CO_2 TECHNOLOGY SCENARIOS SEMINAR
Copenhagen, June 2001
Organised by CO2NET

Report Number PH4/3
May 2002

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1. Background

The seminar was the second such event to be organised by CO2NET[1], which is a European Commission (EC) supported initiative to assist the dissemination of information from EC funded projects on CO_2 sequestration. The first seminar, which engaged EC policy makers in the discussion on CO_2 sequestration, was held in Trondheim in February 2001 and was reported in PH4/2, May 2001.

The members of the CO2NET project are currently: Technology Initiatives (UK), GEUS[2] (Denmark), Statoil (Norway) and the IEA Greenhouse Gas R&D Programme (IEA GHG). GEUS are the co-coordinators for the EC supported GESTCO[3] project whilst Statoil are the co-coordinators of the SACS[4] project. Both GEUS and Statoil represent their respective projects as participants in CO2NET. IEA GHG is supporting CO2NET by providing expertise and experience in network management and to assist in engaging international co-operation with the network. The CO2NET project commenced in December 2000 and ended in April 2002. A proposal for a broader project to establish a European Thematic Network on CO_2 sequestration has been submitted for consideration to the EC for support for the period 2002 to 2005. The EC have agreed to support the Thematic Network and the development of the project contract is now underway, ready for project commencement in late 2002.

The aim of the seminar was to review the CO_2 sequestration work underway within Europe and to identify research gaps and future research needs.

This report provides an overview of the seminar and provides a summary of the key findings.

The detailed results from this seminar were used as input to the proposal for the European Thematic Network on CO_2 sequestration and will be used to guide EC research activities for the 6th Framework Programme that is due to commence in 2002.

2. Seminar Summary

The seminar was attended by 40 people and took place on the 6th and 7th June 2001. The delegates were mostly from Europe but also included a number from the USA. A full delegate list is provided in Appendix 1.

The programme began with a welcoming address by Niels Peter Christensen of GEUS, followed by an opening address by Lars Stromberg of Vattenfall AB. The opening address discussed the potential and cost for different CO_2 emission avoidance options in Europe. Lars expressed the opinion that fossil fuels are a major factor in Europe's energy supply and cannot be replaced in the near future. For Europe, the fastest and least expensive way to reduce CO_2 emissions in the energy sector was by increased energy efficiency, replacing old plant with new and utilising CHP.
However, he pointed that you cannot eliminate CO_2 emissions this way only reduce them. New energy supply systems that remove CO_2 can be based on renewable fuels by using fossil

[1] CO_2 Sequestration – European Technology Network Development Programme, 2000-2001.
[2] Geological Survey of Greenland and Denmark
[3] European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion
[4] Saline Aquifer CO_2 Storage Project

fuels with sequestration. He concluded that CO_2 sequestration was probably cheaper than most of the renewable energy sources available today and, in terms of technology status, was many years ahead. A copy of the presentation is given in Appendix 2

There then followed a series of presentations to set the scene for the meeting, which included:

- Sleipner CO_2 injection system and the SACS project – operations overview (how the whole thing works), Tore A. Torp, Statoil.
- CO_2 Enhanced Oil Recovery at Weyburn: commercially viable CO_2 geo-sequestration from a coal based power plant, Nick Riley, British Geological Survey.
- ICBM Project – technical issues relevant to coal and CO_2 sorption, diffusion, flow, well bore effects etc., Sevket Durucan, Imperial College.
- ECBM Potential in the Netherlands: can it be commercial? Harry Schreurs, NOVEM.
- TotalFinaElf's Expectations for CO_2 Capture, Rodolphe Bouchard, TotalFinaElf
- Transmission of CO_2 – experiences to be gained from CO_2-EOR projects, John Gale, IEA Greenhouse Gas R&D Programme

Copies of the presentations that are available are given in Appendix 3.

On the afternoon of the first day, 4 breakout groups were formed to consider what gaps were present in current research activities on CO_2 sequestration. The groups were:

Group A	CO_2-ECBM
Group B	CO_2-EOR
Group C	CO_2 storage in a saline aquifer
Group D	CO_2 Capture

The first three breakout groups were required to work through an example case study then compile an overview of research gaps and future research needs for each area. For the capture group background information relating to research activities underway on CO_2 capture were provided. Following this activity the other break out groups were given the opportunity to critique each overview. Each breakout group then reformed to consider the critique comments. On the second day of the meeting the break out groups reported back on their analysis of the cases set.

3. Summary of Break Out Group Activities

Summaries of the reports by the four breakout groups are presented below. Groups were requested to report back in a consistent approach using the following criteria to as a guide:

- Social
- Technological
- Economic
- Environmental
- Political

Group A ***CO_2-ECBM***

The key points noted by the group were:

Topic:	**Key Points Identified**
Social	Not discussed in depth by Group
Technological	CO_2-ECBM technology at earlier stage of development than CO_2-EOR or CO_2 storage in aquifers
	Injection issues to be addressed • Well spacing • Use of horizontal wells to improve injectivity • Use of chemical/mechanical effects to improve permeability • Thermal effects of CO_2 injection • Potential well bore effects
	Issues relating to the geological setting that need to be resolved: • Effect of pressure, temperature, moisture and rank of coal • Local hydrology • Inherent permeability • Seam thickness and density • Structural setting • Storage capacity of intermediate layers in coal seams
	Rock and fluid characteristic issues to be resolved: • PVT behaviour of CO_2 and impact of impurities • Matrix swelling/shrinkage effects on permeability and flow • Diffusion characteristics of gas mixtures • Hydrochemistry All need to be considered under representative reservoir conditions
	Storage capacity and integrity issues to be resolved: • Type and integrity of cap rocks • Depth criteria for unminable seams in North Sea • Migration in and out of reservoir – will it occur? • How to prevent mining after storage?
Economic	Comparative costs of CO_2-ECBM with other options to be confirmed
Environmental	Produced water could be an issue – needs to be either recycled/reinjected or treated and disposed of.
	Leakage potential – detailed risk assessment needs to be undertaken
Political	Not discussed

The key technical gaps identified were:

1. Technical understanding of reservoir properties and impacts of CO_2 injection on permeability, swelling/shrinkage etc.,
2. Knowledge of CO_2 leakage potential from coal seams
3. Modelling tools need to be developed and calibrated against real data

Research priorities were considered to be:

1. Development of detailed understanding of rock and fluid characteristics in coal seams
2. Resolution of injection issues i.e. well spacing, horizontal versus vertical wells, methods to improve in-seam permeability
3. Understand issues relating to storage capacity and CO_2 longevity in coal seams – detailed risk assessment needed

Group B ***CO_2-EOR***

The key points noted by the group were:

Topic:	Key Points Identified
Social	There may be large barriers to the development of CO_2-EOR in Europe
	An onshore demonstration project could assist in lessening opposition allowing people to see at first hand advantages of storage. However Offshore CO_2-EOR may be more acceptable because of NIMBY[5] lobby
	Public may not accept CO_2 sequestration unless better understanding of long term storage uncertainties could be achieved
	Environmental pressure groups will oppose CO-EOR in Europe as it is perceived as “business as usual” for oil companies
	Marine law (OSPAR and London Convention) could be used to hinder CO_2-EOR developments and window of opportunity might be missed
	There are positive social benefits, such as continued employment in oil industry that need to be played up.
Technological	Few perceived technological barriers to offshore CO_2-EOR
	Principal barrier was cost of CO_2 capture – cheap sources of CO_2 near to oil fields were needed
	New CO_2 supply infrastructure in North Sea would be needed – who would bear the cost – industry or Governments?
	Existing infrastructure in North Sea will be decommissioned in next 10 to 20 years – short deadline for CO_2-EOR in North Sea
	Wells in North Sea are more widely spaced than in Texas – could cause problems with sweep efficiency
	Development of new simulators might be needed to address long term fate of CO_2 in reservoir – current simulators look at 20-30 year reservoir lifetimes
	CO_2-EOR may not be practical in Chalk reservoirs due to dissolution of host rock.
Economic	Suitable economic climate needed - prime driver being low cost supply of CO_2.
Environmental	Important to establish timescales for long term fate of CO_2 in reservoir – needs for climate change and human health effects due to contamination will be different
	Old wells could act as fast leakage pathways - corrosion of liners/cements needs to be understood
	A proven trap for oil may not mean CO_2 is secure due to different properties of fluids
	Mineral fixation cannot be ignored but in Europe most reservoirs do not contain reactive minerals
	Long term monitoring strategy needed an important issue – cost of such systems an important consideration
Political	Political issues important in development of CO_2-EOR
	Governments need to create market opportunities for CO_2 sequestration.
	Long tern legislative and economic need to be put in place for oil companies to consider long term investment plans
	Profile of CO_2 sequestration with policy makers and regulators is needed – onshore demo. could help

No key technical gaps were noted and no future research needs were highlighted by the Group

[5] NIMBY – NOT IN MY BACK YARD

Group C ***CO_2 Storage in Aquifers***

The key points noted by the group were:

Topic:	
Social	Gaining public acceptance is an absolute priority
	CO_2 storage needs to be undertaken in a way that is transparent to the layman – issues are long term security and local contamination
	Basic education needs to be improved i.e. getting CO_2 storage into the school books
	Issues that need to be debated openly with detractors are: What are the consequences of not taking up the technology? Where do we get our energy from if we don't use fossil fuels?
	Clear definition of CO_2 – is it a waste or a byproduct?
	Regulation needed to gain public acceptance
Technological	Injection of CO_2 into an aquifer is a proven technology – issues are linked to establishing long term fate of injected CO_2.
	Monitoring issues need to be considered – what is most cost effective approach
	Nature of trapping mechanisms needs to be fully understood
Economic	What are the technology costs in relation to benefits? A life cycle analysis could be undertaken
	Some optimization of costs required e.g. impact of well diameter
	Macro economic costs of using clean fossil fuels versus renewables needs to be determined
Environmental	Will CO_2 storage affect potable water?
	Modelling of escape scenarios related to cap rock needed to understand implications of leakage.
	Will injection offshore be more acceptable than onshore?
Political	What if CO_2 accidentally leaks out – what emergency plans are required and by whom?
	How long is long enough to store CO_2? – needs to be debated
	Governments need to establish CO_2 market
	Who will bear extra costs of sequestration (taxation, fuel prices, and consumer prices)?
	Injection into reservoirs may be illegal under National/international law - Onshore injection prohibited in Germany, Offshore under OSPAR/London Convention

A series of actions were recommended by the group. High priority actions to gain public acceptance were considered to be:

1. An onshore demonstration project in Europe
2. Long term coupled monitoring and modelling was required at Sleipner
3. Expanding the EU mapping work to the whole of Western and Eastern Europe
4. CO2NET to debate how long CO_2 should be stored for.

Low priority actions were:

1. Further research work on natural analogues
2. Testing of gravity surveying onshore
3. Development of safety assessment methods

Group D ***CO_2 Capture***

The CO_2 capture group focused its activities on reducing the costs of CO_2 capture, which is seen as the key economic barrier. Three CO_2 capture technology areas were reviewed and ways of reducing the costs for each area outlined. The results are summarised below:

Capture Area	**Key technology issues/actions to reduce costs**
Precombustion	Development of Mixed Conductive Membranes (MCM) for oxygen production for use in partial oxidation or steam reforming processes
	Hot gas cleaning – overcome challenges from gasification of solid hydrocarbon fuels
	Develop H_2/CO_2 membranes to simplify process
	Develop designs that maximise H_2 content in gas turbine (GT) fuels
Oxyfuel	MCM development
	Development of GT materials for low oxygen environments
	Consideration of effects of excess O_2 on separation process and corrosion
	Is it possible to achieve complete burnout without oxygen excess?
	Design of exhaust gas cycle needs to be considered
	Effects of exhaust gas mixture composition on boiler heat transfer needs to be examined
Post Combustion	Multi-purpose treatment of off-gas i.e. simultaneous removal of CO_2 and SO_2
	New solvents need to be developed with high efficiency and low degradation rates
	Reduce volume flow to reduce costs
	Amines: will they work at high (10%) O_2 contents?
	Handling of waste streams – degraded solvents
	What impurities can be tolerated at the scrubber?
General issues	What value can be placed on CO_2?
	What are the CO_2 pipeline purity requirements?
	What are the purity requirements for CO_2 injection?
	Corrosion information needed for CO_2 transportation needed
	Costs are a function of capture, sources, transmission and storage

High priority issues for future research were considered to be:

Pre-combustion capture	Development of MCM O_2 production Overcoming issues for hot gas cleaning for solid fuels in gasifiers
Oxyfuel combustion	Development of MCM O_2 production Understanding effects of excess O_2 on separation process GT Materials – effects of low O_2 contents Understanding of stoichiometric combustion in low O_2 atmospheres
Post Combustion capture	Development of multipurpose deSOx/CO_2 systems Development of low cost solvents

4. Summary

1. With regard to the activities on geological storage the Group discussions clearly show that CO_2-ECBM is at a much earlier stage of technical development than CO_2-EOR and CO_2 storage in aquifers. The focus of the CO_2-ECBM discussion was weighted on the technical uncertainties that still exist around this storage option, whilst for the other two groups the discussion focused more on socio/political and public acceptance issues relating to implementation of the technology. It would appear that there is much to be learnt from CO_2 injection projects in coal seams planned or underway in the USA, Canada and Poland. These projects need to be effectively monitored so that a decision can be made whether CO_2-ECBM can be promoted as a safe and secure CO_2 storage option. However, such information may not be available for several years and in essence the jury on CO_2-ECBM is still out.

2. Both the CO_2-EOR and aquifer storage groups thought that gaining public acceptance of the technology was a high priority. One of the key issues that needed to be addressed was considered to be the effectiveness of CO_2 storage both from a short term environmental perspective and long term in relation to climate change. Both groups advocated research to understand the potential for CO_2 leakage from reservoirs was needed as well as an understanding of the effects (i.e. environmental) that might occur as a result. Such research would be fundamental to gaining public acceptance for the technology.

3. Both the CO_2-EOR and aquifer storage groups promoted the idea of an onshore demonstration project in Europe as a way of overcoming the political and social barriers to geological storage. The idea behind this is that politicians and the public can visit the site and (hopefully) gain confidence that there are no significant environmental issues with CO_2 injection. Such a demonstration site would need to be well considered, but also should be representative. A demonstration project of this type might also attract the attention of the environmental lobby against sequestration during its planning stage and a lengthy consultation period might be required that will need strong Government support.

4. A regulatory system was also required as a component to gain public acceptance for CO_2 storage. The regulatory system needs to be clear who is responsible in the event of a leak and what emergency plans are needed. The long term monitoring of storage sites needs to be carefully considered.

5. The CO_2-EOR and aquifer storage groups both considered that some form of Government intervention was necessary to develop a market for CO_2. They also questioned who will bear the costs of establishing the necessary infrastructure for offshore CO_2 injection, will these be Governments (through taxation etc.,) or industry and what market incentives might be provided (CO_2 credits, increased consumer prices etc.,). In the case of CO_2-EOR in the North Sea there appears to be a window of opportunity, after which time the current extraction infrastructure will be decommissioned and the cost to establish new facilities will be significantly increased.

6. The cost of CO_2 capture was recognised as an impediment to the introduction of the technology; hence the CO_2 capture group focused its activities on identifying ways of reducing capture costs. The group identified a number of areas where new technology developments could make an impact on reducing the cost of capture.

