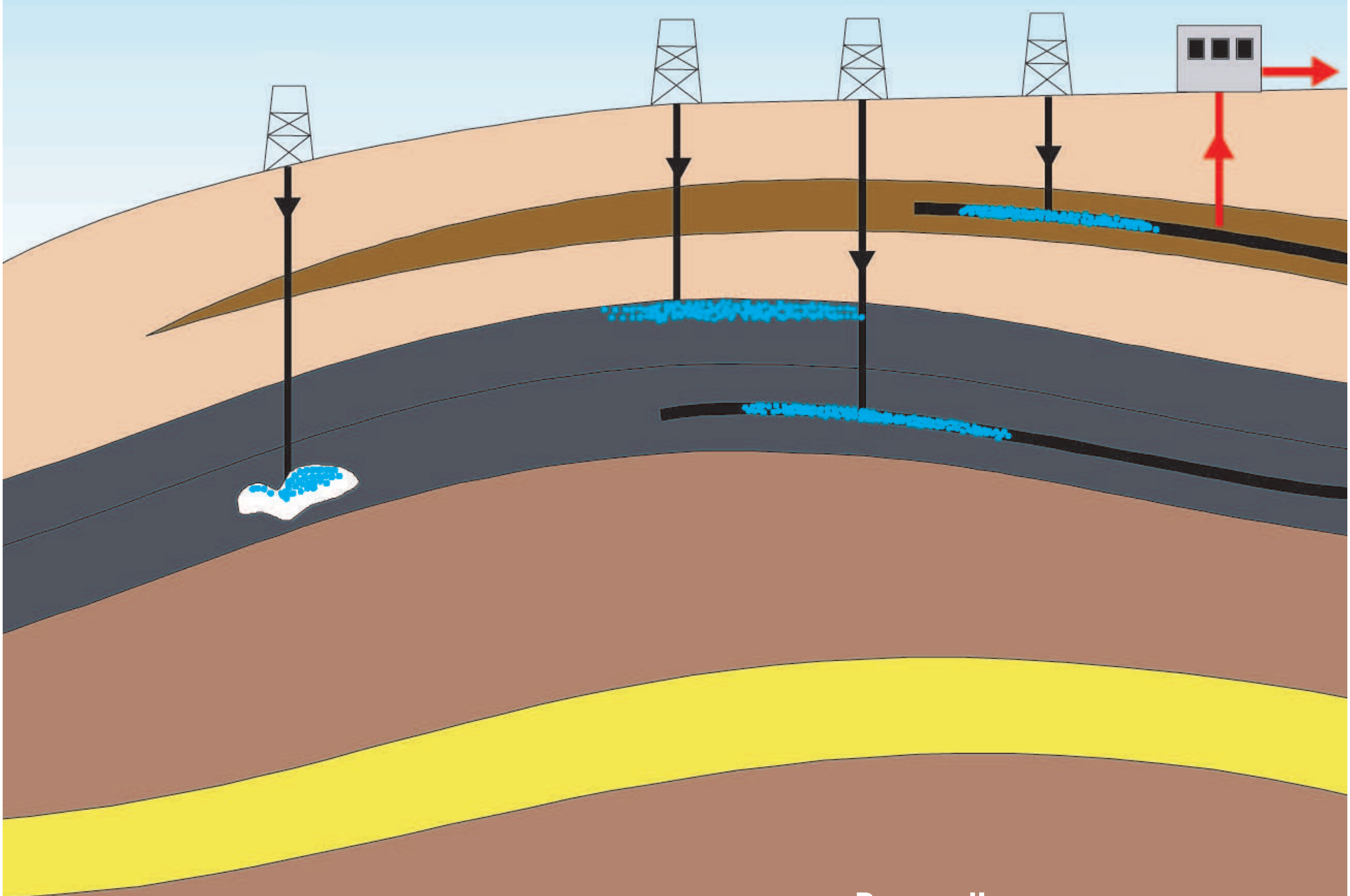
SUSTAINABLE*economy*



Proceedings

CO_2 Capture and Sequestration In Future International R&D Programmes

Berichte aus Energie- und Umweltforschung

24/2004

bmvit

ENERGY SYSTEMS of Tomorrow

Impressum:

Eigentümer, Herausgeber und Medieninhaber:
Bundesministerium für Verkehr, Innovation und Technologie
Radetzkystraße 2, 1030 Wien

Verantwortung und Koordination:
Abteilung für Energie- und Umwelttechnologien
Leiter: DI Michael Paula

Liste sowie Bestellmöglichkeit aller Berichte dieser Reihe unter http://www.nachhaltigwirtschaften.at
oder unter:

Projektfabrik Waldhör
Nedergasse 23, 1190 Wien
Email: versand@projektfabrik.at

CO_2 Capture and Sequestration in Future International R&D Programmes

Proceedings

WKO Vienna, 17th November 2004

prepared by E.V.A.

