 here contain no CH_4 abatement (i.e. they are the baselines to which reduction strategies are compared), P2 and Q2 contain moderate methane abatement, and P3 and Q3 contain maximum methane abatement. The storylines of the P1 and Q1 baseline scenarios, and of the CH_4 reduction strategies P2 and Q2 and P3 and Q3, are given below.

Table 5.4 *Basic assumptions of scenarios from the* Special Report on Emission Scenarios

Scenario	A1Biofuels	B1	A2	B2
Population 2020	7.5 billion	7.6 billion	8.2 billion	7.6 billion
Population 2050	8.7 billion	8.7 billion	11.3 billion	9.3 billion
Population 2100	7.1 billion	7.1 billion	15.1 billion	10.4 billion
World GDP in 2020	56 10^{12} $US\$_{1990}$	53	41	51
World GDP in 2050	181	136	82	110
World GDP in 2100	525	330	243	235
Resource base	Includes unconventional (oil, hydrates etc.)	Identified resources	Includes unconventional (oil, hydrates etc.)	Identified resources

Note: GDP = gross domestic product.
Source: IPCC (2000)

Scenario P describes a prosperous world with an economic growth of 3 per cent per year, with relatively low population growth, resulting in 8.7 billion people in 2050 and 7.1 billion in 2100. Present trends in globalization and liberalization are assumed to continue, in combination with a large technological change through innovations. This leads to relatively high economic growth in both the industrialized and the non-industrialized regions of the world. Affluence, in terms of per capita gross regional product, converges among world regions, although the absolute differences in affluence are growing. Increasing affluence results in a rapid decline in fertility. The global economy expands at an average annual rate of 3 per cent to 2100, reaching around \$525 trillion. This is about the same as average global growth since 1850. Global average income per capita reaches about \$21,000 by 2050 contributing to a great improvement in health and social security for the majority of people. High income translates into high car ownership, sprawling suburbia and dense transport networks. Increasing service and information orientation leads to a significant decline in intensity of energy and materials. Energy and mineral resources are abundant in this scenario because of the rapid technical progress. This reduces resource use per unit of output, but also the economically recoverable reserves. Methane emissions from fossil sources are growing. Final energy intensity (end use energy per GDP) decreases at a rate of 1.3 per cent per year. With the rapid increase in income, dietary patterns are assumed to shift initially to a high meat and milk diet with related increasing animal numbers and increasing methane emissions from animals and manure, but this may decrease subsequently with increasing emphasis on the health of the ageing society. Growth could produce increased pressure on the global resources. Conservation of natural areas is changing in management of natural resources.

Scenario Q is a contrasting scenario with a much lower demand in all sectors because of the lower GDP development (<3 per cent per year growth). The Q scenario describes a world where the modernization of the OECD countries has spread to the other regions over the period 2000 to 2100. A shift takes place from an economy predominantly relying on heavy industry towards a society with an economy predominantly based on services with an increasing dematerialization of production, recycling of materials and increasing energy efficiency. As in scenario P, the world population starts to drop after 2050 from 8.7 billion downward to 7.1 billion people. Combined with a population that peaks in 2050 and returns to numbers below the expected 2020 world population, this leads to a moderate increase of CO_2 and non-CO_2 greenhouse gas emissions and resulting concentrations in the atmosphere for Q. Increasing affluence leads to better living conditions, birth control and health care. Reduced fertility leads to a stabilizing global population in the middle of this century and a gradual decrease of global population between 2050 and 2100. Urbanization is halted or even reversed to more decentralized living supported by the information revolution. Affluence measured as the per capita gross regional product converges among world regions at a faster rate than in the BAU IPCC92 scenarios. The economy becomes more oriented to services and information exchange. As a consequence there is an increasing decline in the energy intensity and materials intensity of production. Renewable resources increasingly replace fossil fuels. The methane emissions from fossil sources will decrease compared to scenario P. The growing energy demand in the tropical regions and the high degree of energy efficiency measures makes electricity the most important energy carrier. Technology transfer from OECD countries to less developed regions is very successful in Q, and the industry in the more populous regions such as India and China is converted to comply with the highest pollution prevention standards in the world. Fuel desulphurization is becoming standard. The energy efficiency of power production and production in iron and steel and the chemical industry in India and China is increasing at a high rate of at least 1–1.5 per cent per year. In power production the conversion efficiency increases with at least 10 per cent between 2000 and 2100 to 48 per cent for coal, 53 per cent for oil and 58 per cent for gas. Transmission losses in power lines decrease to 8 per cent in all regions in 2100. Lower energy and material intensity in manufacturing results in falling energy demands in industry. Technology transfer from the industrialized countries to the less industrialized regions is accelerated to combat pollution. Materials recycling becomes a global business. Increasing recycling of waste reduces landfill methane emissions. To solve congestion, public transport is boosted by large investments. Examples are subways in larger cities, bicycling lanes and clean electric buses. Fast trains connect the larger cities. Air traffic is largely intercontinental. Private cars remain important, but saturation occurs in use at lower than present-day levels in the US. Hybrid and electric cars are increasing because of low petrol use, low noise and reduced pollution. Bicycling also increases. The rapid expansion of telecommunication and information technology gives the less developed regions large opportunities. Cell phones and satellite systems become the means of communication in Africa and Latin America. The growth of mega-cities is slowing down. Governments understand that in metropolitan areas large investments are needed in public transport to reduce urban pollution. The quality of systems to collect garbage and of landfill management needs improving. Landfill gas recovery and use is improved, but especially in the methane reduction strategies. Traditional burning of biomass is abandoned and biomass is increasingly used to produce liquid fuels or in BIG/ISTIG technology.

Especially for the land-rich regions such as Latin America and Africa the production costs of biomass-derived fuels drop to \$2–3/GJ. The land surface that is used for biomass fuels is at least 800 million ha or the size of Brazil to meet demands. Plantations for biomass or biofuels show a strong increase in all regions. Trade in biomass-derived liquid fuels between regions is increasing. Cultivation occurs on surplus agricultural land and does not lead to additional deforestation. In earlier scenario analysis with a low energy supply system (Leemans et al, 1998), plantation forests were assumed to encroach on virgin tropical forests with a risk of declining biodiversity. Globally, the pressure due to the major increase in the demand for food and fodder in the period 1990–2030 is almost completely compensated by an increase in productivity. In agriculture, average yields in cereals for example in non-OECD countries increase by a factor of four. In OECD countries, these increase by a factor of two. Forest area is declining until 2030 but expanding after 2030. More efficient agriculture and improved production relieve the pressure on pristine forests. The improved production in agriculture leads to an expansion of forest area of 30 per cent in the period between 2030 and 2100. Large forest reserves are implemented and developed for eco-tourism. The number of dairy cattle shows a decline in this century because the improvement in production efficiency is faster than the growth of milk consumption. The number of slaughtered animals for beef increases in the period 1995 to 2060 as a result of increasing consumption of meat notwithstanding the increasing animal productivity. The consumer trend is away from the Western-style diet with high meat consumption, as people become aware of its implications on land use and health. This results in lower livestock numbers and related reductions in methane emissions. Farmers shift to sustainable practices. As a result, fertilizer use starts declining. This reduces nitrous oxide emissions from high input agriculture. Subsistence agriculture and fuelwood use rapidly decline. Self-sufficiency in food production is increasing but food trade remains large in a safe world. Logging becomes sustainable and most wood is produced from plantations. In some regions, production of commercial biofuels is increasing. Large pristine forest areas are converted to conservation areas to safeguard biodiversity. Promoting compact cities and major transport and communication corridors controls human settlements. Current infrastructure is improved rather then extended.
The total costs of the efforts needed to limit CH_4 emissions in a growing economy under the P2, P3 and Q2, Q3 scenarios are then calculated by comparing with the baselines of P1 and Q1.

5.4.2 Assumptions about costs of measures

Often a cost curve of measures is made to illustrate that profitable and cheap options will be chosen first and the more expensive options will be taken later. In general an assumption is made that costs of the same measures will be reduced when taken later in time. I have taken a different approach. Reduction options have been introduced simultaneously in different sectors. I assumed that the cheapest options (i.e. < \$50 per ton of CH_4) for each sector would be chosen before 2025. I assumed that the more expensive options would be introduced in reduction package P3 and Q3 (maximum CH_4 reduction) only after 2025.

Biomass burning
For a reduction of CH_4 emissions from biomass burning a cost estimate is used of \$200 per ton of reduced CH_4 for reduced deforestation for all regions and for all years from Byfield et al. (1997).

Waste and savanna burning

For agricultural waste and savanna burning a cost estimate of $150 per ton of reduced CH_4 is used, based on reduced burning of agricultural waste and savanna in all regions and all years from Byfield et al. (1997).

Landfills

For landfills it is assumed that the most profitable measures could only be taken after development of the gasification technique. Therefore a "cost" is assumed of $-50 in 1990 and 2000 for the introduction of landfill gas recovery for heat generation (where a negative cost denotes a net profit), based on information from AEAT (1998) and Blok and De Jager (1994). A "cost" is assumed of $-200 per ton of reduced CH_4 in 2025 and 2050 for landfill gas recovery and upgrading, based on Meadows et al (1996) and AEAT (1998). A "cost" is assumed of $-350 in 2075 and 2100 for controlled gasification of waste based on Blok and De Jager (1994). Because of a lack of information no distinction between regions could be made, therefore it is assumed that the costs are the same in all regions.

Sewage treatment

For CH_4 reductions in sewage treatment a steady cost increase is assumed from $50 in 1990 to $500 in 2100 for all regions, based on information from Byfield et al. (1997) for the increased on-site use of biogas. A cost of $50 is assumed in 1990-2010 in OECD regions where sewage treatment plants have already been build, and $100 in 2000, $200 in 2025, $300 in 2050, $400 in 2075 and $500 in 2100 in non-OECD regions. The reason for the increase in costs is that the investment costs for sewage treatment plants is rather high and sewage treatment plants will have to be build in the non-OECD regions. As noted earlier, wastewater and sewage treatment plants are mainly developed to improve the health and living conditions of the people. Anaerobic digesters can be flared or the CH_4 used for cogeneration to reduce CH_4 emissions from biomass or liquid effluents with high organic content. Because most centralized systems automatically either flare or capture and use CH_4 for safety reasons, add-on abatement technology for existing wastewater treatment plants do not exist. As a result potential emission reductions depend on large scale structural changes in wastewater management. For this reason the cost of CH_4 reduction in sewage treatment is difficult to estimate. Overriding economic and social factors influence wastewater treatment practices throughout the world. The benefits of installing wastewater systems in developing countries for the purpose of disease reduction greatly outweigh potential benefits associated with CH_4 reduction. It would be misleading to imply that costs of CH_4 measures would be the only driving force behind investment decisions that influence CH_4 emissions from wastewater.

Rice paddies and wetlands

A reduction in CH_4 emissions from rice fields is relatively easy to achieve. Costs for CH_4 reduction in wetland rice are only $5 per ton CH_4 for intermittent draining and other cultivation practices, based on information from Byfield et al. (1997). Methane reduction from natural wetlands is not practised, although reclaiming wetlands is a feasible but expensive measure, only to be used to increase agricultural lands. Natural drainage of wetlands also risks enhancement of CO_2 losses from these systems. No significant net emission reductions from this latter strategy are expected therefore.

Enteric fermentation
The reduction of CH_4 emissions from ruminant animals is a combined effect of increased genetic merit resulting in more efficiency in meat and milk production and reduced animal numbers. The costs of genetic improvement are very low, with and estimated \$5 per ton reduced CH_4 for improved feeding (EPA, 1998). Production-enhancing agents are more expensive (about \$400, according to AEAT, 1998) and also unacceptable to many consumers in Europe. Products to increase rumen efficiency are in the experimental stage. They are even more expensive (about \$3000 to \$6000 according to AEAT, 1998), are also unacceptable to many consumers and have not yet been introduced.

Animal waste
Methane emission reduction by anaerobic digestion in animal waste management systems with biogas recovery and use is expensive. Costs are variable depending on climate and an overall cost of \$500 is assumed in all OECD regions. Costs are higher - with \$1000 - in non-OECD regions, where manure digestion can only be introduced at high investment costs.

Fossil fuel exploitation
For CH_4 emissions from fossil fuel exploitation it is assumed that the most profitable measures would be taken first. Therefore, increased maintenance is assumed at a “cost” of \$-200 per ton CH_4 in 1990 and increased on-site use of otherwise vented gas at a cost of \$-100 in 2000 and 2025. Other measures are taken later in time at a cost of \$100 in 2050, \$200 in 2075 and \$300 in 2100. In 1990, the introduction of improved inspection and maintenance is assumed. In 2000 and 2025 extra measures are taken to increase on-site gas use from vents and flares. The more expensive measures are taken between 2050 and 2100. Cost estimates are based on AEAT (1998) and De Jager et al. (1997). The cost development is based on my own assumptions.

The content of the CH_4 reduction options are summarized in Table 5.5 along with the assumptions made on the costs of measures.

Table 5.5 Overview of options and costs that were used in the six CH_4 reduction strategies in this study to reduce CH_4 emissions

Source of CH_4	Description of option	US$$_{1990}$/ ton of avoided CH_4 per year	Reference
Oil and gas production	Increased inspection and maintenance	-200	De Jager et al., 1996
	Increased own use of otherwise vented methane at oil and gas production sites offshore	-100-10	De Jager et al., 1996
	Increased flaring instead of venting	200-400	De Jager et al., 1996
Oil and gas transmission	Accelerated pipeline modernisation	500-1000	De Jager et al., 1996
Gas distribution	Improved leak control and repair	200	De Jager et al., 1996
Coal mining	Pre mining degasification	40	IEA, 1999
	Enhanced gob-well recovery	10	IEA, 1999
	Ventilation air use	10	IEA, 1999
Cattle enteric fermentation	Improved production efficiency	0	Blok and De Jager, 1994
	Improved feeding	5	EPA, 1998
	Production enhancing agents	400	AEAT, 1998
	Reducing animal numbers	0	Blok and De Jager, 1994
	Increase rumen efficiency	3000-6000	AEAT, 1998
Manure	Dry storage	200	AEAT, 1998
	Daily spreading	2000	AEAT, 1998
	Large scale digestion and biogas recovery	1000	AEAT, 1998
	Small scale digestion and biogas recovery	500	AEAT, 1998
Sewage treatment	Increased own use of biogas	50-500	Byfield et al. 1997
Landfills	Reduction of biodegradable waste to landfill by paper recycling	-2200	Meadows et al. 1996
	Controlled gasification of waste	-350	De Jager et al., 1997
	Landfill gas recovery and upgrading	-200	Meadows et al. 1996
	Landfill gas recovery and use for heat	-50	Meadows et al. 1996
	Reduction of biodegradable waste to landfill by composting or incineration	1000-1800	Meadows et al. 1996
Rice	Intermittent draining and other cultivation practices	5	Byfield et al. 1997
Biomass burning	Improved burning of traditional fuelwood	-100	Byfield et al., 1997
	Reduced deforestation	200	Byfield et al.1997
	Reduced agricultural waste and savanna burning	150	Byfield et al.1997

Table 5.6 Costs of reduction measures $\$_{1990}$/ton of CH_4/yr in the period 1990-2100 (based on literature and own assumptions).

Costs of reduction measures in US$\$_{1990}$/ton of CH_4/yr in	1990	2000	2025	2050	2075	2100
Biomass burning	200	200	200	200	200	200
Agricultural waste burning	150	150	150	150	150	150
Savanna burning	150	150	150	150	150	150
Landfills	-50	-50	-200	-200	-350	-350
Sewage	50	100	200	300	400	500
Wetland rice	5	5	5	5	5	5
Animals	5	5	5	5	5	5
Animal waste	500	500	500	500	500	500
Fossil fuel exploitation	-200	-100	-100	100	200	300

The content of the CH_4 reduction packages is given in chapter 6. It is assumed that the more expensive options are taken after 2025 and that measures costing more than $500 per ton avoided CH_4 were too expensive for adoption. Table 5.6 gives an overview of the costs of mitigation by source sector and its assumed variation over time.

5.5 Results

Twenty eight CH_4 mitigation options have been identified in this analysis. At least nine profitable options are apparently available, mainly in coal, oil and gas production. The most expensive options involve manure management. The cost estimates vary, but at least a common methodology is used to arrive at broadly comparable results. The overall costs per sector for six CH_4 reduction strategies in the scenarios are now estimated. Costs of reduction strategies are estimated against baseline scenario's. Scenario's are described in more detail in the next chapter.

Cost estimates of six reduction strategies

The total cost estimates for the different reduction packages are estimated relative to the baseline reduction strategies P1 and Q1. The cost estimates are given in terms of $\$_{1990}$ for six time steps between 1990 and 2100. The estimates beyond 2025 must be interpreted with caution because the reduction strategies P1 and Q1 are based on a number of important implicit assumptions about future economic policies at the macroeconomic and sectoral levels, including sectoral structure, resource intensity, prices and technology choice. Costs of moderate abatement in P2/Q2 is given in Table 5.7 and costs of maximum abatement in P3/Q3 is given in Table 5.8.

To put these costs in perspective, 1 per cent global GDP increase equals $250 billion (IPCC, 2001). The profits in P2 in 2100 are about 0.1 per cent GDP. The costs are lower than 0.1 per cent GDP in all years according to these tables. Total costs in 2000 are $67-93 million. In 2025 total costs are negative in all strategies, so profits can be made by reducing CH_4 of between $1.7 billion and $6.7 billion. After 2050, in the moderate CH_4 strategies P2 and Q2, profits can also be made. In 2050, in the maximum abatements strategies P3 and Q3 costs have to be incurred because some expensive options are included. After 2050, costs are variable in the maximum CH_4 abatement strategies P3 and Q3 because both the profits in landfills and the costs in the sewage sector and fossil fuel industry are high. However, costs are negative in all measures where CH_4 is captured and used for energy generation. Costs become higher after 2050 in the sewage sector because more regions are including sewage treatment, and in addressing leakage in the fossil fuel industry because increasingly expensive options are deployed.

Costs to reduce CH_4 from landfills and the fossil fuel industry depend to a large extent on the value of the CH_4 for the energy companies involved in utilizing any captured CH_4. Measures will be less profitable in a market with abundant alternatives. Recently, over-capacity of electricity production in different regions in the world resulted in lower prices for CHP and in the price for alternative fuels. In such a situation, investment in technical measures for CH_4 reduction from landfills and the fossil fuel industry will be more difficult to obtain. It is very difficult to look far into the future to predict the profits from CH_4 capture. Here, only a first attempt has been made. The results beyond 2025 must be considered as very preliminary. From table 5.7 it seems that, overall, profitable reductions in CH_4 are possible in the moderate CH_4 reduction packages. The profitable reductions in the maximum CH_4 abatement packages in Table 5.8 seem to be outweighed by the more expensive options, resulting in high costs in 2050, reduced costs in 2075 and high costs in 2100 for P3, but profits for Q3.

Methane capture from landfills can be very profitable because of the potential for energy generation and related revenues. Sewage treatment with increased on-site use of CH_4 is very expensive because the energy that is generated is not sold to another party. In sewage treatment, the investment costs in terms of CH_4 mitigation alone are very high and sewage treatment has yet to be introduced in many regions in the world. However, the benefits of investment will likely also include improved human health and reduced water pollution. Methane capture in the coal, oil and gas sectors is very expensive in the longer term because the cheap/very profitable options have already been taken before 2025.

Table 5.7. Worldwide costs in US$$_{1990}$ thousands of CH_4 abatement in reduction strategies P2 and Q2.

