VLEEM – Very Long Term Energy Environment Modelling

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ANNEX 2

Monograph: Options for CO_2 sequestration and enhanced fuel supply

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Abstract

Depletion of fossil fuel resources is not a short-term issue. Just like anthropogenic emission of greenhouse gases (GHG), it may have long-term impacts. There are several options to sequester CO_2 as a means to reduce GHG emissions. CO_2 from power plants based on fossil fuels may be stored in depleted gas or oil reservoirs, aquifers, oceans, etc. However, one of the most promising options is CO_2 Enhanced Oil Recovery (EOR). In case of EOR, CO_2 is sequestrated in combination with enhanced oil production. Also, CO_2 Enhanced CoalBed Methane (ECBM) production is an interesting option. In case of ECBM, CO_2 is sequestrated in deep coal seams and coalbed methane contained in the coal seams is produced. ECBM is interesting because of its GHG reduction potential, optimal use of locally available fossil fuels - deep coal resources - and security of energy supply. This study focuses on the CO_2 sequestration options EOR and ECBM. From the point of view of rational use of fossil fuel resources they are deemed to be superior to CO_2 sequestration in depleted oil and gas reservoirs, aquifers, and oceans. Although CO_2 sequestration in oceans has a tremendous potential, there are no benefits of enhanced fuel production when compared to EOR and ECBM. Also, CO_2 sequestration in oceans tends to be a temporary solution because CO_2 may surface in significant amounts within a few hundred years.

Based on the cost of current CO_2 supply options, ECBM would not become a ‘big’ option in the Netherlands, unless tremendous financial incentives would be available. In the long term, dedicated coal-fired power plants could supply CO_2 at more competitive terms, thereby increasing the potential of ECBM. Also advanced gas-based power generation (e.g. based on fuel cells) could offer potential for ECBM.

In order to assess the global potential of EOR and ECBM, production profiles have been made for conventional and unconventional oil, conventional gas and coalbed methane, and CO_2 sequestration by EOR and ECBM for ten world regions. Other sources of unconventional gas, such as clathrates (hydrates) on the ocean floor or in permafrost regions, have not been considered for the reason that exploitation of such resources is extremely uncertain until now.

The study shows that the global production of oil could be maintained at a high level due to increasing production of unconventional oil. In 2100, oil production could be a few percent below the level of 2000. Production of gas could be increased by more than 25% in 2100 compared to the current production level, both by increased production of conventional gas and introduction of coalbed methane. The associated level of CO_2 sequestration could be 1,400 Mt/a in 2100, 93% of which would be related to ECBM and the balance to EOR.

CONTENTS

SUMMARY

Depletion of fossil fuel resources is not a short-term issue. Just like in case of the anthropogenic emission of greenhouse gases (GHG), it may have long-term impacts (year 2100). According to e.g. the authoritative US Geological Survey, the resource/production ratios of fossil fuels are:

- about 190 years for the combined resources of conventional and (recoverable) unconventional oil,
- about 180 years for conventional natural gas,
- about 230 years for the proved recoverable coal reserves.

The figures for oil and gas are higher than the commonly reported figures for proved reserves. Note that these figures refer to current consumption rates (year 2000). Also, these figures are characterised by large uncertainties, particularly in case of conventional oil and gas resources.

What is more, there are huge amounts of clathrates - methane hydrates - in Arctic areas and at the ocean floor. The uncertainty with regard to unconventional gas resources is extremely large.

Because of the relatively limited reserves/production ratio of the proved conventional oil reserves and the dominance of the Middle East, oil remains a strategic fossil fuel and (price) crises cannot be excluded. The supply conditions of natural gas are more favourable. However, if both the industrialised countries (Annex 1 countries) and developing countries would massively switch from coal to gas, security of supply of natural gas would become an issue relatively soon.

One of the options to reduce greenhouse gas emissions is CO_2 Enhanced Oil Recovery (EOR). Of course, the net effect of CO_2 sequestration depends from the assumptions made. A number of CO_2/EOR projects are operational today. There is a substantial additional potential in North America, the Former Soviet Union, and the Middle East. CO_2 Enhanced CoalBed Methane production (ECBM) is interesting because of its GHG reduction potential, optimal use of locally available fossil fuels - deep coal resources - and security of energy supply. Even in countries where conventional coal production has been terminated for economic reasons, ECBM deserves attention. The fossil fuel ‘depleted’ is coal, but the fuel produced is coalbed methane, which has a much lower specific GHG emission (g CO_2 equivalent/GJ) than coal itself.

This study focuses on the CO_2 sequestration options EOR and ECBM. From the point of view of rational use of fossil fuel resources they are deemed to be superior to CO_2 sequestration in depleted oil and gas reservoirs, aquifers, and oceans. Although CO_2 sequestration in oceans has a tremendous potential, there are no benefits of enhanced fuel production when compared to EOR and ECBM. Also, CO_2 sequestration in oceans tends to be a temporary solution because CO_2 may surface in significant amounts within a few hundred years.

The cost of coalbed methane largely depends on the investment cost of drilling injection and production wells. Whether the coalbed methane price is acceptable depends on:

- the necessity of deep inseam drilling or not, direct or late injection, etc. (these terms are elucidated in this study),
- the level of the investment cost of drilling injection and production wells,
- the supply of CO_2 and the dependence between cost and supply,
- the availability of financial incentives for ECBM (carbon tax and the like).

The most important cost factors for ECBM are drilling injection and production wells, and - to a lesser extent - supply of CO_2. The economics of ECBM may profit from the availability of large

CO_2 sources and sinks, not necessarily from large-scale transport of CO_2. This is because transport of CO_2 generally represents only a small fraction of the total cost of coalbed methane.

The price of coalbed methane in the Netherlands - e.g. € 6.5-8.7/GJ for three ECBM production scenarios analysed in depth - is really high due to relatively unfavourable geological conditions. The price corresponds to 5 Mtonne/a CO_2 sequestrated. In case of an amount of 15 Mtonne/a, the price would rise to a range of € 7 to € 10/GJ depending on the production scenario. Based on current CO_2 supply options, ECBM would not become a 'big' option in the Netherlands, unless tremendous financial incentives would be available. In the long term, dedicated power plants could supply relatively cheap CO_2 in terms of marginal and average CO_2 supply costs.

A study on behalf of the IEA Greenhouse Gas R&D Programme ranks four countries in descending order with respect to the prospects of ECBM: Australia, China, Poland, and India. The geological characteristics in those countries are more favourable than in the Netherlands.

Production profiles for conventional and unconventional oil as well as conventional gas and coalbed methane are presented for ten world regions. The resources of conventional oil and gas are based on data from the US Geologic Survey. It is assumed that 50% of the 'futures' of conventional oil and 75% of the recoverable unconventional oil are left for production after 2100. The term 'futures' refers to the category of oil resources beyond identified reserves and mean undiscovered reserves. This category is characterised by much more uncertainty than e.g. the identified oil reserves. In 2100, the main oil producing areas could be in descending order:
- North Africa & Middle East (44%)
- Former Soviet Union (20%)
- South America (12%)
- North America (10%).

Due to increasing production of heavy oil, tar sands, and oil shale, these kinds of unconventional oil could cover 31% of the global oil demand in 2100. Oil production could remain almost flat from 2020 to 2070 and decline towards 2100, ending up at 147 EJ, a few percent below the level of 2000.

In most of the world the 'futures' of conventional gas are assumed available for production after 2100. However, in North America and Asia (except China) the identified and undiscovered gas reserves are relatively limited. Therefore, it has been assumed that 50-67% of the conventional 'futures' in those regions may be produced until 2100. Also, production of coalbed methane is assumed for all the regions. In 2100, the main gas producing areas could be in descending order:
- North Africa & Middle East (33%)
- Former Soviet Union (28%)
- North America (12%)
- South America (8%).

Considering the large amounts of CO_2 needed for CO_2 enhanced coalbed methane production (ECBM) and the (correspondingly) high price of coalbed methane in several world regions, ECBM could have a share of 11% in the total gas production in 2100. Global gas production could peak in 2060 and decline to a level of 116 EJ towards 2100, 27% more than in 2000.

All the above mentioned figures are speculative, because of the uncertainty with regard to (economically recoverable) oil and gas resources and with regard to their production profiles.

The sequestration of CO_2 for enhanced oil recovery could peak around 2060, declining thereafter due to the decreasing potential for EOR. Sequestration of CO_2 for ECBM starts at a modest level in 2010 and increases steadily towards 2100. The total amount of CO_2 sequestrated in 2100 could be approximately 1,400 Mt/a, 93% of which is assumed to be related to ECBM.

1. INTRODUCTION

The issues of global energy demand, emission of greenhouse gases (GHG), and fossil fuel depletion are strongly interrelated. If mankind wishes not to threaten the world climate, painstaking efforts will have to be undertaken to curtail world-wide GHG emissions, and to stabilise their concentrations in the atmosphere. The debate on how to curtail the (growth of) fossil fuel consumption and of GHG emissions, is characterised by several revolving questions:

1. What is the potential of energy conservation, energy efficiency, etc.?
2. How much may fossil fuel substitution (gas for coal) contribute to the emissions reduction?
3. What is the potential of ‘CO_2 sequestration’, viz. compression, transport, and injection of CO_2 in the deep underground - oil reservoirs (CO_2 enhanced oil recovery), depleted gas reservoirs, aquifers, coal seams - (geological storage) or oceans (oceanic sequestration)?
4. Are renewable energy sources able to fulfil the world’s future energy demand?
5. What is the potential of the nuclear options, fission and fusion?

In a nutshell these questions mimic the ongoing debate on energy policies to prevent a dramatic climate change. The aforementioned third question is the central theme of this monograph in the framework of the VLEEM project. (VLEEM is the acronym for Very Long Term Energy-Environment Model) CO_2 sequestration is the capture of CO_2 from large point sources, the compression to liquid CO_2, the transport of ‘supercritical’ CO_2 to some area with favourable geological characteristics, and the injection of CO_2 in oil wells (CO_2 Enhanced Oil Recovery, EOR), depleted gas reservoirs, aquifers or deep coal seams. In the latter case, CO_2 may replace coal-bed methane: CO_2 Enhanced CoalBed Methane (ECBM). Another sequestration option is sequestering of CO_2 in the deep oceans, viz. between 1,000 and 3,000 m depth (CO_2 solution) and below 3,000 m depth (‘CO_2 lake’).

This study focuses on the CO_2 sequestration options EOR and ECBM. From the point of view of rational use of fossil fuel resources they are deemed to be superior to CO_2 sequestration in depleted oil and gas reservoirs, aquifers, and oceans. Although CO_2 sequestration in oceans has a tremendous potential, there are no benefits of enhanced fuel production when compared to EOR and ECBM. Also, CO_2 sequestration in oceans tends to be a temporary solution because CO_2 may surface in significant amounts within a few hundred years.

Chapter 2 starts with related questions with respect to fossil fuel availability and climate change. This is because the production of coalbed methane is just one of the fossil fuel options, although it is highly interesting due to the opportunity to combine it with CO_2 sequestration. Chapter 3 shortly addresses the potential of CO_2 sequestration in oil reservoirs, gas reservoirs, aquifers, and oceans. This Chapter also presents information about the potential of CO_2 Enhanced Oil Recovery (EOR). Chapter 4 is devoted to the concept of CO_2 Enhanced CoalBed Methane (ECBM), which is elucidated by the results of and comments on a recent study on the prospects of ECBM in the Netherlands. Chapter 5 briefly summarises the potential of ECBM in a few other countries, based on a study for the IEA Greenhouse Gas R&D Programme. The potential of oil and gas production as well as the CO_2 sequestration potential (EOR and ECBM) for ten world regions is addressed in Chapter 6. Finally, a few conclusions are drawn in Chapter 7.

2. FOSSIL FUEL SUPPLY AND CLIMATE CHANGE

2.1 Introduction

Reduction of GHG emissions and stabilisation of CO_2 concentration as well as depletion of fossil fuel resources - connected to 'sustainability' - are 'hot' issues today. The extent to which supplies of oil and gas resources could limit the global GHG emissions depends on judgements about their global availability. Section 2.2 shortly addresses views on the relation between fossil fuel resources and GHG emissions. Section 2.3 gives an overview of the fossil fuel availability, mainly based on recent data. Section 2.4 presents a synopsis of the main findings.

2.2 Recent views on fossil fuel resources and climate change

At the COP meetings (Framework Convention on Climate Change) - the last of which in Bonn and Marrakesh in 2001 - it has been agreed that Annex 1 countries - OECD countries, Russia, etc. - will reduce GHG emissions in 2008-2012 compared to 1990, with a few 'escape' options:

- Clean Development Mechanism (CDM): GHG emissions reduction in non-Annex 1 countries.
- Opportunities agreed upon to make use of carbon sinks in Annex 1: mainly growing forests.

The position of the EU, the US and other Annex 1 countries is quite different. The EU is likely to meet its target of GHG emissions reduction. In the US, GHG emissions are rising. The US administration does not endorse the Kyoto target and the US will fail to meet 'their' target.

GHG emission reduction policies critically depend on the relations between 'autonomous' trends in anthropogenic CO_2 emissions, fossil fuel resources, and climate change. Fossil fuel resources could be limiting to global GHG emissions. Therefore, long-term scenarios and availability of fossil fuels have to be analysed. Grubb did so recently in an article in 'Energy Policy' (Grubb, 2001). He analysed the carbon content (GtC) of global fossil energy reserves, resources and occurrence (based on an IPCC energy compilation). Table 2.1 shows the results.

Table 2.1 *Carbon content of global fossil energy resources (GtC)*

		Conventional resources remaining to be discovered at probability			Unconventional resources Recoverable			
	Reserves identified	95%	50%	5%	Currently recoverable	Technological progress	Resource base	Additional occurrence
Oil								
Conventional	120	36.0	50.0	110.0		180.0	170.0	>200.0
Unconvention	142						322.0	>300.0
Gas								
Conventional	73.4	41.3	67.3	166.8		272.3	140.8	>153.0
Unconvention	105.6				33.7		411.6	>336.6
Hydrates						2,229.1		>12,240
Coal	650.2	>77.3	>117.3	>276.8	358.6	>2,681	3,237.9	3,354.0
Total	1,091				>392.3		>4,282	>16,584

Source: *M. Grubb, Energy Policy 29 (2001), 837-84*5.

The resources of conventional oil and gas are several times larger than their identified reserves (e.g. as published by BP in the 'Statistical Review of World Energy'). Even then, coal is still

more abundant in its resource base. Gas hydrates on the ocean floor and in permafrost regions (called ‘clathrates’) represent a huge amount of gas, not much of which is known up to now.
Next to the assessment of Grubb (derived from an IPPC compilation), UNDP’s ‘World energy assessment’ contains an estimate of the world’s fossil fuel resources (Table 2.2).

Table 2.2 *Carbon content of global fossil energy reserves, resources, and occurrences [GtC]*

	Consumption					
	1860-1998	1998	Reserves	Resources	Resource base	Additional occurrence
Oil						
Conventional	97	2.65	120	121	241	
Unconventional	6	0.18	102	305	407	914
Natural gas						
Conventional	36	1.23	83	170	253	
Unconventional	1	0.06	144	364	509	14,176
Coal	155	2.40	533	4,618	5,151	
Total	294	6.53	983	5,579	6,562	15,090

Source: *M. Grubb, Energy Policy 29 (2001), 837-84*5.

According to the IPCC, levels of CO_2 stabilisation in 2100 correspond to specific levels of cumulative carbon emissions (GtC, period 1991-2100). For a number of stabilisation cases the cumulative carbon emissions are compared to the availability of several fossil fuels (Table 2.3).

Table 2.3 *Characteristics of different CO_2 stabilisation levels: cumulative emissions compared against fossil fuel deposits [GtC]*

Stabilisation level [ppmv CO_2]	Cumulative carbon emissions [GtC; 1991-2100]	Comparable carbon quantities [GtC]			
400	<500		Conventional oil and gas deposits		
			Reserves	Resources	Resource base
		Gas	82	179	261
		Oil	118	153	271
450	630-650	Coal reserves (Table 2.1), or reserves and conventional (discovered) resources (Table 2.2)			
500	750-820	Total conventional and unconventional oil resource base (650)			
550	870-990	Total conventional and unconventional natural gas resource base (915) Additional unconventional oil occurrences (914)			
600	950-1100	Total proven fossil fuel reserves (983-1090)			
650 and higher	1030-1200 and higher	Total coal resource base (5000 +) Additional gas occurrences (clathrates: 14,000)			

Source: *M. Grubb, Energy Policy 29 (2001), 837-84*5.

Some of the most stringent CO_2 reduction scenarios aim at stabilisation at 400 ppm CO_2 in 2100. The corresponding amount of carbon emissions (<500 GtC) is of the same order of magnitude as the combined resource base of conventional oil and gas. In the still very ambitious 450 ppm case, the amount of carbon emitted (630-650 GtC) is equal to the global coal reserves from the IPCC compilation (Table 2.1) or from the UNDP World energy assessment (Table 2.2). In the case of 500 ppm - ‘middle of the road’ in terms of long-term scenarios - unconventional oil and gas resources would have to be phased in before the turn of the century.

2.3 Availability of fossil fuels

2.3.1 Introduction

Resources of fossil fuels - hydrocarbons based on crude oil, natural gas, natural gas liquids and coal - are not only determined by geological occurrence, but also by technological development. The percentage of oil that can be recovered from an oil reservoir has increased steadily since the last few decades. Also, exploration technologies have been improved dramatically.
Conventional and unconventional oil resources are covered by Section 2.3.2, and conventional and unconventional gas resources by Section 2.3.3. Section 2.3.4 focuses on the world's proved coal reserves, which are only a fraction of the total resource base for coal.

2.3.2 Oil

Conventional oil

The US Geological Survey (USGS), a science agency of the U.S. Department of the Interior[1], publishes detailed assessments of the world's conventional oil and gas resources (USGS, 2000). The USGS distinguishes three categories of resources, viz.

- identified reserves
- mean undiscovered reserves
- futures.

Identified (proved) reserves are reported by both the USGS and BP (BP, 2000). The proved reserve is the amount of oil to be recovered from known natural reserves, which has been both carefully measured and assessed as exploitable under present and expected local economic conditions with existing technology. The next category is the mean undiscovered reserve (50% probability). 'Futures' represent relatively speculative resources. Table 2.4 shows conventional oil resources according to the USGS data[2].

Table 2.4 *Conventional oil resources according to the USGS [billion barrels]*

Region	Annual production (2000)	Cumulative production	Identified reserves	Mean undisc. reserves	Futures	Identif. + mean undisc. + futures
Europe	2.539	24.7	40.4	23.5	60.3	124.2
FSU	2.933	112.0	129.0	151.0	297.5	577.5
North America	3.816	178.6	62.1	75.2	163.7	301.0
Latin America	3.754	80.7	116.9	91.1	289.8	497.8
Sub-Sahara Africa	1.420	21.6	31.7	27.5	49.2	108.4
North Africa & ME[1]	9.826	222.4	592.3	154.8	738.7	1,485.8
South Asia	0.287	3.7	7.0	2.4	10.3	19.7
China	1.184	14.1	31.4	42.7	67.1	141.2
Asia Pacific OECD	0.297	3.2	3.0	3.2	7.8	14.0
Other Asia Pacific	1.141	19.6	20.0	25.7	43.7	89.4
World	27.196	680.6	1,034	597	1,728	3,359

[1] ME = Middle East

Source: *USGS Digital Data Series 60,* www.usgs.gov.

Annex A provides more details about the distribution of the resources within the regions. Also, the distinction between the regions is shown in Annex A. According to the USGS, the world's

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[1] The USGS serves as an independent fact-finding agency, with 10,000 scientists, technicians and support staff.

[2] Oil resources are reported in billions of barrels, gas resources in billions of m^3 and coal reserves in million tons of oil-equivalent (Mtoe). For reasons of comparison, the data are summarised in Section 2.4 in the unit of energy EJ.

conventional oil resources amount to 3,360 billion barrels, or 124 years of oil production. The identified reserves are equivalent to a Reserves/Production (R/P) ratio of 38 years.

The Middle East - Saudi Arabia, Iraq, the United Arab Emirates, Kuwait, and Iran - holds 64% of the world's identified conventional reserves and 40% of the total conventional resource base. Currently, the Middle East produces 30% of the world's oil. Therefore, the Middle East will be able to increase its share of the world's conventional oil production to 40% in the long term.

Tar sands

Canada is a country with large unconventional oil resources. The resources of tar sands occur entirely within the province of Alberta and are found in the oil sands regions Athabasca, Cold Lake en Peace River, covering an area comparable in size to Scotland or Belgium. The ultimate volume of oil is 259 billion m^3 of crude bitumen, of which 50 billion m^3 or 315 billion barrels are deemed recoverable (Canada's Oil Sands, 2000/ Alberta Energy and Utilities Board, 2001). (Possibly 70% of the global recoverable tar sands)

Since the start of commercial tar sands production in 1967, mining technology has improved a lot. The same holds for extraction and upgrading processes. Today's extraction processes are able to extract about 91% of the bitumen contained in the oil sands, compared to 84% in 1975.