An International Workshop within the R&D Subprogram

ENERGY SYSTEMS of Tomorrow

Austrian Program on Technologies for Sustainable Development

An Initiative by the Austrian Federal Ministry for Transport, Innovation and Technology

Welcome Note

The Federal Ministry for Transport, Innovation and Technology welcomes you to the international workshop on the topic of: „CO_2 capture and sequestration in future international R&D programmes".

Technologies for sustainable development play a dominating role within the activities of our ministry. An orientation towards sustainability not only contributes to a relief of the environment, it also opens up completely new opportunities for the economy. For this reason the Federal Ministry for Transport, Innovation and Technology put major efforts to this issue and initiated the **Austrian Program on Technologies for Sustainable Development**.

The program pursues clearly defined emphases, selects projects by means of tendering procedures and is characterized by networking between the individual research projects. Three subprograms are presently carried out in this framework: "Building of Tomorrow", "Factory of Tomorrow" and "Energy Systems of Tomorrow".

The goal of the subprogram "Energy Systems of Tomorrow" is to develop technologies and concepts for a sustainable energy system. Such an energy system is based on the use of renewable energy sources, energy efficiency and fuel flexibility in order to meet our energy needs over the long term.

As an accompanying measure of this program, a major focus is also on new developments – like CO_2 capture and sequestration (or short CCS) technologies – in order to give orientation to international priority RTD topics, to identify and to assess future RTD potentials.

In this respect the Federal Ministry of Transport, Innovation and Technology initiated this international workshop with the following specific goals:

(i) to transfer information about latest European and International RTD topics to relevant Austrian stakeholders,

(ii) to identify the opportunities and barriers of RTD activities in CCS technology fields, and

(iii) to support the Austrian decision makers of industrial and public sectors, scientific bodies and NGOs in their future positions and decision making.

Especially the positions of the European Commission play a major role for the Austrian research and technology activities. In this context it is expected that this workshop will contribute to ongoing activities within the European Union involving Austrian public and industrial institutions. These are in particular:

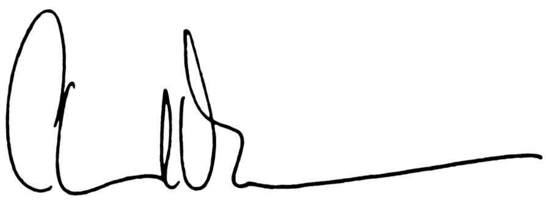
(i) the present discussion about the contents and RTD priorities within the 7th RTD framework program,

(ii) the present activities within the European Growth Initiative namely the Quick Start Projects, and

(i) the possible future role of CCS technologies in EU technology platforms and initiatives.

Furthermore, the European Union is part of the CSLF, the carbon sequestration leadership forum, an international climate change collaboration initiated by the United States of America presently involving 17 countries with the goal to develop improved cost-effective technologies for the separation of CO_2, its safe transport and long-term underground storage. In this context EU member states like Austria – not being part of this multilateral RTD collaboration – appreciate the regular meetings organised by the European Commission prior to these CSLF meetings in order to have the possibility to contribute to common European positions.

This workshop is the first one on this topic in Austria. The results of this workshop in general and the positions of the Austrian industry and scientific bodies in particular will be of major importance in order to provide orientation to future RTD activities for CCS technologies.



Mag. Eduard Mainoni

State Secretary

Federal Ministry for Transport, Innovation and Technology

Austria

Introduction

This workshop is part of an E.V.A. project that was authorised by the Federal Ministry for Transport, Innovation and Technology with the goal to analyse international and national activities on CO_2 capture and storage and to formulate a strategy for the ministry to suggest future positions (and activities) on this topic.