APPENDIX 1

LIST OF ATTENDEES

CO_2 Technology Scenarios Convention

Delegates List

6th and 7th June 2001

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APPENDIX 2

OPENING PRESENTATION BY LARS STROMBERG OF VATTENFALL AB

Discussion on the potential and cost for different CO_2 emission avoidance options in Europe

CO_2 NET. CO_2 Technology Scenarios Convention. Copenhagen June 6 2001VGB

Lars Strömberg

Vattenfall AB

Electricity Generation

Stockholm, Sweden

Chalmers University of Technology

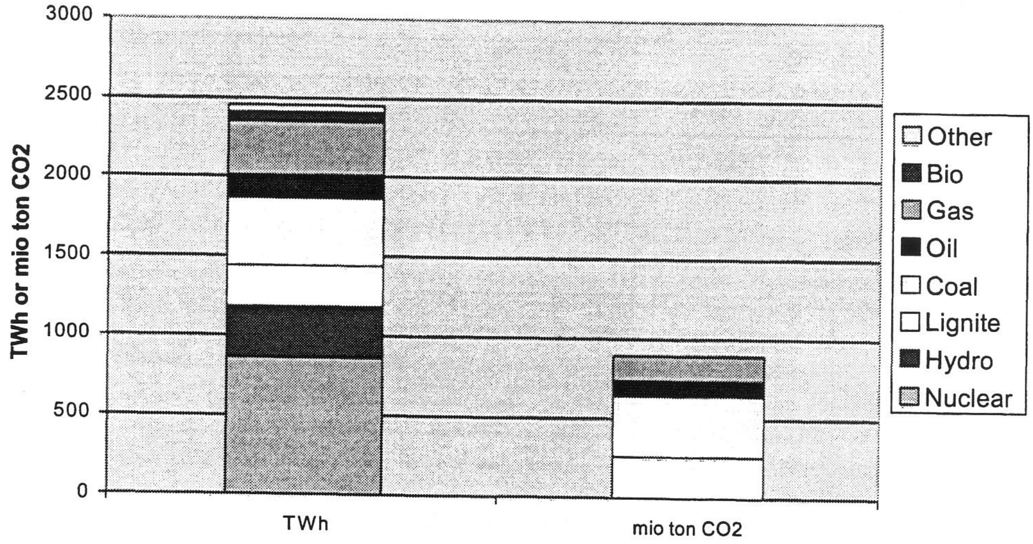
Dept. of Energy Technology

Göteborg, Sweden

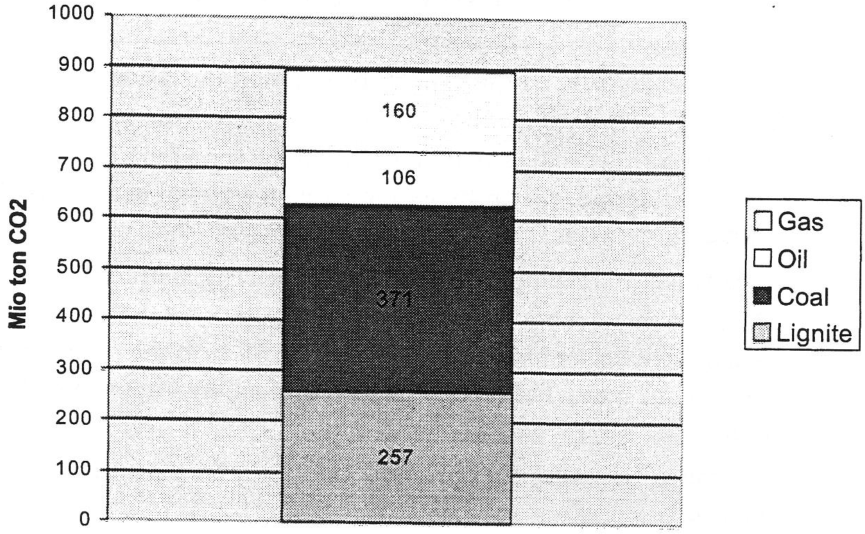
Fossil Fuels are needed

- At present a majority of the energy production in stationary plants is produced from fossil fuels
  - This proportion will remain high in Europe for a long time, and fossil fuel usage will probably increase on a global basis, regardless of measures taken
- It is desirable to develop new sustainable energy sources.
  - Within a foreseeable future new energy sources cannot replace fossil fuels, so we have to live with up to 65 % of the production from fossil fuels. The rest is nuclear, biofuel, hydropower and some renewable energy sources, i.e. wind.
- Coal is the dominating fuel in many countries for stationary production

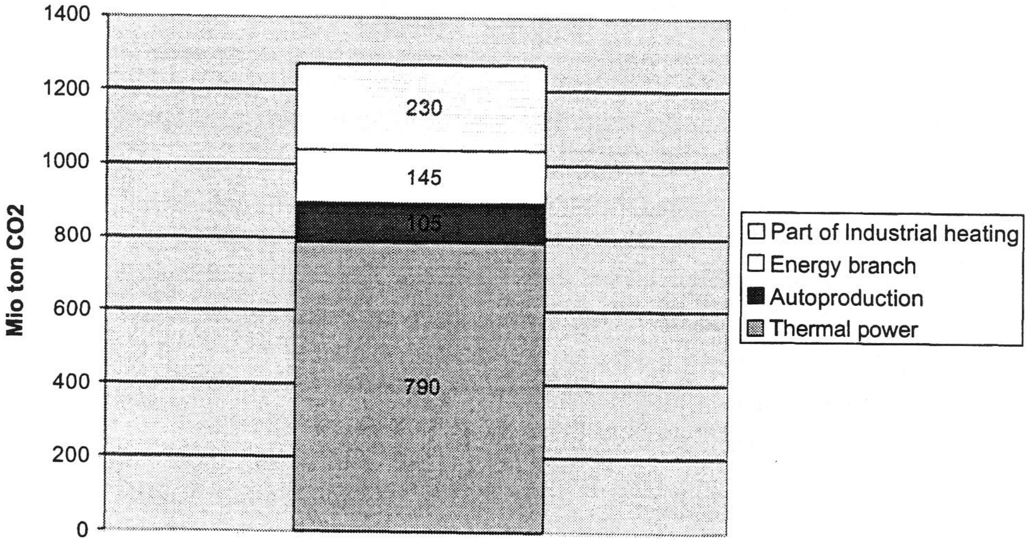
Electricity generation and emissions of CO2 in Europe



Emission of CO2 from electricity production



Emission of CO2 from the Energy supply sector



Long term - short term

- The obligations in the Kyoto protocol is not sufficient to stabilize the global warming. CO_2 emissions have to be reduced by some 60% to achieve that
- Within the Kyoto time frame the Energy sector in Europe probably has to take on a higher proportion of CO_2 emission reduction than the average - 8 %
- If a least cost burden shall be shared for all sectors the Energy sector has to reduce its emissons by some 13 % according to calculations within the EU ECCP (Report by M. Vainio DG ENV)

Long term - short term (contd.)

- Within Europe our short term (within the Kyoto protocol agreement time frame) obligations can be fulfilled by
  - Improve efficiency of the energy production system, by exchange of old technology with modern and utilizing combined heat and power
  - Exchange of fuels from oil and coal to gas
  - Use renewable energy sources
- In the long term we must
  - Utilize the renewable energy sources as far as possible
  - Develop sustainable solutions for fossil fuels.
  - Or find new, unknown sustainable technologies

Efficient use of energy

- Efficient use of energy might be the easiest way to reduce CO_2 emission, but it cannot eliminate it
- Energy conversion efficiency describes the amount of fuel used to produce the sellable product. Modern power plants for coal has an efficiency over 45%, as compared to very old, often at 30%, thus emitting 50 % more CO_2
- Cogeneration of heat and power is efficient and shall be utilized if feasible, but the consumption of heat does not correspond to more than a fraction (20 - 30%) of the electricity demand.
- New technologies like fuel cells might increase efficiency further, but the whole system must be taken into account in the efficiency calculus. Hydrogen is not a natural fuel and has to be produced somehow
- Replacing old plants with new, thus reduces the emitted amount of Carbon dioxide.

The alternatives

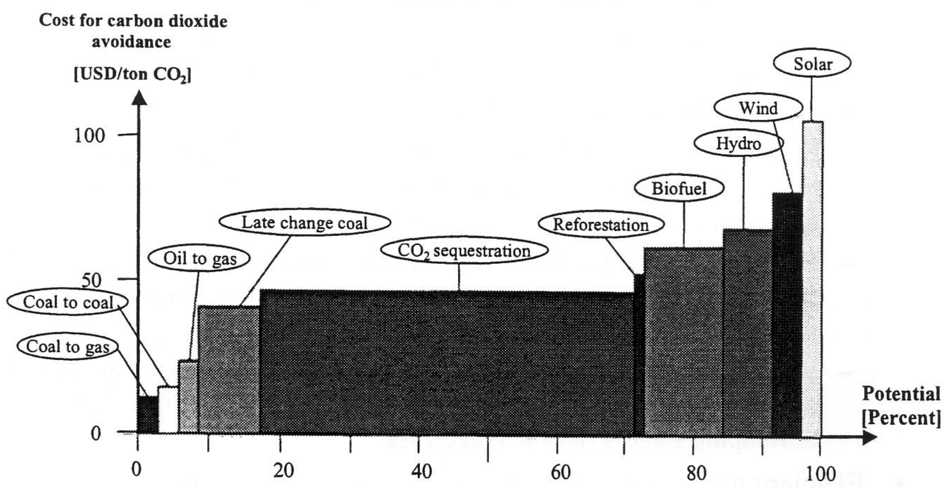
- The renewable sources are estimated to be able to submit some 16 % of the energy within the EU in 2020
  - Hydro power is only available in some countries and has a limited expansion potential. New plants are very costly and has a restricted acceptance
  - Biofuels are very good and widely used in some countries, but can only submit a fraction of what is needed. Also in developed markets fuel cost is very high
  - Wind and solar energy are developing rapidly. Windpower can submit several percent of the need in future, while solar is still in an early developing stage. Prices will decrease
- Efficient use of any fuel is of course advantageous and shall be supported

Sustainable solution for fossil fuels?

- CO_2 emissions from coal and other fuels can probably be eliminated by CO_2 separation and underground deposition at lower cost than most of the renewable alternatives.
- If so at least coal can be considered a sustainable solution, since resources are so large and widespread.
- This would also satisfy the strive for security of supply
- CO_2 separation and storage will not be effective during the next ten years period
- Demonstration plants will probably be in operation during this period

Cost and Potential of options to reduce CO_2 emissions

Principal example



The picture will look different when different time perspectives are adopted

Conflicts

- Deregulation of the energy market is favorable for the customers within the EU and will probably be pursued in spite of present hinders and delay
- The market deregulation has led to that an over capacity exists for power generation in countries with a developed commercial market
- The electricity prices on the market are very low, and will remain so many years ahead
- Investments in new plants or investments in upgrading and rehabilitation are not possible under present commercial conditions.
- Thus the deregulation, which is good, hinders any reinvestment in new technology for any purpose

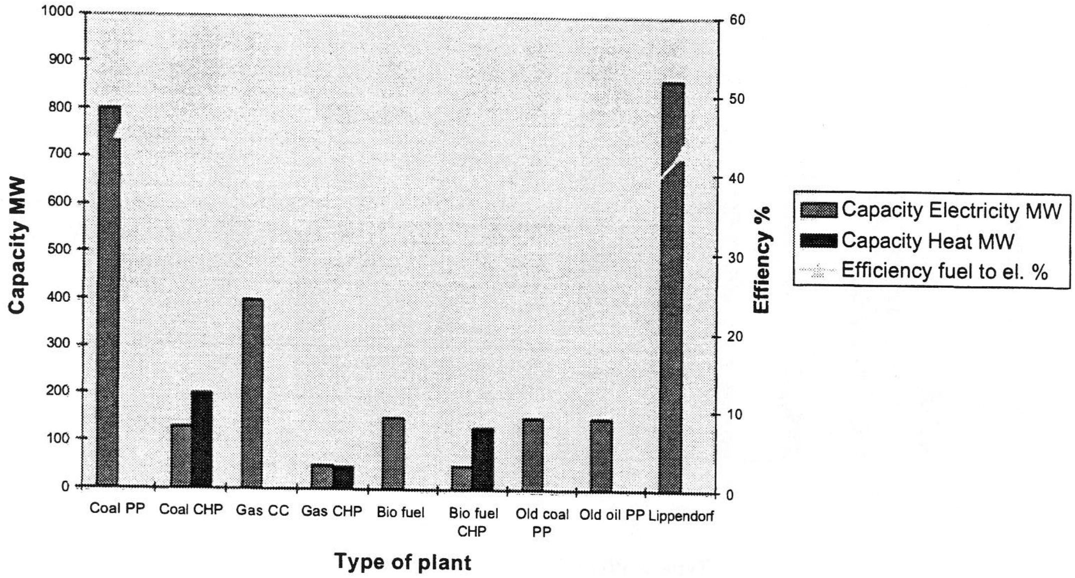
Calculation assumptions for different power plants

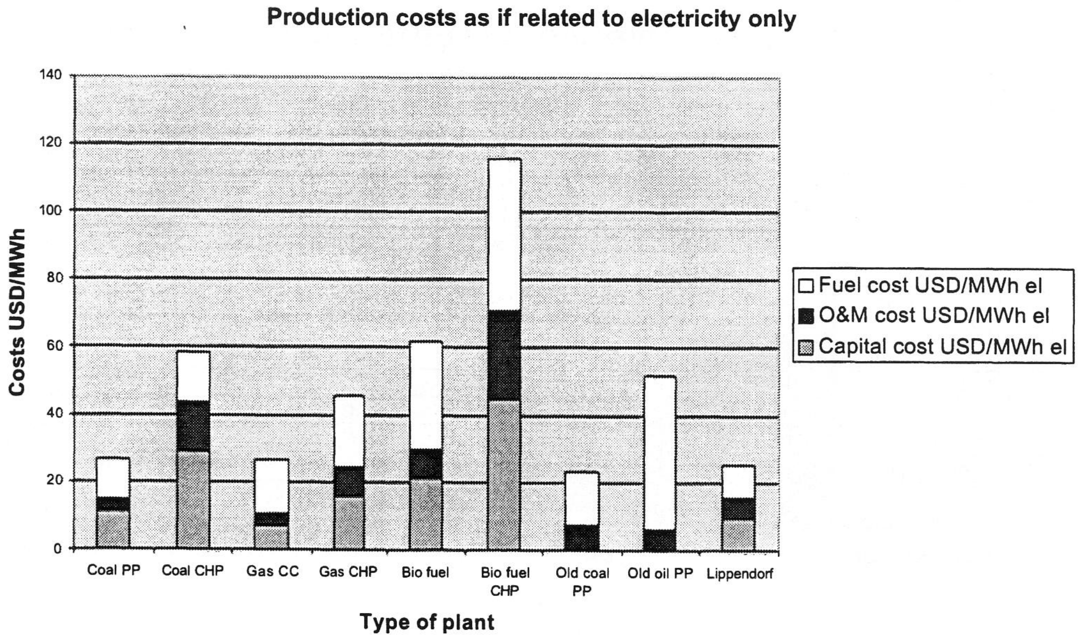
	Plant type	Fuel	Power rating MW	Heat capacity MW	Specific Investment USD/kWe	Eq. full load operation hours/year	Efficiency fuel to electricity %	Total efficiency %	Status
1	Power plant	Coal	800	0	1000	7500	45	45	New
2	CHP	Coal	130	200	1400	4000	35	89	New
3	Combined cycle	Gas	400	0	560	7500	57	57	New
4	CHP GT and HOB	Gas	50	47	740	4000	42	81	New
5	Power plant	Bio	150	0	1800	7000	40	40	New
6	CHP	Bio	50	130	2100	4000	29	104	New
7	Power plant	Coal	150	0	0	8000	31	31	Old
8	Power plant	Oil	150	0	0	8000	33	33	Old
9	Lippendorff	Lignite	865	230	1000	7500	42,5	46	Exist

Interest rate for calculation 7 %
Depreciation time 25 years

Fuel costs excl. taxes
- Coal 5 USD/MWh (40 USD/ton)
- Lignite 4 USD/MWh (20 DM/ton)
- Gas 9 USD/MWh
- Biomass 13 USD/MWh
- Oil 15 USD/MWh

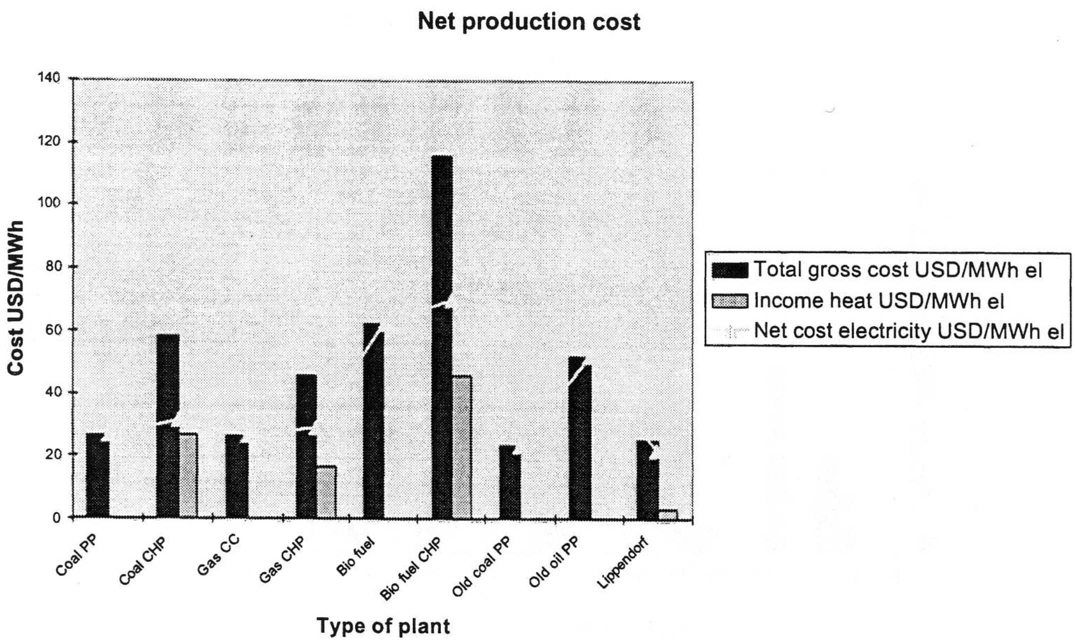
Capacities, efficiencies for the plants





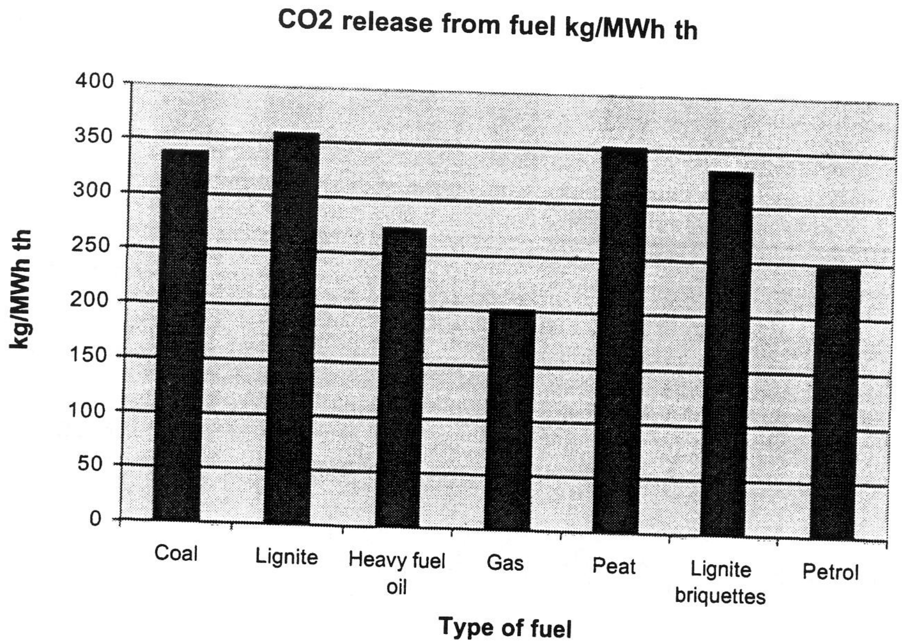
Lars Strömberg Vattenfall AB, June 1 2001