P2	1990	2000	2025	2050	2075	2100
Biomass burning	0	-2000	44200	-15000	17200	-10200
Agricultural waste	0	80550	625950	1355100	1499250	1406700
Savanna burning	0	900	360300	700350	1069200	1552650
Landfills	0	0	-3558400	-10788400	-26329800	-28511000
Sewage	0	0	0	0	0	0
Wetland rice	0	-25	-5	-45	440	625
Animals	0	-10	-250	165	50	-245
Animal waste	0	-100	900	-2200	-2500	300
Leakage	0	0	0	0	0	0
Total sectors	0	79315	-2527305	-8750030	-23746160	-25561170

Q2	1990	2000	2025	2050	2075	2100
Biomass burning	0	-12800	-4200	51800	44200	4800
Agricultural waste	0	79500	493650	1329450	1423200	1242750
Savanna burning	0	0	300450	822450	1260750	1897200
Landfills	0	0	-2476400	-10365800	-24123750	-27186600
Sewage	0	0	0	0	0	0
Wetland rice	0	75	-40	770	-500	185
Animals	0	70	-20	-410	-700	-220
Animal waste	0	200	-1400	-2100	-2400	-800
Leakage	0	0	0	0	0	0
Total sectors	0	67045	-1687960	-8163840	-21399200	-24042685

Note: Negative costs are profits

Table 5.8. World-wide costs in thousand $\$_{1990}$ of CH_4 abatement in reduction strategies P3 and Q3.

P3	1990	2000	2025	2050	2075	2100
Biomass burning	0	-11400	39400	53000	21000	0
Agricultural waste	0	0	300	-3150	-7500	47550
Savanna burning	0	150	455400	877050	1496550	2331450
Landfills	0	0	-4448400	-13486200	-36861650	-42767550
Sewage	0	0	1873600	6191700	11033600	15031500
Wetland rice	0	0	8125	40640	52785	57430
Animals	0	35	60	690	2230	-975
Animal waste	0	-400	3000	1300	1300	-600
Leakage	0	80900	-3816400	7902700	21690400	30019500
Total sectors	0	69285	-5884915	1577730	-2571285	4718305

Q3	1990	2000	2025	2050	2075	2100
Biomass burning	0	12600	1000	3800	79400	4800
Agricultural waste	0	79800	493350	1329450	1423050	1242900
Savanna burning	0	-900	373950	1031400	1724250	2847900
Landfills	0	0	-3095800	-12956800	-33170900	-40779200
Sewage	0	0	1444400	6191700	10616800	15031500
Wetland rice	0	75	45	46140	57300	66625
Animals	0	175	-620	-1385	455	1360
Animal waste	0	600	-4500	-5100	1900	1200
Leakage	0	0	-5924800	9210200	14190600	11583300
Total sectors	0	92350	-6712975	4849405	-5077145	-9999615

Note: Negative costs are profits

5.6 Conclusions

I calculated the technological potential for CH_4 reduction – the amount by which it is possible to reduce greenhouse gas emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated. The emission reduction is calculated with respect to a baseline scenario of development (see chapter 6).

The economic potential is the proportion of the technological potential for CH_4 emission reductions or energy efficiency improvements that could be achieved cost effectively through the creation of markets, reduction of market failures, increased financial and technological transfers. The achievement of economic potential requires additional policies and measures to breakdown market barriers. Measures are cost-effective when the benefits of the measures are larger than the costs (including interest and depreciation). We could not calculate the economic potential of CH_4 reductions because it is difficult to assess the direction of future policies aimed at stimulating CH_4 reductions through the reduction of market failures. It is also difficult to assess the future price of oil, which helps to dictate the willingness to search for alternatives.

Our research question was: which options are available to reduce CH_4 emissions? We concluded that, in total, 28 options can be selected based on demonstrated technologies that can be deployed immediately. Another research question was: What are the overall costs of the options? From calculations of the total reduction costs of the maximum CH_4 reduction strategies P3 and Q3 we can conclude that options to reduce CH_4 from landfills are very promising indeed. Options to reduce CH_4 from leakage in the fossil fuel industry are more expensive after 2025. Options to reduce CH_4 from sewage treatment are expensive because investment costs are high and CH_4 can rarely be sold to a third party.

Overall, it can be concluded that CH_4 emission reductions are relatively cheap in 2050 and 2100 with less than 0.1 per cent of GDP. The benefits include both global climate change mitigation and an improved public health through improvements in local air quality and sewage treatment. Methane emissions reductions are all profitable until 2025 and again in 2075 and 2100 for Q3. Options to reduce leakage in oil and gas will become more expensive after 2025. The emission reductions of CH_4 after 2025 are very profitable for landfill gas. This option is so profitable that it reduced the overall costs of all options. Sewage treatment can become more profitable if CH_4 can be sold to third parties.

6. SCENARIO ANALYSIS

Based on: Van Amstel, 2005: Integrated assessment of climate change with reductions of methane emissions. Environmental Sciences 2, 2-3: 315-327.

6.1 Introduction

In this chapter a scenario analysis is carried out to assess the effect of methane reductions on the future climate. Two baseline scenarios are described with contrasting developments in carbon dioxide emissions. The effect of six methane reduction strategies is evaluated. It will be assessed if methane reductions alone would already have an effect on the future climate, while taking into account the developments of all the other important trace gases.

The increase in greenhouse gas emissions that took place over the last decades is influencing climate (IPCC, 2007). Hansen et al. (2000) started a scientific debate on the individual contributions of the different trace gases to such climate change. They argued that most of the warming in recent decades has been driven mainly by the non-CO_2 greenhouse gases, such as chlorofluorocarbons, methane and nitrous oxide, and less by the products of fossil fuel burning (CO_2). Their main argument was that the positive and negative climate forcing of fossil fuel related CO_2 and aerosols cancel each other out largely. Therefore, immediate reductions in the anthropogenic emissions of the non-CO_2 greenhouse gases will have the maximum positive effect on reducing climate change in the near future. This is not entirely the case because of the differences in lifetime in the atmosphere of CO_2 and the short lived aerosols. Swart et al. (2004) in response to Hansen argue that all anthropogenic emissions of trace gases should be reduced at the same time to reduce both the greenhouse effect and local air pollution to increase public health.

An integrated analysis of the future climate as affected by changes in fluxes of trace gases is complicated. In an integrated assessment the linkages between the physical processes in the different compartments and the socio-economic developments are taken into account. The costs of possible measures to reduce emissions are taken into account. Some authors have studied the costs of reductions of non-CO_2 greenhouse gases for the period 1990 – 2025 (e.g. IEA, 1999; Hayhoe et al., 1999 and 2000; DelaChesnaye and Kruger, 2002; USEPA, 2002; Gallaher et al., 2005; Schaefer et al, 2009). Climate change benefits were not assessed in most of these studies and therefore no definite conclusions could be drawn on the climate benefits of the proposed CH_4 reductions. De Vries et al. (2000), however, have applied an integrated approach with IMAGE to assess the effects on future climate of a more sustainable development path in the 21st century. They found that a sustainable development path could reduce the CO_2 emissions and postpone the effects on the climate. However in their analysis the effect of methane reductions was not taken into account.

The debate started by Hansen et al. (2000) has shown the importance of an integrated approach to climate change. In an integrated approach the effect of methane reductions alone is analysed while defining the developments in the other greenhouse gases in scenarios. Only an integrated approach can verify their claims. In such an approach the consequences of various strategies reducing the enhanced greenhouse effect can be established. In this chapter therefore the aim is to adopt an integrated approach to answer the following research question:

What are the effects of methane emission reductions on future climate change?

The methodology for answering this question contains several building blocks. First I will describe two contrasting scenarios and develop three methane emission reduction packages for each scenario for the long run (1990-2100). These reduction packages are: no methane reduction, moderate methane reduction and maximum methane reduction. The scenarios depict different possible futures and the reduction packages show different ways of combining methane abatement options. Finally an existing integrated assessment model (IMAGE) is used to analyse the consequences on the future climate of six emission reduction strategies. The indicators chosen are: trace gas concentrations, temperature change, sea level change. I define a reduction strategy as a scenario plus a methane abatement package.

This chapter has the following structure. In section 6.2 I will describe the IMAGE model. The input to IMAGE is described in the scenarios (section 6.3), and six emission reduction strategies (section 6.4). In section 6.5 I combine the scenarios and emission reduction packages and run the IMAGE model. The control costs are estimated off-line. These were reported in chapter 5. In section 6.6 conclusions will be given. It is shown that methane reductions alone can already reduce the climate impact of the scenarios. The effects on the chosen indicators of the different packages proved to be small.

6.2 Description of the IMAGE model

The Integrated Model to Assess the Global Environment, IMAGE version 2.1, described by Alcamo et al. (1998) is used for the integrated assessment of climate change under two different scenarios for the future (1990-2100) each with three different methane reduction packages. IMAGE is developed at the National Institute for Public Health and the Environment (RIVM, Bilthoven, the Netherlands), and a wide variety of publications on IMAGE exist (Alcamo et al., eds. 1998; Leemans et al., 1998; Posh et al., 1998; Swart et al, 1998). IMAGE 2.2 with the implementation of the SRES scenarios is documented on RIVM CD-ROM Publication 481508018, National Institute of Public Health and the Environment, Bilthoven.

Description of three linked systems in IMAGE

IMAGE consists of three fully linked systems of models: the Energy-Industry System (EIS), the Terrestrial Environment System (TES) and the Atmosphere-Ocean System (AOS). The driving forces are population, technological change and economic developments (Alcamo et al., 1998).

The energy-industry system EIS

The objective of the Energy-Industry System is to compute the emissions of greenhouse gases, ozone precursors and sulphur dioxide from 13 world regions and for five sectors as a function of energy consumption and industrial production. Model calibration is based on IEA statistics 1971-1990. The Energy-Industry System is designed especially to investigate the effectiveness of improved energy efficiency and technological development on future emissions in each region. It can be used to assess the consequences of different policies and socio-economic developments on future emissions. Regional population and regional economic activities are used in the EIS to calculate greenhouse gas emissions from fuel use, industrial processes and biofuel demand. The greenhouse gas emissions are linked to the Atmosphere Ocean System and the biofuel demand is linked to the Terrestrial Environment System. The energy economy model divides the energy economy of each world region into five energy sectors (residential, industrial, commercial, transport and others) and computes the demand for two end-use energies (heat and electricity) in each of these sectors. Seven energy carriers (coal, oil, gas, fuelwood, modern biofuels, nuclear and renewables) are used to generate end-use energy. In the long run the energy per unit activity that is required to satisfy the end-use energy demand will fall as the economy becomes more efficient. Autonomous energy efficiency improvements and price induced energy efficiency improvements reduce the energy demand per unit activity. The energy emissions model finally applies emission factors to the regional energy consumed in each energy sector to compute the emissions of carbon dioxide, methane, nitrous oxide, nitrogen oxides, carbon monoxide, volatile organic compounds and sulphur oxides from energy use (De Vries et al., 2000).

The terrestrial environment system TES

The objective of the TES is to simulate global land use and land cover changes and their effects on emissions of greenhouse gases and ozone precursors, and on carbon fluxes between the biosphere and the atmosphere. This subsystem is used to investigate the effects of population, economic and technological changes on global land cover. It can be used to assess the land consequences of large scale use of biofuels (Leemans et al., 1998). The model has been calibrated for the period 1971-1990 using statistics of the Food and Agriculture Organisation (FAO). The agricultural economy model has been developed to compute the demands for a number of commodities that require land. Four demand categories are taken into account: food, feed, timber and biofuels. Calculations are performed for the 13 world regions. The agricultural economy model begins by calculating per capita human consumption of different crops and meat products taking into account preferred consumption patterns. The resulting regional demands for food consumption are translated into regional demands for food production by including world food trade. The demand for meat products is converted into livestock and livestock feed requirements by taking into account animal productivity and slaughter rates. Simulation of world timber production is used for the calculation of demand for forestland. The Terrestrial Vegetation Model calculates the productive potential of available land resources on a grid basis from local (grid) climate, terrain, and soil conditions. The Land Cover model links the regional land use demands with the grid based productive potential. If the available land is insufficient to satisfy the land use demands, the land use dominated land cover types (agricultural land or secondary forest) expand at the expense of natural vegetation. If the available land exceeds the demand for agricultural produce, agricultural land is abandoned and reverts back to the potential natural vegetation under the local climate (De Vries et al., 2000).

The land cover changes are used as input to the Terrestrial Carbon model which simulates the terrestrial carbon fluxes. Four major land cover conversions are taken into account: natural vegetation to agricultural land (cropland or pasture), agricultural land to natural vegetation, forest to secondary forest, natural vegetation shifts from one type to another. One of these conversions is deforestation. Then, natural vegetation with a high carbon stock is converted into agricultural land or secondary forest. Part of the carbon is then emitted to the atmosphere through biomass burning, part of it is stored in wood products, part of it is used as traditional fuel wood and part moves into nonliving biomass and decomposes. Finally, the Land Use Emissions model simulates the non-CO_2 greenhouse gas emissions from land-use related sources (De Vries et al., 2000). Emissions from changed demands from society for biofuel, crops, fodder and animal products are calculated. The emissions are used to calculate resulting concentrations of greenhouse gases in the Atmosphere-Ocean System. AOS takes into account feedbacks from the climate system to the terrestrial vegetation and carbon.

The atmosphere-ocean system AOS

The objective of the Atmosphere-Ocean System of models is to compute climate change, sea level rise, and the build-up of greenhouse gases and aerosols in the atmosphere. The Atmospheric Composition model computes the atmospheric concentrations of greenhouse gases based on CO_2 fluxes and other emissions computed by EIS and TES. The atmospheric concentration of CO_2 depends on the important flux of CO_2 between the atmosphere and the ocean. The uptake is computed in the Ocean Biosphere and Chemistry model. The final concentrations of greenhouse gases determine changes in radiative forcing. This is calculated in the Zonal Atmospheric Climate Model, which is then coupled with the Ocean Climate model to compute the earth's heat balance. Climatic change is calculated by changes in surface temperatures and precipitation. Feedbacks on the carbon flux between the biosphere and the atmosphere, the occurrence of sea ice and other processes are taken into account in IMAGE simulations. IMAGE requires Global Circulation Model results to downscale zonal average temperature and precipitation patterns to the grid level. In the AOS the following important specific links are included. The temperature effect on atmospheric moisture and hydroxyl radicals. Increasing temperature in the troposphere leads to higher water vapour, this increases the formation of hydroxyl (OH) radicals. This increases the atmospheric sink for methane. The effect of changes in gas concentrations on radiative forcing is also taken into account in the AOS system. Methane and HCFC's are removed from the troposphere mainly by bimolecular reactions. Atmospheric lifetimes are determined by these reactions. Thus the lifetimes of these gases are not constant in time. This influences the global warming potential and the contribution to the radiative forcing. For example the lifetime of methane in 2100 varies by more than 50% between the different scenarios computed by IMAGE.

Modelling the methane concentrations in IMAGE

Krol and Van der Woerd (1994) and De Haan et al. (1994) describe the modelling of methane concentrations in the atmosphere and the related radiative forcing in IMAGE for the period 1990 to 2100. In 1996 the cooling effect of SO_2 was included in the IMAGE model for Europe and Asia as described by Posch et al. (1996). In the IMAGE model the effect on its own lifetime of changes in the concentrations of methane are included. In IMAGE atmospheric chemistry of all greenhouse gases and other pollutants are included. The future radiative forcing by non-CO_2 greenhouse gases depends on the behaviour of the OH radical, the primary sink for CH_4, CO and HCFCs in the atmosphere. In table 6.1 values for the parameters in the concentration equations are given for the compounds that are assumed not to be in equilibrium in the atmosphere. Note that the lifetime for methane is not given but calculated for each timestep in the model.

Table 6.1: Values for the parameters in the concentration equations of the compound assumed not to be in equilibrium as used in the IMAGE 2.1 atmosphere-ocean module. (Source: Krol and Van der Woerd, 1994).

Compound	pX (1990)	Em_x (1990)	f_x	lft_x	K_{x+OH}	L_x
CO_2	354 ppmv	7.4 Pg	0.469			
CH_4	1.72 ppmv	506 Tg	0.00039		$1.23\ 10^{-7}$	0.0091
CO	0.095 ppmv	1164 Tg	0.000222		$5.93\ 10^{-6}$	0.473
N_2O	308 ppbv	12.9 TgN	0.212	150		
CFC-11	272 pptv	298 Gg	0.0413	55		
CFC-12	471 pptv	362 Gg	0.049	116		
CFC-113	70 pptv	147 Gg	0.0316	110		
CFC-114	18.5 pptv	13.1 Gg	0.0347	220		
CFC-115	5 pptv	6.5 Gg	0.0384	550		
CCl_4	109 pptv	119 Gg	0.0385	47		
HCFC-22	113 pptv	138 Gg	0.0723		$9.05\ 10^{-8}$	0.0042
CH_3Cl	600 pptv	4000 Gg	0.124		$8.79\ 10^{-7}$	0.02
CH_3CCl_3	140 pptv	378 Gg	0.0469		$2.20\ 10^{-7}$	0.0213

pX and Emx are the atmospheric concentration and emission in the base year 1990 for the compounds. The conversion factor from emissions to concentrations is fx (in their respective units). Kx+OH is the reaction rate for the oxidation of x by OH in $cm^{-3}.a^{-1}$. Lftx is the average atmospheric lifetime in years. Lx is the transport loss to both stratosphere and biosphere per year.

The main sink is the oxidation of methane by OH, proportional to both the methane and the OH concentration. The OH production is calculated as a function of the concentrations of its precursors: the exited oxygen atom and tropospheric water vapour. The loss of OH is taken to be caused by CH_4 and CO alone. Details are given by Krol and Van der Woerd (1994). The radiative forcing is calculated from concentrations of all greenhouse gases. For most gases a globally averaged concentration is used except for O_3. Ozone distribution for the troposhere is taken from the TNO-Isaksen model, and changes in this field between present and scenario's is given as basic profiles (De Haan et al. 1994).

6.3 Scenario description

6.3.1 General description

Introduction

Two scenarios, P and Q, will be described in terms of their driving forces: population development, economic growth, energy use and technological change. Scenarios P and Q are developed by the IMAGE team at RIVM as input to the development of scenarios for the IPCC Special Report on Emission Scenarios (IPCC, SRES, 2000). I used these two scenarios from this IMAGE exercise to develop six reduction strategies for methane.

Relation with SRES scenarios

In a Special Report by IPCC on Emission Scenarios (SRES) the existing scenario literature was reviewed. Because the range of possible futures is very large and diverse, different existing scenarios were grouped by IPCC in scenario families A1, A2, B1, B2 (Table 6.2). Scenario families are groups of scenarios from different institutes in the world with comparable assumptions. The P and Q scenarios were developed before the SRES scenarios. Therefore, the scenarios differ to some extent from the published SRES scenario results..The P scenario can be categorised in the A1B (A1 balanced) scenario (IPCC, 2000). The Q scenario can be categorised in the B1 scenario (IPCC, 2000; De Vries et al., 2000). The A1B scenario describes a world with increasing affluence because of a 3% annual economic growth. In A1B population peaks at 8.7 billion in 2050 and is reduced to 7.1 billion in 2100. The B1 scenario describes a world with less economic growth in which energy efficiency measures are taken and material intensity of production is reduced. Population development is the same as in A1. In terms of the resource base in B1 only identified resources are available and in A1 also the unconventional resources are included (Rogner, 1997; Bentley, 2002).

One of the key characteristics of the P and Q scenarios is that they are based on relatively low predictions for future population. The United Nations regularly produces and updates population outlooks into the future. Even their low expectations still assume growth over the 21st century. The choice for low population outlooks in P and Q is justified by information on population developments in the future from the International Institute for Applied Systems Analysis (IIASA) by Lutz et al. (2001). Because of increasing affluence in all regions in the world, fertility is expected to decline and the world population is expected to stabilise by 2050. World population is expected to slowly decrease between 2050 and 2100 to below the envisaged 2020 level.