About 20% of the recoverable unconventional oil in Alberta is considered amenable to surface mining. The operating costs of mining of oil sands are currently $11-$14 per barrel, with a target of $10 or less before 2005.

Oil sands deposits deeper than about 75 meters are too deep to be surface mined economically. They require some form of in situ recovery, for instance by Cyclic Steam Stimulation (CSS) or Steam-Assisted Gravity Drainage (SAGD). The supply costs of bitumen produced by primary or 'cold production' in the Cold Lake area are $10-$13/b (barrel), and in the Wabasca area they are $7-$10/b. In situ production costs are $10-$16/b for CSS and $8-$14/b for SAGD.

Starting with a price of $11/b in the field for in situ or mining operations, and considering transportation charges, exchange rates, blending costs and a $5 light/heavy differential, a price of $18/b for the marker crude WTI (Western Texas Intermediate) is deemed a competitive price.

In 1999, production from oil sands mining was 325,000 b/d (barrels/day), equivalent to 15% of the total Canadian oil production. The production is expected to increase nearly three-fold, reaching 1 million b/d by 2015. The production of bitumen from in situ production is projected to increase from 165,000 b/d in 1999 to 650,000 b/d in 2015. So, Canada's unconventional oil production could rise from 0.5 million b/d in 1999 to 1.65 million b/d in 2015.

Heavy and extra heavy oil

Venezuela has vast resources of heavy and extra heavy oil. The Eastern and Maracaibo basins rank prominently among the 10 largest oil basins of the world. The state oil company Petroleos de Venezuela S.A. (PdV) has identified 1,800 billion barrels of heavy and extra heavy oil in place. Some 270 billion barrels - possibly 45% of the world's (extra) heavy oil resources - may be classified as recoverable as a result of current projects and technology (Inciarte, 1991).

Oil shale

There are major deposits of oil shales in China, the USA, Brazil, Australia, Syria, the FSU, Morocco, Estonia, Thailand, and Israel. Production of oil shale is in an early stage of development. Production costs are deemed to be higher than for tar sands and heavy oil, and environmental impacts could be significant unless new technology would become available. Some 880 billion out of the 13,900 billion barrels 'oil-in-place' are recoverable with current production technology (Bundesanstalt für Geowissenschaften und Rohstoffe, 1989/ Warfield, 1995).

Summary of unconventional oil

Data on the ‘recoverable’ unconventional oil resources (opposed to the sometimes reported ‘oil-in-pace’) have been derived from a number of (recent) literature sources (Table 2.5).

Table 2.5 *Recoverable unconventional oil resources [billion barrels]*

Region	Heavy oil	Tar sands	Oil shale	Total
Europe	8		23	31
FSU	130	117	32	279
North America	44	315	198	557
Latin America	310	6	88	404
Sub-Sahara Africa	6		11	17
North Africa & ME	61	5	106	172
South Asia				
China			352	352
Asia Pacific OECD	13		56	69
Other Asia Pacific			14	14
World	572	443	880	1,895

With a wide uncertainty margin, the world’s recoverable unconventional oil resources are estimated at 1,895 billion barrels. This is equivalent to 70 years of oil production (2000).

2.3.3 Gas

Conventional gas

The United States Geological Survey (USGS) also publishes detailed assessments of the world’s conventional gas resources, with the same categories (identified reserves, mean undiscovered reserves, and futures) as in case of conventional oil. In order to end up with the total gas resources for world regions, another resource estimate of Enron has been used (Carson, 1997). Table 2.6 summarises the total conventional gas resources according to the USGS and Enron.

Table 2.6 *Conventional gas resources according to the USGS and Enron [billion m^3]*

Region	Annual production (2000)	Identified reserves	Mean undiscovered	Futures (Enron)	Total
Europe	287.9	7,832.1	11,020.3		18,852
FSU	674.2	47,256.0	44,137.7	55,316	146,710
North America	723.4	6,223.2	15,617.4	46,933	68,774
Latin America	132.2	7,821.5	15,239.3		23,061
Sub-Sahara Africa	16.7	3,040.4	7,380.0		10,420
North Africa & ME	322.5	52,576.5	39,230.1	53,688	145,495
South Asia	55.4	1,515.7	2,618.3	764	4,898
China	27.7	962.8	2,429.2	627	4,019
Asia Pacific OECD	31.1	2,605.6	3,226.8	1,078	6,910
Other Asia Pacific	151.2	5,578.1	7,064.6	2,338	14,981
World	2,442.3	135,412	147,964	160,744	444,120

Sources: *USGS Digital Data Series 60,* www.usgs.gov, *and Enron (Carson, 1997).*

Annex B contains more detailed information about the distribution of the conventional gas resources within regions. According to both the USGS and Enron the conventional gas resources are 437 trillion m^3, which is tantamount to an R/P ratio of about 180 years. BP makes reference of proved reserves of 146 trillion m^3, equal to 60 years production at the current level.

With respect to the global distribution two regions stand out, viz. the Former Soviet Union and North Africa & Middle East, with 33.0% and 32.8% respectively of the conventional gas resources (Table 2.6). Note that the Middle East is a main although not dominant gas region.

Unconventional gas

Unconventional gas is coal-bed methane, tight formation gas, and clathrates - methane hydrates found in Arctic areas and at specific depths of the ocean floor. One estimate is that 98% of the clathrates are offshore. The remaining 2% in permafrost zones on land could contain more than 300 trillion m^3 of methane, or twice the proved conventional gas reserves (Collet, et. al., 1998/ Henriet, et. al., 1998). The amount of gas in place at the ocean floor is 3,100 to 7,600,000 trillion m^3.

Gas hydrates have been known to form and exist in nature since 1966. They occur mainly in the sub-polar regions of continents and in deepwater regions (at the ocean floor). The first naturally occurring gas hydrate field was discovered in 1967.

Much more work needs to be done on understanding the potential of this resource. Also, techniques have to be developed for exploitation of the resource. Hydrates may have an effect on the earth's thermal regime and the generation of greenhouse gases, and they may also hold clues about the formation and dynamics of cosmic bodies (????, 2001). For these various reasons gas hydrate research got more interest lately in countries like the USA, Japan, and India.

2.3.4 Coal

The WEC (1996) provides data of the world's proved coal reserves that are included in BP's 'Statistical review of world energy'. Note that the proven coal reserves are only a fraction of the resource base. Table 2.7 gives an overview of these proven coal reverves.

Table 2.7 *Proven coal reserves according to WEC (World Energy Conference) & BP [Mtoe]*

Region	Annual production (2000)	Hard coal	Lignite	Total
Europe	241.4	27,776	26,789	54,565
FSU	197.4	64,984	44,234	109,218
North America	624.5	77,231	46,473	123,704
Latin America	42.3	5,799	4,695	10,494
Sub-Sahara Africa	122.8	40,775	83	40,858
North Africa & ME	0.8	129		129
South Asia	155.8	48,489	1,643	50,132
China	498.0	41,467	17,433	58,900
Asia Pacific OECD	162.3	32,131	14,547	46,678
Other Asia Pacific	108.7	880	2,342	3,222
World	2,137.4	339,660	158,240	497,900

Sources: *WEC (1996): Survey of Energy Resources, www.worldenergy.org, and BP (2000): Statistical Review of World Energy, www.bpamoco.com/worldenergy.*

WEC's 1996 data show that world's proved recoverable coal reserves are nearly 500 billion tonnes of oil-equivalent. This represents an R/P ratio of 230 years. Because of the shear magnitude of the proven reserves the total resource base of coal is not considered here.

2.4 Synopsis

2.4.1 Resource base

The resource base of the fossil fuels should be regarded with prudence. The resources of oil and gas and the proven reserves of coal have been presented in Section 2.3. They are summarised in EJ in Table 2.8, except for the unconventional gas resources[3]. The resources of clathrates - methane hydrates found in Arctic areas and at the ocean floor - are huge. However, they are only reported as in situ resources with a wide margin of uncertainty. What is more, there is no experience with exploitation of hydrates and their production costs and environmental impacts are unknown. So, they are not presented here on a par with conventional fossil fuel resources.

Table 2.8 *World's fossil fuel resources [EJ]*

Region	Ultimately recoverable oil resources			Ultimately recoverable gas resources		Proved coal reserves
	Conventional	Unconventional	Total	Conventional	Unconventional	Hard coal and lignite
Europe	709	177	886	710		2,285
FSU	3,299	1,594	4,893	5,528		4,573
North America	1,719	3,181	4,900	2,595		5,179
Latin America	2,843	2,308	5,151	869		439
Sub-Sahara Africa	619	97	716	393		1,711
North Africa & ME	8,487	982	9,469	5,482		5
South Asia	113		113	185		2,099
China	807	2,011	2,818	151		2,466
Asia Pacific OECD	80	394	474	260		1,954
Other Asia Pacific	511	80	591	564		135
World	19,186	10,824	30,010	16,738		20,846

Main Sources: *USGS Digital Data Series 60,* www.usgs.gov*, Enron (1997), and WEC (1996).*

Oil

According to the USGS and Enron the conventional oil resources - identified reserves, mean undiscovered reserves, and futures - amount to 3,360 billion barrels of oil or 19,190 EJ. From literature sources it has been derived that the recoverable unconventional oil resources, based on current production technology, could be 1,895 billion barrels of oil, or 10,820 EJ. Therefore, the recoverable conventional and unconventional resources are estimated at 5,250 billion barrels, or 30,000 EJ. These resources represent a resources/production ratio of about 190 years.

Gas

According to data of the USGS and Enron the total conventional gas resources amount to some 440 trillion m^3 of gas, or 16,740 EJ, which is equivalent to an R/P ratio of 180 years.

Besides the conventional gas resources, there are large unconventional resources of coal-bed methane, and tight formation gas. Furthermore, huge amounts of clathrates - methane hydrates found in Arctic areas and at the ocean floor - have been reported. However, exploitation of clathrates is not possible today, and it could have adverse environmental consequences.

Coal

According to the WEC the world's proven recoverable coal reserves are equal to nearly 500 billion tons of oil-equivalent, or 20,850 EJ. They represent an R/P ratio of 230 years.

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[3] The amount of (recoverable) coalbed methane will be examined in more detail in the next chapters.

2.4.2 Implications for GHG emissions

Evidently, the end of the world's oil resources is not nearby. However, the proven oil reserves have an R/P ratio of only 40 years. Also, the Middle East is a dominant oil province. Unconventional oil - tar sands, (extra) heavy oil - is a tiny fraction of the oil production today. So, oil is a strategic fossil fuel. What is more, future oil (price) crises cannot be excluded. If the demand for oil continues to rise at the current pace of 1-2%/a, the consequences for GHG emissions, stability of the world's climate, and depletion of oil resources may be severe.

Just like in case of oil, the resources of conventional natural gas are more ample than the proven reserves suggest. The Former Soviet Union and the North Africa & Middle East comprise a large fraction of the conventional gas resources (33% each). Considering that the global demand for gas is still appreciably lower than that for oil, the resources/production ratio (180 years) is relatively high. However, if both industrialised and developing countries would switch from coal to gas, security of supply could become an issue, just like in case of oil (Lako en Jansen, 2001). The future of the huge resources of methane hydrates is clouded due to absence of exploitation experience, and lack of knowledge about exploitation costs, environmental impacts, etc.

The proven coal reserves represent an R/P ratio of 230 years. They are rather evenly distributed around the globe. Compared to the world oil market, the amounts of coal exported by countries like Australia, South Africa, and the United States are small. What is more, the international coal market is highly competitive. Therefore, sudden price escalations are really exceptional.

The amount of fossil fuel resources remains a matter of debate. Maybe conventional oil and gas resources are not so ample as shown here. However, even in case of ample conventional oil and gas resources such as presented in Section 2.2 based on compilations by Grubb, stabilisation of the global CO_2 concentration at 500 ppm is tantamount to their depletion before 2100. Or, in the words of Grubb, there is simply not enough carbon in conventional oil and gas deposits to get near the atmospheric stabilisation levels that are currently under political discussion.

3. CO_2 SEQUESTRATION POTENTIAL

3.1 Introduction

One of the options to reduce CO_2 emissions is so-called CO_2 Enhanced Oil Recovery (EOR). Another one is sequestering CO_2 in (depleted) gas fields. Although CO_2 enhanced oil recovery was developed and practised on a large scale well before GHG emission reduction became a hot issue, nowadays it may be viewed as a way to both enhance the recovery of oil and reduce CO_2 emissions. The latter is only true, if the CO_2 is supplied by an anthropogenic CO_2 source, e.g. a coal-fired power plant: CO_2 sequestration/EOR.

On the one hand, 'CO_2 flooding' based on CO_2 from a natural CO_2 source does not serve CO_2 sequestration but only enhanced fuel supply. On the other hand, if CO_2 from e.g. a coal-fired power plant is used to sequester CO_2 in a depleted oil or gas field, this is useful from the point of view of CO_2 sequestration but it is of no use from the perspective of enhanced fuel supply.

This Chapter addresses CO_2 sequestration (and enhanced fuel supply if applicable, notably in case of EOR). CO_2 originating from an anthropogenic source requires CO_2 capture, e.g. by chemical absorption, compression and drying, transportation as a 'supercritical' fluid (i.e. at a pressure high enough to prevent boiling and cavitation) through a pipeline, and finally injection.

Section 3.2 gives a short overview of the potential of CO_2 sequestration/EOR from current projects. Section 3.3 presents a concise global view of the CO_2 sequestration potential in oil and gas reservoirs and a rough estimate of the total CO_2 sequestration potential of the world.

3.2 Current EOR projects

In the US about 190,000 barrels/day originate from enhanced oil recovery projects using CO_2 injection. Most of them have been established in Texas, generally based on naturally occurring CO_2 sources. Pure, naturally occurring CO_2 deposits, such as McElmo dome in Colorado and Jackson dome in Mississippi, supply most of the CO_2 used in EOR projects (Stevens, et. al., 2001).

Figure 3.1 shows the origin of CO_2 supply for EOR in Texas as a function of time.

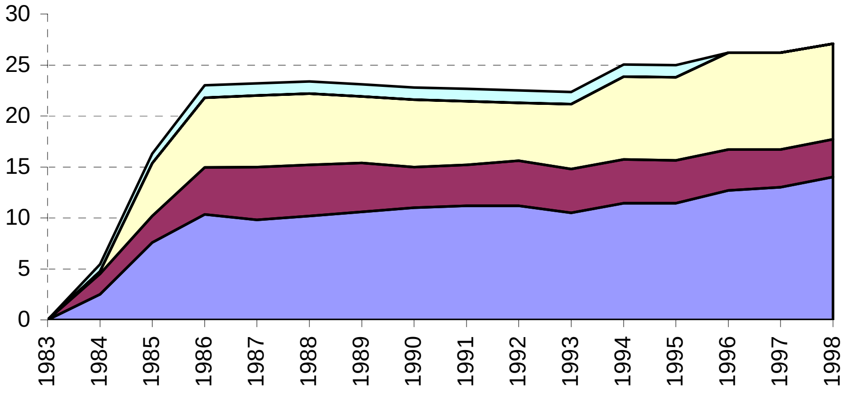

Figure 3.1 *CO_2 supply for enhanced oil recovery in Texas [Mt/a]*
Source: *Stevens, S.H. et al: Geologic CO_2 sequestration. Oil & Gas Journal, 15 May 2001.*

There are four CO_2 sequestration/EOR projects from anthropogenic CO_2 sources (Table 3.1).

Table 3.1 *CO_2 sequestration/EOR projects based on anthropogenic CO_2*

State/ Province	EOR fields	Field operator	CO_2 source	CO_2 purchase	Estimated ultimate sequestration
				[Mm^3/day]	[Mt]
Texas	Sharon Ridge, others	Exxon/Mobil	Gas processing	2.1	20
Colorado	Rangely	Chevron	Gas processing	4.2	36
Oklahoma	Enid	Occidental	Fertiliser	1	4
Saskatchewan	Weyburn	PanCanadian	Coal gasification	2.7	19
Total				10.0	79

Source: *Stevens, S.H. et al: Geologic CO_2 sequestration. Oil & Gas Journal, 15 May 2001.*

EOR is practised on a large scale in Texas. Still, there is potential for incremental oil production from EOR according to a recent study (Holtz, et. al., 1999). Oil reservoirs in the Permian basin of Texas have suitable geologic characteristics for CO_2 sequestration/EOR. As oil is produced from a reservoir the initial pressure is reduced. A highly pressure depleted reservoir may be a poor candidate for CO_2 sequestration in conjunction with EOR (even if the CO_2 sequestration potential as such may be large). Generally, CO_2 flooding is preceded by waterflooding, the production stage of injecting water into a reservoir to displace and repressurise the oil. It leaves behind the residual oil that is the target for CO_2 sequestration/EOR projects. A high level of the reservoir pressure will make the CO_2 miscible in oil, thereby increasing the oil recovery efficiency.

Reservoir depth is a very important factor because start-up and field operating costs increase with depth. Deeper wells result in greater drilling costs and greater operating costs to inject and pump out fluids. The effectiveness of EOR depends on pressure, and deeper reservoirs are therefore preferred because minimum miscibility pressure is more likely to be reached. In the USA all CO_2 miscible projects are at depths greater than 2,000 ft (610 m). A minimum pressure of 100 bar (10 MPa) is generally regarded as a target reservoir pressure for CO_2 flooding. Generally, waterflooding is needed to increase the pressure after the primary recovery stage.

Figure 3.1 shows the forecasted additional oil production from existing CO_2 EOR projects in the USA and Canada.

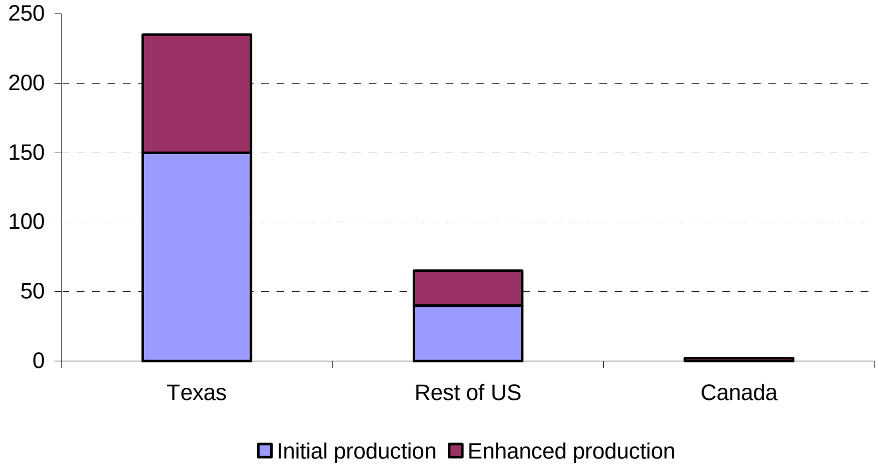

Figure 3.1 *Additional oil production from existing CO_2 EOR projects (1000 barrels/day)*
Source: *Stevens, S.H. et al: Geologic CO_2 sequestration. Oil & Gas Journal, 15 May 2001.*

The forecasted additional potential from existing projects is some 130,000 b/d (barrels/day). Together with the current production from EOR projects, the potential of CO_2/EOR in the USA amounts to 320,000 b/d (equivalent to a demand for CO_2 of 40 Mt/a). Just like in case of the current production, most of the forecasted output will come from CO_2/EOR projects in Texas. Some 1,700 oil reservoirs were screened with regard to their suitability for CO_2 sequestration. The original oil in place of the reservoirs is 197 billion barrels, 147 billion of which remains in place at this date. The remaining reserves are put at 7 billion barrels, leaving 140 billion barrels as a target for additional reservoir development including CO_2 sequestration/EOR.

With additional 'CO_2 flooding' from CO_2 sources within a radius of 145 km (90 miles) of the oil reservoirs 8 billion barrels might be recovered (10% recovery from 80 billion barrels of oil in place). Within a radius of 190 km (120 miles) the amount might be 10 billion barrels. The latter is equal to 3,400 Mt of CO_2, presuming CO_2 miscible conditions after waterflooding.

The recoverable 8 or 10 billion barrels from additional CO_2/EOR projects are based on a screening analysis of power plants within a radius of 145 km and 190 km respectively from the reservoirs. Coal-fired power plants are the most likely candidates for CO_2 supply, as these power plants are used as base-load facilities as opposed to gas-fired power plants. It was assumed that CO_2 would be captured with a chemical absorption process - monoethanolamine (MEA) recovery. The average break-even costs of CO_2 capture (including 'disposal' costs), assuming a 30-year project life and including a 100 mile (160 km) pipeline, are $37.5/tonne.