VATTENFALL



Lars Strömberg Vattenfall AB, June 1 2001

VATTENFALL



Lars Strömberg Vattenfall AB, June 1 2001

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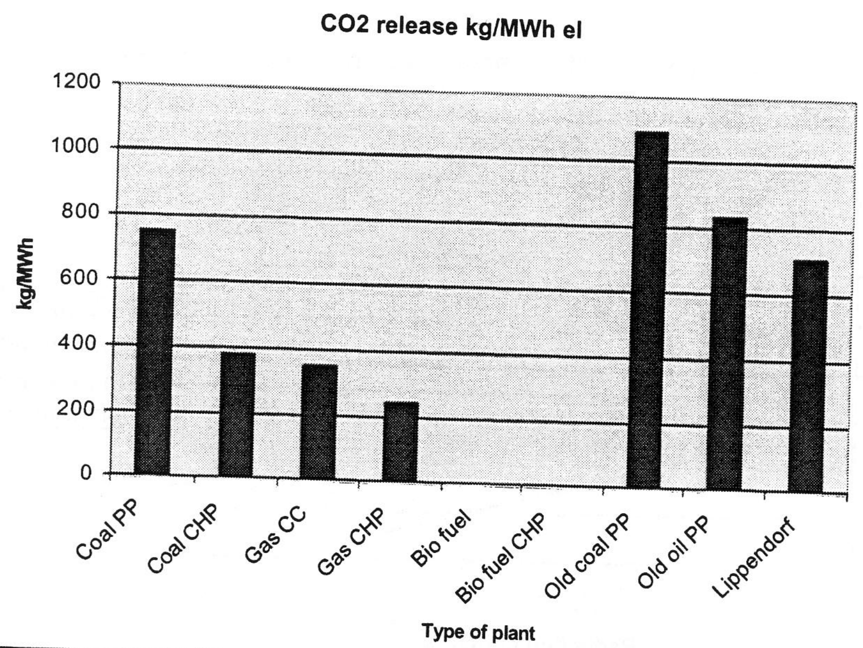
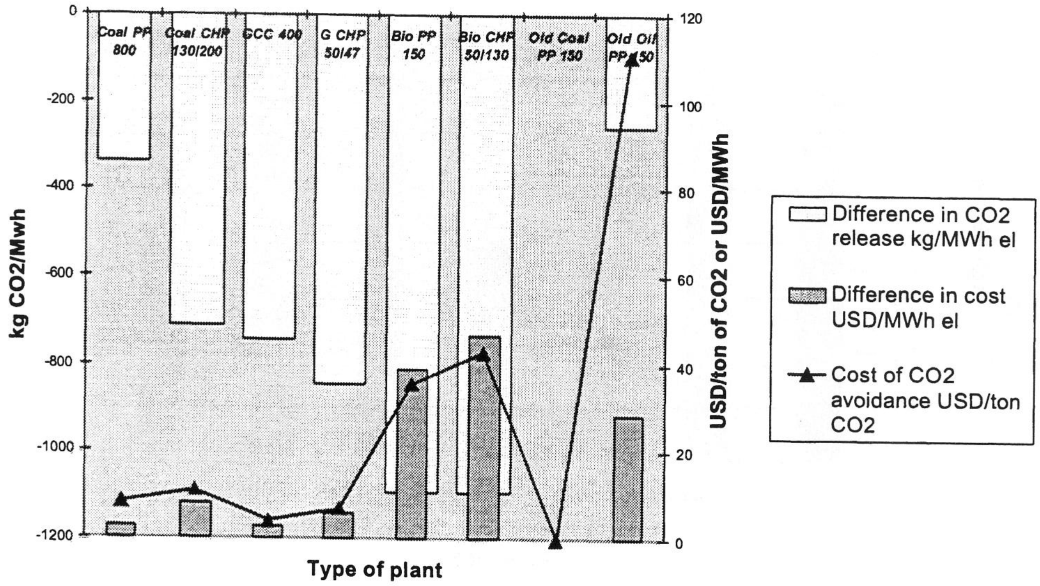


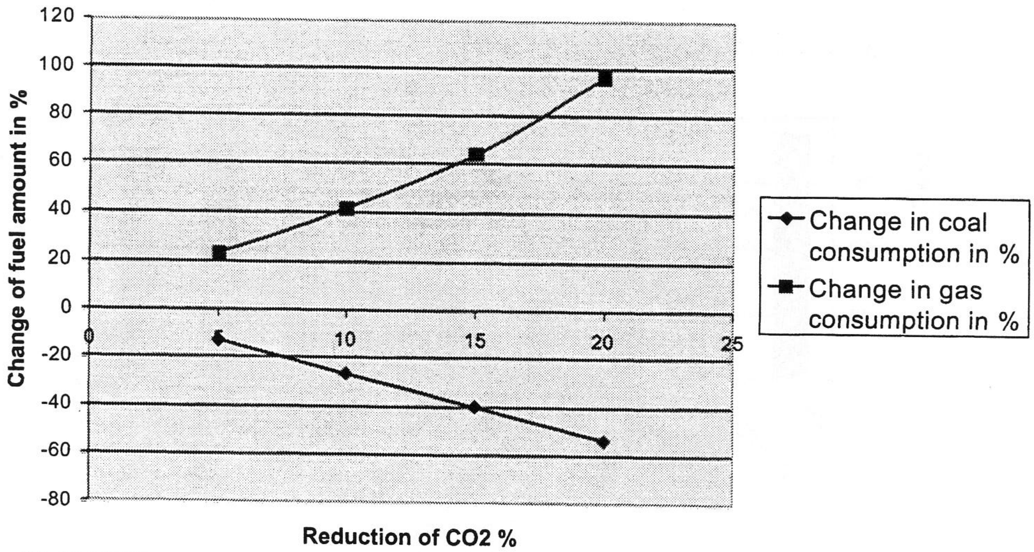
Lars Strömberg Vattenfall AB, June 1 2001

VATTENFALL

Calculation of avoidance cost for CO2

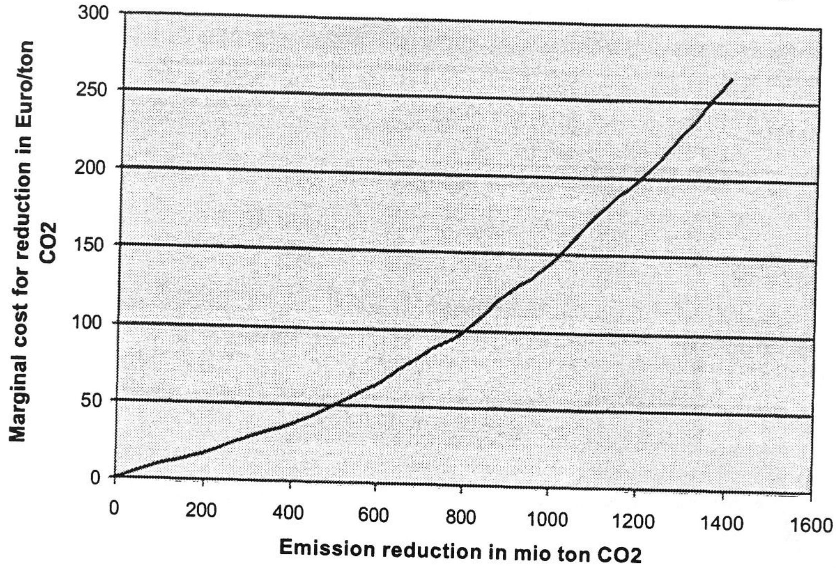


Change of fuel for different CO2 reduction in Europe



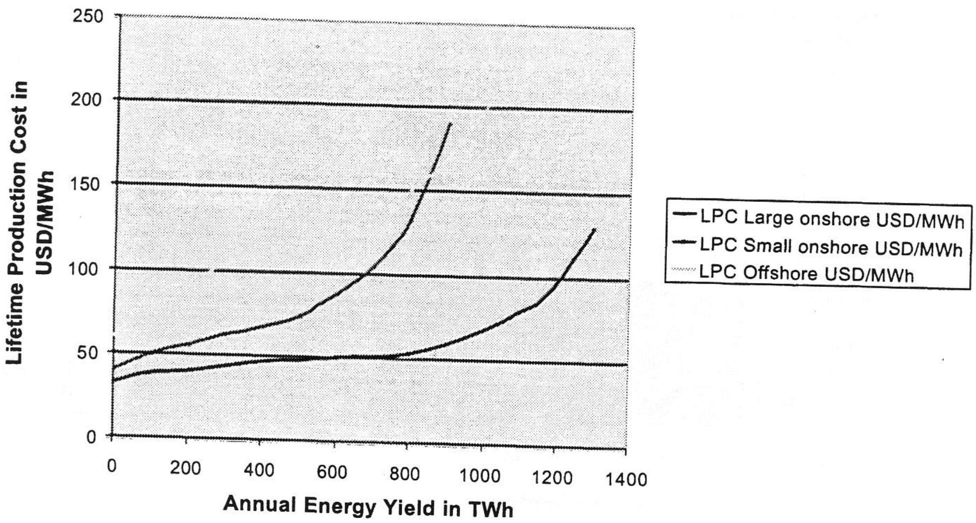
Marginal cost vs. reduction of CO2 emissions in Euro/ton CO2

source: ECOFYS Economic Evaluation of sectorial Emission Reduction Objectives for Climate Change



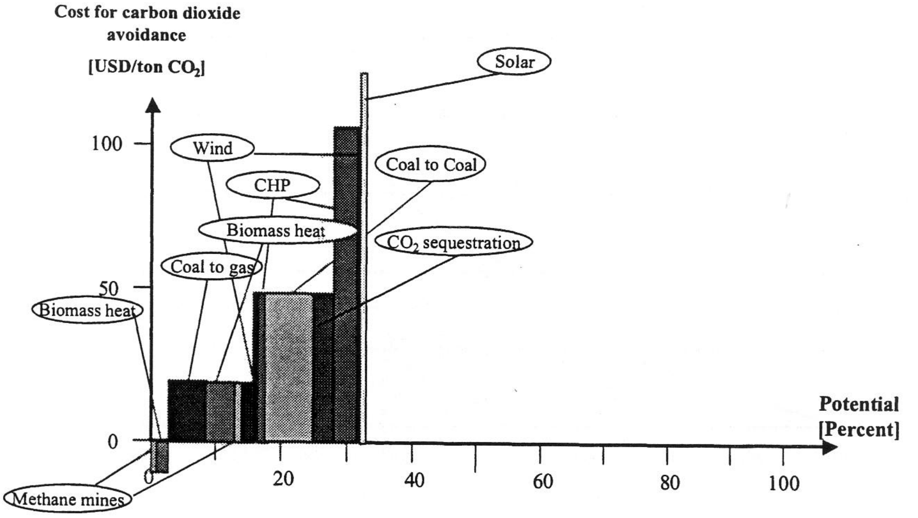
Lifetime Production Cost for Wind energy as a function of annual energy yield in Europe

Source: Garrad Hassan: The potential of wind energy to reduce CO2 emissions



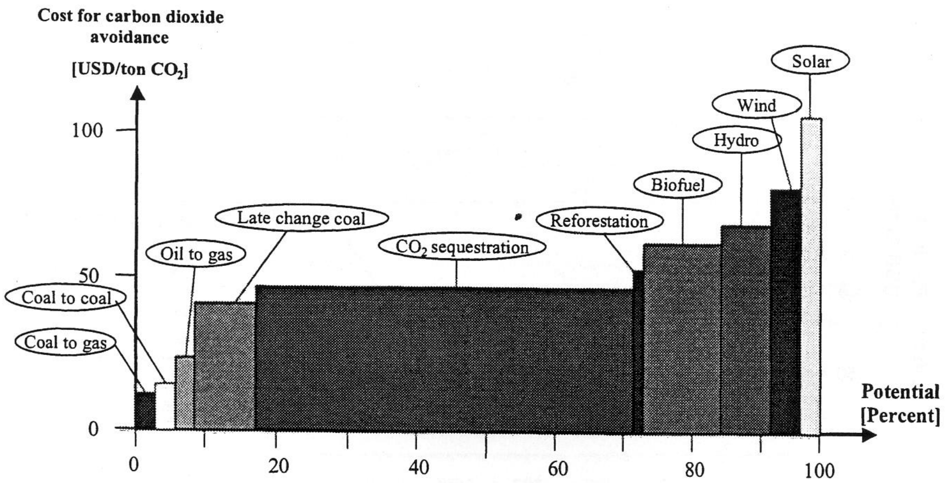
Cost and Potential of options to reduce CO_2 emissions until 2010

Derived from ECCP Energy Supply Preliminary report. Datasource: ECOFYS



Cost and Potential of options to reduce CO_2 emissions

Principal example



The picture will look different when different time perspectives are adopted

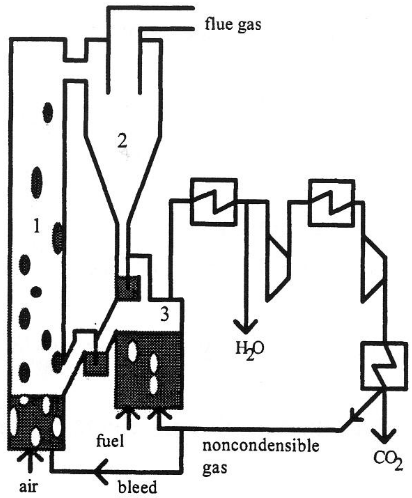
Capture and deposition of CO_2

- Capture and deposition of CO_2 is an option to eliminate the CO_2 emissions from fossil fuels
- Technically it is well established and commercial technology exists both for capture of the CO_2 and the storage, however not optimized for this purpose
- Capture and storage is expensive
- Total cost is estimated at 50$/ton CO_2 whereof the storage contribute with less than 25%.
- The production cost of electricity increases 50-60% with present technology
- It is however cheaper than producing electricity from biomass

CO_2 separation from flue gases

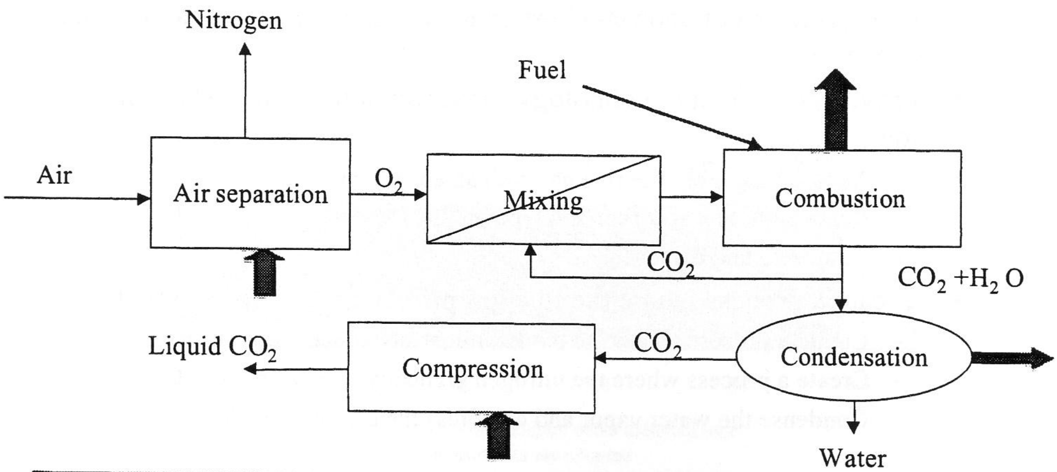
- Flue gas from common combustion mainly consists of CO_2 water vapor and nitrogen.
- Proven commercial technology for separation is established since long.
  - Absorb CO_2 from the flue gas with an absorber media
  - Regenerate the absorber and separate the CO_2
  - Compress and dispose.
- Create a process where the flue gas primarily consists of only CO_2
  - Create a process where the oxidator does not contain any nitrogen
  - Create a process where the nitrogen gradually is replaced by CO_2
  - Condense the water vapor and compress the carbon dioxide