In the following, storylines of the scenarios P and Q are described with respect to the most important characteristics of the scenarios. These storylines are based on the existing SRES scenarios because the scenarios P and Q are in general agreement with SRES scenarios A1B-IMAGE and B1-IMAGE (De Vries et al., 2000).

Table 6.2. Basic assumptions of scenarios from the SRES scenario families (Source: IPCC, 2000).

Scenario family	A1	B1	A2	B2
Illustrative scenarios	A1B	B1	A2	B2
Population 2020	7.5 billion	7.6 billion	8.2 billion	7.6 billion
Population 2050	8.7 billion	8.7 billion	11.3 billion	9.3 billion
Population 2100	7.1 billion	7.1 billion	15.1 billion	10.4 billion
World GDP in 2020	56 10^{12} $US\$_{1990}$	53	41	51
World GDP in 2050	181	136	82	110
World GDP in 2100	525	330	243	235
Resource base	Including unconventional Oil, Hydrates etc	Identified resources	Including unconventional Oil, Hydrates etc.	Identified resources

Storyline for Scenario P

A storyline is a qualitative description of a scenario. Later in this section a quantitative implementation of these storylines in IMAGE will be described. A description of the main driving forces will be given here. Economic growth and the energy efficiency of production and consumption drive the energy demand of society. The International Energy Agency regularly produces world energy outlooks for the energy use in the future (2000). These have been used together with assumptions on energy efficiency improvements to assess the energy demand in both scenarios. The food, fibre and wood demands of a growing population are driving land use changes. These are calculated in the scenarios to assess the encroachment of permanent agriculture and plantations on virgin forests.

Economy, population growth and energy.
Scenario P describes a prosperous world with an economic growth of 3% per year, with a relatively low population growth, resulting in 8.7 billion people in 2050 and 7.1 billion in 2100. Present trends of globalisation and liberalisation are assumed to continue, in combination with a large technological change through innovations. This leads to relatively high economic growth in both the industrialised and the non-industrialised regions in the world. Affluence in terms of per capita Gross Regional Product converges among world regions, although the absolute differences in affluence are growing. Increasing affluence results in a rapid decline in fertility. The global economy expands at an average annual rate of 3% to 2100, reaching around US$ 525 trillion. This is about the same as average global growth since 1850. Global average income per capita reaches about US$ 21.000 by 2050 contributing to a great improvement in health and social security for the majority of people (IPCC, 2000).

Mobility and communications
High income translates into high car ownership, sprawling suburbia, and dense transport networks (IPCC, 2000).

Manufacturing
Increasing service and information orientation leads to a significant decline in intensity of energy and materials. Energy and mineral resources are abundant in this scenario because of the rapid technical progress. This reduces resource use per unit of

output, but also the economically recoverable reserves. Methane emissions from fossil sources are growing. Final energy intensity (end use energy per GDP) decreases at a rate of 1.3% per year (IPCC, 2000).

Land and food
With the rapid increase in income, dietary patterns are assumed to shift initially to a high meat and milk diet with related increasing animal numbers and increasing methane emissions from animals and manure, but this may decrease subsequently with increasing emphasis on the health of the ageing society. Growth could produce increased pressure on the global resources. Conservation of natural areas is changing in management of natural resources (IPCC, 2000).

Storyline for Scenario Q

Economic modernisation
To really engage on a future that is developing in a more sustainable way than at present much effort is needed from the policy makers. The Q baseline describes what is needed to make this happen. Compared to the P baseline it is a contrasting scenario with a much lower demand in all sectors because of the lower GDP development (<3% per year growth) (See table 6.1). The Q scenario describes a world where the modernisation of the OECD countries has spread to the other regions over the period 2000 to 2100. A shift takes place from an economy predominantly relying on heavy industry towards a society with an economy predominantly based on services with an increasing dematerialisation of production, recycling of materials and increasing energy efficiency.

Economy, population growth and energy.
As in scenario P, the world population starts to drop after 2050 from 8.7 downward to 7.1 billion people. Combined with a population that peaks in 2050 and returns to numbers below the expected 2020 world population, this leads to a moderate increase of CO_2 and non-CO_2 greenhouse gas emissions and resulting concentrations in the atmosphere for Q. Increasing affluence leads to better living conditions, birth control and health care. Reduced fertility leads to a stabilising global population in the middle of this century and a gradual decrease of global population between 2050 and 2100.

Urbanisation is halted or even reversed to more decentralised living supported by the information revolution. Affluence measured as the per capita Gross Regional Product converges among world regions at a faster rate than in the "Business as usual" IPCC92 scenarios (IPCC, 1995). The economy becomes more oriented to services and information exchange. As a consequence there is an increasing decline in the energy intensity and materials intensity of production. Renewable resources increasingly replace fossil fuels. The methane emissions from fossil sources will decrease compared to scenario P. The growing energy demand in the tropical regions and the high degree of energy efficiency measures makes electricity the most important energy carrier (De Vries et al., 2000).

Power and industry
Technology transfer from OECD countries to less developed regions is very successful in Q and the industry in the more populous regions like India and China is converted to comply with the highest pollution prevention standards in the world. Fuel desulfurization is becoming standard. The energy efficiency of power production and production in iron and steel and the chemical industry in India and China is increasing at a high rate of at least 1-1.5% per year. In power production the conversion efficiency increases with at least 10% between 2000 and 2100 to 48% for coal, 53% for oil and 58% for gas. Transmission losses in power lines decrease to 8% in all regions in 2100 (De Vries et al., 2000).

Manufacturing
Lower energy and material intensity in manufacturing results in falling energy demands in industry. Technology transfer from the industrialised countries to the less industrialised regions is accelerated to combat pollution. Materials recycling become a global business. Increasing recycling of waste reduces landfill methane emissions (De Vries et al., 2000).

Mobility and communications
To solve congestion, public transport is boosted by large investments. Examples are subways in larger cities, bicycling lanes, clean electric buses. Fast trains connect the larger cities. Air traffic is largely intercontinental. Private cars remain important, but saturation occurs in use at lower than present-day levels in the USA. Hybrid and electric cars are increasing because of low noise and pollution. Bicycling also increases. The rapid expansion of telecommunication and information technology gives the less developed regions large opportunities. Cell phones and satellite systems become the means of communication in Africa and Latin America. The growth of mega-cities is slowing down (De Vries et al., 2000).

Urban environmental management
Governments understand that in metropolitan areas large investments are needed in public transport to reduce urban pollution. The quality of systems to collect garbage and of landfill management needs improving. Landfill gas recovery and use is improved, but especially in the methane reduction strategies.

Biomass
In the future in Q traditional burning of biomass is abandoned and biomass is increasingly used to produce liquid fuels or in biomass integrated gasifier/intercooled steam-injected gas turbine BIG/ISTIG technology. Especially for the land rich regions like Latin America and Africa the production costs of biomass derived fuels drop to US$ 2-3/GJ. The land surface that is used for biomass fuels is at least 800 million ha or the size of Brazil to meet demands (see also Leemans et al., 1998). Plantations for modern biomass or biofuels show a strong increase in all regions. Trade in biomass derived liquid fuel between regions is increasing. In contrast to earlier analysis cultivation occurs on surplus agricultural land and does not lead to additional deforestation. In earlier scenario analysis with LESS, a low energy supply system (Leemans et al., 1998), plantation forests were assumed to encroach on virgin tropical forests with a risk of declining biodiversity.

Agriculture and pressure on the land
Globally, the pressure due to the major increase in the demand for food and fodder in the period 1990-2030 is almost completely compensated by an increase in productivity. In agriculture average yields in cereals for example in non-OECD countries increase by a factor of four. In OECD countries these increase by a factor of two. Forest area is declining until 2030 but expanding after 2030. More efficient agriculture and improved production relieve the pressure on pristine forests. The improved production in agriculture leads to an expansion of forest area of 30% in the period between 2030 and 2100. Large forest reserves are implemented and developed for eco-tourism. The number of dairy cattle shows a decline in this century because the improvement in production efficiency is faster than the growth of milk consumption. The number of slaughtered animals for beef increases in the period 1995 to 2060 as a result of increasing consumption of meat notwithstanding the increasing animal productivity.

Land and food
The consumer trend is away from the western style diet with high meat consumption, as people become aware of its implications on land use and health. This results in lower livestock numbers and related reductions in methane emissions. Farmers shift to sustainable practices. As a result fertiliser use starts declining. This reduces nitrous oxide emissions from high input agriculture. Subsistence agriculture and fuelwood use rapidly decline. Self-sufficiency in food production is increasing but food trade remains large in a safe world. Logging becomes sustainable, most wood is produced from plantations. In some regions production of commercial biofuels is increasing. Large pristine forest areas are converted to conservation areas to safeguard biodiversity. Promoting compact cities and major transport and communication corridors controls human settlements. Current infrastructure is improved rather then extended (De Vries et al., 2000).

Implementation of P and Q in IMAGE

The qualitative storylines have to be interpreted for the implementation in the IMAGE model. Here a summary will be given of this more quantitative implementation in IMAGE.

Population and economy

As mentioned above, in population a continuing decline in fertility is assumed. The assumption is that under increasing education and affluence fewer children are born. This results in a stabilisation of world population by 2050 and a decline in world population thereafter. We chose SRES scenarios with a low population development because IIASA expects an end to world population growth in 2050 (Lutz et al., 2001). A different population development path is implemented for each of the 13 different world regions in IMAGE.

Economic growth is simulated within the energy-industry system of models (EIS). Gross world product has been fixed in scenario P at US$ 525 10^{12} in 2100 and in scenario Q at US$ 330 10^{12} in 2100. Technological change is converging towards the levels of the leader regions (either Japan or the United States). These convergence processes start in 2010. The leader region grows at some rate and the other regions are trying to catch up with this leader. Increasing environmental awareness leads to lower values of energy-intensive manufacturing sectors, which ultimately decline to 7.5% of total consumption for all regions.

Energy supply and demand and power industry emissions

The fossil fuel resource base in scenario P is large with identified resources and unconventional resources, in Q it is smaller with only identified resources: 20000 to 30000 EJ for oil and 20000 to 30000 EJ for gas. For coal resources 60000 EJ are proven recoverable (Rogner, 1997). Rogner's regional estimates are used to construct the long term supply cost-curves for oil and gas. The regional useful energy intensity as a function of per capita sectoral activity level (UEI in GJ/US$) was estimated from 1971-1990 International Energy Agency data. A saturation level at high per capita activity levels was preset for each region based on past trends and regional differences in climate, population density and industrial characteristics. UEI will decrease over time as a result of energy efficiency improvement. The assumptions on these energy efficiency improvements are based on empirical evidence from the past decades as part of the model calibration. For future years they are chosen in line with the P and Q storyline.

Energy related emission factors are assumed to remain constant or show a modest decline from abatement. For example, future sulphur emissions are mitigated to combat acid deposition in line with already implemented policies in P and Q. After 2010 sulphur emissions continue to fall as a result of reduction of energy use, fuel substitution and desulphurisation. In non-OECD regions sulphur emissions in these scenarios will be increasingly controlled to avoid health damage and negative impacts on crops and ecosystems, especially in Asia. In Asia the emission factors are assumed to fall with 75% between 2000 and 2050. In other regions this will start 25 years later.

6.3.2 Baseline assumptions on methane

P1 and Q1 are considered baseline strategies for methane reduction. The costs for reduction will be calculated against these baselines. Baseline assumptions on methane emissions are described here for the scenarios P and Q. The zero methane reduction strategies are denoted P1 and Q1. Four methane reduction packages P2, Q2, P3 and Q3 will be described later in section 6.4. Together these are six reduction strategies: no reduction: P1 and Q1; moderate reduction: P2 and Q2; and maximum reduction P3 and Q3. The emissions in IMAGE are calculated using the size of an activity and an emission factor. Abatement of methane is calculated through an abatement factor linking emissions with abatement.

Methane from combustion

Methane emissions from combustion are estimated from the fossil fuel used in the economy and related methane emission factors. Emissions from non-CO_2 greenhouse gases from fossil fuel combustion in scenario Q1 show a similar pattern as the CO_2

emissions: after an increase of 50-100% in 2050, they gradually decline to below present levels. The methane emissions are reduced by fuel shifts away from coal, oil and traditional fuelwood to gas and modern biomass and an increase in solar and wind power. These fuel shifts are driven by the economic developments in the scenarios in the IMAGE model. Carbon dioxide and non-CO_2 greenhouse gases and aerosols in the Q1 scenario are lower than in the P1 scenario because less fossil fuel is needed for the economy. Methane emissions from combustion in the Q1 scenario are lower than the P1 scenario also because less fossil fuel is needed in the economy. No abatement for methane from combustion is assumed in P1 and Q1.

Methane from fossil fuel, especially the exploitation, production and distribution of coal, oil and gas

Methane emissions from coal mining, and oil and gas production are important sources of methane world-wide. Venting and leaking during energy production and transmission is especially high in Eastern Europe and Russia. Emissions are estimated from the amounts of coal, oil and gas that are produced and distributed. Emission factors are from EDGAR (Olivier et al., 1996, 1999 and 2002). For methane the losses due to fossil fuel production, including gas leakages, in P1 and Q1 are calculated from the emission factors that were held constant throughout the scenario until 2100. The methane emissions in Q1 from venting and leaking from fossil fuel exploitation and distribution is lower than in P1 because less fossil fuel is needed in the Q1 economy. These reductions follow from the different economic developments between P1 and Q1.

Methane emissions from land use and land cover related sources and methane reductions in TES of IMAGE 2.1

Emission estimates in IMAGE for historical years are from EDGAR (Olivier et al, 1999). Emissions from 2000 to 2100 are scenario results estimated from developments in the different economic sectors. The calculation of greenhouse gas emissions from land-use and land cover related sources require assumptions about the food and fibre and wood demand of people and the feed requirements from cattle. In IMAGE dietary preferences, world food trade, animal husbandry and productivity, agricultural technology (cropping intensity and fertiliser use), modern biomass for biofuel and timber demand are scenario driven. In P1 and Q1 no abatement of methane is assumed.

Methane emissions from enteric fermentation in livestock

Methane is emitted from the rumen of cattle mainly. In IMAGE 2.1 methane emissions are calculated in relation to the feed intake of the animals. Feed intake is a function of the productivity and weight of cattle. Methane emissions are assumed to be 3.5-7% of the gross energy intake. Methane emissions are relatively low in high protein feeds and relatively high in low protein feeds like straw. Increasing the production efficiency of the animals can abate methane emissions. The following relations have been established in IMAGE: Methane emission is 3.5% of feed intake if the share of high protein feeds is 20% or higher. The methane emission is 7% of feed intake if no high quality feeds are available. In between a linear relation is assumed. In the IMAGE model the number of animals is driven by the demand for meat and milk. The level of high quality feeds in developing regions is driven by GDP. It is assumed that between 1990 and 2025 the developed regions all grow to the level of high quality feeds as given in 1990 in the

USA. In the developing regions the increase of supplements depends on GDP growth. Thus abatement of methane is depending on the increase in efficiency per unit of product in the model and related to the increase in high protein feeds with economic development and the increase in production efficiency of milk and meat by breeding programmes. The difference between P1 and Q1 is a combination of higher demands and more efficient production. If production becomes more efficient, demand for meat and milk can be covered with fewer animals, leading to less methane emissions. Therefore in scenario Q1 compared to P1 fewer animals are needed to cover the demands. Therefore the methane emissions in Q1 are lower compared to P1.

Methane from manure
Methane is emitted from manure especially if it is stored in anaerobic lagoons or silos. In IMAGE 2.1 manure production is calculated per unit of live weight of different animal types. The methane emission is dependent on the methane potential of the waste and the manure management. Regional emission factors are applied. It is assumed that at this moment only in the OECD and China manure management systems are applied with high methane emissions, which can be abated. With increasing intensification of livestock breeding in other regions the emissions are expected to increase. In P1 and in Q1 in IMAGE a methane abatement factor of 0% was assumed.

Methane emissions from wastewater and sewage treatment
Methane is emitted from anaerobic wastewater treatment systems. Part of the methane is captured and used for energy. Emissions from wastewater systems are still highly uncertain. The OECD countries have invested in anaerobic wastewater treatment plants with methane recovery. The problem is mainly concentrated in regions without this technology. At present, industrial wastewater in developing regions is considered to be the main source (Thorneloe, 1993; Doorn and Liles, 2000). In P1 and in Q1 in IMAGE the methane abatement factor was set at 0%.

Methane from landfills
Methane is emitted because of the anaerobic conditions in the landfills. In IMAGE an emission factor is used per kg Municipal Solid Waste/capita/year. The amount of MSW/cap/yr is growing with Gross Domestic Product. The assumption is that the methane emission factor is converging to 21.5 kg CH_4/cap/yr in regions with lower emission factors to reflect the increasing growth in landfill practices. This results in an overall emission factor of 21.5 kg CH_4/cap/yr in 2050 for most regions. Exceptions are 53.2 kg/cap/yr for Canada and the USA, and 58.3 kg/cap/yr in Australia and New Zealand where the emission factors for methane were high already in 1990. Methane from landfills can be captured and used for energy. In P1 and Q1 in IMAGE no methane abatement was assumed (i.e. an abatement factor of 0%).

Methane from wetland rice
Methane is emitted from rice paddies during flooding of the soils in the growing season. In IMAGE a converging emission factor of 25 Mg CH_4 per km^2 was assumed for all regions. The emission factor was corrected for multiple cropping resulting in 31 Mg/km^2 for China and other South East Asian countries (Olivier et al., 1996 and 1999). Intermittent draining of the rice paddies can abate methane. This can only be done with abundant water at hand. In P1 and in Q1 in IMAGE a zero methane abatement factor

was assumed. So the assumption was that no extra measures for methane mitigation would be implemented.

Trace gases from biomass burning
Emissions of trace gases like methane, NMVOCs, CO and NO_2 in traditional biomass burning are relatively high because of the burning conditions. Especially smouldering during wild fires with moist biomass causes heavy pollution (Levine, 2010). In IMAGE 2.1 emission reduction is assumed according to the rules given in table 6.3. It is assumed that over time traditional biofuels are replaced by modern biofuels and that through the use of controlled burning conditions pollution will decrease. Zero methane abatement was used for methane in P1 and Q1.

Agricultural waste burning
In many regions agricultural waste is burned on the fields. Especially during the smouldering phase methane and other trace gases like CO, NMVOC and NOx are released. The best abatement is to abandon this practice. In most western European countries agricultural waste burning is no longer practised. In many countries it is seen as the best way to prevent diseases in the following crop. In the P1 and Q1 scenario in IMAGE methane abatement in all regions is assumed 0%.

Table 6.3. Summary of P1 and Q1 baseline assumptions on emission factors in the Terrestrial Environment System of IMAGE 2.1.

Indicator	General rule
Livestock methane	Apart from a decreasing emission per unit of product as a result of increasing efficiency in dairy and meat production, no assumptions are made on extra mitigation. A decreasing emission per unit of product as a result of increasing efficiency can be driven by milk-quota as in the European Union.
Rice methane	Country specific emission factors are used for China, India, Indonesia, Italy, Japan, Republic of Korea, Philippines, Spain, Thailand, and USA. The global average is used for other countries. Emissions per hectare of harvested rice are assumed to grow to the 1990 USA level in 2020 (based on no extra organic amendments).
Landfill methane	The emission factor for developed regions increases linearly to the 1990 OECD Europe level in 2050 and remains constant to 2100. Developing regions grow to the 1990 OECD Europe level as their GDP reaches the 1990 GDP of OECD Europe, according to the log of GDP. If the 1990 level exceeds this maximum level (in case of Canada, USA, OECD Europe, and Oceania), the emission factor remains constant. The emission factors are put on top of the regional change in urban population, which is assumed to grow towards 80% of the total regional population.
Biomass burning	For biomass burning the emission factors of Olivier et al. (2000) are used.
Related to deforestation	Clear-cutting forest for agricultural purposes leads to burning of its biomass for warm and tropical forest types. The biomass in temperate and boreal forests is not burnt.
Savanna burning	Emission factors are constant. No abatement of methane.
Burning of agricultural waste	For developed regions, Latin America and East Asia, the emission factors (expressed as unit gas per unit of food production) drop linearly towards the 1990 emission factor in OECD Europe in 2050 and remain constant to 2100. The other developing regions grow towards the 1990 OECD Europe emission factor when their GDP reaches the 1990 GDP for OECD Europe. This increase is linear with the log of GDP. In addition in Q1 no abatement factor is applied.