3.3 Global perspective

In a recent study by Advanced Resources International Inc. (ARI) for the IEA's Greenhouse Gas R&D programme the world-wide potential and costs of CO_2 sequestration in oil and gas fields have been estimated. A global economic model of the world's largest 155 petroleum provinces was used. Key assumptions included:

- CO_2-to EOR ratios of 0.34 tonne/barrel (miscible) to 0.57 tonne/barrel (immiscible),
- $ 15/barrel oil price,
- Empirical EOR recovery to oil gravity and CO_2: methane volume and pressure ratios.

The main results from this study are shown in Table 3.2.

Table 3.2 *Global CO_2 sequestration potential in depleted oil and gas fields*

Rank	Province	Location	CO_2 sequestration capacity[1]		CO_2 sequestration profit (cost)[2]	
					EOR	Gas
			[Mm^3]	[Gt]	[$/tonne]	[$/tonne]
1	West Siberian basin	CIS	94.6	177	(2.9)	(27.9)
2	Quatar arch	Middle East	28.4	53	8.1	(22.9)
3	Zagros fold belt	Middle East	22.5	42	5.4	(23.9)
4	Mesopotamian foredeep	Middle East	22.3	42	8.8	(23.7)
5	Greater Ghawar uplift	Middle East	19.4	36	9.8	(21.6)
6	Rub Al Khali basin	Middle East	12.9	24	10.1	(21.6)
7	Western Gulf of Mexico	US	11.3	21	8.1	(19.0)
11	Gulf Cenozoic OCS	US	9.3	17	3.9	(31.7)
13	North Sea graben	Europe	8.9	17	(8.1)	(36.1)
14	Alberta basin	Canada	8.7	17	12.9	(19.0)
20	Permian basin	US	4.9	9	9.2	(21.0)

[1] Depleted oil and natural gas field capacity combined.

[2] At $ 15/barrel oil, $0.65/Mcf ($ 14/t) supply cost for pure, high-pressure CO_2.

The largest cost for sequestration is to capture, process, and compress anthropogenic CO_2 to prepare it for use by the oil or gas field operator. Generally, the basins show potential for profitable operation of CO_2/EOR projects. CO_2 sequestration in depleted gas fields is not profitable, as such projects (are deemed to) lack benefits from enhanced gas production.

Whether a CO_2/EOR project is profitable or not depends to a large extent on the cost of CO_2 supply. The presumed cost of CO_2 supply is $ 14/t, which is representative of naturally occurring CO_2. CO_2/EOR may be profitable in case of CO_2 originating from a chemical plant producing pure CO_2 as a by-product, e.g. for gas processing, hydrogen production, ammonia production or ethylene oxide production. The cost of supply from a pure anthropogenic CO_2 source (chemical plant) is estimated at $ 18/t.

The cost of capture and processing of CO_2 from a pulverised coal-fired power plant is $18-54/t. CO_2 from an Integrated Gasification Combined Cycle plant (IGCC, a coal-fired power plant based on coal gasification) would cost $\$_{1990}$14-20/t (€ 19-27/t) (Novem, 2001). According to a recent study for the IEA Greenhouse Gas R&D programme, CO_2 from an IGCC would cost $ 31-37/t (IEA, 2000). Another source of cost figures for CO_2 from advanced power plants is (Williams, 1998).

Finally, Table 3.3 shows the global potential of CO_2 sequestration for all the options that have been proposed (Edmonds, et. al., 2000).

Table 3.3 *Global CO_2 sequestration potential for all options proposed*

Carbon storage reservoir	Range of CO_2 sequestration potential [Gt C]
Deep ocean	1,391 – 27,000
Deep saline reservoirs (aquifers)	87 – 2,727
Depleted gas reservoirs	136 – 300
Depleted oil reservoirs	41 – 191
Unminable coal seams	>20

Source: E*dmonds, J.A. et. al. (2000): The role of carbon management technologies in addressing atmospheric stabilisation of greenhouse gases.*

With regard to depleted oil and gas reservoirs, the estimate in Table 3.3 may be compared to that of Table 3.2. In Table 3.3 the potential of depleted oil and gas reservoirs is estimated at 177-491 Gt C. Table 3.2 shows a potential of CO_2 sequestration in such reservoirs of 455 Gt CO_2, which is equal to 124 Gt C. Apparently, the estimate of Table 3.3 is not conservative.

4. CONCEPT OF ECBM

4.1 Introduction

CO_2 sequestration starts with capturing CO_2 from e.g. flue gas of a fossil-fired power plant, and ends with geological storage. The process involves CO_2 capture, liquefaction by compression, pipeline transport of supercritical CO_2, and injection in an area with favourable geological characteristics. An example is CO_2 capture from CO_2 containing natural gas at the Sleipner gas field in Norway. After compression and drying, the CO_2 is stored in an adjacent aquifer. The project is economically feasible owing to high fossil fuel taxes for the offshore industry.

'Pure' CO_2 sequestration is practised on a small scale. However, it has a few drawbacks:
- Due to conversion losses, fossil fuel consumption goes up.
- It incurs significant capital costs and does not have other benefits.
- It is considered as a typical 'end-of-pipe' technology.

For various reasons, novel ways of CO_2 sequestration - CO_2 Enhanced CoalBed Methane (ECBM) production - may deserve attention. Section 4.2 addresses an ECBM concept that has been analysed in the Netherlands. Section 4.3 presents lessons to be learned from this analysis.

4.2 ECBM concept in the Netherlands

4.2.1 Introduction

ECBM is supported by the EU with the initiation of a small pilot project in Poland. The feasibility of ECBM in Poland or elsewhere[4] depends on the replacement of coalbed methane in the coal seam by the waste product CO_2, the last of the 'CO_2 sequestration stages' (Figure 4.1).

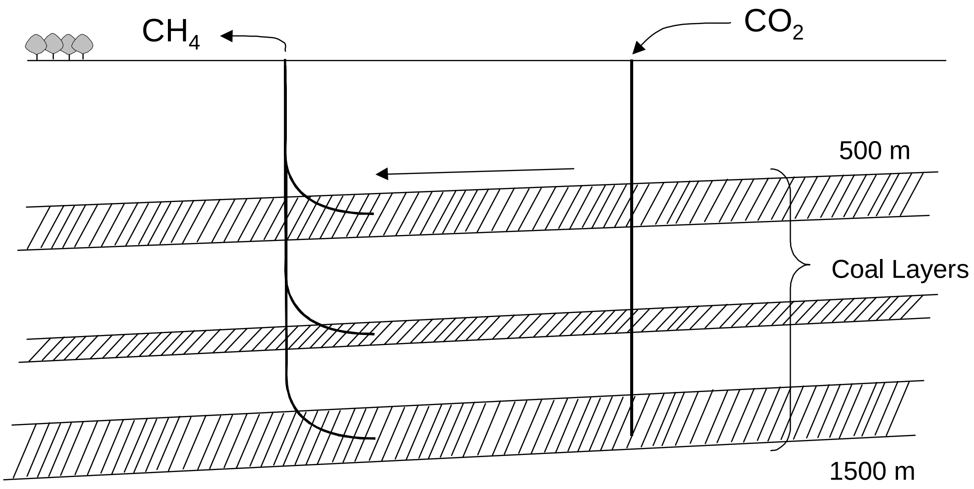

Figure 4.1 *CO_2 enhanced coal-bed methane production (straight wells)*

Large amounts of CO_2 are available at coal-fired power plants and chemical industries. It is captured from flue gases or gas streams (if necessary) by chemical absorption. In some chemical

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[4] Preliminary ranking shows that ECBM demonstration in the Netherlands would incur supply of CO_2 from the chemical industry (DSM, a former coal mining company) in Zuid Limburg and injection of the CO_2 in the Peel area.

plants pure CO_2 is available, which obviates CO_2 capture. After compression to a supercritical liquid, it is transported by pipeline, and injected in deep coal seams containing methane. CO_2 replaces methane in a proportion of 2 to 1 molecules (ECBM).

4.2.2 Sources of CO_2

In the study 'Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands' (NOVEM, March 2001), several sources of CO_2 are distinguished (Table 4.1).

Table 4.1 *Characteristic plants, summarised CO_2 flow per sector and cost of CO_2 capture*

	Load factor	CO_2 concentration	CO_2 capture	CO_2 flow	Cost
	[hours/a]	[weight %]		[Mt/a]	[€/tonne]
Power plants					
Pulverised coal	4000-8000	21	MEA	18	35-50
IGCC[1]	6500	13	MEA	1.3	40
Gas fired steam plant	500-4500	15	MEA	7.9	45-60
Gas fired combined cycle	5000-8000	6	MEA	11	45-60
Industrial cogeneration					
Gas fired combined cycle	7000	6	MEA	14	45-80
Gas turbine	7000	6	MEA	1.0	45-80
Steam turbine	600-8500	15	MEA	0.5	45-80
Waste processing					
Waste incineration plant	8000	17	MEA	3.1	40-50
Chemical industry					
Ammonia plants	8200	100	[2]	2.1	4-5
Hydrogen plants	8200	100	[2]	1.1	4-5
Ethylene oxide plants	8200	100	[2]	0.2	4-5

[1] An Integrated Gasification Combined Cycle power plant (IGCC) will have a load factor of approximately 75% rather than 90% as presumed in the 'Novem study'.

[2] These chemical plants are able to supply pure CO_2 as a by-product.

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

Pulverised coal-fired power plants produce 18 Mt/a of CO_2 and could supply CO_2 in vast amounts. Even more suitable are production plants for hydrogen, ammonia, and ethylene oxide.

4.2.3 Sequence of CO_2 capture & compression & drying

Except for chemical plants producing pure CO_2, CO_2 needs to be captured by a chemical absorption process, notably the MEA process (Figure 4.2). This amine based process is suitable for low concentrations of CO_2 (flue gases). The process has significant economies of scale. The economies also depend on the CO_2 concentration. A MEA plant for a large coal power plant may be three times less expensive than in case of a gas-fired power plant (Table 4.2).

Table 4.2 *Specific investment cost of amine based CO_2 absorption process (MEA)*

CO_2 captured	Specific investment cost of MEA plant [€/tonne/a]	
[Mt/a]	CO_2 concentration 4%	CO_2 concentration 13%
0.5	115	69
5.0	73	44

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

After capturing of the CO_2, it is compressed to 80 bar (8 MPa) making use of a multistage compressor. The investment cost amounts to € 23 million for a capacity of 250 t/hr of CO_2. The CO_2 then passes through a drying tower, where it is dried to a water content of 10 ppm.

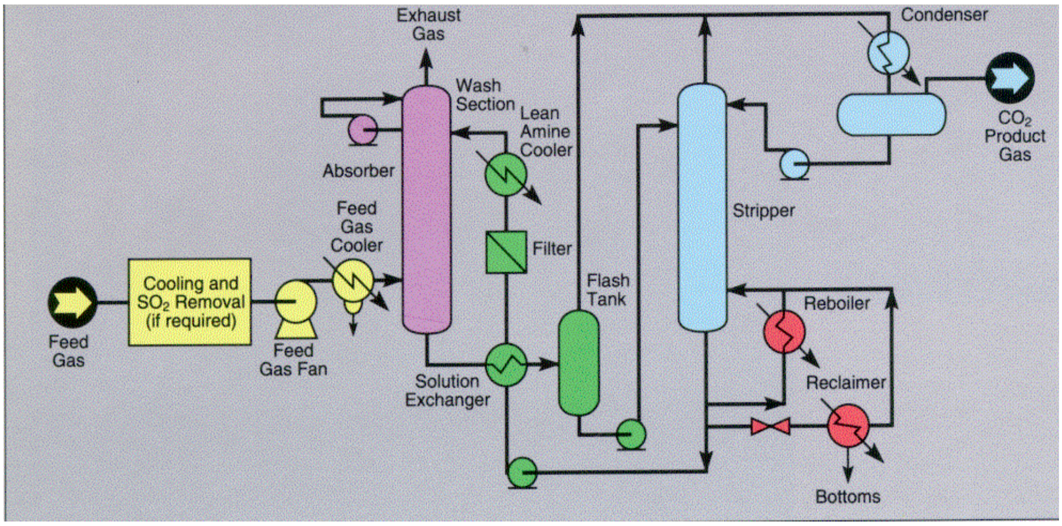


Figure 4.2 *Fluor Daniel Econamine system*

4.2.4 Cost of CO_2 at major point sources

The cost of CO_2 capture, compression, and drying per tonne of CO_2 is shown in Table 4.3.

Table 4.3 *Cost of CO_2 capture, compression and drying*

	CO_2 captured	Capture	Compression & drying
	[Mt/a]	[€/tonne]	[€/tonne]
H_2 plant (130 ktonne/a)	1	-	3.6
600 MW pulverised coal-fired pp	2.4	36	3.7
50 MW waste incinerator	0.33	37.5	4.3
20 MW industrial combined cycle pp	0.054	49.2	5.5

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

The Table shows the dependence on the size of the CO_2 source and the fuel (coal or gas). In Figure 4.3 shows the cost as a function of the CO_2 sequestration potential, based on an interest rate of 5%. CO_2 supply from chemical plants is cheap - € 4-5/tonne - whereas CO_2 from coal- or gas-fired power plants is more expensive: € 35-50/tonne and € 45-70/tonne respectively.

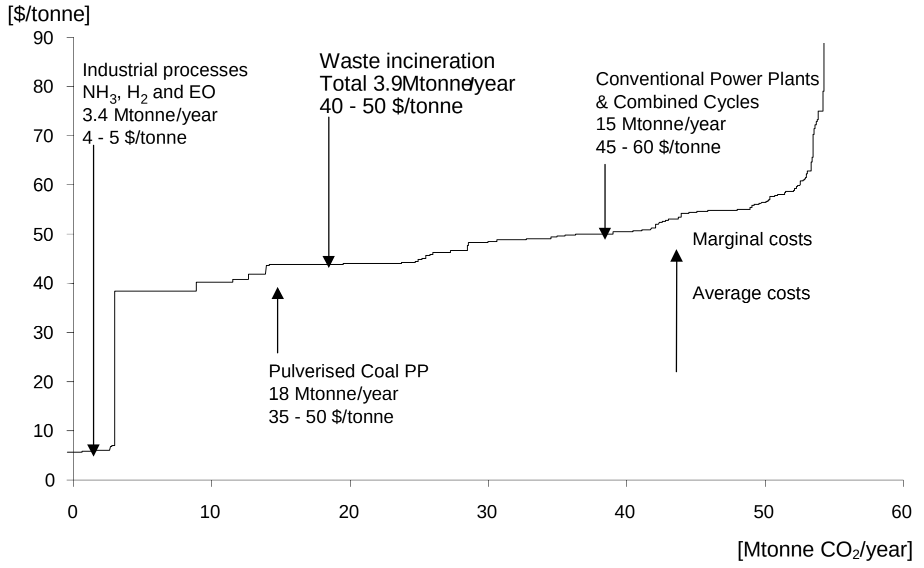


Figure 4.3 *Supply curve of CO_2 in the Netherlands*
Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

4.2.5 CO_2 transport

Transport of CO_2 by pipeline is an established industrial practice. For instance, CO_2 from a very large coal gasification plant in North Dakota (US) is transported by pipeline to an enterprise in Saskatchewan (Canada) active in CO_2 enhanced oil recovery (EOR). In the Netherlands, a demonstration project for ECBM is in an early stage of preparation. It could be started after prior experience from an ECBM pilot initiated in Poland with financial support from the EU.

In case of small demo projects, there is a mismatch between ample supply of CO_2 of and low demand for CO_2. A pilot project for CO_2 enhanced coalbed methane production would need 40 ktonne/a of CO_2. Unless large-scale ECBM would become viable the mismatch would continue. A fully developed ECBM area would be able to absorb several Mt/a of CO_2. Therefore, CO_2 sequestration becomes economically sensible in case of large CO_2 sources and sinks.

Transport of CO_2 by pipeline is rather expensive for relatively small CO_2 sources (0.1-0.5 Mt/a) and accordingly small diameter pipelines over a distance of 300 km (Table 4.4).

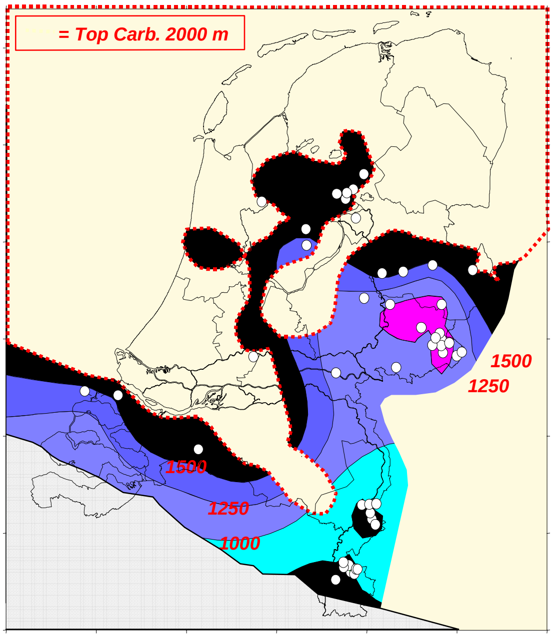
Table 4.4 *Capacity of CO_2 source, pipeline diameter and cost per tonne CO_2 transported (IR 5%, economic lifetime 20 year)*

Capacity	Distance			
	50 km		300 km	
[Mt/a]	Diameter [m]	Cost [€/tonne]	Diameter [m]	Cost [€/tonne]
0.1	0.10	9.2	0.15	66
0.5	0.20	2.6	0.30	21
1	0.25	1.5	0.35	12
5	0.40	0.5	0.65	4.7

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

4.2.6 CO_2 injection in coal seams

Figure 4.4 shows the Dutch part of the North-western European Coal Basin, with iso-depth lines.



Note: Dotted line = the top of the Carboniferous at 2000 m depth.
White dots = exploration wells for oil, gas, and coal.

Figure 4.4 *Map of deep coal seams in the Netherlands*

Research at Delft University of Technology on coal samples shows that CO_2 may replace one molecule of methane in a molecular proportion of (at least) 2:1. CO_2 is preferentially adsorbed, displacing the sorbed methane present at the internal surface of coal layers. Filling the ‘coal cleats’ with CO_2 may enhance the CO_2 storage potential. Results of research at laboratory scale shows that the ECBM process is feasible under extreme conditions up to about 700 m depth.

The thickness of the coalbeds is of great importance for ECBM production: thick coalbeds mean larger volumes and thus more gas. The resolution of seismic data is too low to be used for thickness evaluation of individual coal seams. The thickness information was mainly derived from exploration wells for oil, gas and coal. The data are rather incomplete (dots in Figure 4.4).

Recovery of methane from the coal seams is determined by the recovery factor. This is the amount of gas that can be produced from a coal seam containing coalbed methane. With the process of ECBM with CO_2 injection, the recovery is higher than for conventional CBM production - pumping off large volumes of formation water to allow methane to desorb from coal. Conventional CBM is characterised by a recovery factor of 20-60% of the original ‘Gas In Place’ (GIP). In case of ECBM the recovery factor could be of the order of magnitude of 90%.

The completion factor is the part of the coal that may be exploited. Of all the coal in the depth range considered 50% is deemed to be exploitable. The coal seam thickness for determination of the producible gas is the cumulative seam thickness of all the exploitable seams over 500 to 1500 meter depth, or to 2000 m depth in case of the areas Achterhoek 1 and Zeeland, as shown in Table 4.5. The total gas content of the coal beneath the Netherlands is put at 10 m^3/tonne.

Table 4.5 *Producible Gas In Place for the Peel, Zuid-Limburg, Achterhoek and Zeeland*

Area	Surface	Interval	Proved reserve		Probable reserve		Possible reserve	
	[km^2]	[m]	[Mm^3/km^2]	[EJ]	[Mm^3/km^2]	[EJ]	[Mm^3/km^2]	[EJ]
Peel	536	<1500	8.4	0.16	21	0.40	43.8	0.84
Zuid-Limburg	48.4	<1500	25.6	0.04	53	0.09	102	0.18
Achterhoek 1	3796	<1500	0.80	0.11	5.6	0.76	21.1	2.38
		1500-2000	1.80	0.24	12.2	1.66	46.4	6.30
Zeeland	2346	1500-2000	19.1	1.60	48.0	4.03	99.2	8.34
Achterhoek 2	718	<1500	3.61	0.09	25.5	0.66	96.1	2.47
Peel 3	152	<1500	11.5	0.06	29.6	0.16	62.4	0.34
Total			60.3	2.16	194	6.95	518	18.5

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

Proved, probable, and possible reserves of producible coalbed methane are defined as follows:
- The proven producible coalbed methane reserves have a probability of occurrence of 90%.
- The probable reserves refer to a probability of 50%.
- The possible reserves refer to a probability of 10%.