CO_2 separation
Process design Solid phase oxidator in fluidized beds

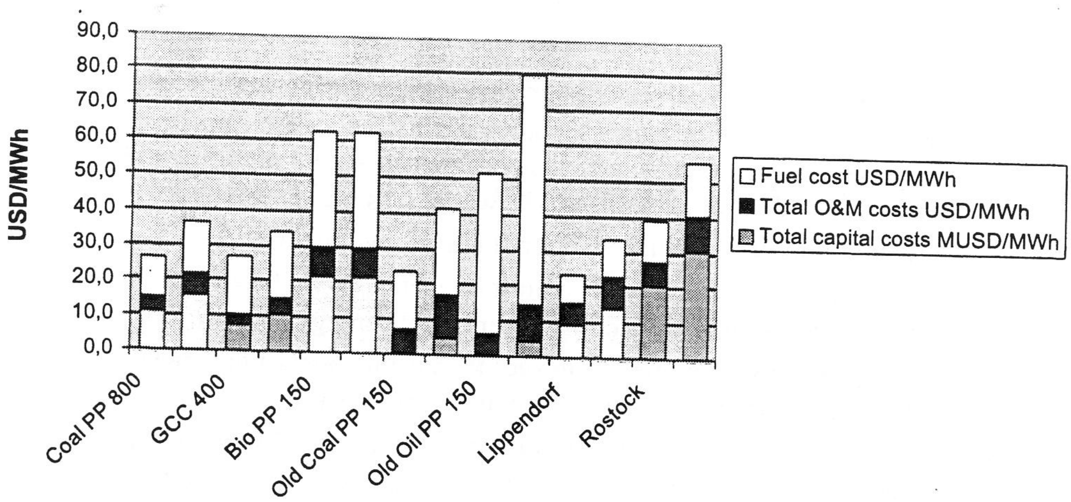


Källa: Anders Lyngfelt

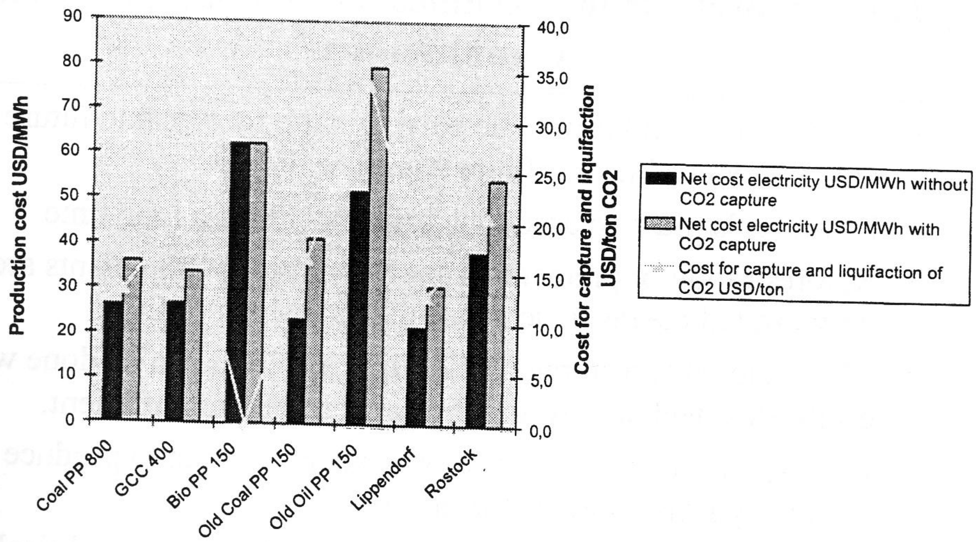
CO_2 separation from flue gases
O_2 /CO_2 combustion



Electricity production costs without and with CO2 capture and liquifaction



Cost for CO2 capture and liquifaction



Summary

- Fossil fuels including coal cannot be replaced in the foreseeable future
- The fastest way and the least expensive way to reduce CO_2 emissions in the short term is to increase the efficiency of the system by replacing old technology with new and utilize CHP where feasible
- CO_2 emissions can be reduced, but not eliminated this way
- A sustainable system can only be built on technology where CO2 is eliminated by sequestration or using renewable energy sources.
- CO_2 sequestration is probably cheaper than using most of the renewable energy sources available today and many years ahead
- The assumed cost for CO_2 sequestration of some 50 USD/ton CO_2 seems possible to be lowered considerably by utilizing new combustion technology

The CO_2 problem in a technical/economical perspective
Conclusions

- The CO_2 problem cannot be solved in the foreseeable future only by renewable or infinite energy sources.
- Fossil fuels must be used to a large extent for a long time
- Reforestration or premature renewal of production plants are only limited means to decrease the emissions of CO_2
- CO_2 removal and storage is not impossible. It can be done with established technology and the capacity seems sufficient.
- It is expensive, but it is not more expensive than to produce electricity from biofuels for instance.
- It seems to convert from a technical problem into a political one.

APPENDIX 3

PRESENTATION MATERIAL PROVIDED

Sleipner CO_2 injection system and the SACS project, Tore A. Torp, Statoil.

ICBM Project, Sevket Durucan, Imperial College.

ECBM Potential in the Netherlands, Harry Schreurs, NOVEM.

TotalFinaElf's Expectations for CO_2 Capture, Rodolphe Bouchard, TotalFinaElf

Transmission of CO_2 – experiences to be gained from CO_2-EOR projects,
John Gale, IEA Greenhouse Gas R&D Programme

Saline Aquifer CO2 Storage - The Sleipner Case and the SACS Project

by

Dr. Tore A. Torp, Statoil

E-mail: tat@statoil.com

Saline Aquifer CO2 Storage

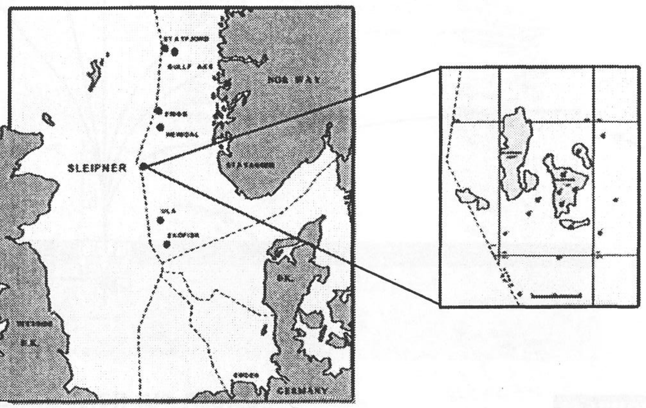
CONTENT :

*** The Sleipner CO2 Injection Case**

*** The SACS R&D Project**

*** Long Term Consequences?**

Sleipner Field Map

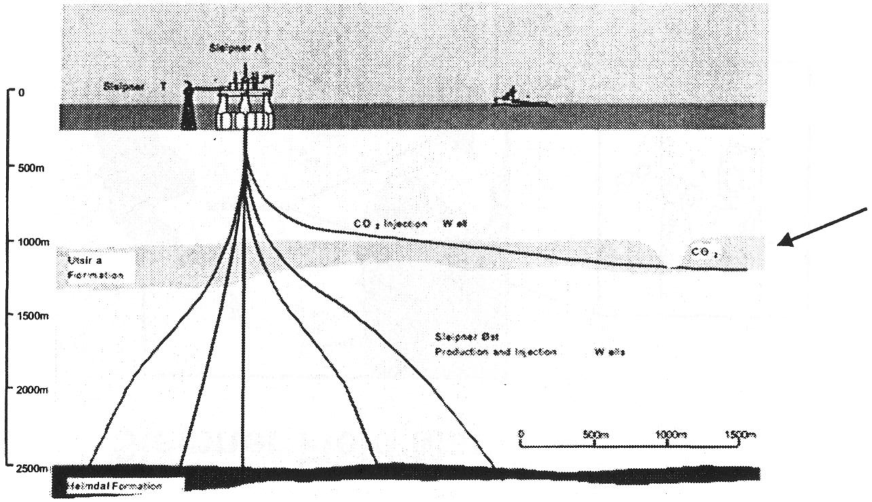


Why store CO2 from Sleipner West field?

- **Too much CO2 in the produced natural gas**
  - pays for the separation of CO2
- **High Norwegian tax on CO2 emissions**
  - pays for the injection

CO2 Injection Well in "Utsira"

STATOIL



Saline Aquifer CO2 Storage

STATOIL

GOALS:

- ***Verify under what circumstances CO2 storage in an aquifer is safe and reliable***
- ***Validate models for geology, geochemistry, geophysics and reservoir tools***
- ***Initiate new R&D related to above topics***
- ***Start development of "Manual of Good Practice"***

Saline Aquifer CO2 Storage

STATOIL

SACS - European co-operation project

Participants:

Industry:	Research foundations:	
- Statoil (Co-ord.)	- BGS	UK
- BP	- BRGM	FR
- ExxonMobil	- GEUS	DK
- Norsk Hydro	- IFP	FR
- Vattenfall	- SINTEF	NO
Assistant:	- NITG-TNO	NL
- IEA GHG	- GECO	NO
	- NERSC	NO

Saline Aquifer CO2 Storage

STATOIL

WHY THE INTERNATIONAL INTEREST ?

- ***First time CO2 injected underground outside EOR***
- ***"Utsira" is vast - what about smaller saline aquifers ?***
- ***Aim is to avoid emitting fossil CO2 into the atmosphere - climate change implications ?***
- ***VISION - a possible carbon free use of fossil fuels***

Saline Aquifer CO2 Storage

STATOIL

DELIVERABLES:

- *Confidence improved in a potentially important way for CO2 sequestration among authorities, industry and environmental organisations*
- *Acceptance internationally of available res&geo tools and methods*
- *New R&D efforts initiated in EU and IEA member countries as spin-off*
- *First version of a "Manual of Good Practice"*

European Standard for gas storage

STATOIL

EUROPEAN STANDARD — EN 1918-1

NORME EUROPÉENNE
EUROPÄISCHE NORM

February 1998

ICS 75.200

Descriptors: storage, natural gas, definitions, specifications, environmental protection, design, safety, leaktightness, inspection, maintenance, operating requirements, wells, tests

English version

Gas supply systems - Underground gas storage - Part 1: Functional recommendations for storage in aquifers

Réseaux de gaz - Stockage souterrain de gaz - Partie 1: Recommandations fonctionnelles pour le stockage en nappes aquiféres

Gasversorgungssysteme - Untertagespeicherung von Gas - Teil 1: Funktionale Empfehlungen f~ir die Speicherung in Aquiferen

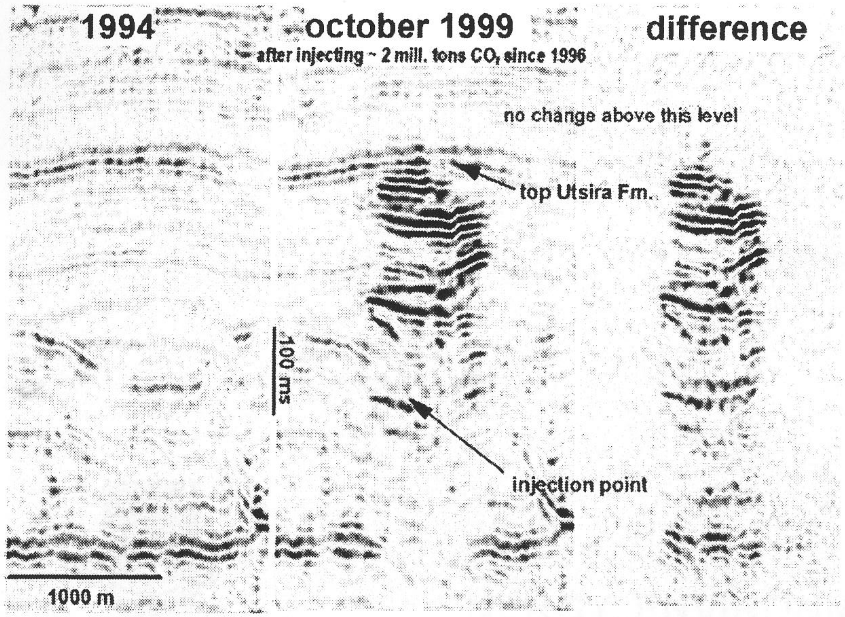
This European Standard was approved by CEN on 22 January 1998.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

Sleipner CO_2 injection seismic monitoring — E-W section



SALINE AQUIFER CO_2 STORAGE PROJECT

STATOIL

Statoil
BP
ExxonMobil
Norsk Hydro
Vattenfall

SACS — CO_2

BGS
BRGM
GEUS
IFP
NITG-TNO
SINTEF

IEA Greenhouse Gas R&D Programme
Geco-Prakla
Nansen Research Centre

Development of advanced reservoir characterisation and simulation tools for Improved Coalbed Methane recovery

ENK6-2000-00095

S. Durucan
Royal School of Mines
Imperial College, London

Background

Description of Work

Major Coal Basins and Coalbed Methane Resources of the World

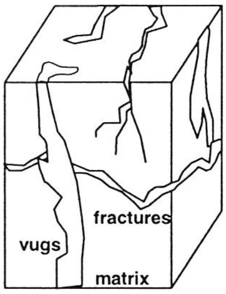
Continent	Country	Coal Resources x 10^9 tonnes	Methane Resources x 10^{12} m^3
Europe and the Russian Federation	Belgium		0.075
	France		0.600
	Germany	320	2.85
	Hungary		0.085
	Poland	160	2.85
	Russia	6,500	17-113
	Ukraine	140	1.7
	UK	190	1.7
North America	Canada	7,000	5.7-76
	USA	3,970	11
Asia	China	4,000	30-35
	India	160	0.85
	Indonesia	6	
	Kazakhstan	170	1.13
Australia		1,170	8.5-14
Africa		150	0.85
World Totals		**~25,000**	**~84 - 262**

Source: ARI, 1992

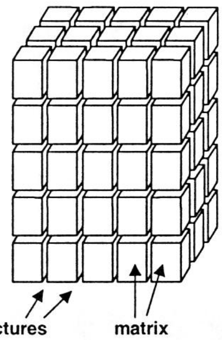
S. Durucan – CO2NET
06 June 2001

Coal as a Reservoir Rock - Structure

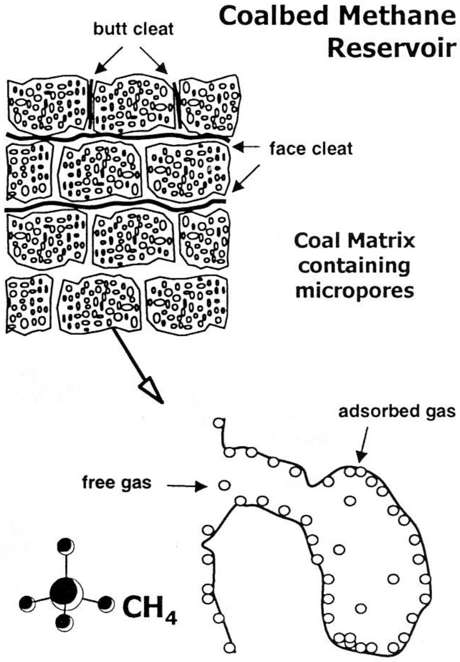
Oil Reservoir



Model Reservoir



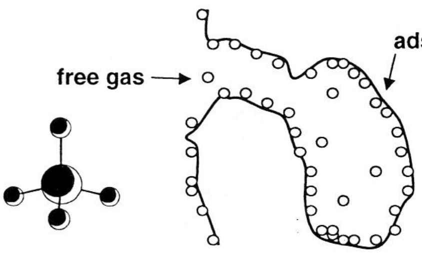
Coalbed Methane Reservoir

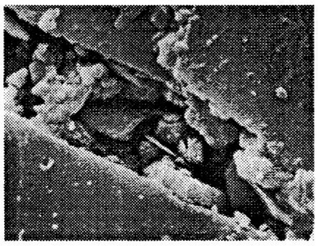


- **Coal matrix with micropores**
- **Micron sized fractures and cavities (0.01 mm - 20mm)**
- **Cleat system (2mm - 25 mm)**
- **Fractures and faults**