6.4 Reduction strategies for methane emissions

6.4.1 Introduction

Two contrasting methane reduction packages are defined to make comparisons of the effect of methane reductions strategies on anticipated future climate against the baselines: a package with moderate methane abatement and a package with maximum methane abatement. These abatement packages are combined with the two scenarios P and Q to form four reduction strategies (P2, P3 and Q2, Q3). In table 6.4 an overview is given of the reduction strategies.

Table 6.4. Overview of the methane reduction strategies.

	Scenario P	Scenario Q
Abatement package 1	Baseline * No methane reductions	Baseline No methane reductions
Abatement package 2	Moderate methane reductions Reductions from landfill gas recovery	Moderate methane reductions ** Reductions from landfill gas recovery and fossil fuel leakage
Abatement package 3	Maximum methane reductions Reductions from landfill gas recovery, sewage gas recovery, rice, and fossil fuel leakage. Reductions in other source areas like methane from biomass burning	Maximum methane reductions Reductions from landfill gas recovery, sewage gas recovery, rice and fossil fuel leakage. Reductions in other source areas like methane from biomass burning.

* as in A1B-IMAGE (IPCC, 2000)
** as in B1-IMAGE (De Vries et al., 2000)

6.4.2 Assumptions on methane in reduction strategies P2 and Q2

Methane from combustion
As in P1 and Q1 no methane abatement factor is assumed in P2 and Q2.

Methane from fossil fuel, especially the exploitation, production and distribution of coal, oil and gas
Methane losses due to fossil fuel production, including gas leakages are assumed to decrease and approach current OECD Europe levels in Q2. The methane emissions from venting and leaking from fossil fuel exploitation and distribution in Q2 are lower than in P2 because less fossil fuel is needed in the economy. These reductions follow from the different economic developments between P2 and Q2. It is assumed that the cheaper options for methane reduction are introduced in Q2. These options are increased maintenance to reduce leakage and increased own use of otherwise vented gas. In P2 no reductions are assumed from abatement. The following maximum abatement factors have been used in Q2: 10% in 2000, 20% in 2025, 30% in 2050, 40% in 2075 and 50% in 2100 for increased use of otherwise vented and flared gas from exploitation of fossil fuels.

Methane emission reduction from enteric fermentation in livestock
The same assumptions on the increase in production efficiency are used as in P1 and Q1. If production becomes more efficient, demand can be covered with fewer animals, leading to less methane emissions. It is assumed that no abatement of methane in the

individual animals through feed supplements will be introduced because the consumers do not accept production-enhancing agents. The products to increase rumen efficiency are in the experimental stage and too expensive to be introduced. Therefore the methane emissions from animals in P2 and Q2 is the same as in P1 and Q1.

Methane from manure
Assumptions on emission factors are the same as in P1 and Q1. With increasing intensification of livestock breeding in other regions the emissions are expected to increase. In P2 and Q2 in IMAGE no abatement is assumed because of the high investments involved to apply manure digestion (AEAT, 1998).

Methane emission reductions from wastewater and sewage treatment
Assumptions on emission factors are the same as in P1 and Q1. In P2 and Q2 in IMAGE the abatement factor for methane is 0% because of the high investments involved in sewage treatment. US$ 50 - 500/ton of avoided methane in OECD regions (AEAT, 1998).

Methane from landfills
Emission factors as in P1 and Q1. In P2 and Q2 in IMAGE a maximum methane abatement factor of 0% in 2000, 40% in 2050 and 60% in 2100 was assumed and linear in between these years (see table 6.5). It is assumed that landfill gas recovery schemes as developed in the OECD are a success and technology could spread to the other regions as well.

Methane from wetland rice
Emission factors for methane from wetland rice are the same as in P1 and Q1. Intermittent draining of the rice paddies can abate methane. This can only be done with abundant water at hand. In P2 and Q2 it is assumed that this is not the case and therefore in IMAGE an abatement factor is assumed of 0%. It is assumed that water management does not change in the rice growing regions.

Trace gases from biomass burning
Emission factors as in P1 and Q1. In P2 and Q2 in IMAGE 2.1 emission reduction is assumed according to the rules given in table 6.5. One option to reduce methane emissions is to increase the burning efficiency of biomass. Modern technology for biomass burning leads to lower emissions. One such promising technology is biomass integrated gasifier/intercooled steam-injected gas turbine (BIG/ISTIG) technology. If introduced, trace gas emissions from traditional fuelwood will be reduced with 90% in all regions at low costs. The main reduction is from the assumption that over time traditional biofuels are replaced by modern technologies to increase the burning efficiency of biofuels.

Agricultural waste burning
In many regions agricultural waste is burned on the fields. Especially during the smouldering phase methane and other trace gases like CO, NMVOC and NOx are released. The best abatement is to abandon this practice. In most western European countries agricultural waste burning is no longer practised. In many countries it is seen as the best way to prevent diseases in the following crop. An aggressive abatement is

assumed in the P2 and Q2 in IMAGE maximum methane abatement in OECD Europe is assumed of 75% already in 2010 and 90% from 2020 to 2100. The other regions follow later but with the same rigorous abatement.

Table 6.5. Scenario P2 and Q2 assumptions for emission factors in the Terrestrial Environment System of IMAGE 2.1.

Indicator	General rule
Livestock methane	Apart from a decreasing emission per unit of product as a result of increasing efficiency in dairy and meat production, no assumptions are made on extra mitigation. A decreasing emission per unit of product as a result of increasing efficiency can be driven by milk-quota as in the European Union.
Rice methane	Country specific emission factors are used for China, India, Indonesia, Italy, Japan, Republic of Korea, Philippines, Spain, Thailand, and USA. The global average is used for other countries. Emissions per hectare of harvested rice are assumed to grow to the 1990 USA level in 2020 (based on no extra organic amendments).
Landfill methane	The emission factor for developed regions increases linearly to the 1990 OECD Europe level in 2050 and remains constant to 2100. Developing regions grow to the 1990 OECD Europe level as their GDP reaches the 1990 GDP of OECD Europe, according to the log of GDP. If the 1990 level exceeds this maximum level (in case of Canada, USA, OECD Europe, and Oceania), the emission factor remains constant. For this emission factor, all regions are assumed to have an abatement factor of 0% in 2000, 40% in 2050, 60% in 2100, and linear in between. The emission and abatement factors are put on top of the regional change in urban population, which is assumed to grow towards 80% of the total regional population.
Biomass burning	For biomass burning the emission factors of Olivier et al. (2000) are used.
Related to deforestation	Clear-cutting forest for agricultural purposes leads to burning of its biomass for warm and tropical forest types. The biomass in temperate and boreal forests is not burnt.
Savanna burning	For all regions an abatement factor is assumed of 0% in 2000, 40% in 2050 and 60% in 2100, and linear in between.
Burning of agricultural waste	For developed regions, Latin America and East Asia, the emission factors (expressed as unit gas per unit of food production) drop linearly towards the 1990 emission factor in OECD Europe in 2050 and remain constant to 2100. The other developing regions grow towards the 1990 OECD Europe emission factor when their GDP reaches the 1990 GDP for OECD Europe. This increase is linear with the log of GDP. In addition in Q2 an abatement factor is applied. For OECD Europe this factor is 0% in 1990, 50% in 2000, 75% in 2010, 90% from 2020 to 2100, and linear in between. For the other regions this factor is 0% in year T_0, 25% in T_0+10, 50% in T_0+20, 75% in T_0+30, 90% from year T_0+40 onward, and linear in between. T_0 = 1990 for Canada, USA, Oceania and Japan. T_0 = 2000 for Eastern Europe, CIS and China + centrally planned countries, and T_0 = 2010 for Latin America, Africa, Middle East, India and East Asia.

6.4.3 Assumptions on methane in reduction strategies P3 and Q3

Methane from combustion

Methane emissions from combustion are estimated from the fossil fuel used in the economy and related emission factors. Methane from combustion of fossil fuels is a small source. No abatement factor for methane is assumed in P3 and Q3 because the technical improvements in burning are mainly driven by technological change with high costs.

Methane from fossil fuel, especially the exploitation, production and distribution of coal, oil and gas
Methane losses due to fossil fuel production, including gas leakages, in Q3 are assumed to decrease and approach current OECD Europe levels. The methane emissions from venting and leaking from fossil fuel exploitation and distribution are lower than in P3 because less fossil fuel is needed in the economy. These reductions follow from the different economic developments between P3 and Q3. The following maximum abatement factors for methane have been used in P3 and Q3: 10% in 2000, 20% in 2025, 90% in 2100, and linear in between 2025 and 2100. Increased use of otherwise vented and flared gas from exploitation of fossil fuels is assumed to be successful in all regions. The more expensive options will be introduced after 2025. These are increased flaring instead of venting and accelerated pipeline modernisation.

Methane emission reduction from enteric fermentation in livestock
The same assumptions on the increase in production efficiency are used as in P1 and Q1. It is assumed that the consumers do not accept production-enhancing agents (US$ 400 per ton of avoided methane). The products to increase the rumen efficiency (US$ 3000-6000 per ton of avoided methane) are still in the experimental stage and assumed too expensive to be introduced in all regions (AEAT, 1998). In general it is assumed that a cost of US$ 500 per ton avoided methane is too expensive to be included in the methane abatement packages. Therefore the methane abatement factor is 0% in P3 and Q3. Therefore the methane emissions in P3 and Q3 are the same as in P1 and Q1.

Methane from manure
Regional emission factors are applied. It is assumed that at this moment only in the OECD and China manure management systems are applied with high methane emissions, which can be abated. With increasing intensification of livestock breeding in other regions the emissions are expected to increase. In P3 and Q3 in IMAGE no abatement of methane was assumed because of the high investments involved to apply manure digestion (US$ 500-1000 per ton of avoided methane) (AEAT, 1998).

Methane emission reductions from wastewater and sewage treatment
Two routes for reduction of methane emissions can be followed. Aerobic treatment technologies can be selected, which prevents the formation of methane. On the other hand, anaerobic treatment technologies can be used, with methane recovery for energy purposes (Lexmond and Zeeman, 1995). Anaerobic treatment is commercially available. Fuel can be produced from the methane for about 1 $US\$_{1990}$ per GJ (Lettinga and Van Den Haandel, 1993).

Sewage treatment can result in methane emissions if stored and treated under anaerobic conditions and if the methane is released instead of recovered for energy purposes. A methane emission factor is assumed of 4.74 kg CH_4/cap/yr for all regions. In the OECD countries methane is recovered in closed systems, there only a small reduction potential is expected (10%). In other regions larger reduction potentials of up to 80%, are expected if these closed systems are introduced. But in the OECD countries methane is recovered in closed systems, there only a small reduction potential is expected (10%). In other regions larger reduction potentials, of up to 90%, are expected if these closed systems are introduced. In P3 and Q3 in IMAGE the abatement factor for methane was assumed to be 0% in 2000, 15% in 2025 and 90% in 2100, and linear between 2025 and 2100. Although high investments are involved in anaerobic sewage treatment, US$ 50-500/ton of avoided methane in OECD regions (AEAT, 1998), it is assumed to become standard in all regions in P3 and Q3.

Methane from landfills

Emission factors for methane as in P1 and Q1. In P3 and Q3 in IMAGE an abatement factor for methane of 0% in 2000, 20% in 2025 and 90% in 2100 was assumed and linear in between these years (see table 6.6). It was assumed that landfill gas recovery schemes as developed in the OECD were a success and technology would spread to other regions as well.

Methane from wetland rice

Methane is emitted from rice paddies during flooding of the soils in the growing season. In IMAGE an emission factor of 25 Mg CH_4 per km^2 was assumed for all regions. The emission factor was corrected for multiple cropping resulting in 31 Mg/km^2 for China and other South East Asian countries (Olivier et al., 1996, 1999 and 2009). Intermittent draining of the rice paddies can abate methane. This can only be done with abundant water at hand. In P3 and Q3 in IMAGE an abatement factor was assumed of 0% in 2000, 15% in 2025 and 90% in 2100, and linear in between. It was assumed that water is abundant in the rice growing regions and all cheap options would be introduced like intermittent draining and the reduction of incorporation of organic material like rice straw.

Trace gases from biomass burning

Emission factors as in P1 and Q1. In P3 and Q3 in IMAGE 2.1 emission reduction is assumed according to the rules given in table 6.6. The main reduction is from the assumption that over time traditional biofuels are replaced by modern biofuels. In Q3 this replacement is comparable to Q2.

Agricultural waste burning

In many regions agricultural waste is burned on the fields. Especially during the smouldering phase methane and other trace gases like CO, NMVOC and NOx are released. The best abatement is to abandon this practice. In some western European countries agricultural waste burning is no longer practised. In many countries it is seen as the best way to prevent diseases in the following crop. In the P3 and Q3 scenario in IMAGE abatement in OECD Europe for methane is assumed of 75% already in 2010 and 90% from 2020 to 2100. The other regions follow later but with the same rigorous abatement. The abatement of methane in Q3 is comparable to Q2.

Table 6.6. Scenario P3 and Q3 assumptions on emission factors in the Terrestrial Environment System of IMAGE 2.1.

Indicator	General rule
Livestock methane	Apart from a decreasing emission per unit of product as a result of increasing efficiency in dairy and meat production, no assumptions are made on extra mitigation. A decreasing emission per unit of product as a result of increasing efficiency can be driven by milk-quota as in the European Union.
Rice methane	Country specific emission factors are used for China, India, Indonesia, Italy, Japan, Republic of Korea, Philippines, Spain, Thailand, and USA. The global average is used for other countries. Emissions per hectare of harvested rice are assumed to grow to the 1990 USA level in 2020 (based on no extra organic amendments). Abatement factors are assumed of 0% in 2000, 15% in 2025 and 90% in 2100, and linear in between.
Landfill methane	The emission factor for developed regions increases linearly to the 1990 OECD Europe level in 2050 and remains constant to 2100. Developing regions grow to the 1990 OECD Europe level as their GDP reaches the 1990 GDP of OECD Europe, according to the log of GDP. If the 1990 level exceeds this maximum level (in case of Canada, USA, OECD Europe, and Oceania), the emission factor remains constant. For this emission factor, all regions are assumed to have an abatement factor of 0% in 2000, 20% in 2025, 90% in 2100, and linear in between. The emission and abatement factors are put on top of the regional change in urban population, which is assumed to grow towards 80% of the total regional population.
Biomass burning	For biomass burning the emission factors of Olivier et al. (2000) are used.
Related to deforestation	Clear-cutting forest for agricultural purposes leads to burning of its biomass for warm and tropical forest types. The biomass in temperate and boreal forests is not burnt.
Savanna burning	For all regions an abatement factor is assumed of 0% in 2000, 20% in 2025 and 90% in 2100, and linear in between.
Burning of agricultural waste	For developed regions, Latin America and East Asia, the emission factors (expressed as unit gas per unit of food production) drop linearly towards the 1990 emission factor in OECD Europe in 2050 and remain constant to 2100. The other developing regions grow towards the 1990 OECD Europe emission factor when their GDP reaches the 1990 GDP for OECD Europe. This increase is linear with the log of GDP. In addition in B1 an abatement factor is applied. For OECD Europe this factor is 0% in 1990, 50% in 2000, 75% in 2010, 90% from 2020 to 2100, and linear in between. For the other regions this factor is 0% in year T_0, 25% in T_0+10, 50% in T_0+20, 75% in T_0+30, 90% from year T_0+40 onward, and linear in between. T_0 = 1990 for Canada, USA, Oceania and Japan. T_0 = 2000 for Eastern Europe, CIS and China + centrally planned countries, and T_0 = 2010 for Latin America, Africa, Middle East, India and East Asia.

6.5 Results

6.5.1. Emissions in P1 and Q1

Land use emissions of methane

The methane emissions from land use dominate over those from energy. The increase in population and livestock results in increasing emissions of methane from land use in the first half of this century and a decline after 2050. The number of animals and the related N-excretion and the use of synthetic fertiliser dominate the nitrous oxide emissions. The emissions of trace gases from biomass burning are related to the trend in deforestation and the resulting carbon dioxide emissions.

Table 6.7. Carbon dioxide emissions (Gt C/yr) and concentrations (ppmv) in the atmosphere 1990 - 2100

	P1	P2	P3	Q1	Q2	Q3
CO_2 emissions						
1990	7.4	7.4	7.4	7.4	7.4	7.4
2000	8.5	8.5	8.5	8.4	8.4	8.4
2050	19.7	19.7	19.7	12.1	12.1	12.1
2100	14.1	14.1	14.1	5.7	5.7	5.7
CO_2 concentrations						
1990	357	357	357	357	357	357
2000	375	375	375	375	375	375
2050	550	550	550	492	492	492
2100	745	745	745	543	543	543

Carbon dioxide emission
CO_2 emissions due to deforestation remain an important source up to 2030. After deforestation stops in 2030 global emissions due to decay of timber products with an assumed lifetime of 10-100 years become more important. These two sources result in an emission of 1 Gt C/yr up to 2030 and about 0.5 Gt C/yr in the period 2030-2100.

The carbon dioxide emissions in the P1 scenario increase to a much higher level than in the Q1 scenario, from 7.4 Gt C/yr in 1990 to about 19.7 Gt C/yr in 2050 and then declines to about 14.1 Gt C/yr in 2100. The carbon dioxide emissions in the Q1 scenario are much smaller with an increase from 7.4 Gt C/yr in 1990 to 12.1 Gt C/yr in 2050 and then a decline to 5.7 Gt C/yr in 2100 (Table 6.7).

Emissions of other gases
Emissions of non-CO_2 greenhouse gases show another pattern, after an increase until 2050 some gradually decrease to about present levels for the P1 and Q1 scenario, others are stable. (See Table 6.8 and 6.9). Especially the reductions in the emissions of CO, NO_2, SO_2 from flue gas desulfurization and VOC reductions to below present levels are apparent in the Q1 baseline.