The probable coalbed methane reserves are 6.95 EJ, which is equivalent to 220 billion m^3 of Groningen gas. The ‘probably producible reserves’ are equal to 8% of the original reserves of the Groningen gas field. The ‘possible reserves’ (10% probability) would amount to 585 billion m^3 of Groningen gas, equivalent to approximately 20% of the original Groningen reserves.

Zuid Limburg has the highest (producible) methane content per km^2. The Peel has a high methane content and an intermediate size (688 km^2) compared to the Achterhoek (4,514 km^2).

The amount of storable CO_2 for the investigated areas is summarised in Table 4.6.

Table 4.6 *Amount of storable CO_2 for the Peel, Zuid Limburg, Achterhoek and Zeeland*

Area	Interval [m]	Proved storable [Mt]	Probably storable [Mt]	Possibly storable [Mt]
Peel	<1500	31	76	156
Zuid Limburg	<1500	6	13	25
Achterhoek	<1500	17	116	431
	1500-2000	36	249	938
Zeeland	1500-2000	214	561	1,184
Total area	<2000	304	1,015	2,734

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

Approximately 1,000 Mt of CO_2 might be stored in coal seams with a probability of 50% (‘probably storable’), and approximately 2,700 Mt with a probability of 10% (‘possibly storable’). In 2000 the emission of CO_2 in the Netherlands was 174 Mt (RIVM, 2001). In other words:
- The CO_2 storage potential with 50% probability is roughly 6 times the annual CO_2 emission.
- The CO_2 storage potential with 10% probability is about 16 times the annual CO_2 emission.

Gas production is initiated by pumping off large volumes of formation water in order to decrease reservoir pressure and allow methane desorption from the coal (CBM). Instead of straight vertical wells, deviated drilling may be practised. The injection well and the production well may be drilled simultaneously, or drilling of the injection well may be postponed until ‘peaking’ of primary recovery of methane (late injection). The concept of the grid of injection wells has dimensions from 400 x 400 m^2 up to 1000 x 1000 m^2 (Figure 4.5).

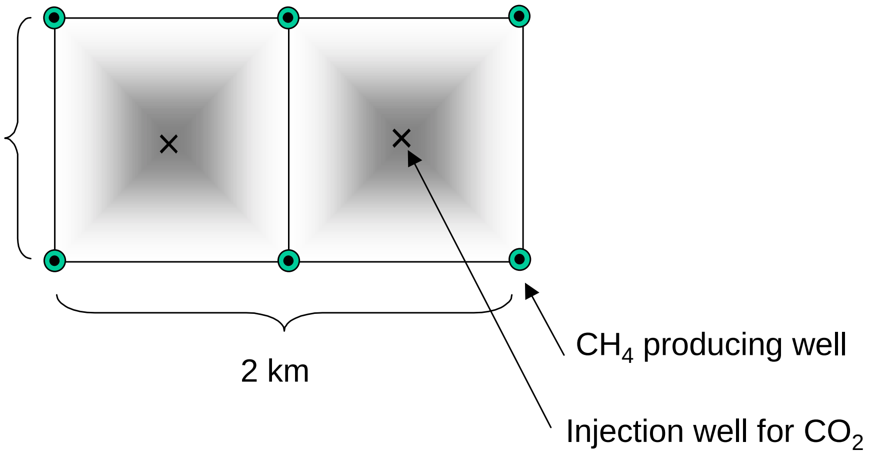


Figure 4.5 *Dimensions of grid of production and injection wells [1000 x 1000 m^2]*

Especially in large production fields, the contact surface of the well with the coal seam has to be increased further by means of inseam drilling. For this reason the concept of a five-spot ECBM-project has been proposed. Four injection wells and one production well are drilled from one location, with or without in-seam drilling of the coal seams (Figure 4.6).

4.2.7 Economics of ECBM

The study on ECBM in the Netherlands investigates the total cost of ECBM, starting with cost parameters for CO_2 sequestration and an assumed cost of CO_2 supply of € 15/tonne (Table 4.7). The cost parameters are default values for the cost of production wells, injection wells, coalbed methane gas gathering, treatment and compression, as well as the cost of cleaning and discharge of formation water. The interest rate (IR) used for computation of ECBM costs is 10%.

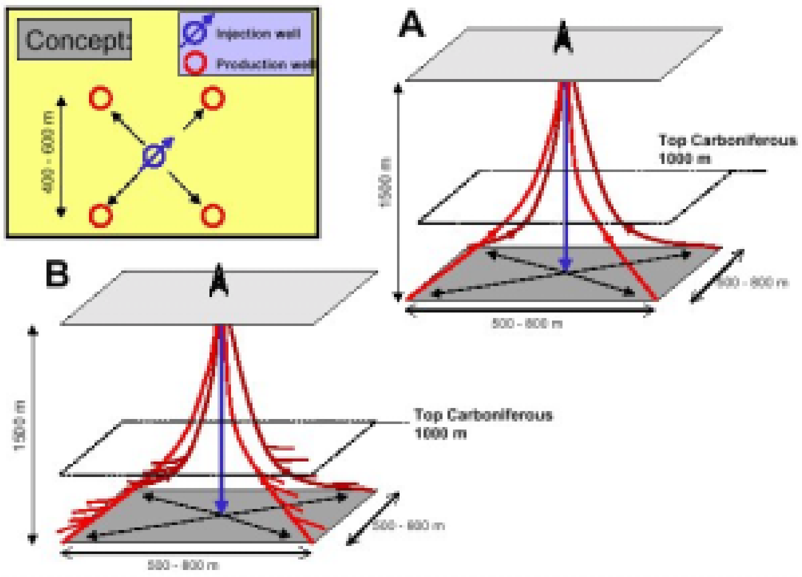


Figure 4.6 *Concept of a five-spot ECBM-CO_2 project with drilling from one location (A = without inseam drilling, B = inseam drilling)*

Table 4.7 *Parameters for economic analysis of CO_2 sequestration in coal seams*

Cost item	Unit	Cost
Production well		
Basic investment	[million €]	0.5[*]
Add. Investment for inseam drilling	[k€/m]	1.1
Operation and maintenance	[% of basic inv.]	1
Injection well		
Total investment	[million €]	0.3[**]
Operation and maintenance	[% of total inv.]	4
Volume dependent		
Cost of CO_2 at the wellhead	[€/t]	15
Gas gathering, treatment, compression	[€/m^3 methane]	$5.4*10^{-3}$
Water aeration/sedimentation system	[€/m^3 water]	15

[*] two years before production

[**] one year before injection

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

The most economic sources of CO_2 are chemical plants - € 4-5/tonne - and pulverised coal-fired power plants. The figure of € 15/tonne (Table 4.7) could be based on the following assumptions:

- The chemical industry - hydrogen plants, ammonia plants, ethylene oxide plants - could supply 3.4 Mt/a of CO_2 at a cost of € 4-5/tonne (Table 4.1, Figure 4.3).
- Pulverised coal-fired power plants could supply an initial amount of 1.7 Mt/ of CO_2 at a cost of € 35/tonne or more.

The average cost of € 15/tonne could refer to supply of approximately 5 Mt/a of CO_2, originating from the chemical industry and coal-fired power plants in a proportion of 2:1.

The cost of ECBM is analysed with seven scenarios, A through G. These scenarios are distinguished by different assumptions with respect to a number of key variables of drilling:

- The dimensions of the grid of production and injection wells.
- The extent to which inseam drilling may be practised.
- Direct injection of CO_2 or after ‘peaking’ of primary recovery of methane: late injection.

The breakdown of the ECBM cost (€ 8.7/GJ) for scenario F (see Table 4.8) is shown in Figure 4.7. The main cost items are production and injection well investments and CO_2 at the wellhead.

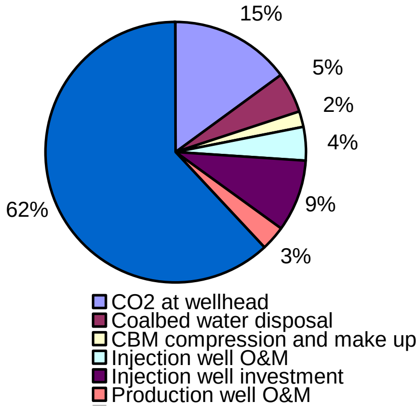


Figure 4.7 *Breakdown of price of coalbed methane for scenario F (€ 8.7/GJ)*

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

The various scenarios that have been defined and analysed are presented in Table 4.8.

Table 4.8 *Scenarios for ECBM production cost assessment (data from Table 4.7)*

Scenario	Characteristics	Production cost [€/GJ]
A	400 x 400 m^2, skin stimulation, late injection	16.4
B	600 x 600 m^2, 27 m inseam, late injection	15.3
C	800 x 800 m^2, 107 m inseam, late injection	7.9
D	800 x 800 m^2, 330 m inseam and skin, direct injection	9.3
E	1000 x 1000 m^2, 220 m inseam, late injection	6.5
F	1000 x 1000 m^2, 410 m inseam and skin, direct injection	8.7
G	1000 x 1000 m^2, 444 m inseam, late injection	8.5

Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

The price of the produced coalbed methane depends to a large extent on the investment costs of production and injection wells, as well as the total drilling costs. The ECBM price of scenario F ranges from € 7/GJ to € 9.5/GJ for low and high drilling costs respectively (Figure 4.8).

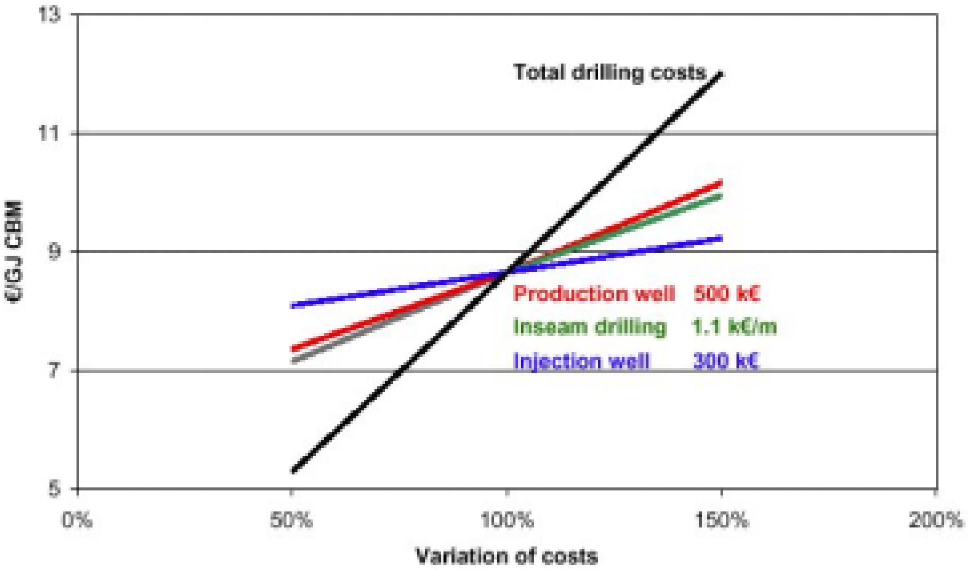


Figure 4.8 *Dependence of price of coalbed methane on well drilling costs for scenario F*
Source: *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands.*

Three of the seven scenarios are analysed in more detail:

- Scenario F is rather ambitious with respect to the well spacing (1000 x 1000 m^2) and the longitude of inseam drilling (410 m). However, CO_2 injection occurs in an early stage (direct injection). Therefore, the price of coalbed methane is relatively high: € 8.7/GJ.
- A more favourable scenario is scenario C. It has a well spacing of 800 x 800 m^2, limited inseam drilling (107 m), and late instead of direct injection. The ECBM price is € 7.9/GJ.
- The most favourable scenario is scenario E. It has the same well spacing as scenario F (1000 x 1000 m^2). However, the inseam drilling is 220 m instead of 410 meter, and it has late instead of direct injection. The price of coalbed methane is relatively low: € 6.5/GJ.

These three scenarios are used to analyse the dependence of the ECBM price on the amount of CO_2 sequestrated (Figure 4.9).

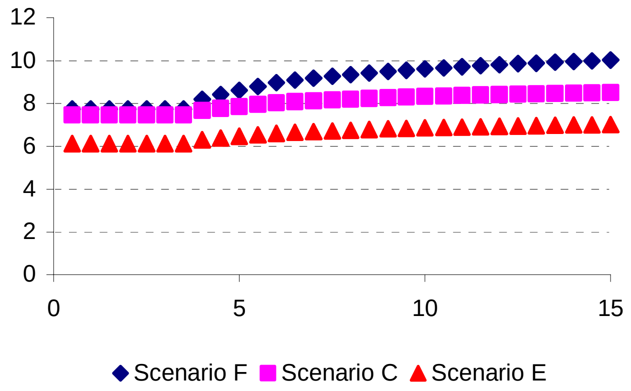


Figure 4.9 *Relation between price of coalbed methane [€/GJ] and CO_2 supply [Mt/a]*

Figure 4.9 shows that the sensitivity to the amount of sequestrated CO_2 is quite different:

- *Scenario F*
  The reported price of € 8.7/GJ is representative of an amount of CO_2 sequestrated of approximately 5 Mt/a. At a level of 15 Mt/a, more expensive CO_2 has to be phased in. The price of coalbed methane rises to approximately € 10/GJ.
- *Scenario C*
  The reported price of € 7.9/GJ refers to an amount of CO_2 sequestrated of 5 Mt/a. At a level of 15 Mt/a, the price of coalbed methane is approximately € 8.5/GJ.
- *Scenario E*
  The price of € 6.5/GJ is representative of an amount of CO_2 sequestrated of 5 Mt/a. At a level of 15 Mt/a, the price of coalbed methane is approximately € 7/GJ.

In case of scenario F, the ECBM price depends more strongly on the amount of CO_2 sequestrated than in the scenarios C and E.

The study on ECBM in the Netherlands shows some applications of coalbed methane. One of them is power generation, using a gas engine, a combined cycle power plant or a fuel cell power plant (SOFC). Another application is production of hydrogen with simultaneous capture and reinjection of the by-product CO_2. Although the latter application looks quite interesting, it will be more difficult to implement than the use of coalbed methane as pipeline gas. Generally, new applications have to compete with the default option to use the gas as a substitute of natural gas. These different applications of coal-bed methane are not analysed in this study.

It should be noted that CO_2 sequestration in general incurs environmental problems and risks. In case of sequestration in aquifers, there is a risk of acidification of groundwater. ECBM and EOR could pose similar risks in case of inadvertent CO_2 leakage (Zwaan, van der, et. al., 2001).

4.3 Lessons to be learned from the ECBM concept

CO_2 enhanced coalbed methane (ECBM) production is not state-of-the-art today. Pilot or demonstration projects (Poland) are needed to show the technical feasibility and the conditions for economic competitiveness. After that, ECBM projects on a larger scale and/or in countries with more demanding geological conditions (the Netherlands) could be the next stage.

The amount of coalbed methane that could be produced from deep coal seams in the Netherlands is substantial, even compared to the giant Groningen gas field. The same holds for the

CO_2 sequestration potential. The magnitude of the coalbed methane and CO_2 sequestration potential critically depends on assumptions with respect availability of suitable coal seams and the extent to which CO_2 may replace coalbed methane. Therefore, more R&D are needed. After initial experience from a pilot in Poland, a demo project in the Netherlands could do the rest.

The cost of coalbed methane largely depends on the investment cost of drilling injection and production wells. Whether the coalbed methane price is acceptable depends on:

- the necessity of deep inseam drilling or not, direct or late injection, etc.,
- the level of the investment cost of drilling injection and production wells,
- the supply of CO_2 and the dependence between cost and supply,
- the availability of financial incentives for ECBM (carbon tax and the like).

The question is whether large-scale transport of CO_2 is a prerequisite for ECBM. Evidently, transport of CO_2 is not as expensive as drilling injection and production wells, and - to a lesser extent - supply of CO_2. The competitiveness of ECBM depends on the availability of large CO_2 sources and sinks, not so much on large-scale transport of CO_2.

The price of coalbed methane - €6.5-8.7/GJ for three scenarios analysed in depth, corresponding to an amount of CO_2 sequestrated of 5 Mt/a - is approximately twice the current gas price for large industrial users in the Netherlands, viz. € 3.7/GJ. If the amount is 15 Mt/a, the ECBM price is € 7/GJ, € 8.5/GJ, or € 10/GJ depending on the production scenario.

Based on the current supply curve for CO_2, ECBM will probably be limited to the amount of CO_2 available from chemical plants. Therefore, ECBM will not become a ‘big’ option, unless tremendous financial incentives would be available. In the long term, dedicated IGCC power plants could supply CO_2 at more competitive prices than the current coal-fired power plants which may not be easily ‘retrofitted’ for CO_2 capture and generally have a rather limited remaining economic lifetime. Today, none of the power plants has been designed for CO_2 capture. Only a few gas-fired power plants are able to supply heat and CO_2 for greenhouses.

5. ECBM POTENTIAL IN VARIOUS COUNTRIES

5.1 Introduction

In the framework of the IEA Greenhouse Gas R&D Programme an analysis has been made of the potential of CO_2 enhanced coalbed methane production in a number of countries (Alberta Research Council Inc., 2001). Today, ECBM technology is developed in North America. In the future the potential could be large in countries where coal is abundant but the conventional natural gas supply is not. China, India, Poland or Australia could possibly host a demonstration of CO_2-ECBM. A commercial demonstration would show payback times of 4-5 years at gas prices of US$ 2/GJ. The prospects are addressed in the Sections 5.2 (Australia), 5.3 (China), 5.4 (Poland) and 5.5 (India).

5.2 Australia

5.2.1 Introduction

Australia contains about 7% of the world's economically demonstrated resources of hard coal (79 Gtonnes, Gt) and very large but unquantified inferred resources. In 1998-1999 286 million tonnes (Mt) of hard coal was produced.

The most prospective seams for coalbed methane production in terms of suitable depth, rank, low ash content, etc. are the deposits of the Bowen-Gunnedah-Sydney basin. This basin is very large, and has previously been assessed as having high gas-in-place. The level of CBM exploration and development has increased very significantly in the past several years. Modest commercial production is or will be realised in three fields in the Bowen and Sydney Basins.

The Bowen, Gunnedah and Sydney Basins are adjacent to the major population and industrial centres in the states of New South Wales (NSW) and Queensland. These are served by an extensive network of gas pipelines.

5.2.2 Prospects by basin

The Bowen Basin covers an area of 75,000 km^2 and has inferred coal reserves in excess of 114 Gt. Assuming a prospective basin area of 22,000 km^2, a pro-rata estimate of contained coal resource available for CO_2 sequestration is 34 Gt. In 1993, the CBM production potential of both the Bowen and Sydney Basins had been conservatively estimated at 20,000 km^2, corresponding to 218 Gt of coal and 1,760 billion m^3 of recoverable gas-in-place. Note that this potential is based on primary recovery, not on CO_2 enhanced CBM production.

The prospects of coal fields of the three basins are highlighted in Table 5.1. The geological parameters are most favourable in case of the Bowen Basin. The southern Bowen Basin has three fields in fairly close proximity - Dawson River, Moura, and Fairview - with two of them producing commercial gas in modest quantity.

The Sydney basin is subject to significant land use competition from urban development, national parks and underground coal mining to depths of 600 m. Therefore, potential for CO_2 sequestration and ECBM may be relatively restricted compared to the total resource.

In the Gunnedah Basin, land use competition is low, mainly from rural activities. Although few coal mining operations exist today, in the long term the possibility of mining seams at depths to 600 m must be considered.

Table 5.1 *Typical parameters characterising the CBM prospects of Australian coal basins*

Parameter	Unit	Bowen Basin				Sydney Basin	Gunnedah Basin
Area	[km^2]	22,000					6,750
Recov. GIP	[10^9 m^3]	1,940 (estimate)					860
Coal field		Dawson River	Moura	Fair-view	Durham Ranch	Camden	Narrabri/Bohema
Area	[km^2]	242	8000	693	691	430	
GIP	[Mm^3/km^2]	240	180	94	92	172	320-440
	[10^9 m^3]	58	1,440	65	65	74	
Seams		8	4	2			
Depth	[m]	421-628	>420	700-800	680-859	>670	>500-700
Cum. seam thickness	[m]	20-25	16-18	7-10	9	15-25	16.2-21.6/ 1.5-3.5
Permeability	[md]	5	1-3	High	High	12-36	18-36
Gas content	[m^3/t]	>11	10-15	>12		11	15
Well cost	[10^6 $]	0.3					
Gas production potential	[m^3/d]	235,000	142,000	200,000	340,000		
	[PJ/y]	3	1.8	2.5	4.3		

Competing land uses in the Bowen Basin are farming, coal mining at shallow depths (generally near the margins of the basin), and existing petroleum leaseholds.

Due to the favourable geological characteristics, the existing CBM activities and the absence of much competition from other land uses, the southern Bowen Basin is recommended as the first rank target for a CO_2 sequestration/ECBM demonstration trial in Australia.