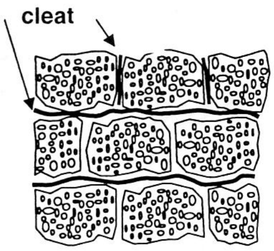
S. Durucan – CO2NET
06 June 2001

Methane Retention in Coal

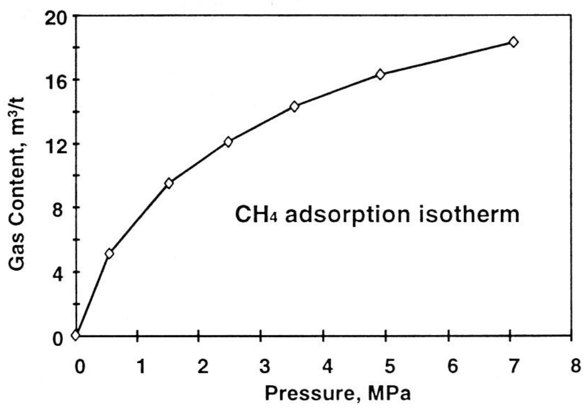




microcleat

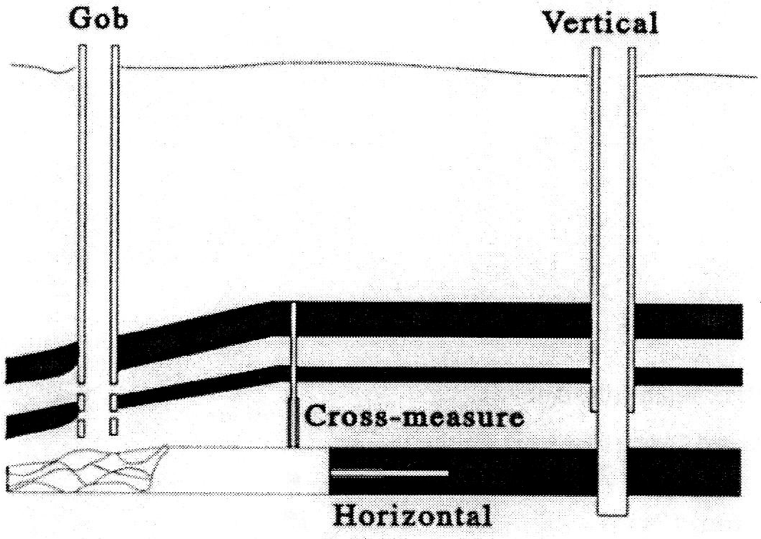


coal matrix

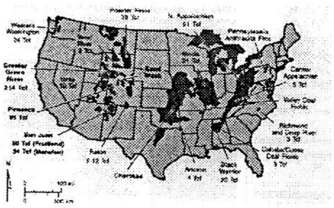


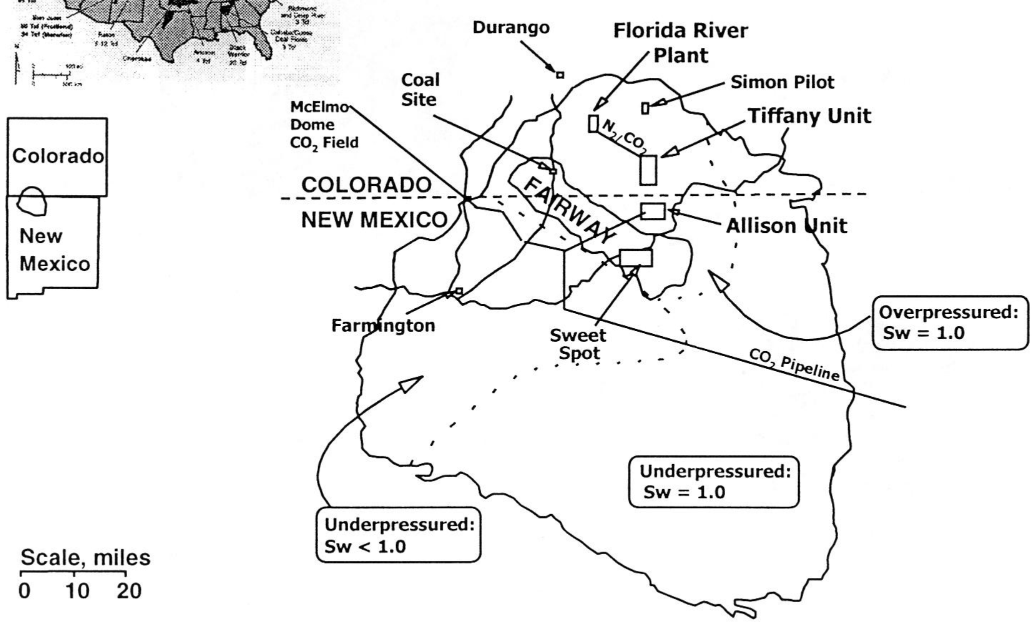
Underground Methane Drainage Practice

Coalbed Methane Technology



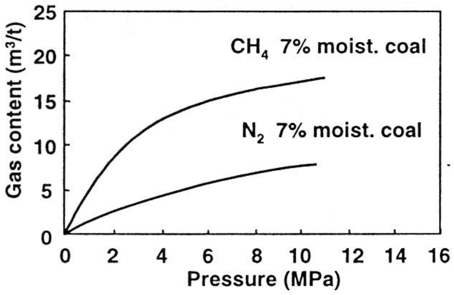
San Juan Basin

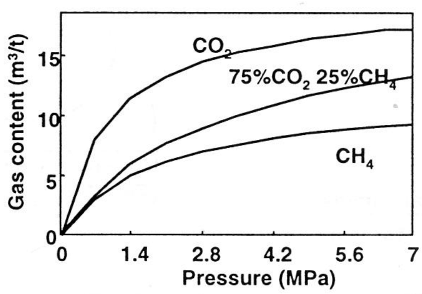




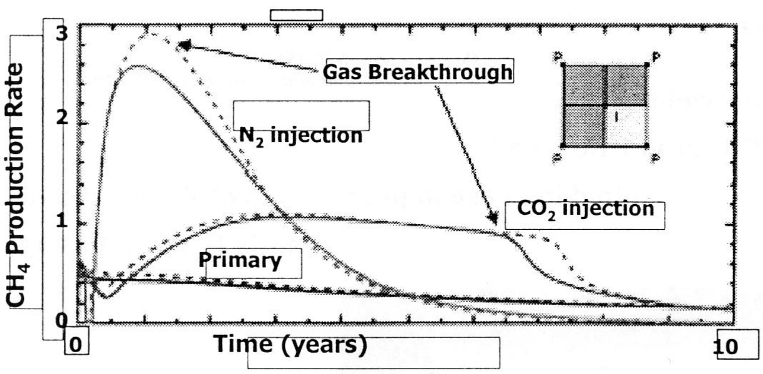
Enhanced Coalbed Methane Recovery (ECBM)

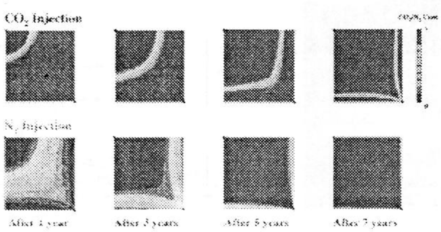
- two principal methods of ECBM, namely N_2 and CO_2 injection (inert gas stripping and displacement sorption respectively)
- injection of nitrogen reduces the partial pressure of methane in the reservoir, thus promotes methane desorption without lowering the total reservoir pressure
- coal can adsorb approximately twice as much CO_2 by volume as methane, therefore, the assumption has been that the CO_2 injection stores 2 moles of CO_2 for every mole of CH_4 desorbed.



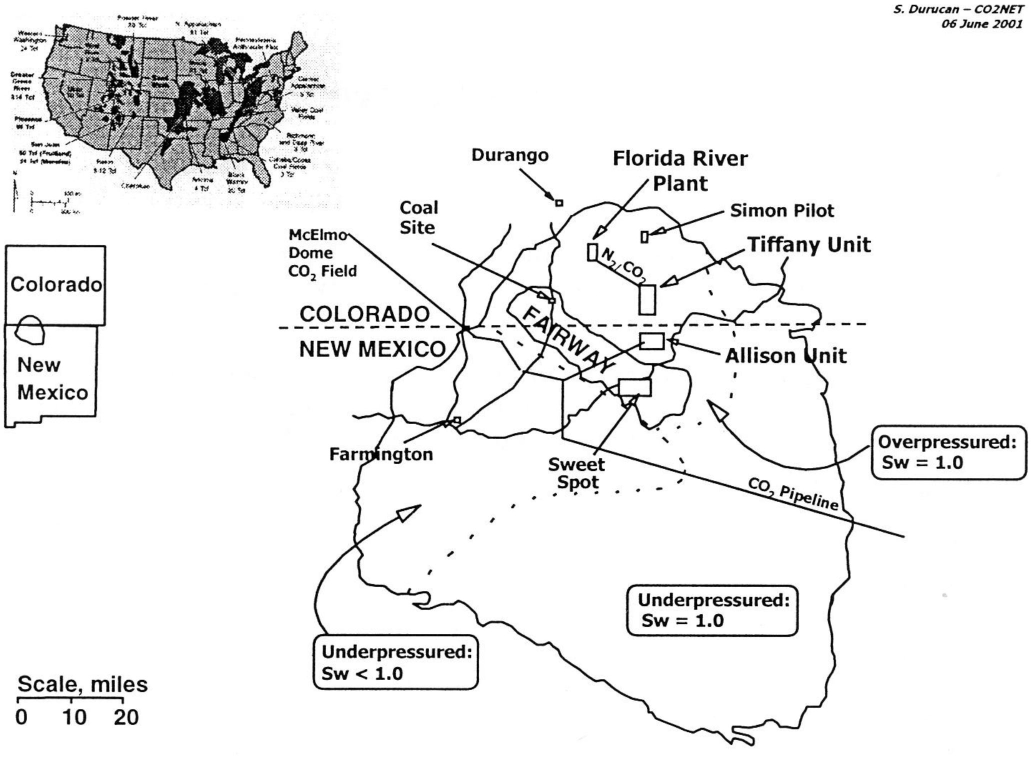


Enhanced Coalbed Methane Recovery (ECBM)





Law, Van deer Meer, Mavor and Gunter 2000



BP Amoco Simon N_2 Injection Pilot

1990-91 Laboratory and theoretical research,

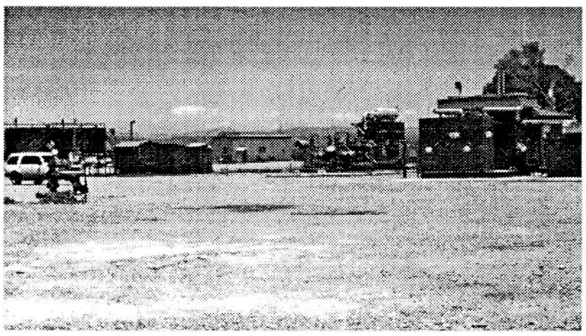
Puri and Yee, SPE 1990
Arri, Yee, Morgan and Jeansonne, SPE 1992

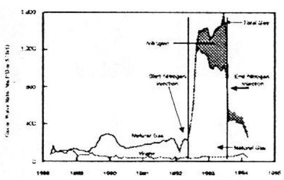
4 N_2 injector wells,

1 CH_4 production well

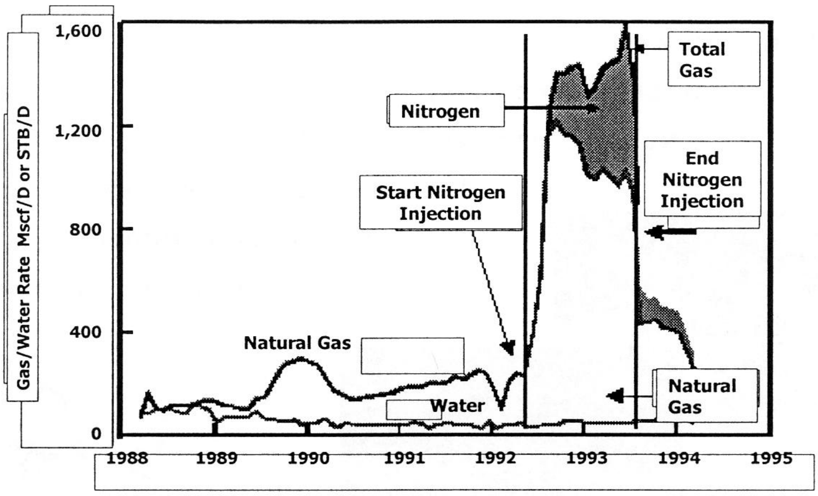
4-6 fold increase in production within one month

early N_2 breakthrough

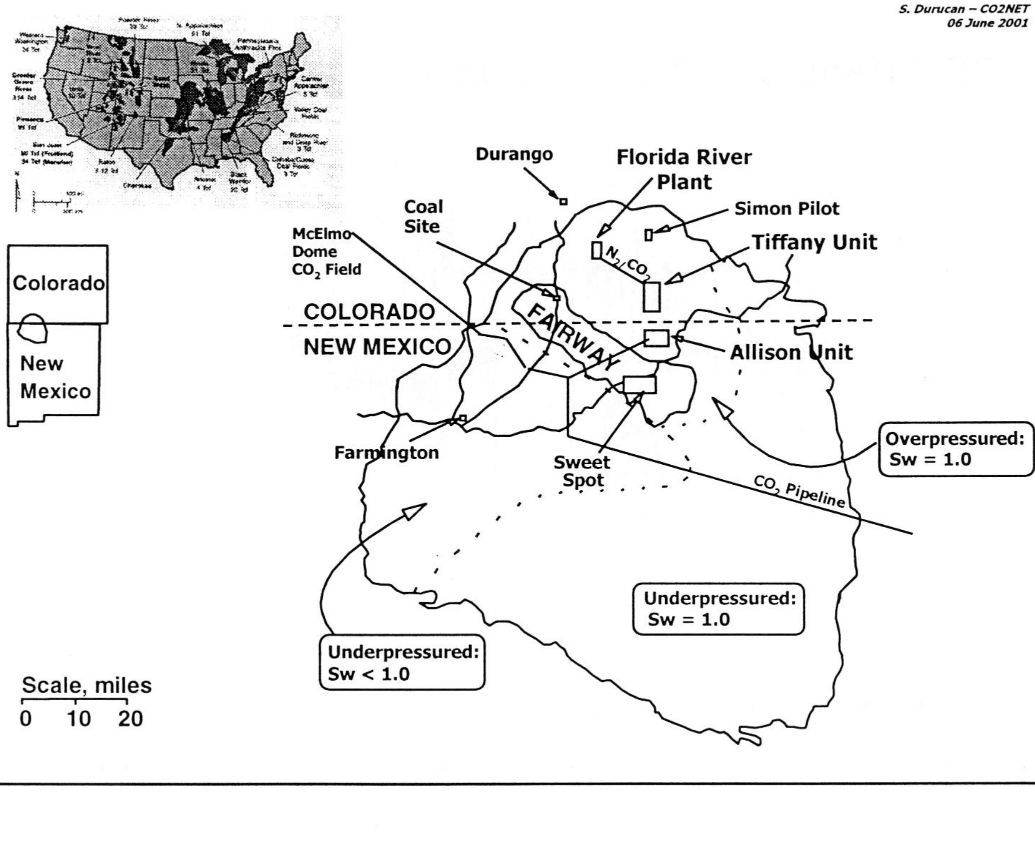




BP Amoco Simon N_2 Injection Pilot



Source: Wong, Gunter, Law and Mavor, 2000



BP Tiffany Unit N_2 Injection (Full Scale Commercial Pilot)

9 Years of primary production,

12 N_2 injector wells,

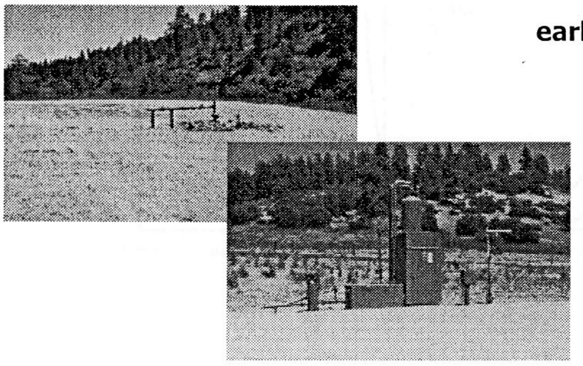
34 CH_4 production wells,

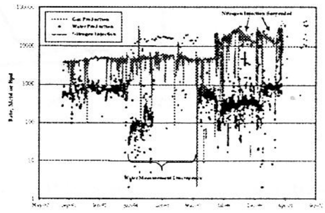
N_2 injection since January 1998,

4-6 fold increase in production

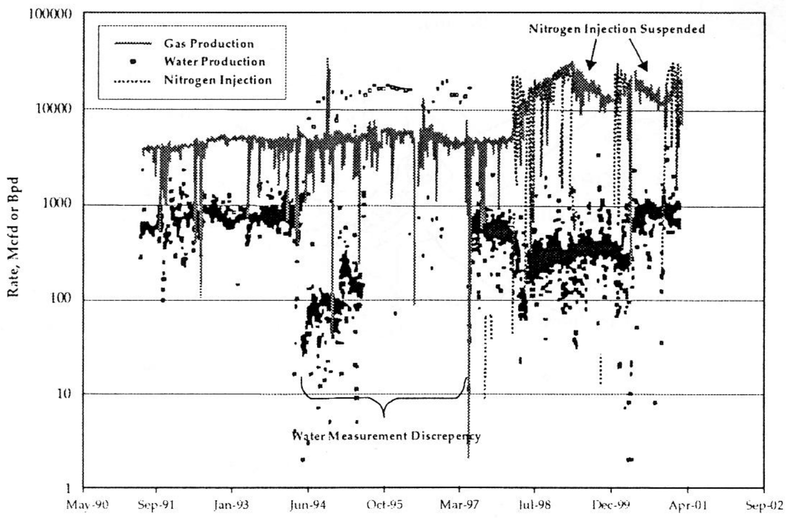
early N_2 breakthrough

Reeves and Peckot, ARI, USCBM Symp, 2001

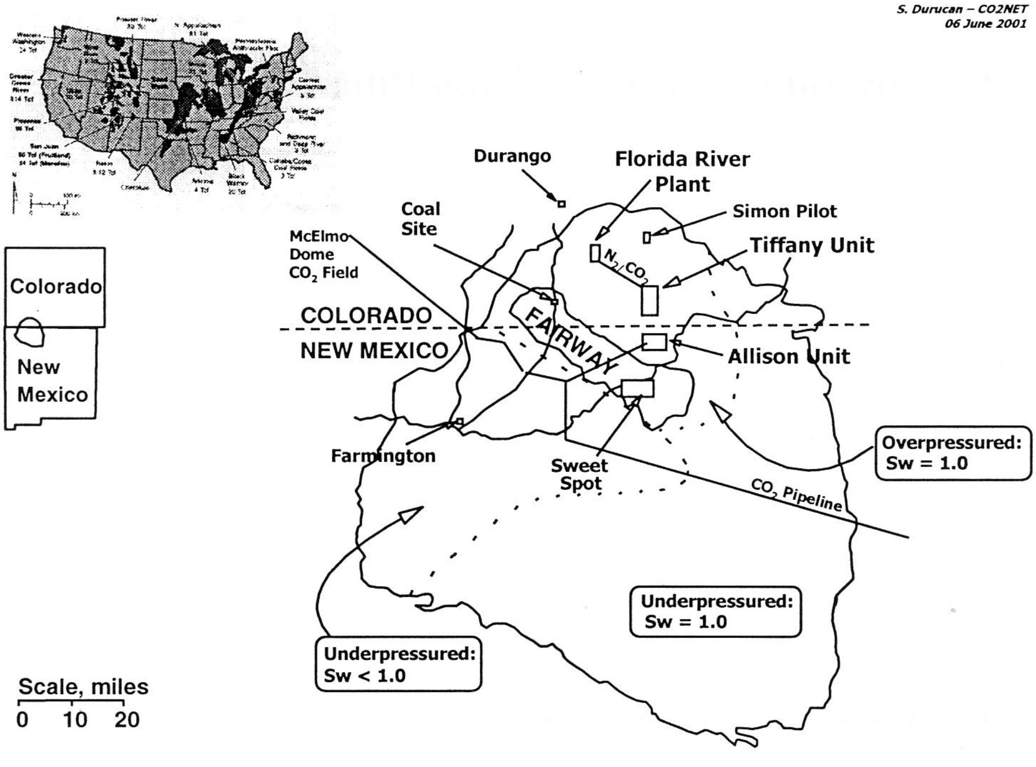




BP Tiffany Unit N_2 Injection (Full Scale Commercial Pilot)