Table 6.8. Emissions of different trace gases in the P1 reduction strategy

P1 scenario	Units	1990	2000	2025	2050	2075	2100
CO_2	Gt C/yr	7.4	8.5	14.9	19.7	18	14.1
CH_4 total	Tg CH_4/yr	442	469	596	659	669	600
CH_4 energy	Tg CH_4/yr	94	100	159	167	154	114
N_2O	Tg N/yr	16	16	19	21	21	20
CO	Tg C/yr	428	466	510	497	558	552
NO_2	Tg N/yr	48	51	71	82	78	65
SO_2	Tg S/yr	87	89	121	139	121	91
VOC	Tg VOC/yr	84	90	109	107	98	83

Table 6.9. Emissions of different trace gases in the Q1 reduction strategy

Q1 scenario	Units	1990	2000	2025	2050	2075	2100
CO_2	Gt C/yr	7.4	8.4	11.6	12.1	8.4	5.7
CH_4 total	Tg CH_4/yr	442	469	552	571	545	481
CH_4 energy	Tg CH_4/yr	92	94	137	148	112	73
N_2O	Tg N/yr	16	16	18	18	17	16
CO	Tg C/yr	428	475	436	410	424	413
NO_2	Tg N/yr	48	51	61	59	48	40
SO_2	Tg S/yr	87	88	96	88	59	44
VOC	Tg VOC/yr	84	91	89	78	67	57

6.5.2 Emission of methane for six reduction strategies.

Total methane emissions are 442 Tg in 1990 and 600 Tg in 2100 for P1 (See Table 6.8). and 480 Tg in 2100 for Q1 (See Table 6.9). In figure 6.1 the total global methane emissions are shown for the following reduction strategies: P1 and Q1 baselines without methane abatement, P2 and Q2 with moderate methane abatement, and P3 and Q3 with maximum methane abatement. As can be seen from this figure total methane emission in P1 peaks at 680 Tg in 2070. In P2 the methane emissions do not exceed 600 Tg and are reduced to 500 Tg in 2100. In P3 the maximum has been reached already in 2025 with a little over 500 Tg. From this figure it can be noticed that the strategy P2 and Q1 are practically the same in terms of total methane emissions. The Q2 strategy shows a little higher methane emissions than strategy P3. Finally Q3 has the lowest total methane emissions with a peak in 2025 of about 500 Tg and steadily declining to 250 Tg in 2100. That the results of the different strategies of P and Q are overlapping is a result of economic developments. In P1 more fossil fuels are used and therefore more methane leaks from fossil fuel exploitation. So much can be reduced from fossil leakage in P3. Table 6.10 gives the resulting global methane emissions per sector.

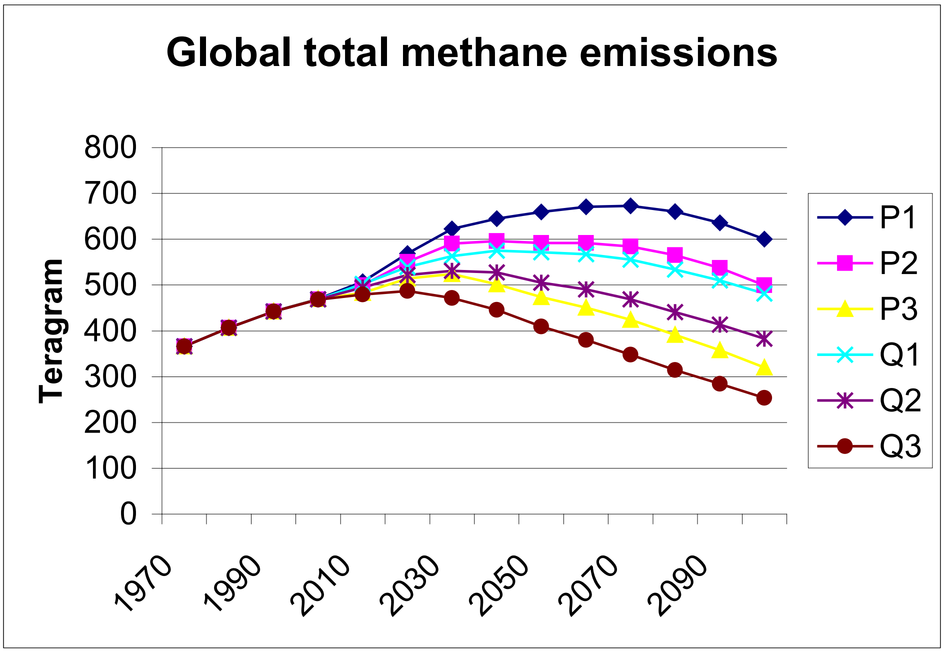

Figure 6.1. Global total methane emissions (Tg) calculated for the period 1970-2100 for six methane reduction strategies

In 2100, emissions in baseline strategy P1 amount to 559 Tg/yr (Table 6.11). For reduction strategy P2, the calculated methane emissions in 2100 are 458 Tg/yr. This is about 18% lower than P1 (table 6.14). For reduction strategy P3, the methane emissions in 2100 are 278 Tg/yr. For reduction strategy P3 the emissions in 2100 are 281 Tg/yr, or about 50% lower than in P1.

In 2100, emissions as calculated in baseline strategy Q1 amount to 466 Tg/yr. In reduction strategy Q2 in 2100 the emissions are 342 Tg/yr, or 27% lower. For reduction strategy Q3, the calculated emissions in 2100 are 216 Tg/yr. The calculated emissions in Q3 in 2100 are 250 Tg/yr or 54% lower than the baseline Q1. So, maximum abatement is 50% in the P3 strategy and 54% (with much higher costs) in the Q3 strategy.

Table 6.11. Global methane emissions per sector (in Tg = 10^{12} g CH_4) for 1990 to 2100 according to six abatement strategies: P1, P2, P3, Q1, Q2 and Q3.

	1990	2000	2025	2050	2075	2100
P1 No abatement						
Biomass burning	10	14	12	1	0	0
Agricultural waste burning	3	5	7	10	10	9
Savanna burning	15	15	13	12	14	18
Landfills	36	46	90	134	150	135
Sewage	26	30	37	42	41	34
Wetland rice	29	28	25	21	18	15
Wetlands	105	105	105	105	105	105
Animals	72	73	92	110	121	112
Animal waste	13	13	16	18	17	16
Fossil fuel leakage	95	99	157	168	153	113
Total methane	403	430	554	620	628	559
P2 Moderate abatement						
Biomass burning	10	14	12	1	0	0
Agricultural waste burning	3	4	2	0	0	0
Savanna burning	15	15	9	6	7	6
Landfills	36	46	71	81	76	55
Sewage	26	30	37	42	40	34
Wetland rice	29	28	25	21	18	15
Wetlands	105	105	105	105	105	105
Animals	72	72	92	111	119	112
Animal waste	13	13	16	18	17	16
Fossil fuel leakage	96	100	160	168	153	113
Total methane	404	431	533	553	536	458
P3 Max abatement						
Biomass burning	10	14	12	1	0	0
Agricultural waste burning	3	4	7	10	9	9
Savanna burning	15	15	8	5	4	2
Landfills	36	46	67	68	45	13
Sewage	26	30	27	19	13	2
Wetland rice	29	28	23	11	7	3
Wetlands	105	105	105	105	105	105
Animals	72	72	92	110	118	112
Animal waste	13	13	16	18	17	16
Fossil fuel leakage	96	100	120	84	46	11
Total methane	404	431	481	433	366	278

Table 6.11 continued...

	1990	2000	2025	2050	2075	2100
Q1 No abatement						
Biomass burning	10	15	9	0	0	0
Agricultural waste burning	5	6	8	11	11	9
Savanna burning	16	14	13	13	18	22
Landfills	37	46	89	129	144	131
Sewage	26	30	38	43	41	34
Wetland rice	29	29	27	26	22	19
Wetlands	105	105	105	105	105	105
Animals	72	75	89	89	80	69
Animal waste	13	13	15	14	14	10
Fossil fuel leakage	92	94	137	148	112	73
Total methane	399	425	524	574	540	466
Q2 Moderate abatement						
Biomass burning	10	15	8	0	0	0
Agricultural waste burning	5	5	2	0	0	0
Savanna burning	16	14	10	8	9	9
Landfills	37	46	70	77	74	53
Sewage	26	30	38	43	41	34
Wetland rice	29	29	27	26	22	19
Wetlands	105	105	105	105	105	105
Animals	72	75	90	89	81	69
Animal waste	13	13	15	14	14	10
Fossil fuel leakage	92	94	112	94	73	46
Total methane	399	425	475	454	410	342
Q3 Max abatement						
Biomass burning	10	15	8	0	0	0
Agricultural waste burning	5	5	2	0	0	0
Savanna burning	16	14	10	7	5	2
Landfills	37	46	64	67	44	13
Sewage	26	30	30	20	13	2
Wetland rice	29	29	25	13	7	5
Wetlands	105	105	105	105	105	105
Animals	72	75	89	89	81	69
Animal waste	13	13	15	14	14	10
Fossil fuel leakage	92	94	62	13	10	7
Total methane	399	425	409	330	278	216

The main reductions in P2 are methane emissions from landfills. The main reductions in P3 are from landfills, fossil fuel leakage and wetland rice. The main reductions in Q2 are from burning, landfills and fossil fuel leakage. The main reductions in Q3 are from burning, landfills, sewage treatment, wetland rice and fossil fuel leakage.

Table 6.12. Global methane emission reductions relative to strategies P1 and Q1.

Methane	2025	2050	2075	2100
P1	0%	0%	0%	0%
P2	4%	11%	15%	18%
P3	13%	30%	42%	50%
Q1	0%	0%	0%	0%
Q2	9%	21%	24%	27%
Q3	22%	43%	49%	54%

The global methane emissions in the reduction strategy P2 are about 11% lower in 2050 and 18% lower in 2100 compared to the baseline P1 (Table 6.12). The global methane emissions in reduction strategy Q2 are about 21% lower in 2050 and 27% lower in 2100 compared to the baseline Q1. The global methane emissions in reduction strategy P3 are 30% lower in 2050 and 50% lower in 2100 compared to the baseline P1. The global methane emissions in reduction strategy Q3 are 43% lower in 2050 and 54% lower in 2100 compared to the baseline Q1.

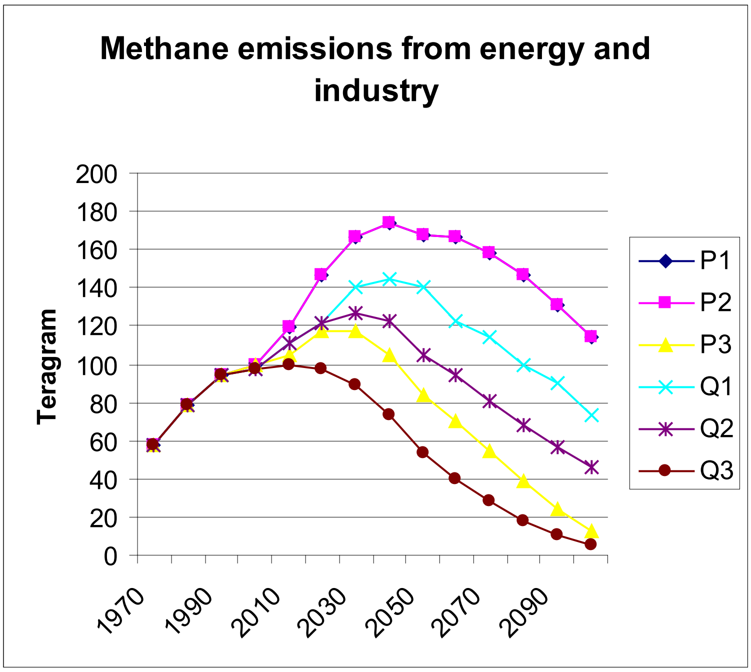

Figure 6.2. Methane emissions from energy and industry calculated for the period 1970-2100, for six methane reduction strategies. P1 is same as P2 in graph.

Energy

Methane emissions from energy and industry are the same for P1 and P2 because no abatements were assumed. The methane emission in P1 and P2 peaks in 2050 at 168 Tg per year (Figure 6.2). The reduction in P1 and P2 between 2050 and 2100 is a result of the reduced demand for coal, oil and gas resulting in reduced methane emissions from exploitation and transmission. The reduction of methane emissions in

P3 is the result of increased own use of otherwise vented and flared methane at production sites and accelerated pipeline modernisation in all regions. The methane emission in Q1 peaks at about 145 Tg in 2050, a bit lower than the peak in P1 because of reduced demand. The reduction from Q1 to Q3 is a result of maximum efforts to reduce emissions from production sites and accelerated pipeline modernisation in all regions.

Land use emissions
The natural wetland methane emissions in all strategies remain constant at 105 Tg (Table 6.11). The methane from biomass burning is reduced to zero after 2050 in P1 and Q1 because of an early change to modern biomass energy use, with no further reductions in the abatement packages. The methane emissions from agricultural waste burning are about 10 Tg around 2050 and reduced to zero in 2050 – 2100 in P2 and Q2/Q3. Methane emissions from savanna burning are increasing in the baselines P1 and Q1 to about 18 Tg in 2100 in P1 and 22 Tg in 2100 in Q1. The methane abatement through reduced burning in P2 and Q2 reduces these methane amounts to about one third in P2 and about half in Q2. Savanna burning in P3 and Q3 is practically abandoned with 2 Tg remaining emissions. The methane emissions from landfills are particularly high in P1 with 150 Tg in 2075 and in Q1 with a maximum of 144 Tg in 2075. The abatement of methane emissions from landfills is successful in P2 and Q2 reducing these emissions in 2075 to about half these amounts. In P3 and Q3 these reductions are successful as well. The remaining methane emissions in 2075 are about one third with 45 Tg in P3 and 44 Tg in Q3. Methane emissions from rice production are reduced only in the P3 and Q3 strategies. Reductions are rather large with only 3-5 Tg remaining in 2100. Methane emissions from animals are not reduced. Only increased production efficiency leads to lower animal numbers and related methane emissions. Methane emissions from animal waste management are not reduced because the investments needed are too high.

Main reductions
The main reductions in P2 compared to P1 are calculated for methane from landfills and methane from agricultural waste and savanna burning. The main methane emission reductions in P3 compared to P2 are from landfills, sewage treatment and rice. See Figure 6.3. No extra reductions compared to the baselines are found from methane emissions from enteric fermentation in animals (Figure 6.4). Methane emissions in the model are calculated from the number of animals and the amount and quality of the feeds given to the animals. Because of increased efficiency, in Q1 considerably fewer animals are needed to cover demand for meat and milk compared to P1 for the same amount of people. No methane reductions from production enhancing agents and from rumen manipulation were introduced because of the high costs. So methane emissions from animals are reduced only because of increased efficiency of production.

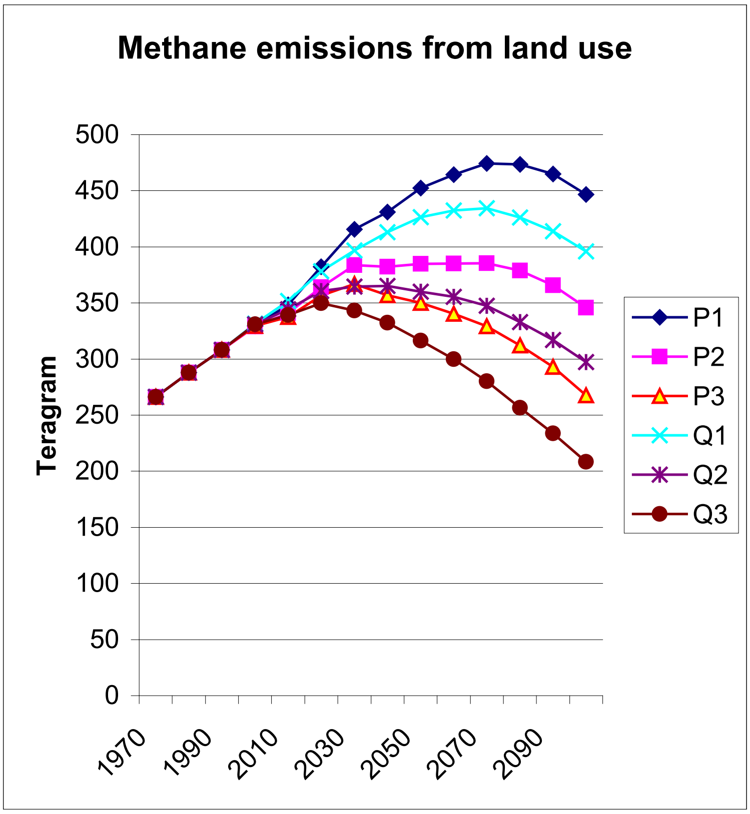

Figure 6.3. Global methane emissions from land use calculated for the period 1970-2100, for six methane reduction strategies.

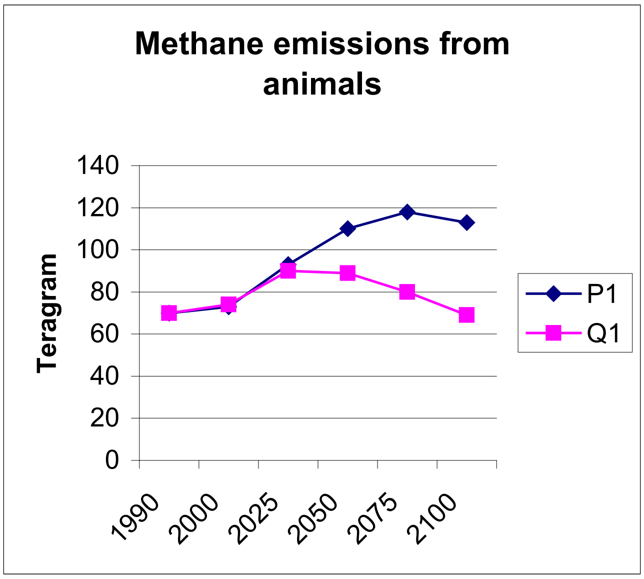

Figure 6.4. Methane emissions from animals calculated for the period 1990 to 2100, for the baselines P1 and Q1. Because of high costs no methane reduction from production enhancing agents or from rumen manipulation are assumed in the four methane reduction packages: P2, P3, Q2 and Q3.

6.5.4 Methane concentrations, temperature increase and sea level rise.

The indicators for climate change are methane concentration, temperature change and sea level rise. These indicators were chosen because they give a global view on the possible effects of abatement. Methane concentrations are a resultant of emissions and processes in the atmosphere. Temperature increase is driven by all greenhouse gases. A noticeable effect of methane abatement was found on temperature change. Sea level rise is an indicator with a large delay. Sea level rise was found to be reduced by methane abatement only.

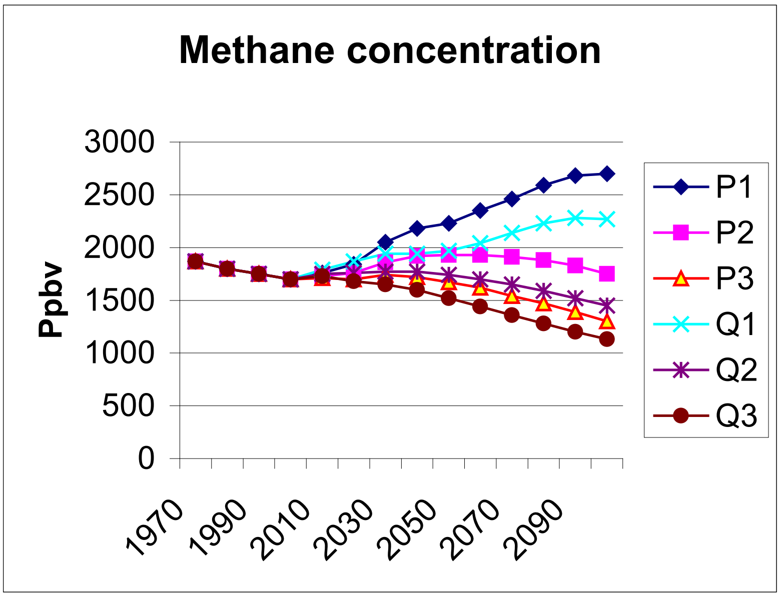

Figure 6.5

Methane concentrations

The methane concentrations between 1970 and 2010 are slowly decreasing from 1750 to 1700 ppbv according to the IMAGE 2.1 model output. Methane from wetlands was estimated too low. The feedback of increased temperature on wetlands was not taken into account. The anthropogenic emissions were central in the analysis. The human induced emissions are increasing in the same period (figure 6.5). This can be explained by the relatively low total emissions of 440 Tg in 1990 (compared to other budgets) and the high methane loss by hydroxyl radicals (OH) in the troposphere of 450 Tg/yr (See Table 3.1 in chapter 3). The emissions in IMAGE are at the low end of the IPCC ranges because recent updated bottom-up estimates were used.