5.3 China

5.3.1 Introduction

China's demonstrated coal resources are of the order of magnitude of 1,000 Gt, with proven reserves accounting for 30% or 296 Gt.

In March 1996, the State Council of the People's Republic of China approved the formation of China United Coalbed Methane Co. Ltd. This together with the creation of a favourable tax regime for CBM projects and the freedom to negotiate the gas price has improved the prospects for early development of CBM in China.

5.3.2 Prospects by basin

Table 5.2 contains estimates of the coalbed methane gas-in-place (GIP) resources of selected coal basins in China. Most estimates show that two-thirds of the country's coalbed methane resources are concentrated in the eastern and central provinces.

Table 5.2 *Coalbed methane resources (gas-in-place) for selected coal basins in China*

Basin	Province	Resources (gas-in-place) [10^9 m^3]
North and Northeast		
Ordos	Shaanxi, Ninqxi	11,324
Qinshui, Daning	Shanxi	6,850
Sanjiang Mulinghe	Heilongjiang	401
Huainan-Huaibei	Anhui, Jiangsu	400
Southern China		
Liupanshui	Quizhon, Yunnan	1,334
Chuannan-Quianbei	Yunnan	1,121
Nortwest China		
Hauin-Turpau	Xinjiang	4,647
Junggar	Xinjiang	2,997
Yili	Xinjiang	925

Rather scattered information (compared to Australia) is available on the CBM prospects of coal fields in these basins (Table 5.3).

Table 5.3 *Typical parameters characterising the CBM prospects of Chinese coal basins*

		Ordos Basin	Qinshui Basin		Henan Prov.	Huanbei Basin	Jiangxi Province
Area	[km^2]	250,000	5,560				
Recov. GIP	[10^9 m^3]		980				
Coal field/block		Hedong, Arco, Texaco	Jincheng field	South Qinshui	Western Henan, Enron	Huanbei block, Texaco	Fencheng coalfields, Saba Petr.
Area	[km^2]		406	550		2,663	1,540
GIP	[Mm^3/km^2]		244	182			24
	[10^9 m^3]		99	100	3		37.1
Seams							
Depth	[m]	1,000	300-1,000	500		610	
Cum. seam thickness	[m]			8-16		10-25	
Permeability	[md]	1-40	6-7	0.1-3.6	1		
Gas content	[m^3/t]	>12	15	12-26	12	10-14	
Well cost	[10^6 \$]						
Gas prod. potential	[m^3/d]						

The assessment indicates that the Hedong Prospect in the eastern part of the Ordos Basin and the south Quinshui area are the two better sites for implementing CO_2 ECBM.

5.4 Poland

5.4.1 Introduction

Poland has proved coal reserves of hard coal of 12.1 Gt. In 1996, the production of hard coal amounted to 138 Mt. Domestic consumption was approximately 109 Mt in 1996.

5.4.2 Prospects by basin

The prospects of a few coal fields of the main Polish basins are highlighted in Table 5.4. The Upper Silesian basin is the basin of choice, as there is little CBM activity in other basins. The former Amoco Concession area is selected as the potential site for the CO_2-ECBM pilot.

Table 5.4 *Typical parameters characterising the CBM prospects of Polish coal basins*

		Upper Silesian Basin		Lower Silesian Basin
Concession		Amoco	McCormick	
Area	[km^2]	488	244	
GIP	[Mm^3/km^2]			
	[10^9 m^3]			
Seams				
Depth	[m]	Up to 1,250		
Cum. seam thickness	[m]	52		
Permeability	[md]	1-5 (est.)		
Gas content	[m^3/t]	8	15	
Well cost	[10^6 $]	0.67		
Gas production potential	[m^3/d]			

5.5 India

5.5.1 Introduction

India has 7% of the world's proved coal reserves (70 Gt). The total coal reserves are listed at 204 Gt (and an additional 68 Gt inferred). Currently, opencast mining is the predominant method used to exploit the 64 Gt of proven reserves (< 300m).

5.5.2 Prospects by basin

India has quite some coalbed methane (CBM) potential. Current estimates by the Directorate General of Hydrocarbons are of the order of 1,000 billion m^3, assuming a gas content of 5 m^3 per ton. Another estimate is 850-4,000 billion m^3 (Kelafant, et. al., 1998). Only two coal basins, Dadomar-Koel Valleys and Cambay Basin, are actively being explored for CBM potential at the present time.

Damodar Valley

The Damodar Valley Coalfields provide a favourable combination of coal thickness, rank and burial depth suitable for coalbed methane development. The have the thickest coal, and highest rank bituminous coals of any of the Indian coalfields. The Geological Survey of India has identified the Jharia, Raniganj and Bokaro fields as food candidates for coalseam gas potential.

The amount of gas-in-place (GIP) of the Jharia field is estimated at 116.5 billion m^3. For the Raniganj field the figure is 96 billion m^3. Only in case of the Raniganj field there is one existing well drilled for CBM.

According to estimates of the Central Mine Planning & Design Institute and Coal India Ltd., CBM from the Damodar Valley could add 400 billion m^3 tot the countries gas resources.

Cambay Basin

The Cambay Basin of Gujarat has very low rank sub-bituminous coals. Essar Oil Company drilled 3 CBM wells using US Agency for International Development funding. The gas content for these coals was encouraging given the low rank of the coals, which is in agreement with experience in the US, where the Powder River Basin demonstrates similar CBM prospects.

Together the Damodar Valley and the Cambay Basin account for most of the total CBM potential, ranging from 400 to 4,000 billion m^3.

6. GLOBAL CO_2 SEQUESTRATION AND FUEL SUPPLY

6.1 Introduction

Based on the estimates of oil and gas resources and the potential of CO_2 sequestration in combination with enhanced oil recovery and coal-bed methane production in the preceding Chapters, this Chapter presents a vision on the production potential for oil and gas and the sequestration potential of CO_2 (EOR and ECBM) in the timeframe 2000-2100.

The assumptions on availability of fossil fuel resources and options for CO_2 sequestration are shortly addressed in Section 6.2. Section 6.3 gives a view on the availability of oil and gas as well as the associated potential for CO_2 sequestration (EOR and ECBM) in ten world regions. The results from Section 6.3 (the ten regions) are summarised for the world in Section 6.4.

6.2 Main assumptions

With respect to the availability of oil in the 21st century the following has been assumed:

- Conventional oil resources: identified and mean undiscovered, plus 50% of the ‘futures’.
- Unconventional oil resources: 25% of the recoverable resources.

Not all of the conventional and (recoverable) unconventional oil resources will be produced in this century. The remaining resources after the turn of the century (50% of the ‘futures’, 75% of the unconventional oil resources) may be sufficient for a gradual ‘phase-out’ of oil after 2100.

With respect to conventional gas in the 21st century the following has been assumed:

- As a general rule: identified and mean undiscovered reserves.
- In addition 67% of the ‘futures’ in case of North America, and 50% of the ‘futures’ in case of South Asia (mainly the Indian subcontinent), Asia Pacific OECD and Other Asia Pacific.

Generally, the identified and mean undiscovered reserves will suffice. However, a number of regions have relatively limited gas reserves compared to their (future) demand for gas:

- North America
- South Asia
- Asia Pacific OECD
- Other Asia Pacific.

These regions bordering the Atlantic, Indian, and Pacific Oceans, could take recourse to exploitation of clathrates if possible. Indeed, some countries (the US, India, Japan) are actively researching clathrates. The remaining ‘futures’ may warrant a gradual ‘phase-out’ after 2100.

CO_2 may be sequestrated by enhanced oil recovery (CO_2/EOR) or enhanced coalbed methane (ECBM). Chapter 3 shows that the potential of CO_2 sequestration in depleted oil and gas reservoirs is huge. CO_2 could also be sequestrated in aquifers or oceans. However, it turns out that the sequestration potential of EOR and ECBM is so large, that other options are not needed.

From the point of view of rational use of fossil energy, EOR and ECBM are favoured over other options. Sequestration in oceans is only a temporary measure. Though this sequestration option may have potential for some countries, on a regional or global scale it may be disregarded. Therefore, the focus is on the potential of EOR and ECBM in each of the ten world regions.

With respect to CO_2/EOR and ECBM the following assumptions have been made:

- EOR: 0.34 t CO_2/barrel of oil (representative of miscible EOR).
- ECBM: 0.1 t CO_2/GJ of coalbed methane (representative of ECBM at a depth of <1,500 m).

6.3 Oil and gas production and CO_2 sequestration by region

6.3.1 Europe

Due to limited remaining conventional oil resources, oil production in Europe will peak soon. The unconventional oil resources are rather marginal. CO_2 enhanced oil recovery is deemed not applicable due to geological and geographical conditions: mostly light crude oil and relatively high cost of 'CO_2 flooding' for offshore oil. Table 6.1, Figure 6.1, and Figure 6.2 present production profiles for oil and gas from 1990 to 2100 based on the aforementioned assumptions.

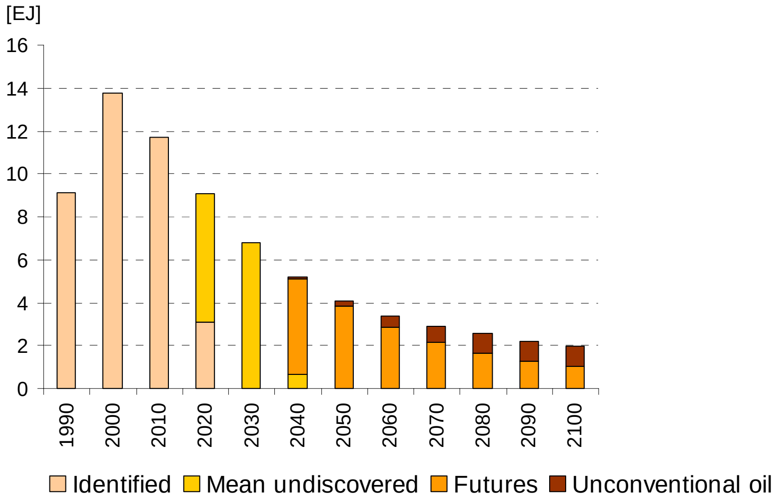


Figure 6.1 *Oil production in Europe 1990-2100*

It has been assumed that CO_2 enhanced coalbed methane production will start around 2010, first at a modest level - representing the relatively high cost of CO_2 supply without dedicated coal-fired power plants - and increasing at a steady rate towards the turn of the century (Figure 6.2).

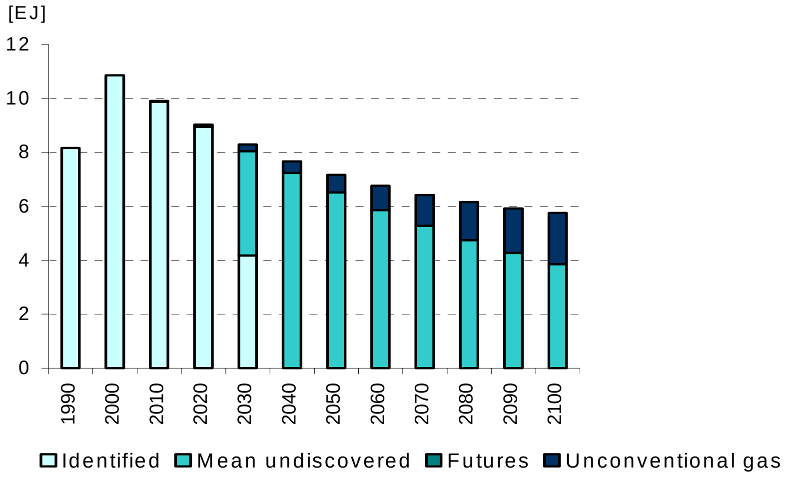


Figure 6.2 *Gas production in Europe 1990-2100*

The cumulative production of coalbed methane could be 84 EJ. This is 40 times the probable reserve of coalbed methane in the Netherlands up to 1,500 m depth. In 2100 the amount of CO_2 sequestrated could be 190 Mt/a. This massive amount of CO_2 has to be captured and transported by pipelines to the injection areas. The cumulative CO_2 sequestration is 8.45 Gt of CO_2, equal to 40 times the probable CO_2 sequestration potential in the Netherlands up to a depth of 1,500 m.

6.3.2 Former Soviet Union

Conventional oil production in the Former Soviet Union may be increased, even taking into account that 50% of the 'futures' are assumed to be left in the ground until 2100 (Table 6.2 and Figure 6.3). The FSU has large unconventional oil resources. Furthermore, it has been assumed that CO_2 will be sequestrated for enhanced oil production (generally after waterflooding).

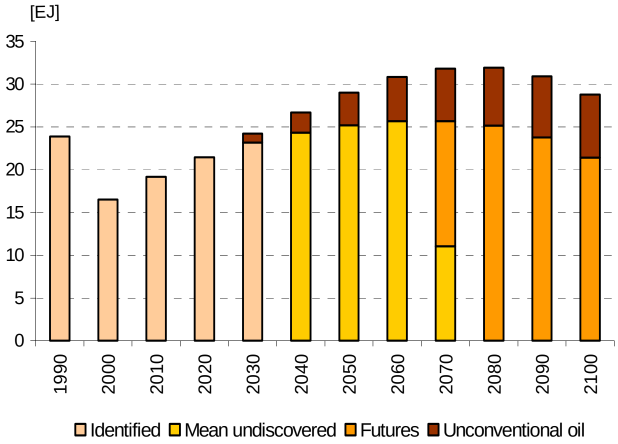


Figure 6.3 *Oil production in the Former Soviet Union 1990-2100*

The FSU has very large conventional gas resources. Even when the 'futures' are left in the ground until 2100, the production may be expanded appreciably. Also, it has been assumed that ECBM will be introduced in 2020 and will be increased steadily after that (Figure 6.4).

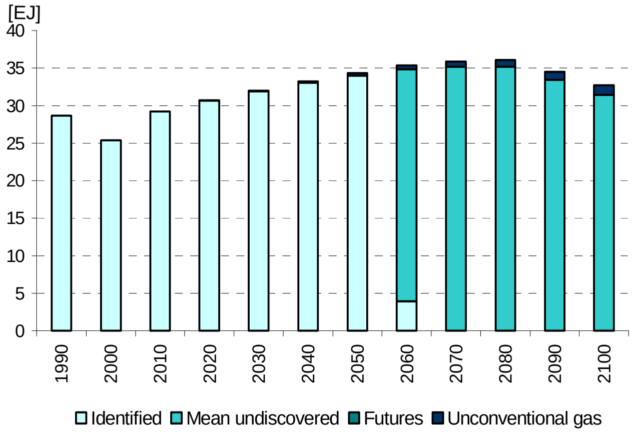


Figure 6.4 *Gas production in the Former Soviet Union 1990-2100*

The cumulative amount of oil produced by enhanced oil recovery ('CO_2-flooding') is assumed to be 10.7 billion barrels. The cumulative production of coalbed methane could amount to approximately 50 EJ. In the year 2100 more than 150 Mt/a of CO_2 would be sequestrated for 'CO_2-flooding' (enhanced oil recovery) and ECBM, which is a very large amount of CO_2.

6.3.3 North America

The conventional oil resources of North America are substantial. There is also much potential for enhanced oil recovery (notably in the US). What is more, North America holds very large unconventional oil resources. As it has been generally assumed that half of the conventional 'futures' and 75% of the recoverable unconventional oil resources are left in the ground until 2100, the total production of oil will decline gradually (Table 6.3 and Figure 6.5).

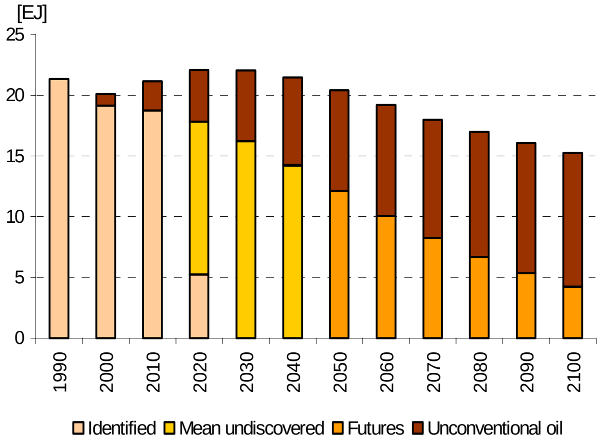


Figure 6.5 *Oil production in North America 1990-2100*

The resource base of conventional gas in North America is rather limited in comparison to the high demand for gas. Therefore, it is assumed that two thirds of the 'futures' will be produced before 2100. As a matter of fact, the US has also other unconventional gas resources, viz. 'tight sands'. Also, the US is already funding R&D on clathrates. Coalbed methane production may start in 2010 and is assumed to increase at a steady rate after that (Figure 6.6).

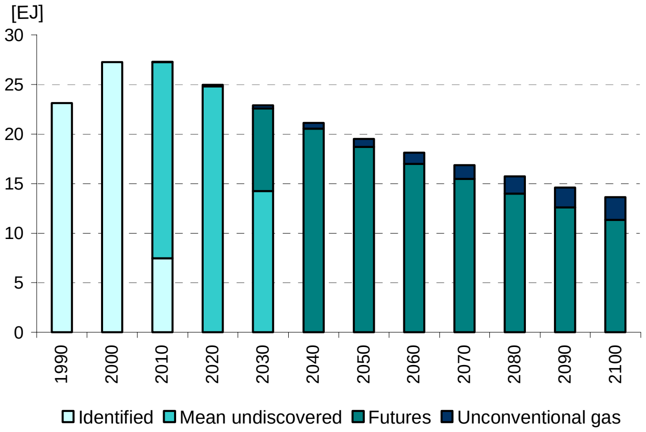


Figure 6.6 *Gas production in North America 1990-2100*

The cumulative amount of oil produced by enhanced oil recovery ('CO_2-flooding') is put at 10 billion barrels, which is in agreement with the additional potential (radius 190 km) in Chapter 3. The cumulative production of coalbed methane is approximately 100 EJ, which is the highest figure for all the regions considered. Coalbed methane is still a small fraction of the total gas production in 2100. However, EOR and ECBM would require an amount of CO_2 sequestrated of more than 250 Mt/a at the turn of the century. This is a very large amount of CO_2, viz. 35 times the amount of anthropogenic CO_2 that is currently used for CO_2/EOR in North America.

6.3.4 Latin America

Latin America holds large resources of both conventional and unconventional oil (heavy and extra heavy oil). Therefore, the production of oil may increase for some time and decline gradually after 2040 (Table 6.4 and Figure 6.7). Also, CO_2 enhanced oil recovery has been taken into account, although part of the remaining conventional resources may be not amenable to CO_2/EOR and a substantial fraction of the remaining conventional resources is offshore oil.

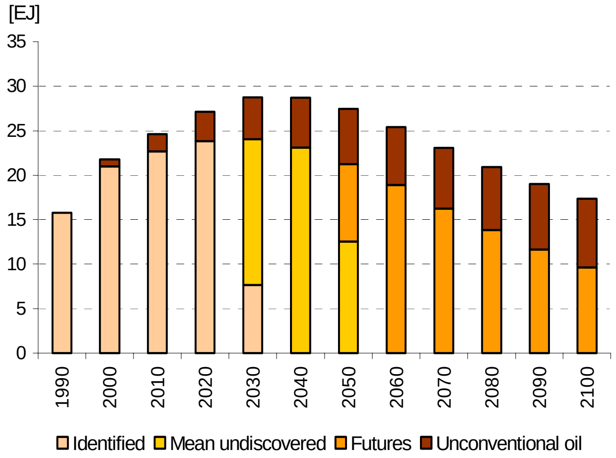


Figure 6.7 *Oil production in Latin America 1990-2100*

The conventional gas resources of Latin America are so large that the production may be increased even taking into account the general assumption that ‘futures’ are left in the ground until 2100. Also, it has been assumed that there is potential for CO_2 enhanced coalbed methane. ECBM is supposed to be introduced in 2030 and increased gradually after that (Figure 6.8).

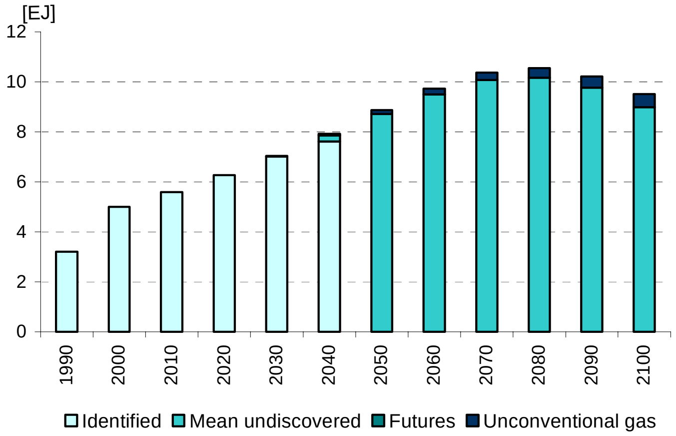


Figure 6.8 *Gas production in Latin America 1990-2100*

The cumulative amount of oil produced by enhanced oil recovery (‘CO_2-flooding’) is assumed to be 2.35 billion barrels. The cumulative production of coalbed methane could be 21 EJ. The quantity of CO_2 sequestrated would amount to 57 Mt/a in 2100.