Source: Reeves and Pecot, ARI, USCBM Symp, 2001



Burlington Resources Allison Unit CO_2 Injection

6 Years of primary production (1988/89 – 1995),

4 CO_2 injector wells,

9 CH_4 production wells,

CO_2 injection since May 1995,

immediate increase in water production,

No CO_2 breakthrough

Reeves and Pecot, ARI, USCBM Symp, 2001

Alberta Research Council, Fenn Big Valley CO_2 Injection

Field micro-pilot testing since 1997

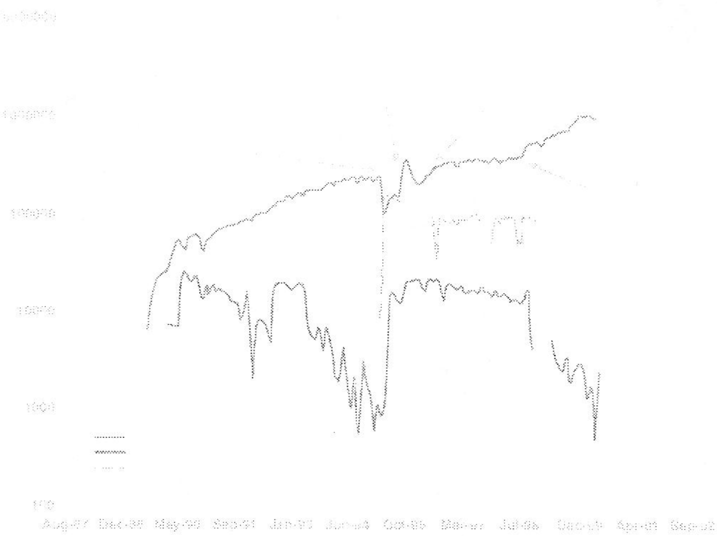
4 CO_2 injector wells,

none of the simulators predicted the gas composition observed accurately

coal swelling and reduced permeability observed

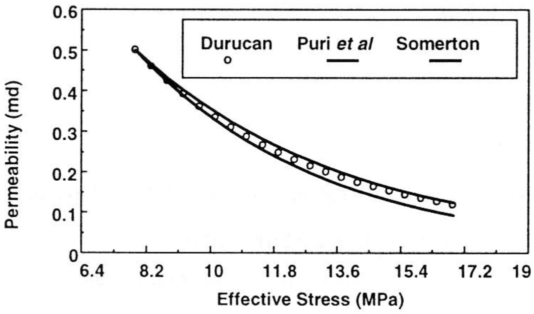
Wong and Gunther, 1999
Law, Van deer Meer, Mavor and Gunter 2000

Burlington Resources Allison Unit CO_2 Injection

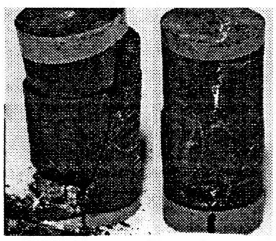


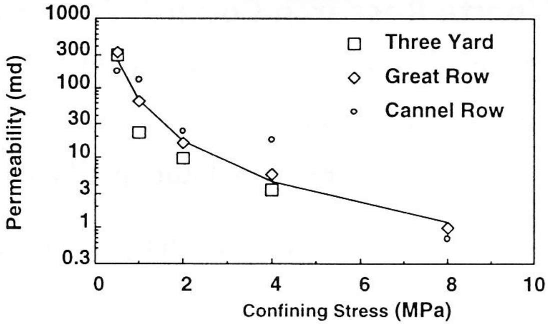
Source: Reeves and Pecot, ARI, USCBM Symp, 2001

Stress - Permeability Relationships for Coal



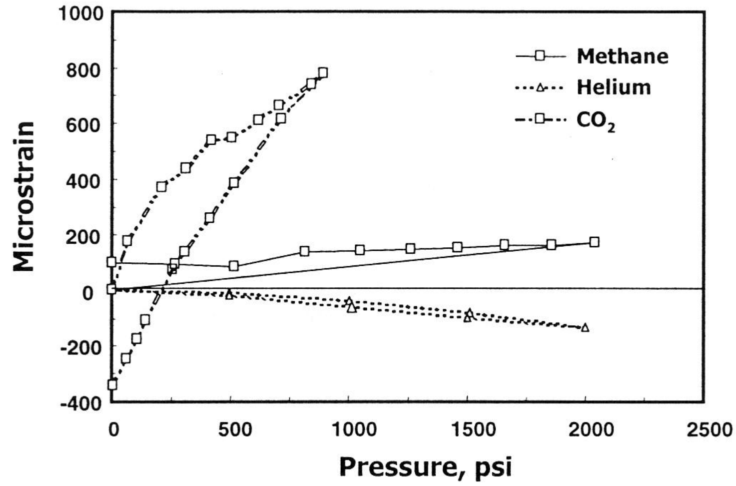
Intact coal





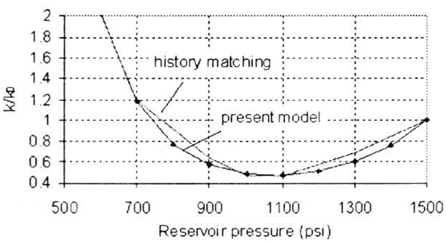
Post-failure

Matrix Shrinkage and Swelling Effect of Gas Sorption



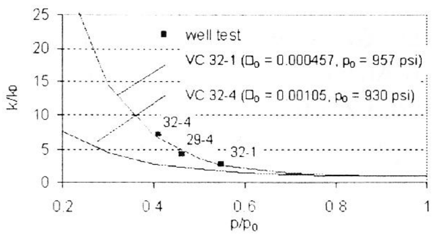
Source: Seidle and Huitt, 1995

Pore Pressure – Permeability Behaviour of Coalbed Reservoirs (Primary CH_4 Production)



San Juan Fairway Well B#1

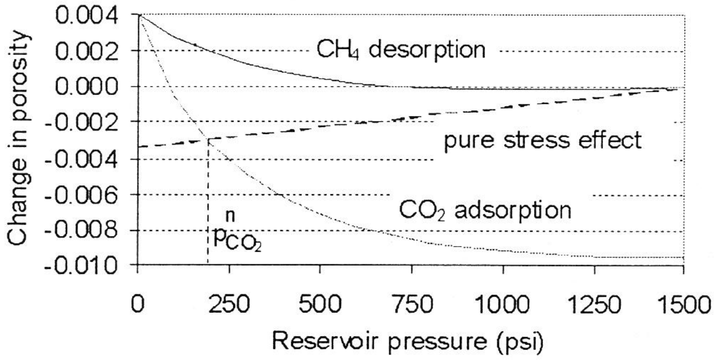
Data Source: Palmer and Mansoori, 1996



San Juan, Valencia Canyon Wells

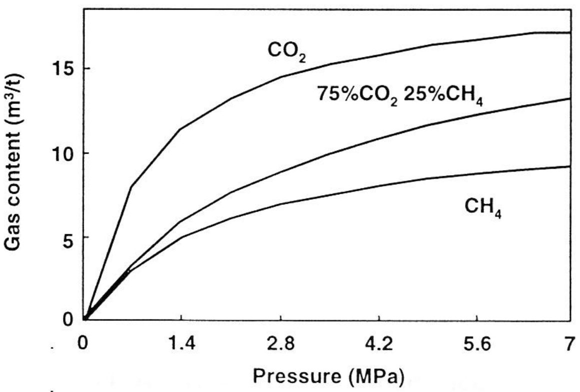
Data Source: Mavor and Vaughn, 1997

Pore Pressure – Porosity/Permeability Behaviour of Coalbed Reservoirs



World Coal CO_2 Storage Potential

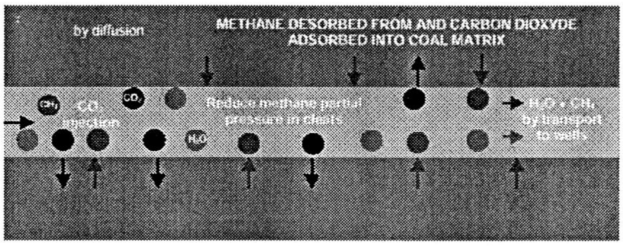
Country	Storage potential ($Gt\ CO_2$)
USA	35
Australia	30
Indonesia	24
Russia & Ukraine	19
China	13
Canada	12
Zimbabwe	5.1
India	5
France/Germany	1.9
South Africa	1.7
Poland/Czech	1.6
Total	**148.3**



Source: ARI 1998

Enhanced Coalbed Methane Recovery/CO_2 Storage: Technical Challenges

- Sorption, diffusion and flow of binary gas mixtures in coalbed reservoirs
  - binary gas sorption behaviour
  - phase behaviour of gas mixtures
  - matrix swelling/shrinkage effect on permeability and flow
  - relative permeability behaviour
  - diffusion and counter diffusion of gases
- Multicomponent simulator incorporating the above characteristics



Development of advanced reservoir characterisation and simulation tools for Improved Coalbed Methane recovery

Description of Work

Research Partners

Co-ordinator:

Imperial College of Science, Technology and Medicine, GB

Contractors:

BP Exploration Operating Company Limited,	GB
Technische Universiteit Delft,	NL
Deutsche Steinkohle Aktiengesellshaft,	D
Wardell Armstrong,	GB
Institut Francais du Petrole,	FR

ICBM Project Objectives

- Investigate the basic scientific phenomena of CO_2 injection and retention in coal:
  - water and CO_2-CH_4 adsorption/desorption
  - diffusion/counter diffusion
  - two-phase flow under simulated reservoir conditions (stress, pore pressure and temperature)
- Develop a CO_2-ECBM recovery and CO_2 storage simulator
- Develop the technology and the tools to enable a more accurate assessment of the potential for improved methane recovery and CO_2 storage

ICBM WorkPackages

- Petrographical and petrophysical characterisation of coals
- Characterisation of sorption and diffusion behaviour of CH_4-CO_2 mixtures in coal
- Relative permeability and capillary pressure characterisation of the cleat-matrix structure in coal
- Capillary pressure and adsorption/desorption characteristics of CH_4-CO_2 mixtures at high pressure/high temperature environments
- Stress-permeability-stimulation characterisation of coals for the flow of CH_4-CO_2 mixtures
- Geostatistical and fractal characterisation and upscaling of natural fractures
- Development of a two-phase, multicomponent CH_4-CO_2 simulator
- Optimisation of enhanced methane recovery and CH_4-CO_2 storage

Existing CBM Simulators:

- **Employ the extended Langmuir isotherm for binary gas mixtures**
  - Latest research revealed that *Pore Filling Models* are more appropriate to characterize the binary gas mixtures (CH_4-CO_2)
- **Modify the conventional hydrocarbon compositional simulators**
  - They are not able to handle diffusion of the gas components in the coal matrix

ICBM CO_2 Simulator With Enhanced Features:

- 3D, 2-Phase and Multi-Component (Water, CH_4 and CO_2)
- Equilibrium adsorption/desorption of binary gas mixtures
- Counter-diffusion of CH_4 and CO_2 between the coal matrix and matrix/cleat interface
- dissolution of CO_2 in water
- Stress/pore pressure dependent permeability correlation for CO_2 and CH_4
- coupled wellbore and dynamic reservoir model

Carbon Dioxide Storage and ECBM: can it be commercial?

A Feasibility Study on Dutch Potential

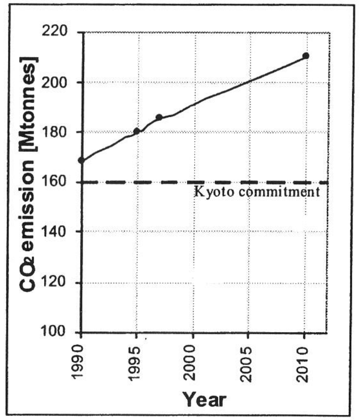
by

Harry Schreurs, NOVEM BV

Copenhagen, June 6, 2001

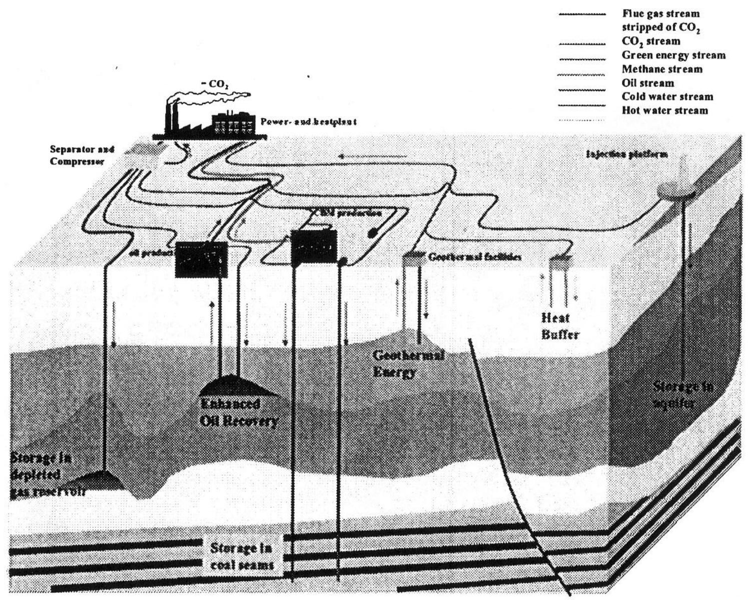
CO_2 problems: the Kyoto convention

- Commitment of the Netherlands on Climate-top in Kyoto: CO_2-emissions in 2010 reduced by 6% with respect to the level of 1990
- Predicted 2010 level of The Netherland: 210 Mton CO_2-equivalents. This means for The Netherlands an emission reduction of 50 Mton (25%) CO_2-equivalents
- Conclusion: The Netherlands seek for ways to reduce their CO_2-emission



Measures for atmospheric CO_2 reduction: Subsurface solutions

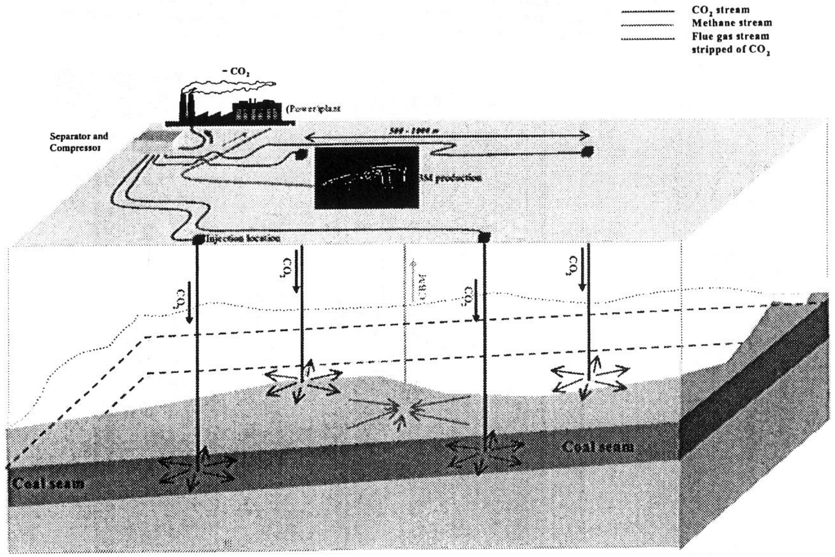
- Reduction of emissions
  - Alternative energy
    - Geothermal energy
  - Energy efficiency
    - Peak shaving (Surplus electrical energy produced during the night can be retrieved during peak energy demands during the day)
      - Underground Pump Accumulation Central
    - Heat buffers (Storage of seasonal heat in the subsurface)
- Increased rate of removal
  - Storage of CO_2
    - CO_2 storage without energy benefits (Storage in depleted gas reservoirs or aquifers)
    - CO_2 storage with energy benefits (Enhanced Oil Recovery and **Enhanced Coalbed Methane Recovery**)