From 2000 concentrations are rising in all abatement strategies. The methane concentration for the moderate methane abatement strategy P2 increases to about 1900 ppbv in 2050 and returns to 1700 ppmv in 2100. The methane concentration in Q2 increases to about 1700 ppmv in 2050 and returns to below 1500 ppbv in 2100.

The concentration in the methane abatement strategy P3 is stable at about 1750 before 2050 and is reduced to about 1300 ppbv in 2100. The methane concentration in the atmosphere of the methane abatement strategy Q3 is at its maximum in 2010 with 1750 ppbv and thereafter gradually decreasing to 1100 ppbv in 2100.

The methane concentration in the atmosphere can be stabilised at values below 1750 ppbv only in the reduction strategies Q2, P3 and Q3. No reduction of methane from fossil leakage was assumed in P2. It is clear that those reductions are necessary if the stabilisation of methane concentration in the atmosphere is the aim.

Temperature change

With the methane abatement that already takes place before 2050 in the methane reduction strategies P2, Q2, P3 and Q3, hardly any difference can be seen in the temperature change (figure 6.6). But the methane abatements are important so that a reduced temperature increase becomes prominent after 2050. The IMAGE results concerning climate change show that in 2100 about half a degree less temperature change can be expected from methane abatement both in the P1-3 and Q1-3 set of reduction strategies. The exact result is 0.5 ^{o}C difference from 2.8 to 2.3 ^{o}C temperature change in P1 to P3 and from 2.0 to 1.5 ^{o}C temperature change in Q1 to Q3.

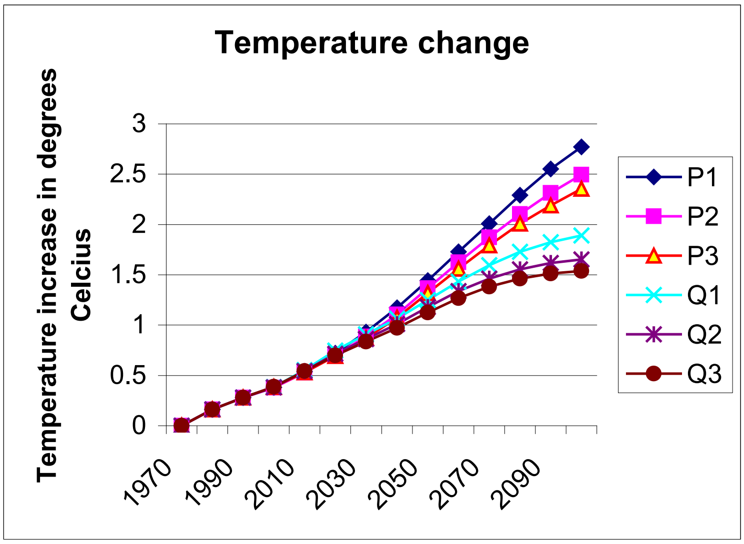

Figure 6.6. Global temperature change 1970 – 2100

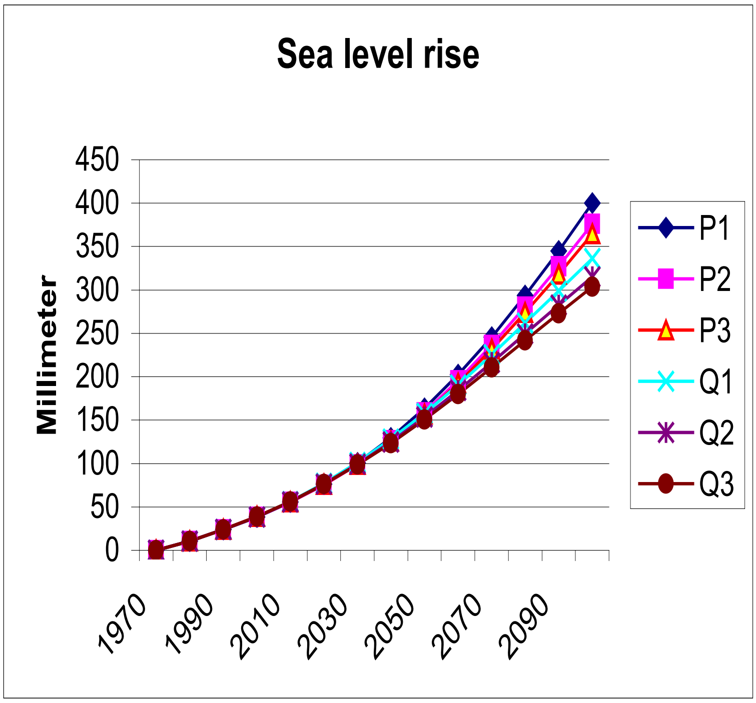

Figure 6.7 Sea level rise in the period 1970 – 2100 under six methane reduction strategies.

Sea level rise

40 mm less sea level rise in 2100 (on a total expected rise of about 400 mm in P1 and 350 mm in Q1) is found in P3 and Q3 compared to the P1 and Q1 baselines.

The differences in sea level rise become prominent only after 2050 because of the long reaction time of the ocean system. The sea level rise is about 400 mm in 2100 in the P1 methane reduction strategy. Methane reductions in the P2 and P3 strategy reduce this sea level rise to 375 mm and 360 mm respectively. In the methane reduction strategy Q1 a sea level rise is expected of 340 mm in 2100. The methane reduction strategy Q2 reduces this to 310 mm in 2100 and Q3 to 300 mm in 2100. The expected sea level rise can not be reduced to less than 300 mm in 2100 by these strategies.

6.6. Discussion and conclusions

Discussion of results

The strategic advantage of first reducing methane in a situation with higher CO_2 emissions in the P scenario compared to methane reductions in a situation with lower CO_2 emissions in the Q scenario is not so obvious. From our analysis it turns out that methane reductions are profitable in both the P2 and Q2 strategy. So those are no regret options anyway. The positive climate and sea level effect of the Q strategies with lower CO_2 and non-CO_2 greenhouse gas emissions are larger than in the P strategies.

Differences between P and Q variants

The differences between the P1 and Q1 strategies are mainly the result of differences in the economic developments and the related carbon dioxide and trace gas emissions in the future. In the P and Q strategies because of economic developments simultaneous reductions take place in the other trace gases like carbon monoxide, nitrogen oxides, sulphur and volatile organic carbons. One would assume that the effects on the climate would have been more favourable without reductions in the emissions of cooling aerosols like SO_2. This effect however is hardly noticeable in the results. It could be related to the effect of reduced demand for fossil fuels in Q1 compared with the P1 baseline, because the aerosols emissions would be smaller as well. Another effect is that methane emissions from the exploitation, transmission and distribution of fossil fuels is reduced in Q1 compared to P1. The costs of these reductions have not been assessed as only the costs of reductions have been assessed relative to the baselines. In our analysis sink strategies have not been analysed. For example the sequestration of carbon by landfilling of organic material in the form of wood and garbage (Marxsen, 2001), or the improved protection of tropical forests (Leemans et al., 1998).

Comparison with results from others

DelaChesnaye and Kruger (2002) assess the feasibility of stabilising global methane emissions over the period 2000 to 2050, with the help of the Mini Climate Assessment Model (Minicam model). They analysed methane reductions against the B2 scenario of IPCC SRES. For methane stabilisation they assumed a reduction of 20% in 2025 and 35% in 2050. Their analysis showed that methane stabilisation could nearly be achieved in 2025 based on the emission reduction potential associated with four major methane sources: landfills, coal mines, natural gas and oil systems, and manure management systems. Many options could be introduced for less than US$ 100/ton of carbon equivalent of avoided emissions. They also concluded that stabilisation through 2050 necessitated more expensive emission reduction options across a wider array of sources, particularly ruminant livestock and rice production.

My conclusions go beyond that. I also expect large reductions between 2000 and 2050 based on existing relatively cheap options like methane recovery and use in landfills, methane recovery and use in fossil fuel exploitation and reduced burning in land use. However, I am less optimistic on the possible reductions of methane emissions in livestock and manure management, because of the high costs that are related to rumen manipulation and anaerobic manure digestion.

Integrated analysis

It is important to improve the possibilities for integrated analysis of different environmental issues (like climate change, acid deposition, air pollution in cities, deforestation, and health and biodiversity problems).

In this analysis an existing sustainable scenario Q was used and the effects of methane reductions on climate change were analysed in the Q strategies and effects of methane reductions together with other trace gas reductions, like CO, NO_x, SO_2 and VOC emissions. Compared with the analysis by De Vries et al. (2000) extra assumptions were made on methane abatement strategies.

It was made plausible that methane emissions can be abated relatively easily and cost-effective solutions are possible in moderate abatement strategies in P2 and Q2. Even the maximum methane abatement strategies have low costs in terms of lost GDP growth.

Not all aspects have been analysed in the integrated analysis. The feedback of changed climate on wetland emissions has not been taken into account. The positive or negative feedback of policy decisions on climate and the emissions have been included but have not been analysed in detail. For example, in some countries policy measures are in place to reduce acid deposition from power, industry, transport, agriculture and consumers. These policies do have side effects on the emissions of greenhouse gases. An example is Brink et al. (2001). They have analysed the effects of ammonia abatement on emissions of nitrous oxide and methane from agriculture for Europe. The influence of ammonia abatement is positive on methane emissions but negative on nitrous oxide emissions. The overall effect for Europe has been estimated for three different scenarios. A scenario with an ammonia abatement of 36% had a negative effect of 14% on nitrous oxide emissions and a slight positive effect on methane emissions. To reduce ammonia emissions in the Netherlands sub-surface application of liquid manure is obligatory. Brink et al. (2001) conclude that this enhances the nitrous oxide emissions from the agricultural soils.

The combined effects of different policies to combat acid deposition, climate, nature and biodiversity can be analysed in an integrated way. Boudri et al. (2002) have analysed the potential contribution of renewable energy in air pollution abatement in China and India. They compared the costs of sulphur dioxide emission control through the switch to renewable energy sources with the costs of controlling emissions from flue gas desulphurization. Their conclusion is that an increased use of renewable energy could cut SO_2 emission control costs in China by 17-35%, and in India by more than two thirds. It would be interesting to analyse this together with the effects on the climate.

Conclusions

Substantial reductions in methane emissions are possible through the world-wide introduction of currently available abatement technologies. From my analysis it can be concluded that these technologies can be cost-effectively introduced for the whole period of 2000 to 2100 in the moderate methane reduction strategies of P2 and Q2. If the more expensive methane reduction options are deployed in the maximum reduction strategies of P3 and Q3 cost effectiveness is reduced in the period after 2050. Still the costs are low in terms of lost GDP growth. Costs are smaller than 0.1%/yr of GDP. The more expensive options that were not deployed in this analysis are reductions in methane from ruminant livestock and methane reductions in manure management. More research is needed however to substantiate the cost estimates after 2025 for the different regions in the world.

Even in a situation with a low CO_2 baseline like the Q1 scenario the reductions in climate change and sea level rise are significant and point to the fact that methane reductions alone, all other variables being equal, already make a difference in reducing climate change. The positive effect on the climate is combined in the Q strategies with simultaneous reductions in aerosol emissions possibly resulting in improved health. As some of these methane measures are not very costly, at least until 2025, measures should be taken as soon as possible. The most promising measures are methane recovery and use in landfills and methane recovery and use from methane leaking during production, transmission and distribution of fossil fuels.

Methane reductions alone lead to a reduction of expected climate change between 2050 and 2100. Methane reductions before 2050 have no significant effect on expected climate change. Research is needed in methane emissions reductions taken together with reductions in other GHG emissions. The question is: will this strategy lead to reduced climate change already in 2020?

7. DISCUSSION AND CONCLUSIONS

7.1 Introduction

This thesis shows the opportunities to cost effectively reduce human enhanced emissions of methane. Methane can be reduced because of the many profitable options available for methane. Methane reduction is expected to reduce global warming within 20 years.

Five research questions were formulated:

1. What are relevant atmospheric processes that involve CH_4? (chapter 2).
2. What are the global CH_4 emissions and sinks? (chapter 3).
3. How do estimates from a comprehensive global emissions database for atmospheric research (EDGAR) compare to aggregated national emission estimates? (chapter 4).
4. Which options are available to reduce CH_4 emissions and what are the costs of each option? (chapter 5).
5. What are the effects of CH_4 emission reduction packages on future climate change and what are the associated costs of these packages? (chapter 6).

This chapter summarises the answers to the research questions. In addition some recommendations are given for future research to improve the knowledge on methane. In this study an integrated assessment is performed of the contribution of methane to climate change and the options for methane control. The main aim of the thesis was to analyse future trends in global methane emissions, the associated climate change and the costs of emission control. Some of the chapters are based on earlier work, published some years ago. This chapter will also reflect on how that work contributed to international assessments, and indicate that most of it is still relevant.

7.2 Methane 's role in the atmosphere

The first research question was: What are relevant atmospheric processes that involve methane?

The natural greenhouse effect is one of the reasons that we can thrive on this earth. Greenhouse gases such as CO_2, CH_4 and N_2O are transparent for the short wave radiation from the sun, but they absorb part of the long wave radiation (heat) from the earth back into space. Without this natural blanket of greenhouse gases in the atmosphere, if the atmosphere would consist only of oxygen and nitrogen, the average temperature on earth would be -18 ^oC instead of the comfortable +15 ^oC of today. The enhanced greenhouse effect is caused by increased emissions of greenhouse gases due to human activities, and this causes an increase of global mean surface and tropospheric temperatures of 1.4 – 5.8 ^oC with a doubling of the pre-industrial greenhouse gas concentration in the atmosphere. Such warming is accompanied by major shifts in rainfall patterns.

Methane is the most abundant organic trace gas in the atmosphere and, after carbon dioxide, the second most important greenhouse gas emitted by human activities. Average global concentrations of CH_4 have more than doubled since pre-industrial times from 700 ppb to 1780 ppb. The concentration over the Northern Hemisphere is on average higher with 1800 ppb. Over dominant source areas like Western Europe concentrations occasionally increase to 2500 ppb. Methane has a significant warming effect because it absorbs strongly at wavelengths which are otherwise transparent to the earths outgoing radiation.

So, methane is a trace gas in the atmosphere with a large global warming potential. It is 25 times the global warming potential of CO_2 when integrated over 100 years. Integrated over shorter time periods (20 years) the global warming effect of methane is even higher with 72 times the GWP of carbon dioxide. The contribution of CH_4 to global warming is about 0.5 W/m^2. During the last decades the relative contribution of methane to global warming was an estimated 15-20%. The relative contribution has been growing over the years. Due to its relatively short atmospheric lifetime of 12 years, reductions in the anthropogenic emissions are measurable in the atmospheric concentrations within 10 or 20 years time. Methane is emitted into the atmosphere from natural and human sources.

The knowledge about methane's behaviour in the atmosphere has increased over the last decades. Still no satisfactory explanation has been found for the increase in the growth rates of methane in the atmosphere during the 1960s and 1970s and again in recent years from 2006 and the decrease in growth rates during the 1980s and 1990s of the last century. This is related to the difficulty in measuring the individual sources of methane. More research is needed to distinguish between the sources of methane in the atmosphere. More research is needed to evaluate the possibilities to reduce the effects of both climate change and local air pollution from all trace gases in an integrated policy plan. Methane together with other non-methane hydrocarbons and carbon monoxide react in the atmosphere with OH and NOx to form ozone at ground level. This contributes to atmospheric pollution. To reduce climate change and atmospheric pollution at the same time, the hydrocarbon emissions in general should be reduced.

7.3 The global methane sources and sinks

The second research question was: What are the global CH_4 emissions and sinks?

The most important anthropogenic sources of methane emissions are oil and natural gas production and use, coal mining and use, enteric fermentation in cattle, fermentation of animal waste, rice paddies, waste disposal in landfills, domestic sewage treatment and incomplete biomass burning. All these sources of methane have increased with population growth and economic development. The only possible exception is the wetlands, which have been drained at a large scale for agriculture. Rice paddies however have increased since 1950.

The total anthropogenic methane source is 375$\pm$75 Tg. The total methane source including natural sources is 535$\pm$100 Tg according to IPCC. The estimate of the OH sink between Fung (1991) and Lelieveld et al. (1998) has increased from 450$\pm$85

Tg/yr to 510±100 Tg/yr, the estimated soil sink has increased from 10 Tg/yr to 30±15 Tg/yr, and the stratospheric loss has been estimated at 40±8 Tg/yr by Lelieveld et al. (1998). The total sink estimate has therefore increased from 460±100 to 580±100 Tg. The uncertainties remain large.

There is no consensus about the causes of the long-term decline in the annual growth rate of methane since the 1980s and the recent increase since 2006. Analyses of the global methyl chloroform budget and the changing chemistry of the atmosphere argue for an increase in globally averaged hydroxyl radical concentration [OH] of 0.5 per cent per year over the last decades and a parallel increase in global methane emissions by 0.5 per cent per yr (IPCC, 2007). The growth rate of atmospheric methane was nearly zero over 1996 to 2006. In 2007 and 2008, however, concentrations were increasing again. Dlugokencky (2012) listed a number of possible reasons for the recent increase in methane since 2007. The 2007 anomaly coincided with anomalously warm wet conditions in northern wetland regions. Measurements of CO in the same samples measured for methane suggested that biomass burning was not relevant. Measurements of ^{13}C in methane from Alert, Canada were consistent with greater than normal emissions from wetlands. In 2008, most of the increase was driven by changes in the tropics rather than high northern latitudes. Therefore the recent increase in growth rate of methane is explained by increases in 2007 in boreal and in 2008 in tropical wetland emissions by humid and warm circumstances since 2006 (Dlugokencky, 2012).

The knowledge of the atmospheric processes is growing but an increased knowledge on methane emissions and OH concentration fields is needed to drive the atmospheric models. Measurements of methane concentrations can be used to verify the model results, but the estimates of emissions from individual sources have not much improved since 1980 relative to the first estimates of different authors. At a global scale the measurement results are not specific enough to prove emission reductions through mitigation measures for the individual sources. Especially lacking are measurements of methane emissions of the individual sources at the local and regional scale.

The growth rate over the last century indicates growing methane sources since the beginning of methane concentration measurements and during the 1970s. The growth rate has diminished in the period since the 1980s and increased again since 2006. An initial stabilisation of sources is likely, especially in fossil methane, since the collapse of the eastern European economy in 1989 and since oil companies have become more aware of the environmental consequences of venting and flaring. Research is needed to confirm this.

The IPCC estimates on natural emissions and sinks are rather large compared to the budget for the integrated assessment. Our outcomes are still within the IPCC uncertainty range. The estimates of Bergamaschi et al. (2007) for anthropogenic sources are comparable to the estimates used in this thesis. A lower total of 470 Tg/yr was taken for 2000. This is comparable to the latest findings that methane concentrations have essentially been stable in the atmosphere. The assumption was that the fossil methane emissions were not growing as fast as assumed by others, because of the economic crisis in the eighties and nineties in Eastern Europe and the increasing environmental awareness with international, coal, oil and gas companies.

However the uncertainties are large in the individual terms of the budget and the integrated assessment as can be seen in the next table.

Table 7.1 Uncertainties in the different components of the integrated assessment modelling of methane as a greenhouse gas (Source: IPCC and this thesis).

	Global total	Spatially explicit
Emissions methane	Largely uncertain	Very largely uncertain
Emissions methane sources	Very largely uncertain	Extremely uncertain
Emissions methane countries	Very largely uncertain	Extremely uncertain
Concentration methane	Relatively certain	Relatively certain
Hydroxyl concentrations	Very largely uncertain	Extremely uncertain
Radiative forcing	Relatively certain	Relatively certain
Equilibrium temperature change	Largely uncertain	Unknown
Actual temperature change	Largely uncertain	Very largely uncertain
Other effects on climate	Very largely uncertain	Extremely uncertain

Uncertainties are especially large for calculated or estimated total methane emissions, methane emissions per source and per country. Spatially explicit information is even more uncertain. Uncertainties are very large for hydroxyl radical concentration fields needed for the calculation of spatially explicit methane concentration fields. The effects on the temperature and the climate in the future are very uncertain. The calculated concentration of methane given the actual methane emissions is relatively certain. The calculated radiative forcing of methane given a concentration field is relatively certain.