6.3.5 Sub-Sahara Africa

Conventional oil production in sub-Sahara Africa is assumed to peak in the next decades. No credit has been given to enhanced oil recovery, taking into account that most of the oil is ligth crude oil. Moreover, a large part of the remaining conventional oil resources is offshore oil. Also, the potential of unconventional oil is deemed to be relatively modest. Therefore, the total oil production is bound to decrease towards 2100 (Table 6.5 and Figure 6.9).

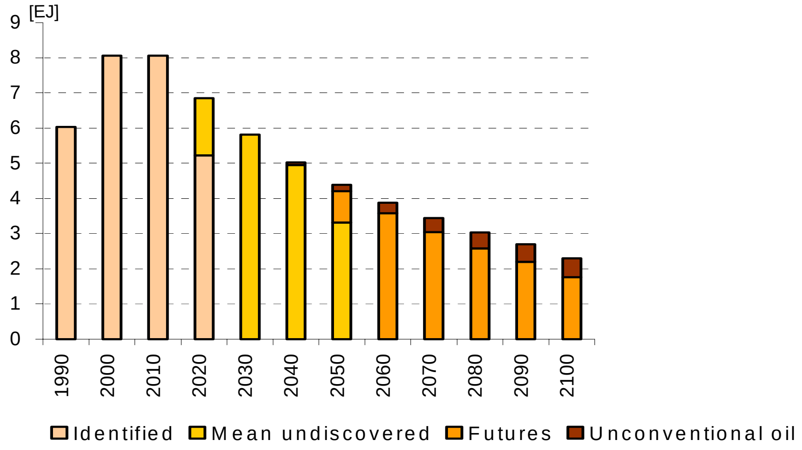


Figure 6.9 *Oil production in sub-Sahara Africa 1990-2100*

The production of conventional gas may be increased until the middle of the century. As it has been assumed that 'futures' are left in the ground for the 22nd century, the gas production is bound to decline after 2060. It has been assumed that Sub-Sahara Africa has potential for coalbed methane production. Production of coalbed methane is assumed to start in 2020 and rise steadily towards 2100 (Figure 6.10).

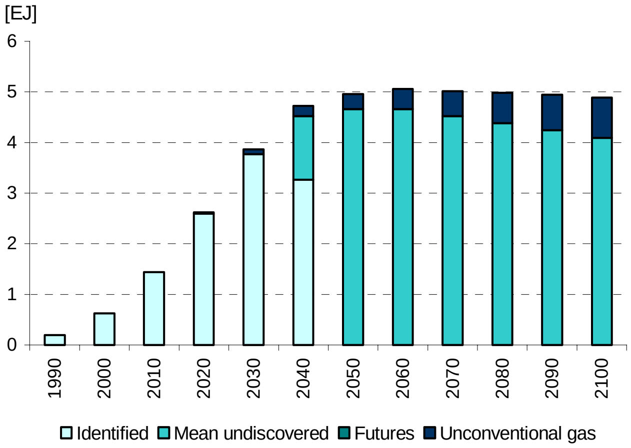


Figure 6.10 *Gas production in sub-Sahara Africa 1990-2100*

The cumulative production of coalbed methane is 36 EJ. This may appear to be a modest quantity. However, the corresponding amount of CO_2 sequestrated in 2100 is 80 Mt/a.

6.3.6 North Africa and Middle East

North Africa and the Middle East hold very large amounts of conventional oil, some of which may be used for CO_2 enhanced oil recovery (generally after waterflooding). Also, the region holds large resources of unconventional oil (mainly oil shales). Even when 50% of the conventional 'futures' and 75% of the unconventional oil are assumed to be left in the ground until 2100, the total oil production may be increased significantly (Table 6.6 and Figure 6.11).

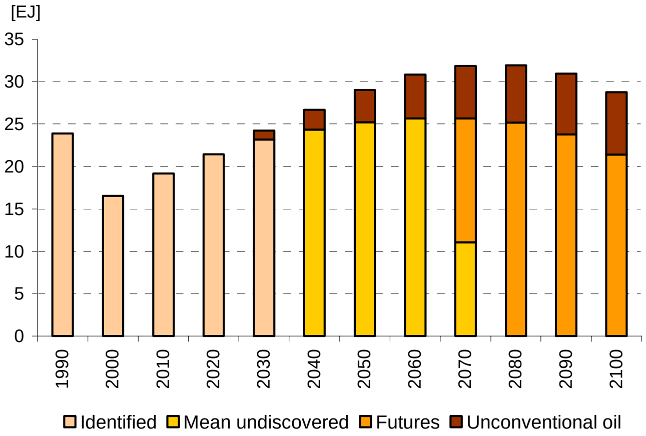


Figure 6.11 *Oil production in North Africa and the Middle East 1990-2100*

Together with the Former Soviet Union, North Africa and the Middle East hold very large conventional gas resources. Based on the general assumption that the conventional 'futures' are left in the ground until 2100, the production may be increased substantially well into the 21st century. Also, it has been assumed that production of coal-bed methane will start in 2030 and be increased gradually after that (Figure 6.12).

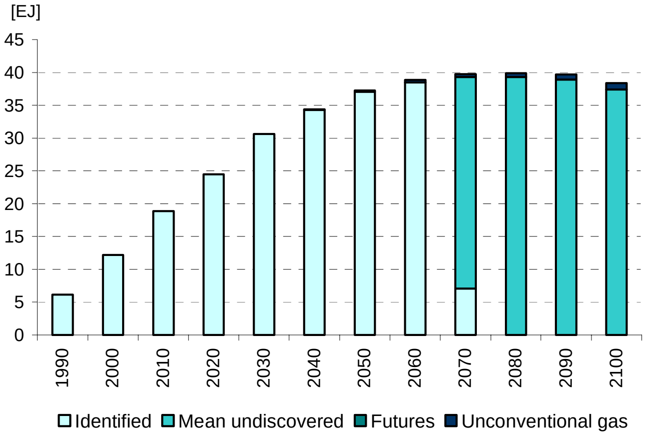


Figure 6.12 *Gas production in North Africa and the Middle East 1990-2100*

It has been assumed that a cumulative amount of 14.6 billion barrels of oil is produced by CO_2 enhanced oil recovery. The cumulative production of coalbed methane could amount to 36 EJ. The total demand for anthropogenic CO_2 could rise to approximately 133 Mt/a of CO_2 in 2100.

6.3.7 South Asia

The region South Asia is not richly endowed with conventional oil and gas resources. Also, unconventional oil resources are very limited. Therefore, the already modest oil production is bound to decline in the short term, taking into account that 50% of the conventional ‘futures’ are assumed to be left in the ground until 2100 (Table 6.7 and Figure 6.13).

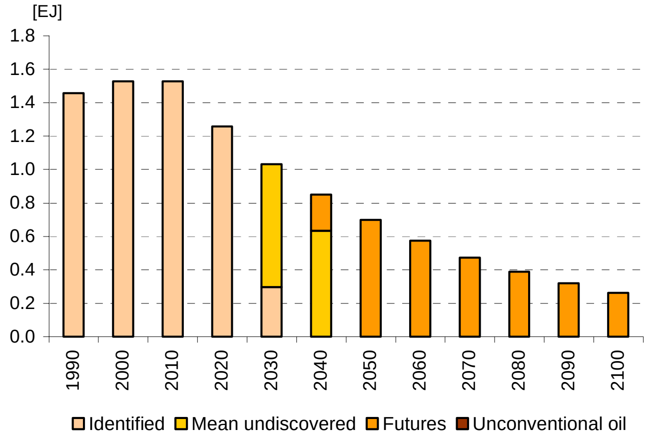


Figure 6.13 *Oil production in South Asia 1990-2100*

The conventional gas resources of South Asia are modest. Therefore, 50% of the ‘futures’ are assumed to be produced before 2100. India - just like the US - has an R&D programme on clathrates. Production of coalbed methane is assumed to start in 2010 and to rise steadily, based on the large resource base of coabed methane reported in Chapter 5 (Figure 6.14).

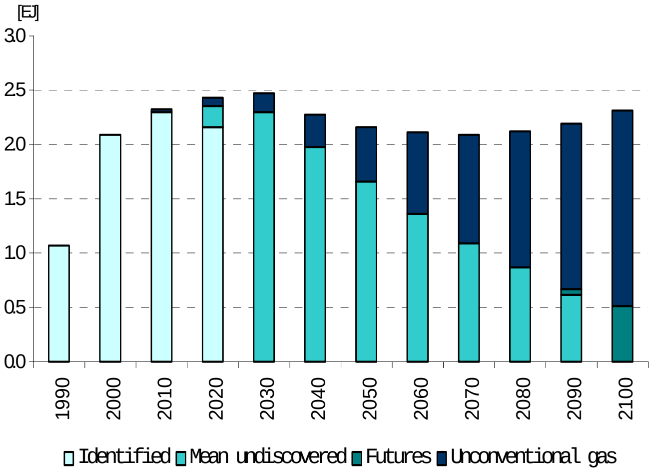


Figure 6.14 *Gas production in South Asia 1990-2100*

The cumulative production of coalbed methane is 73 EJ. Coalbed methane could be the main source of gas from 2070 onwards. It would require 180 Mt/a of CO_2 at the end of the century. Even for the Indian subcontinent (India, Pakistan, Bangladesh) this is a large amount of CO_2.

6.3.8 China

The conventional oil and gas resources of China are modest. However, China holds large unconventional oil resources (oil shales). Based on the general assumption that 50% of the conventional 'futures' and 75% of the recoverable unconventional oil resources are left in the ground until 2100, oil production in China could be increased (Table 6.8 and Figure 6.15).

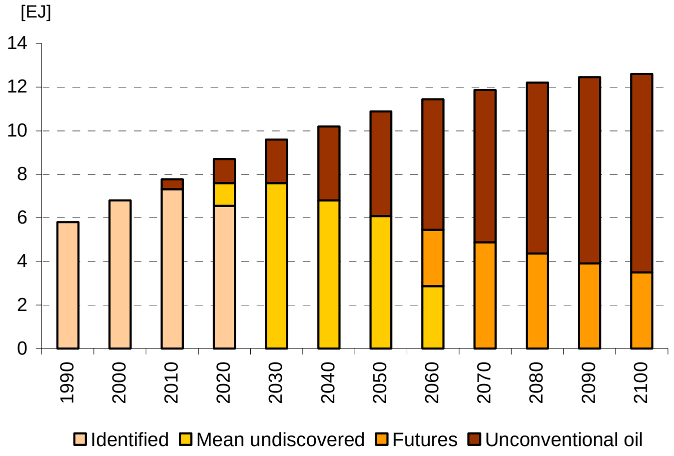


Figure 6.15 *Oil production in China 1990-2100*

China is not well endowed with conventional gas resources. However, the resource base of coalbed methane is very large (Chapter 5). Therefore, it has been assumed that coalbed methane production will start in 2010 and will be increased at a steady rate after that (Figure 6.16).

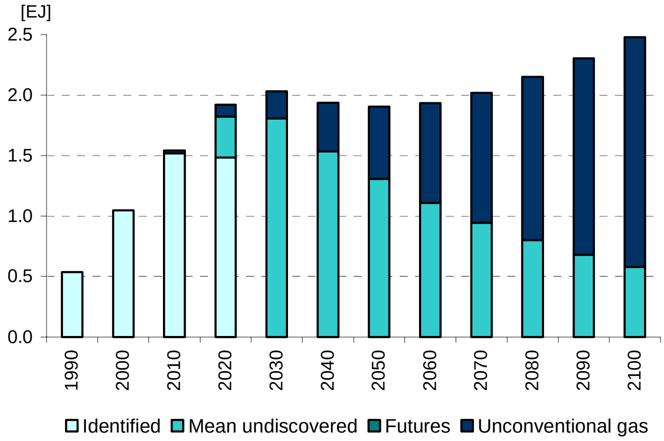


Figure 6.16 *Gas production in China 1990-2100*

The cumulative production of coalbed methane could amount to 81 EJ. Coalbed methane could be a large fraction of the total gas production in 2100. It would require an amount of 190 Mt/a of anthropogenic CO_2 in 2100, a large quantity even for a country like China.

6.3.9 Asia Pacific OECD

The region Asia Pacific OECD holds relatively modest amounts of conventional oil and gas. The potential of CO_2 enhanced oil recovery is deemed to be marginal. However, particularly Australia has substantial resources of oil shale. Based on the assumption that 50% of the conventional 'futures' and 75% of the recoverable unconventional oil resources are left in the ground until 2100, the total oil production could develop as follows (Table 6.9 and Figure 6.17).

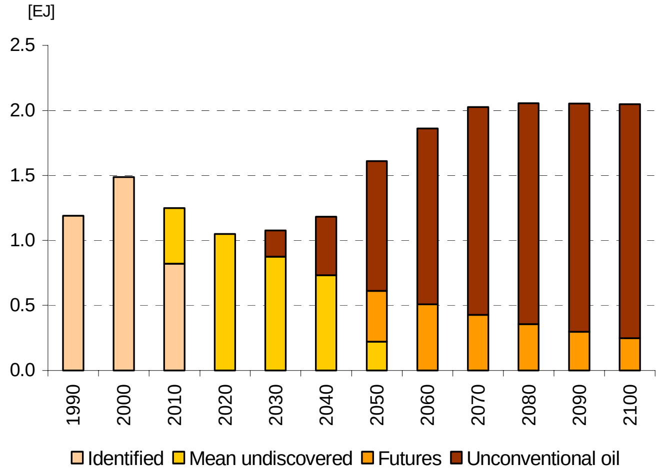


Figure 6.17 *Oil production in Asia Pacific OECD 1990-2100*

Asia Pacific OECD is not richly endowed with conventional gas resources. Therefore, it has been assumed that 50% of the 'futures' are produced before 2100. As a matter of fact, Japan - just like the US and India - has an R&D programme on clathrates. The resource base of coalbed methane in Australia is very large (Chapter 5). It has been assumed that coalbed methane production will start in 2010 and will be increased at a steady rate towards 2100 (Figure 6.16).

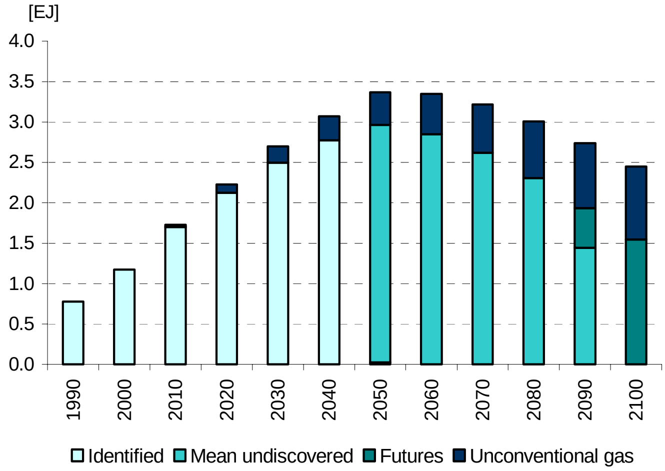


Figure 6.18 *Gas production in Asia Pacific OECD 1990-2100*

The cumulative production of coalbed methane is 45 EJ. Coalbed methane could be a significant fraction of the total gas production in 2100. It would require an amount of 90 Mt/a of CO_2 at the end of the century, which is a large amount of CO_2 for this region (Australia, Japan, Korea, etc).

6.3.10 Other Asia Pacific

The region 'Other Asia Pacific' holds substantial conventional oil and gas resources. Part of the conventional oil resources may be subject to CO_2 enhanced oil recovery. The unconventional oil resources are rather limited. Based on the general assumption that 50% of the conventional 'futures' and 75% of the recoverable unconventional resources are left in the ground until 2100, the production of oil in the region is bound to decline (Table 6.10 and Figure 6.19).

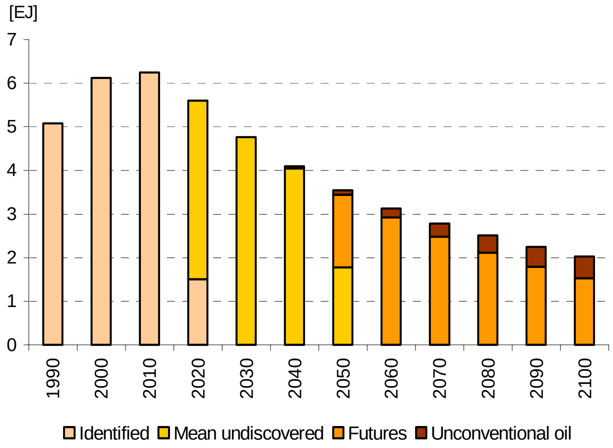


Figure 6.19 *Oil production in Other Asia Pacific 1990-2100*

The conventional gas resources of Other Asia Pacific are substantial. However, the demand for gas is bound to rise. Therefore, it has been assumed that 50% of the 'futures' are produced before 2100. As a matter of fact, Other Asia Pacific has access to the Indian and Pacific Oceans. It is quite conceivable that this region would join R&D research on clathrates. Furthermore, the production of coalbed methane could start at a modest level in 2030 and be increased gradually after that. The total gas production could develop as follows (Figure 6.20).

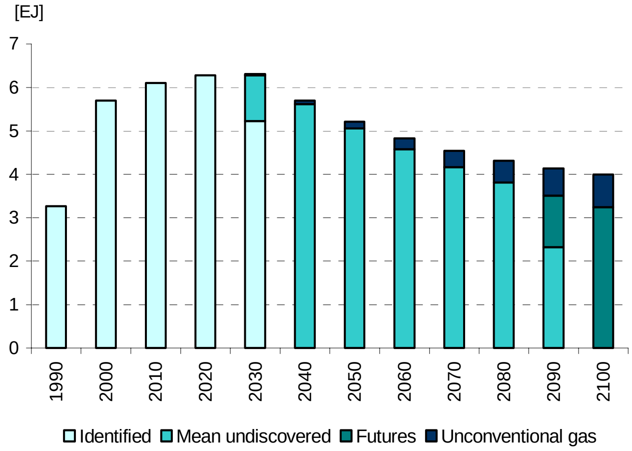


Figure 6.20 *Gas production in Other Asia Pacific 1990-2100*

The cumulative amount of oil produced by enhanced oil recovery ('CO_2-flooding') is assumed to be 2.35 billion barrels. The cumulative production of coalbed methane could be 27 EJ. The quantity of CO_2 sequestrated would amount to 80 Mt/a in 2100.

6.4 The world’s oil and gas production and CO_2 sequestration until 2100

The total production of conventional and unconventional oil and gas as well as the associated CO_2 sequestration (EOR and ECBM) is presented in Table 6.11. Figure 6.21 shows the distribution of the world’s oil production by world region.

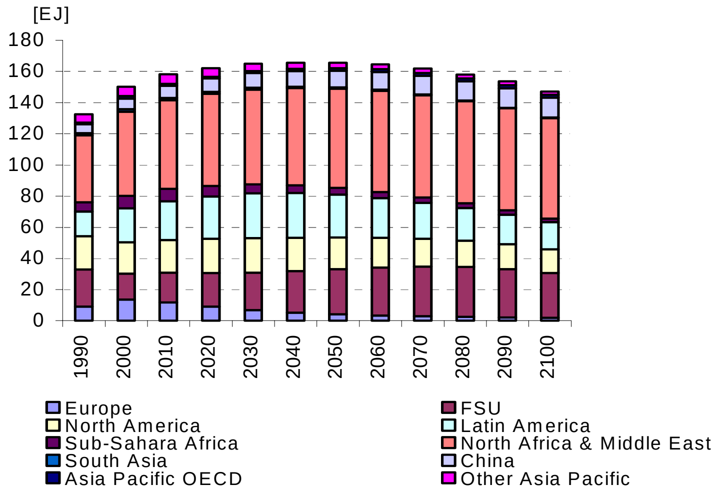


Figure 6.21 *Oil production by world region 1990-2100*

In 2100 the main producing areas in descending order would be:

- North Africa & Middle East (44%)
- Former Soviet Union (20%)
- South America (12%)
- North America (10%)
- China (9%).

The distribution between conventional and unconventional oil is shown in Figure 6.22.