CO_2 storage with energy benefits: Enhanced Coalbed Methane Recovery

- Basic principle of ECBM is the injection of CO_2 in coal seams
- Idea of CO_2 injection originates from coalbed methane (CBM) producing industry, following the successes with EOR, to increase CBM recovery
- Injected gas enhances desorption of the methane by:
  - reducing the partial pressure
  - replacement reaction on adsorption sites: 2 molecules of CO_2 for 1 molecule of CH_4 (based on adsorption curves of pure gases)

ECBM Production with CO_2 sequestration



ECBM Production with CO_2 sequestration

- Advantages
  - Coal seams have proven their capability of holding gas for geological time periods
  - Net CO_2 reduction, since theoretical ratio of stored CO_2 to produced CBM is 2:1 (or higher)
  - ECBM is an attractive option to use unminable coals: you produce fossil fuels that would otherwise not be exploited
  - ECBM could provide clean energy production in remote (but rich in coal) areas, saving transport cost of fuel and energy
- Disadvantage
  - Process has not yet been proven on a large-scale
    - several test sites, all of them in the USA and Canada

Feasibility study of ECBM-CO_2 in the Netherlands

- Financers:
  - Ministry of Economic Affairs
  - Ministry of Housing, Spatial planning and Environment
- Coordinator:
  - Netherlands Agency for Energy and the Environment (Novem)
- Project partners
  - TNO-NITG (geological evaluations, inventory)
  - Delft University of Technology (evaluation of reservoir conditions)
  - Utrecht University (economical evaluation)
  - Netherlands Energy Research Foundation (CO_2 supply and ECBM conversion technologies)

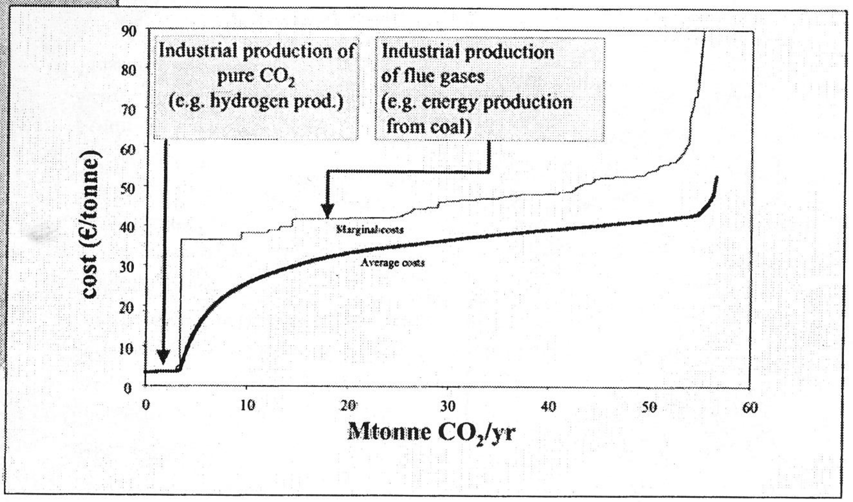
Characterisation of plant types, summarised CO2 flow per sector and range of costs for CO2 capture.

	CO_2 concentration	CO_2 total (Mtonne/yr)	CO2 cost (€/tonne CO_2)
Power plants			
Pulverised Coal boiler	21 wt %	18	35 – 50
Integrated Coal Gasification Combined Cycle	13 wt %	1.3	40
Gas fired Conventional Steam Cycle	15 wt %	7.9	45 – 60
Gas fired Combined Cycle	6 wt %	11	45 – 60
Industrial power supply			
Combined Cycle	6 wt %	14	45 – 80
Gas Turbine with exhaust boiler	6 wt %	1.0	45 – 80
Steam Turbine	15 wt %	0.5	45 – 80
Waste Incineration			
AVI	17 wt %	3.1	40 – 50
Chemical plants			
NH3	100 wt %	2.1	4 – 5
H2	100 wt %	1.1	4 – 5
EO	100 wt %	0.2	4 – 5

Typical costs for CO2 capture and preparation for transport.

	amount CO_2 captured →	Capture €/tonne →	Preparation €/tonne
130 ktonne H2/year plant	1 Mtonne	-	3,6
600 MW PC boiler	2,4 Mtonne	36	3,7
50 MW waste incinerator	330 ktonne	37,5	4,3
20 MW Industrial CC	54 ktonne	49,2	5,5

Costs of captured CO_2 ready for transport Supply curve for the Netherlands situation

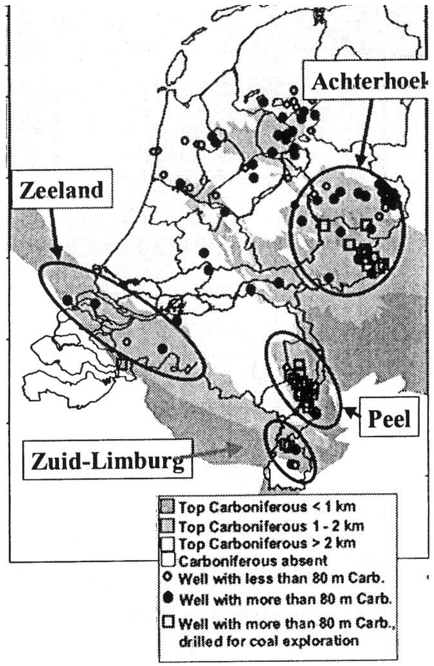


History of coal and CBM in The Netherlands

- Until 1974: coal mining in Zuid-Limburg area
- Peel and Achterhoek areas suitable for conventional mining, but never came into production
- 1992: CBM-well in Belgium
- Due to Groningen Gas Field: No economical potential for conventional coal or CBM production

Selection criteria of inventory

- Area selection:
  - depth < 2000 m
- Definition of exploitation blocks by:
  - faults
  - extension of coalbeds assumed continuous within block
- Coal identification
  - Cored wells (seam thickness exactly known)
  - Well logs: interpreted by new developed tool
  - Minimum thickness of coal seams: 30 cm (resolution of logs)
  - Pressure : hydrostatic



Producible Gas in Place for the Peel, Zuid Limburg, Achterhoek and Zeeland area.

Area	Surface (km^2)	Interval (m)	Proved Reserve (Mm^3/km^2)	Proved Reserve (EJ)	Probable Reserve (Mm^3/km^2)	Probable Reserve (EJ)	Possible Reserve (Mm^3/km^2)	Possible Reserve (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	3796	<1500	0.80	0.11	5.6	0.76	21.1	2.88
		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

	Interval (m)	Proved Reserve (Gm^3)	Proved Reserve (EJ)	Probable Reserve (Gm^3)	Probable Reserve (EJ)	Possible Reserve (Gm^3)	Possible Reserve (EJ)
Areas Total	<2000	60.3	2.16	194	6.95	518	18.5

Amount of Storable CO2 for the Peel, Zuid Limburg, Achterhoek and Zeeland area.

Area	Interval (m)	Proved Storable (Mtonne)	Probable Storable (Mtonne)	Possible Storable (Mtonne)
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	1184
Areas Total	<2000	304	1015	2734

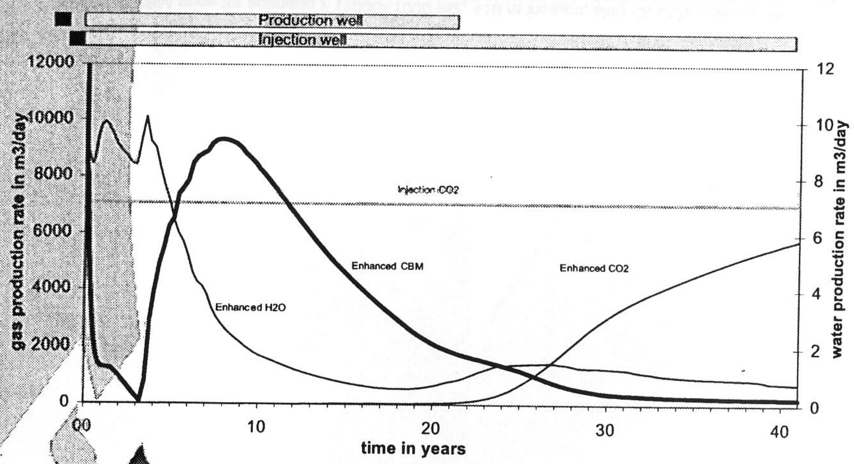
Sweep efficiency results at 90 % CO2-production.

	Methane sweep efficiency ratio (-)	Displaced volume (mole/mole)	Running time (sec)
A: Dry coal, CO_2 gas	52	1.65	$7.5 \cdot 10^5$
B: Water wet coal, CO_2 gas	26	0.55	$1.05 \cdot 10^5$
C: Dry coal, CO_2 liquid	48	4.9	$2.07 \cdot 10^6$
D: Water wet coal, CO_2 liquid	30	3.0	$8.6 \cdot 10^5$
E: Water wet coal, CO_2 super critical*	> 40*	3.82	$1.9 \cdot 10^6$

Researched ECBM scenarios.

Scenario	Field dimensions (m^2)	Inseam (m)	Skin	Exchange ratio (mole CO_2 / mole CH4)	CO2 injection Period (years)	CH4 production period (years)
A	400x400		-3	1.3	11 until 25	1 until 32
B	600x600	27	0	1.9	14 until 41	1 until 44
C	800x800	107	0	1.4	11 until 25	1 until 30
D	800x800	330	-3	2.7	1 until 27	1 until 14
E	1000x1000	222	0	1.7	11 until 38	1 until 38
F	1000x1000	410	-3	2.6	1 until 42	1 until 23
G	1000x1000	444	0	1.4	16 until 60	1 until 42

Gas and water flows for scenario F

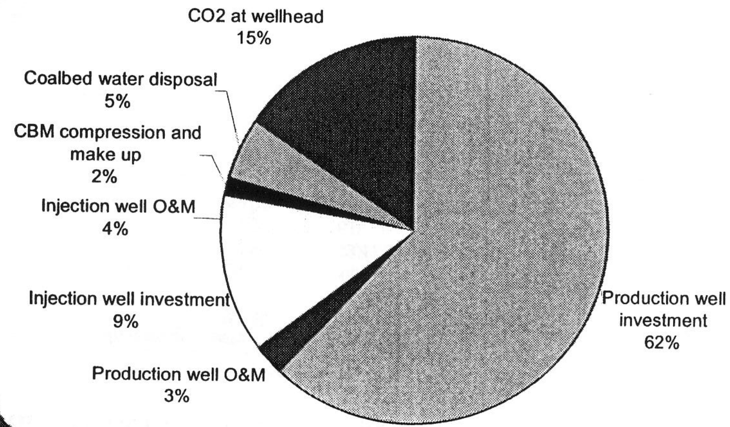


Gas and water flows for scenario F (1000×1000 m2, 410 m inseam, skin -3, CO2 injection from first year). Indicated are also the moment of investment, and the period of operation.

ECBM production costs in €/GJ for all scenarios considered; Base case.

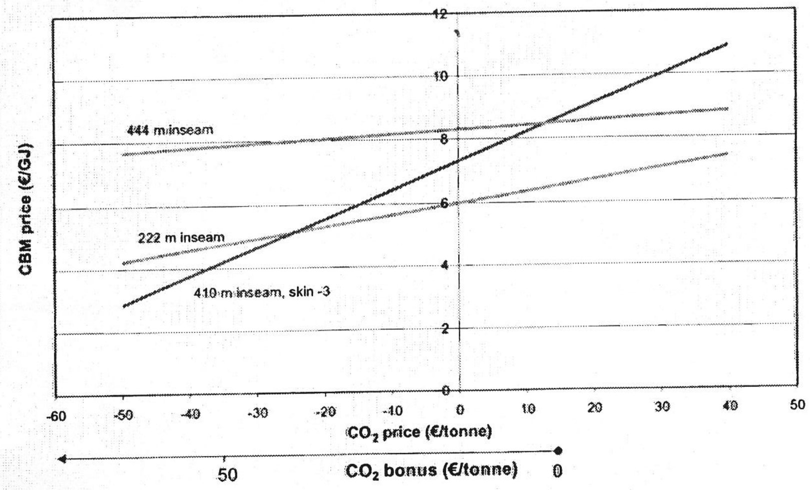
Scenario	Characteristics	Bonus for CO2 sequestration 0 €/tonne CO2	45 €/tonneCO2
A	400x400 m2, skin stimulation, late injection	16.4	14.7
B	600x600 m2, 27m inseam, late injection	15.3	13.4
C	800x800 m2, 107 m inseam, late injection	7.9	6.0
D	800x800 m2, 330 m inseam and skin, direct injection	9.3	4.8
E	1000x1000 m2, 220 m inseam, late injection	6.5	4.9
F	1000x1000 m2, 410 m inseam and skin, direct injection	8.7	4.6
G	1000x1000 m2, 444 m inseam, late injection	8.5	7.9

Breakdown of CBM price (8,7 Euro/t) for scenario F



Breakdown of CBM price for the scenario F (1000×1000 m2, 410 m inseam, skin -3, CO2 injection from first year). CO2 costs are 15 €/tonne (no bonus),

Sensitive Analysis of CO2 price on CBM price

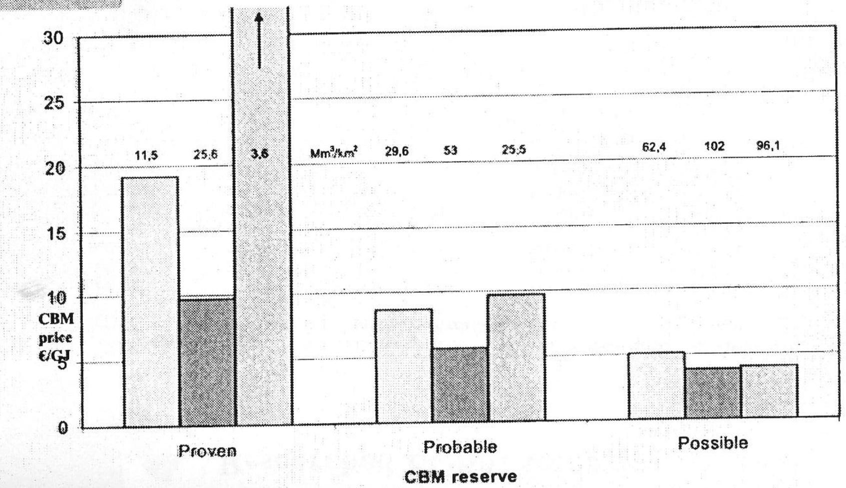


Influence of CO2 price on CBM price for 1000×1000 m2 scenarios E, F and G.

ECBM production costs in €/GJ for all scenarios considered, and sensitivity to investment costs, CO2 price, and interest rate.

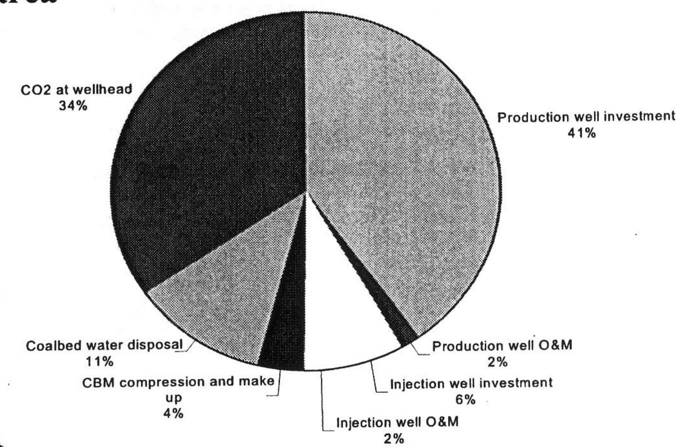
Scenario	Base case	Investment costs		CO_2 price		Interest rate	
		50 %	150 %	-30 €/tonne	30 €/tonne	5%	15 %
A	16.4	8.7	24.1	14.7	17.0	12.6	21.5
B	15.3	8.3	22.2	13.4	15.9	10.3	22.1
C	7.9	4.6	11.3	6.0	8.6	6.1	10.4
D	9.3	5.7	12.9	4.8	10.8	7.6	11.6
E	6.5	3.8	9.3	4.8	7.1	5.1	8.5
F	8.7	5.3	12.0	4.6	10.0	6.5	11.8
G	8.5	4.6	12.4	7.9	8.7	6.2	11.2

Price of CBM as a function of the CBM reserve probability



Price of CBM as a function of the CBM reserve probability for scenario F (1000×1000 m2, 410 m inseam, skin -3, CO2 injection from first year). Producible Gas In Place is indicated.

Breakdown of the CBM price, Zuid Limburg area



Breakdown of CBM price for scenario F (1000×1000 m2, 410 m inseam, skin -3, CO2 injection from first year) based on possible CBM reserve of Zuid Limburg. CO2 costs are 15 €/tonne (no bonus).

Price of small-scale electricity from CBM.