Future research should be directed to finding the autonomous and policy driven reductions in anthropogenic methane emissions, together with finding the answers to natural fluctuations of methane emissions. Therefore top-down and bottom-up estimates are needed. The top-down research should be global and incorporate new knowledge from measurements from space (MOPITT on the TERRA spacecraft and SCIAMACHY on the ENVISAT satellite) combined with long term measurements of methane concentrations at ground stations at clean air (background) and polluted (source) locations. To reduce uncertainties more high tower measurements of the type of the Cabauw site in the Netherlands (tower with measurements at different heights between 10 and 200 m) are needed. Towers should be spaced about 500 km apart to be able to verify national greenhouse gas emission inventories. Measurements should be long term and hourly for more than one year to determine the daily and seasonal fluctuations. Meteorology should be measured at the same frequency. Especially the mixing layer depth is crucial for the accuracy of the estimates of fluxes. The bottom-up research should be local and consisting of measurements of the individual sources of methane. Models should be developed for up scaling to emission estimates per sector and per year for regions and countries. Measurements are needed in all important methane sources.

7.4 Quality of emission estimates

The third research question was: How do estimates from a comprehensive global emissions database for atmospheric research (i.e. EDGAR) compare to aggregated national emission estimates?

The bottom-up methane emission estimates from official national inventories were used to compare with EDGAR estimates. EDGAR used international statistics and simple methodology to estimate methane emissions. The national estimates were based on the IPCC methodology. The EDGAR estimates for OECD countries were comparable with the country estimates except for the agriculture and biomass sources. For non-OECD countries larger differences were found. Especially the methane emission estimates of EDGAR from biomass burning and from some sources like methane from manure management and from waste water treatment were not comparable with country emissions. Some countries use more detailed methods and adjusted the initial estimated time series. International statistics on agriculture, manure, land use and biomass should be improved.

Two databases of national inventories have been used in the comparison: the Climate Secretariat database of national inventories and the EDGAR database. The uncertainties are seldom quantified in the inventories. From some experimental studies we know that uncertainties for methane are in the range of 30-35% for all sources. The uncertainties in the national inventories can not be reduced by validation with top-down model studies, while these are of the same magnitude. Deterministic studies and process model development to get a grip on the processes of methane formation can reduce uncertainties.

This comparison was the first in its kind. The results were used to improve the IPCC methodology for methane emission estimates leading to the IPCC updated 2006 Guidelines (IPCC, 2007). The method has been used by others to make comparisons of more recent national inventory information with EDGAR 4 (Winiwarter et al, 2010). This comparison evolved into a review tool for the Climate Convention.

The country comparison with EDGAR showed that differences are large in all important sectors even in Europe, although the totals match more closely. The reasons for these differences are differences in the emission factors and activity data used.

The comparability of methane emission estimates can be improved in the future by improving the IPCC guidelines and the basic statistics of countries. The IPCC guideline results may be underestimating the sources of methane when compared to the top-down budgets.

Improved reporting and documentation for the official reporting to the Climate Convention could increase transparency, comparability, consistency, completeness and accuracy (TCCCA) and could increase confidence in each others country estimate. The national inventories could be improved by incorporating uncertainty analysis on the estimates. The use of the IPCC 2006 Guidelines for reporting to the Climate Convention should be evaluated. The review of country specific methodology should lead to new methods that go beyond the emission factor approach. We certainly need more process based methods.

7.5 Options for control

The fourth research question was: Which options are available for methane reductions and what are their costs?

Methane emissions are being mitigated along with other greenhouse gases since the United Nations Framework Convention on Climate Change was signed in Rio de Janeiro in 1992 and ratified by over 200 countries. Although the contribution of methane to global warming is less than carbon dioxide, methane is very interesting because of its high global warming potential of 72 over 20 years and 25 over 100 years. Due to the short lifetime of methane in the atmosphere reductions in anthropogenic methane emissions will have a considerable effect within a few decades.

Different methods exist to estimate the costs of methods for methane reduction. Generally speaking top-down macro-economic methods and bottom-up technological methods can be distinguished. The macro-economic costs are calculated differently from the costs of technical measures. Costs of technical measures are usually expressed in US$ per ton of reduced emissions. A distinction can be made between project and sector analysis and an analysis for the whole economy. The project level analysis considers an investment assuming insignificant secondary impacts on markets. Methods used include cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA). Sector level analysis examines sectoral policies in a partial equilibrium context with all other variables assumed to be exogenous. Economy-wide analysis explores how policies affect all sectors and markets, using various macroeconomic and general equilibrium models (Markandya and Halsnaes, 2001).

It is difficult to assess the benefits of greenhouse gas mitigation measures. Assessing the additional costs of emission reduction ideally considers the total value that society attaches to the goods and services that could have been provided with the money used to protect the climate. The sum of benefits and costs should be negative, meaning that society gains from undertaking these actions. The assessment of costs and benefits should be based on a systematic analytical framework to ensure comparability and transparency of estimates. The estimated costs are but one piece of information in the decision making process for climate change, and certainly not the only one. Information on other social objectives, like health care, equity, impacts on key stakeholders and poverty alleviation has to be brought into the picture as well (Markandya and Halsnaes, 2001).

Many options have been identified to reduce methane emissions. Some options are profitable and must be stimulated. Some options are too expensive at the moment (arbitrarily put at > US$ 500 per ton of avoided methane) or not feasible because of other reasons. Methane emission control options have been formulated for the OECD regions (Europe, North America and the Pacific). More information is needed from pilot studies on control options and costs for the other non-OECD regions. The approach to express costs per ton of avoided emissions has been very successful.

Various authors have made estimates of the technical and economic potentials of methane reduction options. Some options are identified mainly in landfill management, coal and oil & gas production, that are profitable. The most expensive options are identified in ruminants, manure management and sewage treatment.

With respect to the estimated costs of reduction of methane emissions more research is needed to substantiate the cost estimates after 2025 for the different regions in the world.

More detailed analysis could be carried out with other submodels within IMAGE with optimisation of options using marginal abatement costs and a constraint like, for example, an emission tax. Options could be formulated to combat different environmental problems at the same time, taking into account the interrelated effects of reductions of different pollutants.

Top-down cost estimates can be made using macro-economic methods in which the reduction on the Gross Domestic Product is estimated of a package of reduction measures. Often measures are classified in different categories: levies, subsidies, regulations and legislation (Edmonds et al., 1996; Reilly et al., 1999). Here bottom-up cost estimates were made that are based on engineering studies using pilot plants. Investment and maintenance costs are calculated per ton of avoided methane emission.

When national goals are set to reduce greenhouse gas emissions, technology assessment to reach these goals can be done at different economic levels. A cross-sectoral and regional level can be chosen to assess the overall priorities and to assess the impacts on income, production and environment of scenarios and to assess the impact of different strategies. Methane emission reductions could be pursued that have the largest global benefits at the lowest possible costs. The Climate Convention states that Parties may take measures jointly in order to reduce costs. A sector level can be chosen to assess the most effective policies and measures within a sector and to assess the costs of alternatives. For example the costs of a lower maximum speed in traffic versus the costs of developing more efficient or even zero emission engines. Micro or project levels can be chosen to assess the costs of programmes or individual projects, like e.g. a landfill gas recovery and utilisation project. More research like the UNEP costing study is needed to estimate bottom-up region specific costs of various options (UNEP, 1994; USEPA, 2002).

7.6 Scenario analysis

The fifth research question was: What are the effects of methane emission reduction packages on future climate change and what are the associated costs of these packages of methane reduction?

The IMAGE model was used to analyse the effects of methane reduction packages on future climate. The associated costs of methane reduction have been estimated. Two scenarios, each with three methane reduction packages, have been described and implemented in IMAGE. Both scenarios had a moderate population development with a global population peak in 2050 of 8.7 billion and declining to 7.1 billion in 2100.

These global population outlooks are lower than UN outlooks and supported by recent research from IIASA (Lutz et al., 2001). The higher scenario P had a world Gross Domestic Product (GDP) in 2100 of 525 10^{12} $US\$_{1990}$ and the lower scenario Q had a world GDP in 2100 of 330 10^{12} $US\$_{1990}$.

The three methane reduction strategies were described as no methane reduction (P1 and Q1), moderate methane reduction (P2 and Q2) and maximum methane reduction (P3 and Q3). In P2 methane reductions from landfill gas recovery were assumed. Q2 contained methane reductions from landfill gas recovery and fossil fuel leakage. P3 assumed methane emission reductions in landfills, sewage, rice, fossil fuel leakage and biomass burning. Q3 assumed methane emission reductions in landfills, sewage, rice, fossil fuel leakage and biomass burning.

Emission reductions of 18% relative to the baseline (P1) were found in P2 in 2100 and of 27% in Q3 in 2100. Reductions of 50% relative to the baselines were possible in 2100 in P3 and Q3. These reductions were enough to stabilise the methane concentrations in P2 and Q2 and to reduce the methane concentrations in P3 and Q3 to below 1500 ppbv in 2100.

These methane reductions already resulted in a reduced climate effect in 2030 and a more pronounced effect in 2100. The expected future temperature change in 2100 was half a degree smaller in P3 compared to no methane policies in P1. The expected future temperature change in 2100 was also half a degree smaller in Q3 compared to no policies in Q1. The expected temperature change in P3 is 2.5 ^{o}C and in Q3 is 1.5 ^{o}C. An expected sea level rise of 400 mm in 2100 in P1 is reduced by 40 mm through methane reductions in P3. An expected sea level rise of 340 mm in 2100 in Q1 is reduced by 40 mm through methane reductions only in Q3.

A methane emission reduction of 20% would be enough to stabilise methane concentrations in the atmosphere. Over the last decades measurements have already shown reduced methane growth rates possibly leading to the stabilisation of the methane concentration. Methane emissions may have been reduced over the last decades but measurements are not conclusive on this. Oil and gas operations in the world have become cleaner. Some oil companies have abandoned methane venting and flaring of associated gas in oil fields. This should be verified through emission measurements and measurements of isotopic fingerprints.

About 50 per cent reductions in methane emissions are possible through the world-wide introduction of currently available technologies. These technologies can be cost-effectively introduced for the whole period of 2000 to 2100. All methane can be reduced if the more expensive methane reduction options are deployed in the maximum reduction strategies of P3 and Q3. Cost effectiveness is reduced in the period after 2050. Still the costs are low in terms of lost GDP growth. Costs are smaller than 0.1 per cent per year of GDP. The more expensive options that were not deployed in this analysis are reductions in methane from ruminant livestock and methane reductions in manure management.

7.7 Overall synthesis

This study on CH_4, (its role in climate change and options for control), aimed at a scenario analysis to assess future climate change under reduced methane emissions. At the same time improving the quality of CH_4 emission inventories and estimating the costs of emission reductions between 2010 and 2100. The quality of emission inventories has been improved by inverse modelling and comparison of national inventories with other authoritative sources like the EDGAR database. This thesis identified and analysed the uncertainties in the different sources and sinks of methane from the scientific literature. The results of this analysis helped to develop the methane section of the 2006 IPCC Guidelines for National Inventories of Greenhouse Gas Emissions and Sinks. The development process of the first draft and later updates was coordinated by IPCC. These IPCC Guidelines have made a large international impact. The developed methodology is highly cited scientifically and used by many governments with obligations to submit official annual national inventories to the Kyoto Protocol. The importance of this work was also recognized by the Norwegian Nobel Peace Prize Committee, who rewarded the 2007-prize to Al Gore and the IPCC. This is a symbol of the international societal relevance of this important collaborative work.

The national inventories, however, consist of a bottom-up approach and sometimes the documented and submitted emission data were biased for political reasons or lack of understanding of relevant processes. Early on in the drafting process of the guidelines, therefore the need emerged to assess the quality of the resulting data by comparing the data from the national inventories with independent global data bases, whose data are collected with more top-down approaches that could provide a more comprehensive budget of the different GHGs. Our comparison of the national inventories and the global EDGAR database (which remains important internationally as the major independent authoritative source of emission data) was one of the first attempts to quantify the inherent uncertainties in the methane budgets. It was shown that differences are large in all important sectors even in Europe, although the totals match relatively well. Differences were related to the use of different emission factors and different activity data. This early work on quality control of methane emissions helped to improve the guidelines and the national inventories.

Inverse modelling is another possibility to improve the national inventories. Since the launch of Envisat and the SCIAMACHY instrument it is possible to retrieve methane concentration fields and vertical columns of methane in the troposphere. These data from remote sensing from space have become extremely valuable for improving the original (a priori) estimates for individual methane sources. The study of Bergamaschi et al (2007) confirmed the plausibility of the bottom up estimates of the anthropogenic sources used by Van Amstel in this thesis. To match the global budget, however, the natural wetland and vegetation estimate for CH_4 has to be increased, causing a lot of scientific debate on CH_4 emissions from wetlands and vegetation.

An additional literature review then identified 28 major options to control or mitigate methane emissions from different sources. The effectiveness and costs of these options were assessed. This study resulted in a database of different options and costs for all the different sources discussed and assessed in Chapters 2 and 3. This database was subsequently used to update the methane module of the IMAGE model and expand it with a simple costing module. The IMAGE model was improved by this work by Van Amstel on methane reduction strategies.

This version of the IMAGE model was then used to analyse the effects of different methane emission reduction strategies on climate change. Two additional scenarios with moderate and maximum methane abatement were used to address the global costs of methane emission reductions. This integrated analysis clearly showed that methane reductions almost immediately start to protect climate and that they are inexpensive. The analysis showed that more than half of all anthropogenic methane emissions can actually be reduced at negative or no costs, while mitigating all methane emissions would cost approximately 0.1 per cent of annual world GDP. Methane reductions also result more rapidly in lower levels of climate change than comparable reductions of other greenhouse gases. This property of methane emission reduction policies could become important on the short term, especially when the role of aerosols in the climate system is considered. Aerosols, which are a major component of air pollution, reflect sunlight and therefore mask some of the climate change regionally. Over the coming decades, aerosol emissions will probably be reduced significantly worldwide because of serious impacts on public health. (As a matter of fact, Europe already achieved an almost 90 per cent reduction over the last 30 years (Vautard et al., 2009; Shindell et al. 2012). These aerosol emission reductions will immediately reduce the climate masking effect. Large methane emission reductions could help to neutralize the additional warming due to reduced aerosols. Policies targeting methane emission reduction are highly commendable because of their rapid effect on climate and their cost effectiveness.

Conclusion

Significant reductions in global methane emissions are both technologically feasible and, in many cases, very cost effective strategies for climate change mitigation. Their wider implementation in coming years and decades will largely depend on the policy and market signals delivered by the UNFCCC conferences of the Parties, but failing to make full use of the potential for methane mitigation globally will inevitably make effective mitigation of climate change through reduction of carbon dioxide emissions alone all the more difficult. The scientific community can provide improved methane flux estimates, reduce uncertainties and enhance our understanding of key climate change feedback mechanisms, such as methane emissions from high latitude wetlands and from clathrate deposits. The technology to deliver deep cuts in methane emissions from a host of important sectors is already available. To put methane mitigation at the heart of a robust and well-integrated framework for tackling global climate change, improved national and international policy is required to facilitate rapid technology transfer and provide financial incentives that will ensure that the myriad potential opportunities for the effective mitigation of methane emissions around the world are made real. It is therefore recommended to remove market barriers and to increase attention for methane abatement options through international cooperation and learning from proven technology. One possible route to overcome market failure in methane reduction is international cooperation between front runners and countries willing to learn. Public-private partnerships can be used to stimulate this international cooperation for example in the International Methane Initiative.

SUMMARY

Methane and climate change

This thesis deals with methane, its role in climate change and options for control. The research aims at an integrated analysis of future non-abated and abated trends in global methane emissions, the associated climate change and the costs of emission control.

Five research questions were formulated:

1. What are relevant atmospheric processes that involve methane? (Chapter 2)
2. What are the global methane sources and sinks? (Chapter 3)
3. How do estimates from a comprehensive global emissions database for atmospheric research (i.e EDGAR) compare to aggregated national emissions estimates? (Chapter 4)
4. Which options are available to reduce methane emissions and what are the costs of each option? (Chapter 5)
5. What are the effects of methane emission reduction packages on future climate change and what are the associated costs of these packages? (Chapter 6)

Here a summary will be given of the findings for each research question

1. What are relevant atmospheric processes that involve methane?

The natural greenhouse effect is one of the reasons that we can thrive on this earth. Greenhouse gases such as CO_2, CH_4 and N_2O are transparent for the short wave radiation from the sun, but they absorb part of the long wave radiation (heat) from the earth back into space. Without the natural blanket of greenhouse gases in the atmosphere (i.e. if the atmosphere would contain only oxygen and nitrogen) the average temperature on earth would be -18^{o}C instead of the comfortable +15^{o}C of today. The enhanced greenhouse effect is caused by increased emissions of greenhouse gases due to human activities, and this causes an increase of global mean surface and tropospheric temperature of 1.4 - 5.8^{o}C with a doubling of the pre-industrial greenhouse gas concentration in the atmosphere. Such warming is accompanied by major shifts in rainfall patterns.

Methane is the most abundant organic trace gas in the atmosphere and, after carbon dioxide, the second most important greenhouse gas emitted by human activities. Average global concentrations of CH_4 have more than doubled since pre-industrial times from 700 parts per billion by volume (ppbv) to 1780 ppbv. The concentration over the Northern Hemisphere is on average higher with 1800 ppbv. Over dominant source areas like Western Europe concentrations occasionally increase to 2500 ppbv. Methane has a significant warming effect because it absorbs strongly at wavelengths which are otherwise transparent to the earths outgoing radiation.

There is little or no consensus on the causes of the long-term stabilization of methane concentrations in the atmosphere between 1980 and 2006 and the increased growth after 2006. The growth rate during the last decades has not been constant indicating a complex of factors, including human activities, affecting sources and sinks. Large volcanic eruptions, for example, cause cooling and inject many aerosols into the higher atmosphere. This influences the sources and sinks of methane as illustrated, for example, by the Mount Pinatubo eruption in June 1991, which has caused a large

anomaly in the methane growth rate. After this eruption the methane growth rate increased in the first few months in the tropics. This has been attributed to short term decreases in solar UV in the tropics immediately following the eruption that decreased OH formation rates in the troposphere. In 1992, a large decrease of the methane growth rate to almost zero was observed, especially in the northern latitudes. This feature has been attributed in part to decreased methane emissions from northern wetlands because of low surface temperatures and in part to stratospheric ozone depletion that increased tropospheric OH. Then, the growth rate returned to a rate of 8 ppb/yr in 1994. A large increase in 1998 and decline in the growth rate was observed around 1999 attributed to the massive forest and peat fires in Indonesia and Russia. The zero growth rate between 2000 and 2006 may have been the result of autonomous reductions in methane emissions or even a success of mitigation measures. Others concluded that the wetlands emitted less methane during those years. Between 2006 and 2010 the methane growth rate increased again. Indicating a decrease of sinks and/or a growth in emissions. It has been attributed to increased wetland emissions in the Arctic as well as in the Tropics because of warm and wet conditions after a period of droughts.

2. What are the global methane sources and sinks?

Inverse modelling can be used to improve the methane estimates for the different sources. This kind of research was boosted especially since the European space agency launched Envisat on 1 March of 2002 to improve methane budgets using "a priori" estimates for sources and remotely sensed methane column measurements. The SCIAMACHY instrument on board Envisat shows real time methane concentration fields and profiles for the troposphere for the first time in history. The results helped make a clearer picture in time and space of global methane emissions and concentrations. The improved or "a posteriori" estimates have been presented in this thesis. A reduction of uncertainties has since been achieved because local measurements at ground stations are verified with measurements from space.