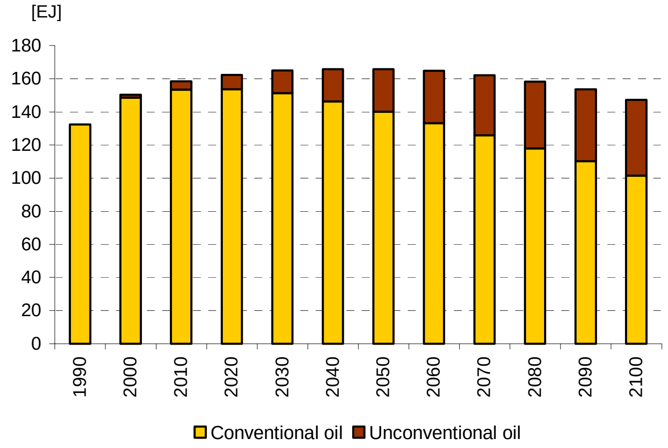


Figure 6.22 *Conventional and unconventional oil production of the world 1990-2100*

Assuming that 50% of the ‘futures’ is left in the ground until 2100, conventional oil could level off around 2010-2020 and decrease gradually towards 2100. The production of unconventional oil could be increased substantially, even assuming that 75% of the recoverable resources would be left in the ground until 2100. Due to increasing production of (extra) heavy oil, tar sands, and oil shale, ‘unconventionals’ could have a share of 31% in the total oil production in 2100. The total oil production could remain almost flat between 2020 and 2070 and decrease steadily after that. The total oil production could be 147 EJ in 2100, a few percent below the level of 2000.

Figure 6.23 shows the distribution of the world's gas production by world region.

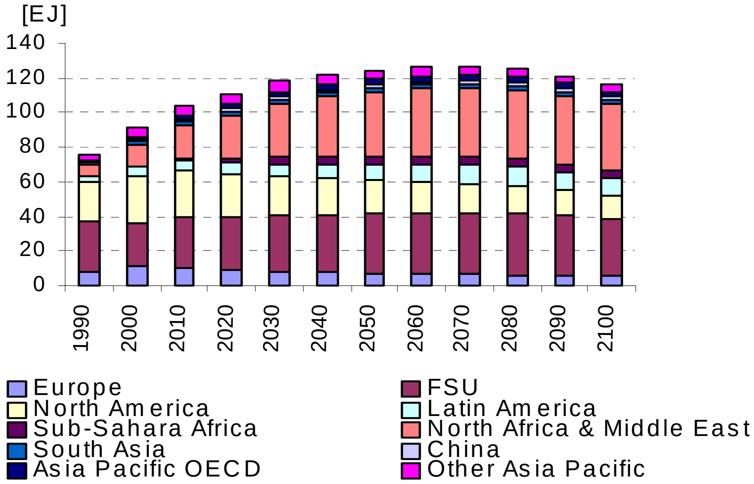


Figure 6.23 *Gas production by region of the world 1990-2100*

In 2100 the main producing areas in descending order would be:

- North Africa & Middle East (33%)
- Former Soviet Union (28%)
- North America (12%)
- South America (8%)

The distribution between conventional and unconventional gas is shown in Figure 6.24.

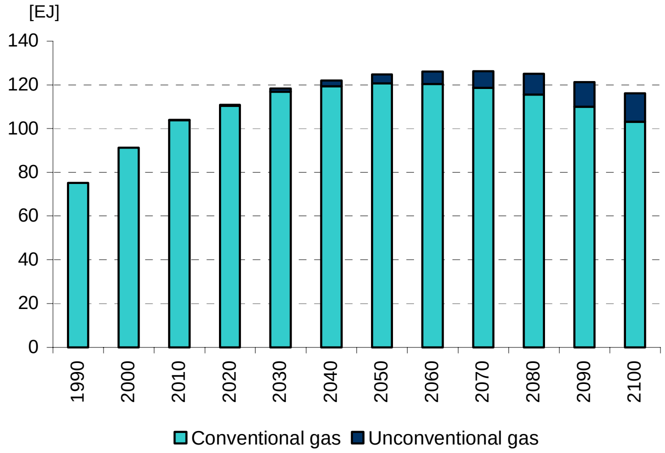


Figure 6.24 *Conventional and unconventional gas production of the world 1990-2100*

Assuming that the 'futures' are left in the ground until 2100 - except for North America, South Asia, Asia Pacific OECD, and Other Asia Pacific, where 50-67% of the 'futures' are assumed to be produced until 2100 - the production of conventional gas levels off around 2050-2060 before decreasing towards 2100. Production of coalbed methane starts around 2010 at a low level. Considering the large amounts of CO_2 needed for CO_2 enhanced coalbed methane (ECBM) and the relatively high price of coalbed methane in a number of world regions, ECBM could have a share of 11% in the world's gas production in 2100. Total production could peak around 2050-2070 and decline gradually towards a level of 116 EJ in 2100 (about 27% more than in 2000).

The development of CO_2 sequestration is presented in Table 6.11 as well as Figure 6.25.

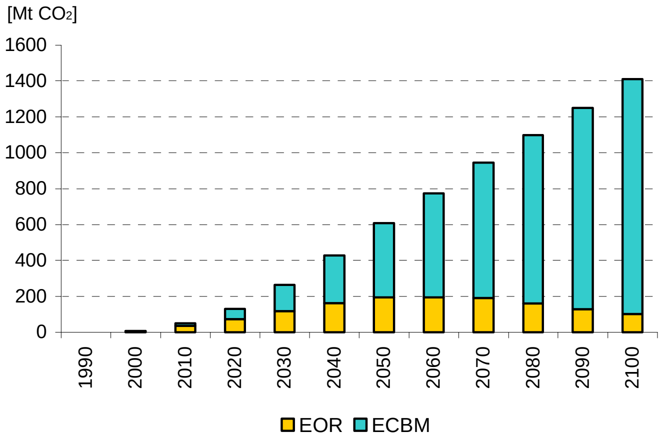


Figure 6.25 *CO_2 sequestration for EOR and ECBM on a global scale 1990-2100 [Mt CO_2]*

Sequestration of CO_2 for enhanced oil recovery could peak around 2060. With the decline of conventional oil production, EOR decreases towards 2100. The sequestration of CO_2 for ECBM starts at a modest level in 2010 and increases steadily towards 2100. In 2030 more than half of the amount of CO_2 sequestrated is related to ECBM. The total amount of CO_2 sequestrated in 2100 is approximately 1,400 Mt/a, 93% of which is related to CO_2 enhanced coalbed methane.

The cumulative amount of CO_2 sequestrated for the period 2000-2100 is estimated at 69 Gt of CO_2, which is equal to approximately 19 Gt C. CO_2 sequestration in coal-seams (ECBM) would account for 56 Gt of CO_2, or 15 Gt C. The latter figure may be compared to the estimate from Chapter 3 (Table 3.3) of CO_2 sequestration in unminable coal seams, viz. 20 Gt C, or with an estimate for the United States of 10 Gt C (Reichle et. al., 1999).

7. CONCLUSIONS

It has been questioned whether depletion of fossil fuel resources may be a limiting factor to GHG emissions in the long term (year 2100). The resource/production ratios of fossil fuels are:

- about 190 years for the combined resources of conventional and (recoverable) unconventional oil,
- about 180 years for conventional natural gas,
- about 230 years for the proved recoverable coal reserves.

There is definitely a wide margin between the conventional resources of oil and gas as reported by the US Geological Survey and the frequently quoted identified reserves of conventional oil and gas (e.g. BP data). Even then, coal is more ample in its resource base than oil and gas.

Besides, there are huge amounts of methane hydrates (clathrates) in Arctic areas and at the ocean floor. The problem is that exploitation technologies are not available. What is more, there is much uncertainty about the magnitude of these resources, their production costs (presumed that they may be produced) and possible environmental impacts of such production.

Evidently, the end of world's oil resources is not nearby. However, the Middle East is and remains a dominant oil province. Unconventional oil - tar sands, heavy and extra heavy oil, oil shale - is still a tiny fraction of the total oil production. Therefore, oil is a strategic fossil fuel. Also, future oil (price) crisis cannot be excluded.

The conventional natural gas resources are ample compared to the current gas demand. Also, gas resources are more evenly distributed around the globe than oil resources. However, if both the industrialised countries (Annex 1 countries) and developing countries would massively switch from coal to gas, security of supply of natural gas would become in issue relatively soon.

One of the ways to reduce GHG emissions is CO_2 enhanced oil recovery (EOR). Today, a number of CO_2 sequestration projects, mostly related to EOR, are operational. There is a vast potential for sequestration of CO_2 in depleted oil and gas reservoirs, as well as in aquifers or oceans (the latter as a temporary measure). However, CO_2/EOR has the advantage of combining CO_2 sequestration and enhanced fuel supply. There is a substantial additional potential for such projects in North America, the Former Soviet Union, and the Middle East.

For reasons of GHG emission reduction, optimal use of locally available fossil fuels - coal seams - and security of supply, novel ways of CO_2 sequestration deserve attention, notably CO_2 Enhanced CoalBed Methane (ECBM). This option is based on the geological occurrence of deep coal seams, but the fuel produced is coal-bed methane, which has a much lower specific GHG emission (g CO_2 equivalent per GJ) than coal itself. ECBM may even be considered in countries where conventional coal production has been terminated for economic reasons. In the Netherlands, the potential of coalbed methane is 220 billion m^3 with a probability of 50%, equal to 8% of the original reserves of the Groningen gas field. Also the CO_2 sequestration potential is large: roughly 6 times the annual CO_2 emission of the Netherlands (50% probability).

The cost of coalbed methane largely depends on the investment cost of drilling injection and production wells. Whether the coalbed methane price is acceptable depends on:

- the necessity of deep inseam drilling or not, direct or late injection, etc.,
- the level of the investment cost of drilling injection and production wells,
- the supply of CO_2 and the dependence between cost and supply,
- the availability of financial incentives for ECBM (carbon tax and the like).

The main cost factors in case of ECBM are drilling injection and production wells, and - generally to a lesser extent - supply of CO_2. The economics of ECBM may profit from the availability of large CO_2 sources and sinks, not necessarily from large-scale transport of CO_2.

The price of coalbed methane - e.g. € 6.5-8.7/GJ for three scenarios analysed in depth - is really high in the Netherlands. The price refers to 5 Mtonne/a CO_2 sequestrated. In case of an amount of 15 Mtonne/a the price rises to a range of € 7 to €10/GJ depending on the production scenario.

Based on the current CO_2 supply options, ECBM would not become a ‘big’ option in the Netherlands, unless tremendous financial incentives would be available. Dedicated power plants could supply relatively cheap CO_2, in terms of marginal and average CO_2 supply costs. ‘Dedicated’ refers to a fossil fuel based power plant that is optimised for CO_2 sequestration.

A study on behalf of the IEA Greenhouse Gas R&D Programme ranks four countries in descending order with respect to the prospects of ECBM: Australia, China, Poland, and India. The potential of coalbed methane in Australia is more than 2,000 billion m^3, in China 30,000 billion m^3 (gas-in-place, a fraction of which is recoverable), and in India 400-4,000 billion m^3. The geological characteristics in those countries are more favourable than in the Netherlands.

Production profiles for conventional and unconventional oil as well as conventional and unconventional gas (coalbed methane) have been presented for ten world regions. In 2100 50% of the ‘futures’ of conventional oil is presumably left in the ground. Also 75% of the recoverable unconventional oil is presumably still available for production in 2100. Unconventional oil could prevent the decline of the world’s total oil production until the middle of the century. In the year 2100 the main producing areas of oil could be (in descending order):
- North Africa & Middle East (44%)
- Former Soviet Union (20%)
- South America (12%)
- North America (10%).

Due to increasing production of heavy oil, tar sands, and oil shale, ‘unconventionals’ could cover 31% of the global oil demand in 2100. Oil production could remain almost flat from 2020 and 2070 and decline towards 2100, ending up at 147 EJ, a few percent below the level of 2000.

In most of the world the ‘futures’ of conventional gas are assumed available for production after 2100. However, in North America and Asia except China, the identified and undiscovered gas reserves are relatively limited. Therefore, it has been assumed that 50-67% of the conventional ‘futures’ in those regions may be produced until 2100. Also, production of coal bed methane is assumed for all the regions. In 2100 the main gas producing areas could be in descending order:
- North Africa & Middle East (33%)
- Former Soviet Union (28%)
- North America (12%)
- South America (8%).

Considering the large amounts of CO_2 needed for CO_2 enhanced coalbed methane (ECBM) and the (correspondingly) high price of coalbed methane in several world regions, ECBM could have a share of 11% in the total gas production in 2100. Global gas production could peak in 2060 and decline steadily towards 2100 to a level of 116 EJ, 27% more than in 2000. All these figures are very uncertain due to uncertainties with regard to resources and production profiles.

The sequestration of CO_2 for enhanced oil recovery could peak around 2060, declining thereafter due to the decreasing resources of conventional oil. Sequestration of CO_2 for ECBM starts at a modest level in 2010 and increases steadily towards 2100. The total amount of CO_2 sequestrated in 2100 could be approximately 1,400 Mt/a, 93% of which is related to ECBM.

ANNEX A CONVENTIONAL OIL RESOURCES

The United States Geological Survey (USGS) has compiled surveys of the world's conventional oil resources by basin. These surveys contain three classes of reserves:

1. *Identified reserves*
   Identified reserves are interpreted to include not only the traditional Proved Reserves but also any additional petroleum we might conclude will be recognised by field growth attained through extension, new reservoirs, or improvements in recovery.
2. *Mean undiscovered reserves*
   Besides the identified reserves, undiscovered reserves are considered. The undiscovered reserves are not based on concrete evidence. The Mean of the undiscovered reserves is used in this survey (other classes are 95% probability, Mode, and 5% probability).
3. *Futures*
   At last another category is considered, viz. the futures. This amount of oil is not related to exploration efforts or other related indications.

Table A.1 *Conventional oil resources of Europe according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
UK	0.971	11.2	19.5	7.9	4.2	31.6
Norway	1.228	5.8	17.1	8.5	47.5	73.1
France					0.1	0.1
Germany					0.0	0.0
Eastern Europe		7.1	2.6	2.7	3.8	9.1
Greece					0.0	0.0
Italy	0.033	0.6	1.2	1.9	2.8	5.9
Spain				2.5	1.9	4.4
Total	2.539	24.7	40.4	23.5	60.3	124.2

Table A.2 *Conventional oil resources of the Former Soviet Union according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Azerbaijan	0.110	9.210				
Kazakhstan	0.272	3.683				
Russian Federation	2.385	96.448				
Turkmenistan	0.055	2.572				
Uzbekistan	0.064	0.079				
Total	2.933	112.0	129	151	297.5	577.5

Table A.3 *Conventional oil resources of North America according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
USA	2.827	163.5	51.1	43.8	106.0	200.9
Canada	0.989	15.1	11.0	31.4	57.7	100.1
Total	3.816	178.6	62.1	75.2	163.7	301.0

Table A.4 *Conventional oil resources of Latin America according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Mexico	1.259	19.5	42.0	35.5	135.8	213.3
Central America					0.1	0.1
Venezuela and Trinidad & Tobago	1.242	44.6	49.0	22.4	104.4	175.8
Colombia	0.259	3.5	3.6	5.9	7.5	17.0
Ecuador	0.148	1.8	3.3	2.8	5.0	11.1
Peru	0.038	1.9	2.2	6.3	4.5	13.0
Guyana, Surinam, and French Guyana				0.0	0.0	0.0
Brazil	0.458	3.4	12.8	12.7	25.2	50.7
Bolivia				1.0	0.4	1.4
Argentina	0.299	5.6	3.8	4.2	5.7	13.7
Chile		0.4	0.2	0.3	1.2	1.7
Total	3.754	80.7	116.9	91.1	289.8	497.8

Table A.5 *Conventional oil resources of sub-Sahara Africa according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Mali Mauritania				0.1	0.0	0.1
NorthWest Africa					0.1	0.1
Mali-Niger					0.0	0.0
Chad			0.5	1.7	1.6	3.8
Sudan		0.6	0.3	3.1	2.7	6.1
Ethiopia				0.1	0.1	0.1
Somalia				0.9	0.6	1.5
Nigeria	0.768	15.1	20.4	6.5	28.0	54.9
Cameroon	0.033		0.4	1.2	0.5	2.1
Gabon	0.119	1.7	1.8	1.7	2.9	6.4
Rep. of Congo	0.100	2.2	4.6	5.2	6.8	16.6
Angola	0.268	2.0	3.7	1.9	1.7	7.3
Namibia					0.0	0.0
South Africa			0.0	0.1	0.1	0.3
Botswana				0.1	0.0	0.2
Zaire				1.6	0.6	2.2
Other Karoo Rift Basins				0.7	0.4	1.1
East African Rift Basins				0.8	0.6	1.4
Mozambique				0.2	0.1	0.3
Tanzania					0.0	0.0
Madagascar				1.5	2.4	3.9
Seychelles				0.1	0.0	0.0
Total	1.420	21.6	31.7	27.5	49.2	108.4

Table A.6 *Conventional oil resources of North Africa and the Middle East according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Algeria	0.577	11.0	8.2	1.9	30.6	40.7
Egypt	0.290	6.0	6.0	2.2	7.8	16.0
Libya	0.538	18.0	31.3	10.1	41.3	82.7
Morocco-Spanish Sahara			0.1	0.1	0.0	0.2
Tunisia	0.029	0.9	1.3	5.5	6.5	13.3
Iran	1.376	33.728				
Iraq	0.958	22.414				
Kuwait	0.785	30.989				
Oman	0.350	3.552				
Qatar	0.290	5.007				
Saudi Arabia	3.338	72.776				
Syria	0.197	1.652				
United Arab Emirates	0.918	15.741				
Yemen	0.161	0.649				
Total	9.826	222.4	592.3	154.8	738.7	1485.8

Table A.7 *Conventional oil resources of South Asia according to the USGS [billion barrels]*

	Annual production (1999)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Pakistan		0.2	0.5	0.3	0.7	1.5
India	0.287	3.5	6.5	2.1	9.5	18.1
Total	0.287	3.7	7.0	2.4	10.3	19.7

Table A.8 *Conventional oil resources of China according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif.+Mean und. +Futures
China	1.184	14.1	31.4	42.7	67.1	141.2

Table A.9 *Conventional oil resources of Asia Pacific OECD according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Australia	0.297	3.17	2.7	3.1	7.4	13.2
New Zealand		0.03	0.3	0.1	0.4	0.8
Total	0.297	3.20	3.0	3.2	7.8	14.0

Table A.10 *Conventional oil resources of Other Asia Pacific according to the USGS [billion barrels]*

	Annual production (2000)	Cumulative production	Identified reserves	Mean undiscovered	Futures	Identif. + Undiscov. + Futures
Myanmar		0.49	0.2	1.5	1.1	2.8
Indonesia	0.522	13.8	13.0	7.7	20.2	40.9
Malaysia	0.294	2.7	3.3	6.0	9.3	18.6
Brunei	0.071	2.4	1.8	0.7	2.8	5.3
Philippines		0.04	0.3	1.8	2.0	4.1
Papua New Guinea	0.026		0.3		0.3	0.6
Pacific Islands					0.0	0.0
Thailand	0.060	0.1	0.2	1.4	1.1	2.7
Cambodia					0.0	0.0
Vietnam	0.117	0.1	0.9	6.6	6.8	14.3
Antarctica					0.1	0.1
Total	1.141	19.6	20.0	25.7	43.7	89.4

ANNEX B CONVENTIONAL GAS RESOURCES

The United States Geological Survey (USGS) publishes data of the world's conventional gas resources. The three classes considered here are the identified reserves (exclusive of cumulative production), the mean undiscovered reserves and the futures according to Enron.