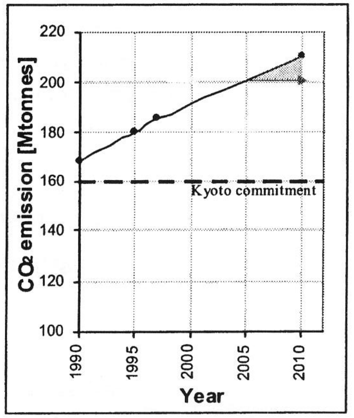
	investment costs	LHV efficiency	Electricity price (€ cent/kWh)	
			102 Mm3 CBM/km2 25 €/tonne CO_2 bonus	29.6 Mm3 CBM/km2 no bonus
Gas engine	700 €/kW	34 %	2.7	7.5
Combined cycle	750 €/kW	42 %	3.3	7.8
SOFC	1500 €/kW	55 %	3.6	6.6

Conclusions (1)

- The subsurface can help to reduce emissions of CO_2
- ECBM-CO_2 could provide a clean source of energy
- Choice of any option, including ECBM-CO_2 depends strongly on local/regional configuration of energy supply and demand, and subsurface conditions
- At this moment, most subsurface options are not cost-efficient, but can become economically competitive in the (near) future as a result of increased international reduction measures and/or a Carbon credit market (IEA: $32 per tonne CO_2)

Conclusions (2)

- ECBM can play an important role to reduce future growth (~ 1% or 2 Mtonnes per year) of CO_2 emissions in the Netherlands
- Further research and demonstration sites are mandatory



Follow-up (1)

- Site selection for eventual field test in the Netherlands
- Prepare 'manual' for selected site, including pre-preparation for permits and geological survey
- Cost calculations concentrated on the selected site(s)
- Interactions between carbon dioxide, methane and water in the coal layer

Follow-up (2)

- Dissemination of results
- International co-operation on R&D
- Participation in European field test

Development of Dutch Policy will give decision on continuation of efforts in first quarter of 2002

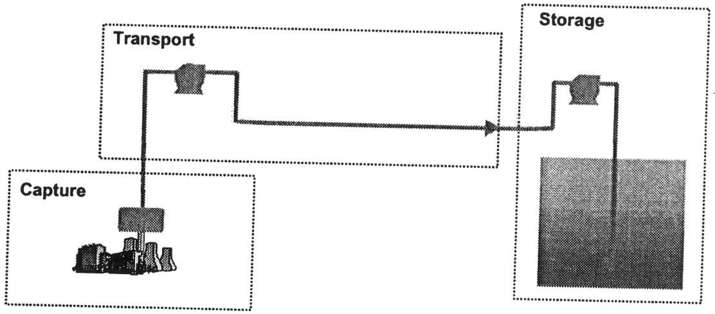
TOTALFINAELF

Capture and Transport of CO_2

6th of June, 2001 - CO2NET, Copenhagen - R. Bouchard

Some definitions

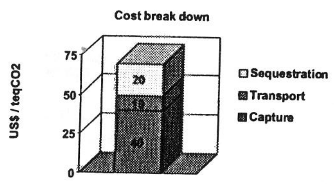
Sequestration = capture + transport + storage



Cost breakdown

The technology for CO2 capture and sequestration is already available

Current technical solutions



20 to 70 US$ / teqCO2

Economic drivers

There is none currently, because there is no policy decided yet.

Who should support the additional cost ?

Norway : 38 US$ / teqCO2

Market : 40 - 50 US$ / teqCO2

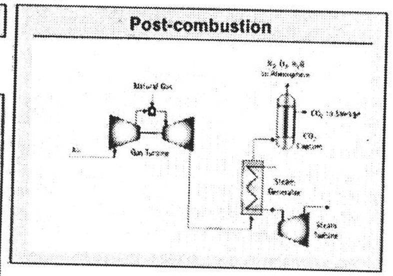
⇩

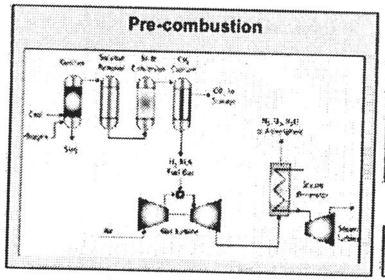
There is a cost challenge ahead of us

Type of capture

removing carbon from flue gas =

Low CO2 concentration (4% to 14%)





= removing carbon prior to burning fuels

High concentration of CO2

Opportunities for capture

Best suited for large sources of CO2

Power generation (Low CO2 concentration (4% to 14%))
- → Pc or Pf-fired Steam Cycles
- → NGCCs
- → IGCCs

Industrial processes (High concentration of CO2)
- → Reforming
- → Decarbonation
- → Energy Carriers (H2)

Capture technologies

Capture

- → Solvent scrubbing :
  - chemical (MEA)
  - physical
  - hybrid

  → High energy demand; At low pressure, large size; Widely used; High outlet CO2 concentration
- → Adsorption :
  - PSA
  - TSA
  - ESA

  → Problem for up-scaling; Attractive for low cction
- → Membranes :
  - inorganic
  - palladium
  - polymeric
  - zeolites

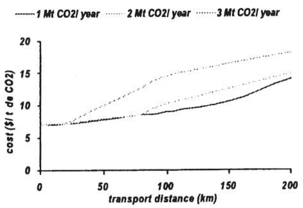
  → Cost issue; Multistage to obtain good purity; Large commercial use
- → Cryogenics → Attractive for high P process; Very high energy requirement

Additional capture cost for Power Plant : 50%

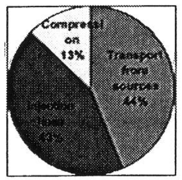
Compression and transport

Issues
- → Corrosion problem
- → Technology of compression
- → Availability of pipeline network

Cost Evolution



Cost Break-out *



(*) study for the Alberta EOR project

R&D issues

- **Technology gaps : leaps are needed**
  - New solvent for absorption
  - Membranes
  - Solid adsorption (Electric Swing Adsorption)
- **Process optimisation**
  - Best use of energy
  - Mix of existing technologies
- **Oxy-combustion**
  - High concentration flow of CO2
  - Burner

Conclusions

- **Why do we need capture**
  - To prevent CO_2 emissions
  - To avoid sequestering huge quantities of gas
- **Why do we need transport**
  - To connect sequestration sites with emission sites
- **What lies ahead of us**
  - Technical challenge
  - Cost reduction challenge

But industry needs to have objectives clearly defined !

Transmission of CO_2
Experiences to be gained from CO_2/EOR projects

John Gale

IEA Greenhouse Gas R&D Programme

CO2NET Meeting, Copenhagen

6-7th June 2001

www.ieagreen.org.uk

Experiences to be gained

Introduction

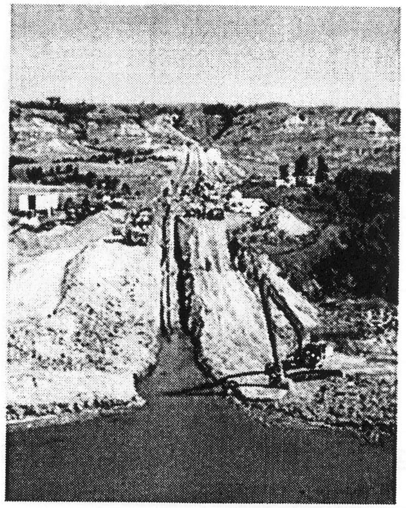
- Transportation of CO_2 common to ALL sequestration projects
- Limited discussion on pipeline issues
- CO_2 pipeline experience from CO_2/EOR projects
- Case study on Weyburn CO_2 pipeline

Experiences to be gained

CO_2-EOR

- 75 Projects worldwide
  - ➢ USA principally
  - ➢ Canada, Trinidad & Tobago, Turkey, Hungary
- CO_2 injected to enhance oil recovery
- Up to 50% of the injected CO_2 can remain in the immobile oil
- CO_2 sequestration occurs but is not planned
- Other production benefits

CO_2- EOR and CO_2 Pipelines



Courtesy of Dakota Gasification.

2400 km of pipelines

- Transport 114 Mt/y CO_2
- High purity CO_2 mostly
- CO_2 transported in dense phase
- 700 km of large lateral lines
- 3100 km in total
- Contrast with other pipelines in USA
  - ➢ Natural gas - 536 000 km
  - ➢ Hazardous - 249 000 km

CO_2 Pipelines

Pipeline Regulations - USA

- 1999 Code of Federal Regulations,
- Part 195; Transport of Hazardous Liquids deals with CO_2 pipelines
- Responsible body is Office of Pipeline Safety
- CO_2 Pipelines Classified as:
  - High Volatile/Low Hazard and Low Risk
- State level - authorities act as Certifying Agents
  - Texas Railroad Commission - Pipeline Safety Programme - Oil & Gas Services Division

CO_2 Pipelines

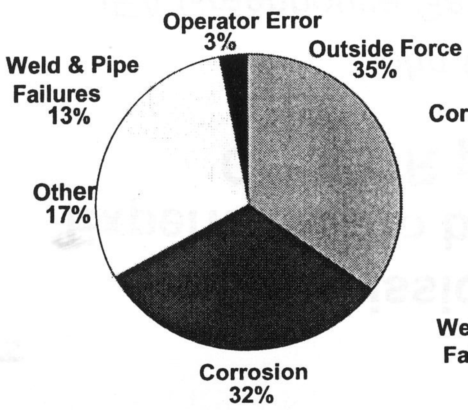
Pipeline Incident Statistics (1994 - 2000)

Pipeline	*Nat. Gas*	*Hazard.*	*CO_2*
Incidents	*510*	*1220*	*5*
Fatalities	*21*	*16*	*0*
Injuries	*75*	*66*	*0*
Damage	*$135 m*	*$370 m*	*$ 54,000*
Incidents/ 1000 kmly	*0.14*	*0.69*	*0.23*

Source: Office of Pipeline Statistics/ US DOT

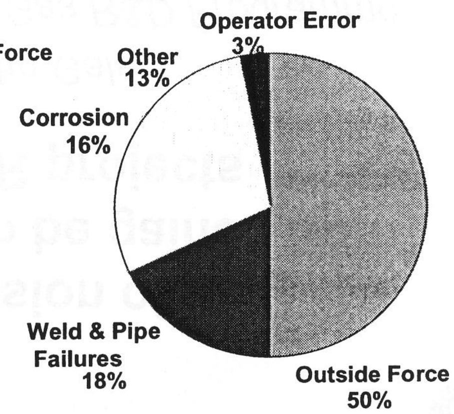
Natural Gas Pipeline Incidents

USA 1988 - 1998



Source: Oil & Gas Journal

Europe 1970 - 1987



Source: Pipes & Pipelines International

CO_2 Pipelines

Key Conclusions from CO_2-EOR Projects

- CO_2 pipeline construction and operating procedures established
- Regulatory procedures established
- CO_2 pipelines no more prone to incidents than natural gas pipelines
- Impact of a CO_2 pipeline incident significantly lower than for a natural gas pipeline.

CO_2 Pipelines

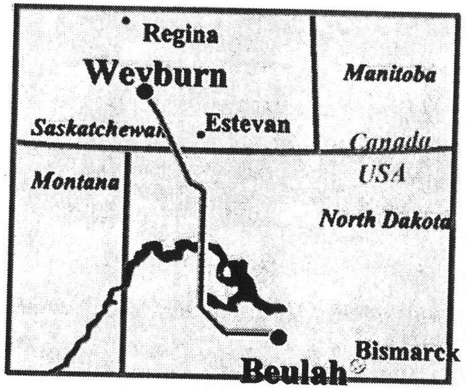
Oil & Gas Journal Study Conclusions

“ If you operate a pipeline you can expect an incident”

“ If the pipeline is short there may only be one incident in 20 years”

“If it is 1000 km long an incident a year could be expected”

Weyburn CO_2 Pipeline

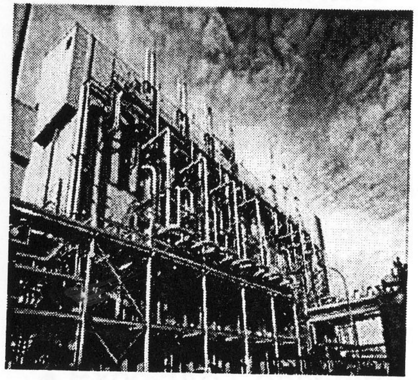


Courtesy of Dakota Gasification.

325 km Pipeline

- Souris Valley section 61 km long
- Approved by National Energy Board
- Class 1 “Sour Service “ Pipeline
- CSA Z662
- Risk Assessment Study & Environmental Impact Assessment

Weyburn Pipeline

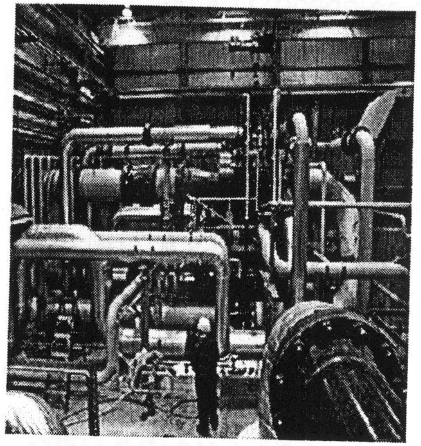


Courtesy of Dakota Gasification.

Gas Production

- Battery of Lurgi fixed bed gasifier fired on Lignite
- Recitsol scrubbing plant
- Pipeline Gas Composition:
  - 97% CO_2
  - 2% N_2 and CH_4
  - 0.8% H_2S
  - Trace - mercaptans

Weyburn Pipeline



Courtesy of Dakota Gasification.

Gas Compression

- Borsig multi-stage centrifugal compressor
- Ambient to pipeline pressure
- Operating since October 2000
- Operating Issues
  - Start up
  - Seal design

Weyburn CO_2 Pipelines

Pipeline Specification (1)

Material of Construction	Carbon Steel (API 5L)
Construction	Seamless line pipe ➢ Fully welded joints ➢ Tested to standards
Siting	Buried ➢ Min. ground cover 1.2m
Line Depressurisation	Designed to cope with rapid temperature change (-78.5^{0}C)

Weyburn CO_2 Pipelines

Corrosion Protection

- Pipeline Design
  - ➢ External coating
  - ➢ Cathodic Protection system
- Control system features
  - ➢ Gas dehydrated to minimise free moisture
  - ➢ Moisture & H_2S contents of gas entering pipeline automatically monitored with control limits
- Routine pipeline testing
  - ➢ Standard procedures & regulatory reporting requirements

Sour Gas Pipeline Experience

Alberta Energy Board Statistics (1980 to 1997)

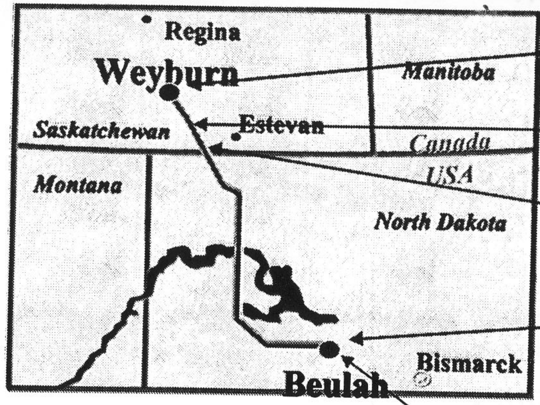
- Principle cause of sour gas pipeline failures
  - ➢ Internal corrosion 53%
  - ➢ External corrosion 20%
- Frequency of failures decreased
  - ➢ 5 failures per 1000 km in 1980
  - ➢ 2 failures per 1000 km in 1997
- Impacts of failure are high due to H_2S
  - ➢ Greater care exercised by pipeline operators
  - ➢ "State of art " corrosion protection technology

Weyburn Pipeline Control

Automatic Monitoring System

- Controlled by SCADA system from Beulah
- Control system monitors
  - ➢ Volumetric flow rate
  - ➢ Pressure
- Control valves set at 30 km intervals
  - ➢ Pressure transducer, controller and valve operator and antenna
- Automatically closed in event of pipeline failure

Weyburn Pipeline Control



Courtesy of Dakota Gasification.

Control Valve Frequency

Key Design Issue

- More frequent
  - ➢ Increases cost
- Less frequent
  - ➢ Decreases cost
  - ➢ Larger volume between valves
  - ➢ Safe distance from pipeline is longer
- ELSAMPROJEKT study in 1996
  - ➢ Densely populated areas frequency down to 5km to get acceptable safety distances.

Risk Assessment Analysis

Weyburn Pipeline

- Utilised pipeline rupture model and meteorological data
- Impact of a leak from a 10 mm hole
  - ➢ Depressurisation slow
  - ➢ 30 minutes for control system to recognise leak
- Impact of a rupture
  - ➢ Section isolated within 3 minutes
- Exposure Concentrations for CO_2 (NIOSH)
  - ➢ LCLo 100 000 ppm for 1 minutes
  - ➢ IDLH 40 000 ppm for 30 minutes

Risk Assessment Analysis

CO_2 Exposure Data

Exposure Limit	Time Period	Limiting Distance	
		Rupture	Leak
LCLo	1 min.	210 m	70 m
IDLH	30 min.	170 m	110 m

Risk Assessment Analysis

Main conclusions of Weyburn Study

- No buildings within 400m of pipeline routing
- Likelihood of pipeline failure deemed to be low
  - Design has corrosion protection measures
  - Control system with corrosion protection features
  - Regular line testing to standard procedures
- Likely impact on public safety - low
- Emergency response plan required
  - Evacuation programme
  - Education programme for residents

CO_2 Pipeline Risk

Considerations for European pipelines

- Limit risk by design, control and regulation
- Greater population density
  - Higher risk & impact
- Careful consideration of pipeline routing
  - Follow existing pipelines routes
- Higher control valve frequency to reduce exposure distances near to population centres
- Other features:
  - Increased pipeline thickness
  - Route marking & surveillance

Experience from Weyburn

Sulphur Compounds

- Leakage from valves
- Significant odour problem
- "Leak identifier"
- High toxicity

CO_2

- Colourless/odourless gas
- Non toxic/asphyxiant

Closing Thoughts

Should we consider adding trace gas to CO_2 to make it identifiable ?

Would adding a marker to the CO_2 improve public acceptability ?