Sources of methane emissions

The most important anthropogenic sources of methane emissions are oil and natural gas production and use, coal mining and use, enteric fermentation of cattle, fermentation of animal waste, rice paddies, waste disposal in landfills, domestic sewage treatment and incomplete biomass burning. All these sources of methane have increased with population growth and economic development. The only possible exception is the wetlands, which have been drained at a large scale for agriculture. Rice paddies however have increased since 1950.

Oil and gas
Methane is present in oil fields. Methane is also the main constituent of natural gas. It escapes to the atmosphere through leaks and vents during exploration, exploitation, production, transport and distribution of oil and gas. In many cases the associated gas from oil fields is vented to the atmosphere in the absence of markets for the liquid petroleum gas e.g. in Saudi Arabia, Nigeria and other main oil producing countries. From gas fields natural gas is transported through high pressure transport pipelines to gas compressor stations and gas treatment facilities, from there it is expanded from high pressure to low pressure and dried with glycol. Then it is distributed to consumers in low-pressure distribution networks. In oil and gas production sites in Siberia and Alaska

the environment is particularly difficult for the companies. The top layer of the permafrost soil thaws in spring and becomes unstable for constructions. It is difficult to construct stable high-pressure pipelines under these circumstances. Therefore it is suspected that especially the Siberian gas transport is very leaky. In Alaska more leak control and modern equipment is used to keep this problem under control. In larger cities especially the old cast iron distribution networks with oakum joints, originally designed for wet town gas made from coal, are very leaky. The dry natural gas leaks from these dried out oakum joints. Increased maintenance and leak control or replacement is urgently needed to reduce this source.

Coal mining
Firedamp is a safety hazard in mines. In the past, thousands of miners have lost their lives because of mine explosions. Therefore ventilation of mine gas in coalmines is needed. Originally, ventilation air with diluted gas was emitted to the air. In Germany as far back as the 1950s this mine ventilation air was used as combustion air. Nowadays increasing awareness of the greenhouse problem has stimulated the use of ventilation air in combustion engines at the mines. At some mines in the United States experiments have started to extract the gas by drilling holes in the strata before mining the coal. This is done in gassy mines like in the Great Warrior Basin and San Juan Basin. It is called pre-mining degasification. The techniques are introduced in China with great success.

Incomplete combustion
Another important source of methane is incomplete combustion of biomass-based fuels. Especially charcoal production or biomass fires when smouldering release relatively much methane. Combustion of charcoal and biomass is an important source of methane in the tropics and less so in other regions.

Wetlands
In wetlands methane is formed under anaerobic conditions from organic material by methanogenic bacteria. Biogenic methane from anaerobic environments like wetlands and marshes is a natural source, but in many cases it is influenced by human action. Wetlands are transformed in wet rice paddies in e.g. Indonesia in the so-called translocation projects in the Indonesian part of Kalimantan and New Guinea, causing increased methane emissions. In some countries like the Netherlands natural wetlands are drained and reclaimed for agriculture. Here methane emissions are reduced. Global warming influences the emissions from wetlands. It is already warming in higher latitudes and permafrost areas are affected. Natural methane emissions can be increasing in these regions.

Rumen fermentation
During fermentation in the rumen of cattle and other grazing animals methane is formed by methanogenic bacteria. This methane escapes to the atmosphere. In principle it is a natural phenomenon but herd sizes have increased at least five fold since the fifties. FAO statistics show a large increase of domestic animals between 1950 and 2008. The most densely populated cattle areas are in the Ganges delta, but also in the dairy farm regions in the lowlands of Western Europe. Other important source areas for cattle are in Russia and Latin- and North America.

Waste treatment
Methanogenic bacteria in anaerobic waste are a source of methane. In the vicinity of large cities waste is landfilled. It becomes anaerobic and methanogenic bacteria produce methane. Methane from landfills can be captured and used for energy. Large amounts of industrial and human waste water were polluting rivers since the fifties. In many countries industrial waste water and sewage treatment plants have been constructed to reduce pollution, but anaerobic sewage treatment systems still are a source of methane. Methane is often used to fuel the systems, but part escapes to the atmosphere.

Rice
Flooded rice fields are an important source of methane in Asia. In some studies, rice is considered a natural source of methane because originally wetlands were located where the paddies are now. This is not entirely true because systems are designed to irrigate new areas, even terraces in the hills. Intensive studies on emissions from rice agriculture have substantially improved these emission estimates.

3. How do estimates from a comprehensive global emissions database for atmospheric research compare to aggregated national emissions estimates?

National greenhouse gas emission inventories.

To facilitate the reporting and review within the framework of the Climate Convention, credible and comparable data from countries are needed. Therefore, the Intergovernmental Panel on Climate Change (IPCC) in collaboration with the United Nations Environment Program (UNEP), the World Meteorological Organisation (WMO), the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD), have developed Guidelines for National Inventories of Greenhouse Gas Emissions and Sinks. These Guidelines were officially adopted by the Parties to the Convention as the common methodology for national inventories. The guidelines have been widely discussed and tested for some years by experts of many countries in order to achieve consensus about the methods. Based on this, IPCC revised these Guidelines in 1996. The Subsidiary body for Scientific and Technical Advice (SBSTA) recommended this update to be used for inventories from industrialised countries. Good Practice Guidelines have also been prepared by IPCC for the reporting of national greenhouse gas emissions and sinks under the Kyoto Protocol. As inventories are inherently uncertain, quality assessment and control of the annual inventories plays an important role. New IPCC Guidelines were released in 2006 (IPCC, 2006). In these guidelines, uncertainty management and quality control is an integral part of the inventory methodology.

Methane inventories

For CH_4 comprehensive inventory methods are currently at a relatively early stage of development, and results still have wide uncertainty ranges. Part of this problem is associated with the difficulty in translating local flux measurement results into emissions estimates for larger areas, such as countries or continents. Another part of the problem is related to the complexity of processes involved in biogenic production of CH_4, for example, by micro organisms in anaerobic soils. Emissions are related to soil types and environmental conditions. Human interference with the soil system is influencing emissions. For example, flooding is known to have various effects on the emissions of methane depending on duration of flooding, temperature van soil carbon content. Thus, because of the dependency of emissions on local climate, soil, and management conditions, extrapolation of local emission results is difficult.

Uncertainty ranges in national inventories are about 5 to 10 per cent for carbon dioxide emissions from fossil fuels, 50 to 100 per cent for CO_2 from land use related sources and sinks, and 100 per cent for N_2O from soils. For CH_4 these uncertainties are also high, being at about 30 to 35 per cent for most sources. Emission inventories rely on statistical information and emission factors. Emission factors can be derived from field scale measurements and appropriate methods for upscaling to the national levels. IPCC has made a great and commendable effort to develop IPCC Guidelines for national emission inventories over the last few decades. Many countries have started measurement campaigns for non-CO_2 greenhouse gases to reduce uncertainties. The uncertainties are likely to be reduced over the coming years in national inventories. Improvements can be made in the national inventories by measurements, improved statistics and a better upscaling. Improved reporting and documentation may increase the confidence in the country estimates.

In this thesis a comparison was made between the official CH_4 inventory estimates and the authoritative data source that is the EDGAR database and we found that the main reasons for differences therein were a result of the different emission factors and activity data used. This comparison also revealed some gaps and omissions in reporting. This kind of comparison has contributed to the validation and verification of both national inventories and EDGAR, and so contributed to the improvement of methodologies to estimate CH_4 budgets. Since my work other authors have made this kind of comparison within the framework of the review of national emission inventories.

4. Which options are available to reduce methane emissions and what are the costs of each option?

Climate control

Methane emissions are being mitigated along with other greenhouse gases since the United Nations Framework Convention on Climate Change (UNFCCC) was signed during the Earth Summit in Rio de Janeiro in 1992 and ratified by over 200 countries. Although the contribution of methane to global warming is less than carbon dioxide, methane is very interesting because of its high global warming potential of 72 over twenty years and 21-25 over 100 years. Due to the shorter lifetime of CH_4 in the atmosphere (12 years for methane in the atmosphere instead of 50-200 years for CO_2), reductions in anthropogenic methane emissions will have a considerable effect within a few decades.

United Nations Framework Convention on Climate Change..

The UNFCCC, signed in Rio de Janeiro in 1992, calls for the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level is to be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. As a first step towards achieving this objective, industrialised countries were required, but failed, to bring their greenhouse gas emissions back to 1990 levels by 2000. Most OECD countries, however, had adopted national emissions reductions targets that are in line with this requirement. Implicitly, a comprehensive approach was adopted taking into account all sources and sinks of all greenhouse gases. All industrialized countries that are a party to the Convention also have to report their national greenhouse gas emissions and their adopted response policies. The emissions and climate policies are reported in the National Communications of the Parties to the Convention. Inventories of emissions and sinks are required annually and independent experts nominated by Parties to the Convention review these inventories and National Communications.

Kyoto protocol

Further reductions of greenhouse gases after 2000 were negotiated in Japan in 1997 in the Kyoto Protocol. An average reduction of greenhouse gas emissions of 5 per cent between 1990 and the commitment period of 2008 to 2012 was agreed between the industrialized nations. Europe agreed to a reduction of 8 per cent, Japan 7 per cent and the US 6 per cent. The United States later withdrew from the Kyoto Protocol, but the Kyoto Protocol came into force in February 2005 following ratification by Russia. The United States will not ratify until developing countries like China, Brazil and India offer a meaningful participation. That is because future economic growth in these countries can increase greenhouse gas emissions far beyond the emissions from the developed world.

A major sticking point in international negotiations over how to best reduce global greenhouse gas emissions has been money, with some economic models predicting very large implementation costs for the measures outlined as part of the Kyoto Protocol. However, where reductions are not just confined to reducing carbon dioxide emissions, but instead the non-CO_2 greenhouse gases, such as CH_4, the predicted price of reductions falls considerably .

In the Kyoto Protocol, a “net flux” approach is adopted for a basket of greenhouse gases, including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. In this net flux approach carbon dioxide emitted from deforestation is counted as an emission, but carbon dioxide sequestered in forests that are planted after 1990 can be subtracted from the emissions. Further sink categories like soils are still under negotiations.

Options were described for methane mitigation. Many options can be implemented at low costs. Some options can be implemented later because they are at the moment more expensive. The cheap options are related to methane capture and use in the fossil fuel industry, especially in coal, oil and gas production and transmission. More expensive options are related to agriculture. The challenge is an increased world food production with lower methane emissions. Especially in dairy farming and meat production it is paramount to reduce methane emissions from rumen and manure fermentation. For human activities, it is apparent that there exist myriad opportunities for improved mitigation of CH_4 emissions in the coming years and decades. Half the emissions can be reduced at only 0.1 per cent of world GDP.

Mitigation

Methane emissions can be reduced. Cost effective and even profitable options are available as is shown in this thesis. Profits can be made for example in methane capture and use in landfills, in coal mines, during oil and gas exploitation, and during transmission and distribution of fossil fuels. Even the costs of the more expensive solutions with methane reductions in sewage systems and animal manure are low with about 0.1 per cent of global GDP.

Methane recovery and use from landfills is a success in many OECD countries. More could be done and should be done early after the start of the operations in landfills and fossil fuel exploitation. Most methane can be captures in the early stages. Methane recovery and use in landfills and fossil fuel exploitation is profitable.

Technology transfer

Technology transfer is important. Clean technologies can be stimulated in Eastern Europe and in developing countries. The Netherlands started programmes to buy emission reduction units and certified emission reduction units from reductions of greenhouse gases in other countries. Landfill gas recovery was one of the approved projects. Pre-mining degasification is another promising technique.

5. What are the effects of methane emission reduction packages on future climate change and what are the associated costs of these packages?

An integrated analysis was performed of the impacts on 21st century climate change that result from a scenario of unabated versus abated emissions of CH_4. The analysis was based on model runs by the IMAGE integrated assessment model. In the IMAGE model, a set of scenarios was developed in close cooperation with the IPCC to assist the climate negotiations for the Kyoto protocol. The IMAGE model was used because it included information on major processes that determine uncertainties that are not included in other models. The analysis showed that CH_4 emissions could be reduced in the future at relatively low cost, while still playing a significant role in reducing climate change and sea level rise. Between 2050 and 2100, the analysis of methane abatement alone (i.e. without mitigation of other greenhouse gas emissions) indicates that the projected temperature increase would be half a degree lower than that without methane abatement, and that sea level rise would be reduced by four centimetres. Methane abatement however did not result in noticeable climate change reduction before 2050.

Overall conclusion

Significant reductions in global methane emissions are both technologically feasible and, in many cases, very cost effective strategies for climate change mitigation. Their wider implementation in coming years and decades will largely depend on the policy and market signals delivered by the UNFCCC conferences of the Parties, but failing to make full use of the potential for methane mitigation globally will inevitably make effective mitigation of climate change through reduction of carbon dioxide emissions alone all the more difficult. The scientific community can provide improved methane flux estimates, reduce uncertainties and enhance our understanding of key climate change feedback mechanisms, such as methane emissions from high latitude wetlands and from clathrate deposits. The technology to deliver deep cuts in methane emissions from a host of important sectors is already available. To put methane mitigation at the heart of a robust and well-integrated framework for tackling global climate change, improved national and international policy is required to facilitate rapid technology transfer and provide financial incentives that will ensure that the myriad potential opportunities for the effective mitigation of methane emissions around the world are made real. It is therefore recommended to remove market barriers and to increase attention for methane abatement options through international cooperation and learning from proven technology. One possible route to overcome market failure in methane reduction is international cooperation between front runners and countries willing to learn. Public-private partnerships can be used to stimulate this international cooperation for example in the International Methane Initiative.

Methane emissions can be reduced at costs lower than 0.1% of GDP. Methane emission reduction leads to a reduced climate change in the future. This reduced climate change is clearly shown for the years between 2050 and 2100. In this thesis we could not proof reduced climate change before 2050 as a consequence of methane reductions alone. It is important to reduce all greenhouse gas emissions at the same time to achieve the maximum effect on the climate.

Acknowledgements

The first idea to write a thesis on methane as a greenhouse gas emerged when I was working at the National Institute for Public Health and the Environment in the Netherlands (RIVM). Professor Leen Hordijk and Professor Carolien Kroeze at the Wageningen University were willing to act as my promotor and co-promotor. Leen and Carolien, I thank you both for patiently reading manuscripts and providing me with valuable comments. When Professor Leen Hordijk left Wageningen University to become the Director of the International Institute for Applied Systems Analysis in Austria, Professor Rik Leemans took over the responsibility as my promotor. I was very fortunate, as Rik Leemans was the team leader for the development of the Integrated Model to Assess the Global Environment (IMAGE) for so many years at RIVM, and a world renowned expert on integrated assessments. Rik, thank you for your support and encouragement.

Although the research structure and implementation are mine, I could not have written this thesis without the help of many colleagues. Thank you, Rob Swart for giving me the opportunity to start this work in the early 1990's on improving the understanding of methane sources and sinks and related policies at the National Institute for Public Health and the Environment (RIVM) in the Netherlands. Together, we wrote several early influential publications on methane. I would like to thank my colleagues at the IMAGE team at RIVM: Bert de Vries, Lex Bouwman, Eric Kreileman, Maarten Krol, Michel den Elzen and Bas Eickhout for cooperating on the implementation of the methane reduction strategies in the IMAGE scenarios. The collaboration with this advanced modelling team is highly appreciated. My research has resulted in updated emission factors in the IMAGE model and the addition of the costing module for methane emission mitigation.

During the early stages of my research, I worked at the United Nations Framework Convention on Climate Change (UNFCCC) headquarters in Geneva, where I started the first database on national emission inventories. I would like to thank Jaap Swager and Vitaly Matsarski at UNFCCC for a wonderful period of data gathering and analysis. With Jos Olivier, I started to work on national emissions inventory quality at the RIVM in the Netherlands. This work was extremely valuable for the National Communications of the Netherlands on which I worked together with Paul Ruyssenaars at the Ministry of Physical Planning and the Environment. I would like to thank you all for stimulating discussions on methods for quality assurance.

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The IPCC/OECD organised several workshops as preparations for the IPCC Good Practice Guidelines. Based on the results we prepared a special journal issue on greenhouse gas

[1] Van Aardenne, J.A. 2002. Uncertainties in emission inventories. PhD-thesis. Wageningen University.

inventory quality. I would like to thank Pierre Boileau and Bo Lim, then at the OECD, now at Environment Canada and the UNDP, for cooperation in these workshops and for good company.

In 2004, I was one of the Coordinating Lead Authors for the Agriculture Forestry and Land Use Volume of the IPCC 2006 Guidelines for national inventories. Together with Keith Paustian from Colorado State University, USA and N.H. Ravindranath from the Indian Institute of Science in Bangalore, we edited many draft chapters. Many of the ideas on quality assurance were incorporated in these 2006 Guidelines. Leandro Buendia from the Philippines was the editor for the volume on agriculture and forestry from the IPCC Taskforce Bureau. Thanks Keith, Ravi and Leandro for the cooperation. The IPCC 2006 Guidelines have made a large international impact. The developed tier methodology is highly cited scientifically and used by many governments to create their national inventories. The importance of this work was also recognized by the Norwegian Nobel Peace Prize Committee, who awarded the 2007 Peace Prize to Al Gore and the IPCC. I appreciate that all coordinating lead authors working on the Guidelines were also recognized with a personalized copy of the Nobel Diploma. It is a symbol of the international societal relevance of this important collaborative work.

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André van Amstel
Doorn, January, 2012

About the author

André van Amstel was born in 1954 on July the 15th in Bloemendaal, the Netherlands. He lived in Santpoort-Zuid until his 19th birthday. Fascinated by nature he roamed the beautiful dunes area of Kennemerland near the coast of North Holland. After high school at the Marnix van Sint Aldegonde College in Haarlem he started as a physical geographer at the University of Amsterdam in September 1973. After his studies with many beautiful fieldwork summers in Switzerland, Austria and Italy he started his work in environmental science.

His first job was at the Institute for Environmental Studies at the Free University in Amsterdam from 1982 to 1989 where the ecological effects of international agricultural trade made him conclude that for our high input agriculture and consumption pattern in the Netherlands, an area at least three times the Netherlands was needed in other countries. From 1990 to 1991 he lectured physical geography at the University of Amsterdam. He worked at the Institute for Public Health and the Environment (RIVM) from 1991 to 1996 where he was responsible for the national greenhouse gas emissions inventories for the National Communications on Climate Policies to the Climate Convention.

Since 1991 André van Amstel is a member of the IPCC Task Force on Guidelines for National Emissions Inventories. From April 2004 to 2007 he was coordinating lead author for the Volume 4 on Agriculture, Forestry and Land Use (AFOLU) of the IPCC 2006 Guidelines. As such he contributed to the Nobel Peace Prize for the IPCC and Al Gore in 2007. IPCC presented him with an honorary diploma for this work.

Since 1996 André van Amstel is working at the Wageningen University and Research Centre at the Environmental Systems Analysis Group. His main interest is integrated assessment and quality control in greenhouse gas emission inventories. André van Amstel was guest editor of several special issues on greenhouse gas emissions of Fertilizer Research in 1994, of Environmental Science and Policy in 1999, of Environmental Sciences in 2005, of Agriculture, Ecosystems and the Environment in 2007 and of the Journal of Integrative Environmental Sciences in 2010 and 2012. Together with Dave Reay and Pete Smith he is co-author and editor of the book Methane and Climate Change, published in 2010.

A list of his publications is available at the Environmental Systems Analysis website:

www.esa.wur.nl

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