Table B.1 *Conventional gas resources of Europe according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Austria		3.3	2.0		5.3
Czech Republic		0.3	15.1		15.4
Denmark & Greenland	8.1	215.7	2307.4		2523.1
France			589.8		589.8
Germany	16.9	320.5	367.9		688.4
Hungary	2.7	99.4	71.0		170.4
Italy	16.8	246.9	772.3		1019.2
Netherlands	57.3	1938.4	242.2		2180.6
Norway	52.4	2725.8	5183.0		7908.8
Croatia		86.5	48.6		135.1
Poland		93.0	79.9		172.9
Romania	13.6	393.4	153.4		546.8
Servia & Montenegro		26.5	7.7		34.2
Slovakia		10.3	7.2		17.5
Slovenia		0.6	0.3		0.9
Spain			503.9		503.9
United Kingdom	108.1	1670.3	662.0		2332.3
Malta			5.8		5.8
Bulgaria		1.2	0.8		2.0
Total	287.9	7832.1	11020.3		18852

Table B.2 *Conventional gas resources of the Former Soviet Union according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Azerbaijan	5.3	339.5	1910.0		
Kazakhstan	10.7	1957.2	2046.0		
Russia	545.0	39933.0	33095.0		
Turkmenistan	43.8	2470.5	5881.2		
Ukraine	16.8	790.7	779.7		
Uzbekistan	52.2	1765.1	425.8		
Total	674.2	47256.0	44137.7	55,316	146710

Table B.3 *Conventional gas resources of North America according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Canada	167.8	1452.7	694.3		
United States	555.6	4870.5	14923.1		
Total	723.4	6323.2	15617.4	46933	68874

Table B.4 *Conventional gas resources of Latin America according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Benin		1.7	20.0		21.7
Grenada			22.8		22.8
Mexico	35.8	940.5	1395.2		2335.7
Argentina	37.3	862.1	1039.1		1901.2
Barbados		0.2	253.9		254.1
Bolivia	3.3	170.4	708.3		878.7
Brazil	7.7	259.8	5505.1		5764.9
Chile		94.5	181.4		275.9
Colombia	5.9	518.9	286.0		804.9
Cuba		2.2	16.5		18.7
Ecuador		32.1	15.6		47.7
Falkland Islands			469.5		469.5
French Guiana			1.0		1.0
Guyana			170.5		170.5
Paraguay		0.3	127.6		127.9
Peru		30.4	179.4		209.8
Suriname			1019.5		1019.5
Togo			8.6		8.6
Trinidad and Tobago	12.6	534.9	900.2		1435.1
Uruguay			32.3		32.3
Venezuela		4373.5	2886.8		7260.3
Total	132.2	7821.5	15239.3		23061

Table B.5 *Conventional gas resources of sub-Sahara Africa according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Eritrea		0.1	309.4		309.5
Gabon		39.5	688.3		727.8
Gambia			1.0		1.0
Ghana		5.0	57.0		62.0
Nigeria	5.7	2365.1	3488.9		5854.0
Angola		177.5	1210.2		1387.7
Cameroon		118.7	158.0		276.7
Congo		63.7	492.6		556.3
Congo (Kinshasa)		2.7	27.8		30.5
Cote d'Ivoire		46.9	171.1		218.0
Equatorial Guinea		25.4	213.5		238.9
Guinea-Bissau			5.8		5.8
Mauritania			7.5		7.5
Namibia		169.9	43.4		213.3
Senegal		1.3	7.8		9.1
South Africa		0.4	59.0		59.4
Sudan		24.2	438.7		462.9
Total	16.7	3040.4	7380.0		10420

Table B.6 *Conventional gas resources of North Africa and the Middle East according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Algeria	89.3	4896.8	1387.0		
Egypt	18.0	150.4	578.7		
Libya	5.5	1449.5	597.7		
Morocco			3.0		
Tunisia		86.6	202.2		
Western Sahara			2.2		
Bahrain	8.6	220.2	467.7		
Iran	60.2	17592.5	8907.6		
Iraq		1965.1	3398.2		
Jordan		5.1	68.6		
Kuwait	9.6	1661.7	167.5		
Kuwait/Saudi Arabia Neutral		306.2			
Oman	8.5	902.9	955.6		
Qatar	28.5	10447.3	1163.8		
Saudi Arabia	47.0	8152.1	19283.8		
Syria		60.8	144.3		
United Arab Emirates	39.8	4181.7	1260.8		
Turkey		12.8	21.2		
Yemen		484.8	620.2		
Total	322.5	52576.5	39230.1	53668	145475

Table B.7 *Conventional gas resources of South Asia according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Bangladesh	10.3	259.6	950.9		
India	26.1	652.3	857.4		
Pakistan	19.0	603.8	810.0		
Total	55.4	1515.7	2618.3	764.4	4898

Table B.8 *Conventional gas resources of China according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
China	27.7	962.8	2429.2	627.2	4019

Table B.9 *Conventional gas resources of Asia Pacific OECD according to the USGS and Enron (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Australia	31.1	2435.2	3098.4		
Zone of Austr/Indo		170.4	128.4		
Total	31.1	2605.6	3226.8	1078	6910

Table B.10 *Conventional gas resources of Other Asia Pacific according to the USGS (futures) [billion m^3]*

	Annual production (2000)	Identified reserves	Mean undiscov.	Futures	Identif. + Undisc. + Futures
Indonesia	63.9	2146.0	3050.0		
Afghanistan		127.2	1210.2		
Brunei	11.6	413.9	351.5		
Cambodia		5.0	49.9		
Thailand/Malaysia		147.2	59.2		
Malaysia	44.2	2356.1	1420.8		
Myanmar		263.3	768.6		
Thailand	17.8	119.4	132.4		
Vietnam			22.0		
Total	151.2	5578.1	7064.6	2338	14980

ANNEX C TABLES CHAPTER 6

Table 6.1 *Oil production, gas production and CO_2 sequestration in Europe*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	9.106	13.775	11.709	9.074	6.806	5.104	3.828	2.871	2.153	1.615	1.252	1.033
Unconventional oil [EJ]						0.100	0.250	0.500	0.750	0.938	0.947	0.952
Total oil [EJ]	9.106	13.775	11.709	9.074	6.806	5.204	4.078	3.371	2.903	2.553	2.199	1.984
Gas												
Conventional gas [EJ]	8.173	10.854	9.877	8.938	8.045	7.240	6.516	5.865	5.278	4.750	4.275	3.848
Unconventional gas [EJ]			0.025	0.100	0.250	0.425	0.650	0.900	1.150	1.400	1.650	1.900
Total gas [EJ]	8.173	10.854	9.902	9.038	8.295	7.665	7.166	6.765	6.428	6.150	5.925	5.748
CO_2 sequestration												
EOR [Mt]												
ECBM [Mt]			2.5	10.0	25.0	42.5	65.0	90.0	115.0	140.0	165.0	190.0
Total [Mt]			2.5	10.0	25.0	42.5	65.0	90.0	115.0	140.0	165.0	190.0

Table 6.2 *Oil production, gas production and CO_2 sequestration in the Former Soviet Union*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	23.886	16.513	19.155	21.454	23.170	24.328	25.180	25.684	25.684	25.170	23.786	21.407
Unconventional oil [EJ]					1.050	2.350	3.850	5.150	6.150	6.750	7.150	7.350
Total oil [EJ]	23.886	16.513	19.155	21.454	24.220	26.678	29.030	30.834	31.834	31.920	30.936	28.757
Gas												
Conventional gas [EJ]	28.663	25.414	29.226	30.687	31.915	33.032	34.023	34.873	35.222	35.222	33.461	31.453
Unconventional gas [EJ]				0.025	0.100	0.200	0.325	0.475	0.650	0.850	1.050	1.250
Total gas [EJ]	28.663	25.414	29.226	30.712	32.015	33.232	34.348	35.348	35.872	36.072	34.511	32.703
CO_2 sequestration												
EOR [Mt]			8.0	18.0	30.0	42.0	54.0	54.0	54.0	43.2	34.6	27.6
ECBM [Mt]				2.5	10.0	20.0	32.5	47.5	65.0	85.0	105.0	125.0
Total [Mt]			8.0	20.5	40.0	62.0	86.5	101.5	119.0	128.2	139.6	152.6

Table 6.3 *Oil production, gas production and CO_2 sequestration in North America*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	21.328	19.127	18.744	17.807	16.205	14.260	12.121	10.060	8.250	6.682	5.346	4.223
Unconventional oil [EJ]		0.964	2.400	4.250	5.850	7.200	8.300	9.150	9.750	10.300	10.700	11.000
Total oil [EJ]	21.328	20.091	21.144	22.057	22.055	21.460	20.421	19.210	18.000	16.982	16.046	15.223
Gas												
Conventional gas [EJ]	23.120	27.256	27.256	24.803	22.571	20.539	18.691	17.009	15.478	14.007	12.607	11.346
Unconventional gas [EJ]			0.038	0.150	0.350	0.575	0.825	1.100	1.400	1.700	2.000	2.300
Total gas [EJ]	23.120	27.256	27.294	24.953	22.921	21.114	19.516	18.109	16.878	15.707	14.607	13.646
CO_2 sequestration												
EOR [Mt]		7.3	13.9	23.3	33.9	41.5	41.5	41.5	41.5	41.5	33.2	26.6
ECBM [Mt]			3.8	15.0	35.0	57.5	82.5	110.0	140.0	170.0	200.0	230.0
Total [Mt]		7.3	17.7	38.3	68.9	99.0	124.0	151.5	181.5	211.5	233.2	256.6

Table 6.4 *Oil production, gas production and CO_2 sequestration in Latin America*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	15.780	21.004	22.684	23.819	24.057	23.094	21.247	18.910	16.262	13.823	11.611	9.637
Unconventional oil [EJ]		0.780	1.950	3.313	4.660	5.600	6.200	6.500	6.800	7.100	7.400	7.700
Total oil [EJ]	15.780	21.784	24.634	27.131	28.717	28.694	27.447	25.410	23.062	20.923	19.011	17.337
Gas												
Conventional gas [EJ]	3.207	4.991	5.590	6.260	7.012	7.853	8.717	9.501	10.071	10.172	9.765	8.984
Unconventional gas [EJ]					0.025	0.075	0.150	0.225	0.300	0.375	0.450	0.525
Total gas [EJ]	3.207	4.991	5.590	6.260	7.037	7.928	8.867	9.726	10.371	10.547	10.215	9.509
CO_2 sequestration												
EOR [Mt]			2.0	4.5	7.9	12.2	12.2	12.2	9.8	7.8	6.2	5.0
ECBM [Mt]					2.5	7.5	15.0	22.5	30.0	37.5	45.0	52.5
Total [Mt]			2.0	4.5	10.4	19.7	27.2	34.7	39.8	45.3	51.2	57.0

Table 6.5 *Oil production, gas production and CO_2 sequestration in Sub-Sahara Africa*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	6.037	8.055	8.055	6.847	5.820	4.947	4.205	3.574	3.038	2.582	2.195	1.768
Unconventional oil [EJ]						0.075	0.175	0.300	0.400	0.450	0.500	0.528
Total oil [EJ]	6.037	8.055	8.055	6.847	5.820	5.022	4.380	3.874	3.438	3.032	2.695	2.295
Gas												
Conventional gas [EJ]	0.193	0.628	1.444	2.600	3.770	4.524	4.660	4.660	4.520	4.384	4.242	4.093
Unconventional gas [EJ]				0.025	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800
Total gas [EJ]	0.193	0.628	1.444	2.625	3.870	4.724	4.960	5.060	5.020	4.984	4.942	4.893
CO_2 sequestration												
EOR [Mt]												
ECBM [Mt]				2.5	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0
Total [Mt]				2.5	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0

Table 6.6 *Oil production, gas production and CO_2 sequestration in North Africa & Middle East*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	42.818	54.144	56.851	59.125	60.899	62.117	62.738	62.738	62.110	60.868	59.651	57.861
Unconventional oil [EJ]						0.250	1.000	2.250	3.500	4.750	6.000	6.810
Total oil [EJ]	42.818	54.144	56.851	59.125	60.899	62.367	63.738	64.988	65.610	65.618	65.651	64.671
Gas												
Conventional gas [EJ]	6.138	12.154	18.839	24.491	30.614	34.287	37.030	38.511	39.282	39.282	38.889	37.421
Unconventional gas [EJ]					0.025	0.100	0.225	0.350	0.500	0.650	0.800	0.950
Total gas [EJ]	6.138	12.154	18.839	24.491	30.639	34.387	37.255	38.861	39.782	39.932	39.689	38.371
CO_2 sequestration												
EOR [Mt]			10.0	22.5	37.5	55.0	75.0	75.0	75.0	60.0	48.0	38.4
ECBM [Mt]					2.5	10.0	22.5	35.0	50.0	65.0	80.0	95.0
Total [Mt]			10.0	22.5	40.0	65.0	97.5	110.0	125.0	125.0	128.0	133.4

Table 6.7 *Oil production, gas production and CO_2 sequestration in South Asia*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	1.457	1.528	1.528	1.257	1.034	0.850	0.699	0.575	0.473	0.389	0.320	0.263
Unconventional oil [EJ]												
Total oil [EJ]	1.457	1.528	1.528	1.257	1.034	0.850	0.699	0.575	0.473	0.389	0.320	0.263
Gas												
Conventional gas [EJ]	1.068	2.089	2.298	2.356	2.297	1.975	1.659	1.360	1.088	0.871	0.668	0.513
Unconventional gas [EJ]			0.025	0.075	0.175	0.300	0.500	0.750	1.000	1.250	1.525	1.800
Total gas [EJ]	1.068	2.089	2.323	2.431	2.472	2.275	2.159	2.110	2.088	2.121	2.193	2.313
CO_2 sequestration												
EOR [Mt]												
ECBM [Mt]			2.5	7.5	17.5	30.0	50.0	75.0	100.0	125.0	152.5	180.0
Total [Mt]			2.5	7.5	17.5	30.0	50.0	75.0	100.0	125.0	152.5	180.0

Table 6.8 *Oil production, gas production and CO_2 sequestration in China*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	5.790	6.795	7.305	7.597	7.597	6.799	6.085	5.446	4.874	4.363	3.905	3.495
Unconventional oil [EJ]			0.465	1.100	2.000	3.400	4.800	6.000	7.000	7.850	8.550	9.100
Total oil [EJ]	5.790	6.795	7.770	8.697	9.597	10.199	10.885	11.446	11.874	12.213	12.455	12.595
Gas												
Conventional gas [EJ]	0.536	1.047	1.518	1.821	1.806	1.535	1.305	1.109	0.943	0.802	0.681	0.579
Unconventional gas [EJ]			0.025	0.100	0.225	0.400	0.600	0.825	1.075	1.350	1.625	1.900
Total gas [EJ]	0.536	1.047	1.543	1.921	2.031	1.935	1.905	1.934	2.018	2.152	2.306	2.479
CO_2 sequestration												
EOR [Mt]												
ECBM [Mt]			2.5	10.0	22.5	40.0	60.0	82.5	107.5	135.0	162.5	190.0
Total [Mt]			2.5	10.0	22.5	40.0	60.0	82.5	107.5	135.0	162.5	190.0

Table 6.9 *Oil production, gas production and* CO_2 *sequestration in Asia Pacific OECD*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	1.189	1.486	1.248	1.049	0.876	0.731	0.610	0.510	0.426	0.355	0.297	0.248
Unconventional oil [EJ]					0.200	0.450	1.000	1.350	1.600	1.700	1.755	1.800
Total oil [EJ]	1.189	1.486	1.248	1.049	1.076	1.181	1.610	1.860	2.026	2.055	2.052	2.048
Gas												
Conventional gas [EJ]	0.779	1.172	1.700	2.125	2.497	2.771	2.965	2.847	2.619	2.305	1.936	1.549
Unconventional gas [EJ]			0.025	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
Total gas [EJ]	0.779	1.172	1.725	2.225	2.697	3.071	3.365	3.347	3.219	3.005	2.736	2.449
CO_2 sequestration												
EOR [Mt]												
ECBM [Mt]			2.5	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0
Total [Mt]			2.5	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0

Table 6.10 *Oil production, gas production and CO_2 sequestration in Other Asia Pacific*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	5.083	6.121	6.244	5.600	4.760	4.046	3.439	2.923	2.485	2.112	1.795	1.526
Unconventional oil [EJ]						0.050	0.100	0.200	0.300	0.400	0.450	0.500
Total oil [EJ]	5.083	6.121	6.244	5.600	4.760	4.096	3.539	3.123	2.785	2.512	2.245	2.026
Gas												
Conventional gas [EJ]	3.266	5.698	6.097	6.280	6.280	5.621	5.059	4.578	4.166	3.812	3.507	3.244
Unconventional gas [EJ]					0.025	0.075	0.150	0.250	0.375	0.500	0.625	0.750
Total gas [EJ]	3.266	5.698	6.097	6.280	6.305	5.696	5.209	4.828	4.541	4.312	4.132	3.994
CO_2 sequestration												
EOR [Mt]			2.0	4.5	7.9	12.2	12.2	12.2	9.8	7.8	6.2	5.0
ECBM [Mt]					2.5	7.5	15.0	25.0	37.5	50.0	62.5	75.0
Total [Mt]			2.0	4.5	10.4	19.7	27.2	37.2	47.3	57.8	68.7	80.0

Table 6.11 *Oil production, gas production and CO$_2$ sequestration of the world 1990-2100*

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Oil												
Conventional oil [EJ]	132.47	148.55	153.52	153.63	151.22	146.28	140.15	133.29	125.76	117.96	110.16	101.46
Unconventional oil [EJ]		1.74	4.82	8.66	13.76	19.48	25.68	31.40	36.25	40.24	43.45	45.74
Total oil [EJ]	132.47	150.29	158.34	162.29	164.98	165.75	165.83	164.69	162.01	158.20	153.61	147.20
Gas												
Conventional gas [EJ]	75.14	91.30	103.84	110.36	116.80	119.38	120.62	120.31	118.67	115.61	110.03	103.03
Unconventional gas [EJ]			0.14	0.58	1.48	2.65	4.13	5.78	7.55	9.38	11.23	13.08
Total gas [EJ]	75.14	91.30	103.98	110.94	118.28	122.03	124.75	126.09	126.22	124.98	121.26	116.10
CO$_2$ sequestration												
EOR [Mt]		7.3	35.9	72.8	117.2	163.0	195.0	195.0	190.1	160.4	128.3	102.6
ECBM [Mt]			13.8	57.5	147.5	265.0	412.5	577.5	755.0	937.5	1122.5	1307.5
Total [Mt]		7.3	49.7	130.3	264.7	428.0	607.5	772.5	945.1	1097.9	1250.8	1410.1

REFERENCES

Alberta Energy and Utilities Board (2001): *Alberta's Reserves 2000 and Supply/Demand Outlook 2001-2010,* Statistical Series 2001-98. www.eub.gov.ab.ca.

Alberta Research Council, Inc.: *Enhanced Recovery of Coalbed Methane/Carbon Dioxide Sequestration,* IEA/CON/99/52, October 2000.

BP (2000): *Statistical review of world energy,* June 2000. www.bpamoco.com/worldenergy.

Bundesanstalt für Geowissenschaften und Rohstoffe (1989): *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen,* Hannover, June 1989.

Canada's Oil Sands: *A supply and Market Outlook to 2015,* October 2000. www.neb.gc.ca.

Carson, M.M. (1997): *Natural gas central to world's energy mix,* Oil & Gas Journal, 11 August 1997, pp 37-47.

Collet, T.S. et. al. (1998): *Hydrates contain vast store of world gas resources,* Oil&Gas Journal, 11 May 1998, pp 90-95.

Edmonds, J.A. et. al. (2000): *The role of carbon management technologies in addressing atmospheric stabilisation of greenhouse gases,* In: 'Proceedings of the GHGT-5: Proceedings of the Fifth International Conference of Greenhouse Gas Control Technologies.' Cairns, Australia, 13-16 August 2000.

Grubb, M. (2001): *Who's afraid of atmospheric stabilisation? Making the link between energy resources and climate change,* Energy Policy 29, pp 837-845.

Henriet, J.-P. et. al. (1998): *Gas hydrates, relevance to world margin stability and climate change,* The Geological Society, London.

Holtz, M.H. et. al. (1999): *Reduction of greenhouse gas emission through underground CO_2 sequestration in Texas oil and gas reservoirs*, Bureau of Economic Geology, Texas (US).

IEA Greenhouse Gas R&D Programme (2000): *Leading options for the capture of CO_2 emissions at power stations,* Report Number PH3/14, February 2000.

Inciarte, J. (1991): *Technology pushes Venezuela's heavy-oil projects ahead.* Oil & Gas Journal, 8 December 1997, pp 52-54.

Kelafant, J. et. al. (1998): *Coalbed methane could cut India's energy deficit,* Oil & Gas Journal, 25 May 1998, pp 42-46.

Lako, P., Jansen J.C. (2001): *What scenario studies tell about security of energy supply in Europe,* ECN-C--01-054, Petten.

Novem (2001): *Potential for CO_2 sequestration and enhanced coalbed methane production in the Netherlands,* Utrecht, March 2001.

Oil & Gas Journal, 5 February 2001, p. 48.

Reichle, F. et. al. (1999): *Carbon Sequestration Research and Development,* US DoE, December 1999. www.ornl.gov/carbon_sequestration.

RIVM (2001): Milieubalans 2001, p. 141.

Stevens, S.H. et. al, (2001): *Geologic CO_2 sequestration,* Oil & Gas Journal, 15 May 2001, pp 40-43.

USGS (2000): *U.S. Geological Survey Digital Data Series 60,* www.usgs.gov.

Warfield, G. (1995): *Oil, gas, coal, uranium, tar sand resource trends on rise,* Oil & Gas Journal, 4 September 1995, pp 104-111.

WEC (1996): *Survey of Energy Resources,* www.worldenergy.org.

Williams, R.H. (1998): *Fuel decarbonisation for fuel cell applications and sequestration of the separated* CO_{2}*,*, In: Ayres R.U. (editor): ‘Ecorestructuring.’ Tokyo, UN University Press, EN-98-04.

Zwaan, B.C.C. van der et. al. (2001): *Geological carbon sequestration: a fix for global warming?* IVM, Free University Amsterdam, D-01/04, July 2001.