Climate change is a problem of global proportions and global concerns. A number of anthropogenic gases are largely responsible for driving this process forward, the most significant one is carbon dioxide produced by burning of fossil fuels.

As a matter of fact fossil fuels provide and will provide in the next decades a large proportion of the world's commercial energy needs and for this reason will provide a challenge for the society concerning its sustainable use.

To ensure that substantial reductions in atmospheric CO_2 levels can be achieved during this century, technological solutions urgently require developments and further applications in order to control the increasing amounts of produced CO_2.

A number of technological solutions offer substantial CO_2 reductions including different technological options, for example, the fuel switch to renewable energy sources, bio fuels, energy efficiency technologies, fuel cells, and – taking into account latest international developments – fossil fuel use with CO_2 capture and storage (CCS technologies in short), the topic of today's international workshop.

The contents of this workshop are on the one side to present the international RTD activities and programmes and on the other side to introduce present, high-level RTD analysis, activities and projects both on a national and international level.

As with any new technological developments, however, there remain open issues not to be fully resolved also at this workshop for example concerning practicalities and environmental safety issues.

In order for CCS technologies to be deemed acceptable by national governments, regulations and the public at large, work needs to be carried out – from E.V.A.´s point of view – to confirm that there are no inherent dangers that could result from either gradual or sudden release of CO_2 from a particular store.

Confirmation that CO_2 leakage is minimal is also required from an economic point of view, in case there are – or will be – financial implications associated with the CO_2 injection into the particular formation. If CCS technologies are to be fully accepted, it would be necessary to develop suitable storage protocols and procedures that can be proven effective and verifiably safe.

In case of demonstration projects comprehensive monitoring studies need to be carried out to follow the fate of the CO_2 injected into a particular formation. This will help to confirm that it remains safely stored within the formation over the required timescale. These investigations may require the development and demonstration of innovative monitoring and tracking technologies. While some technologies exist, others require further development.

Uncertainties also exist concerning the legal aspects of carbon capture and storage technologies in the sense of existing frameworks. This issue is – however – beyond of the goals of this workshop although it should be mentioned that there are some unsolved questions.

Dr. Fritz Unterpertinger

Managing Director

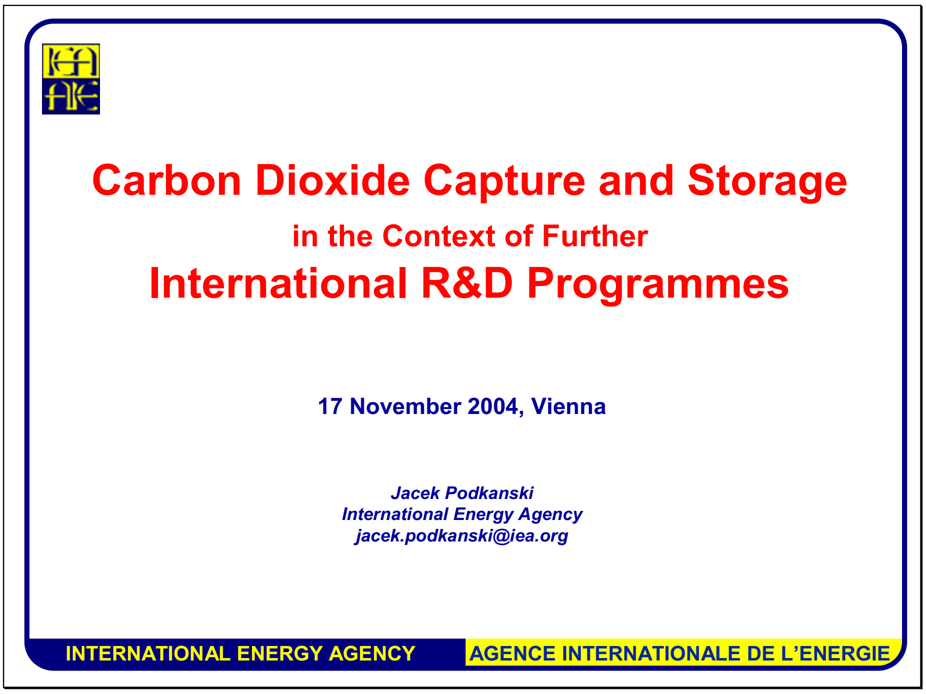
E.V.A. - the Austrian Energy Agency

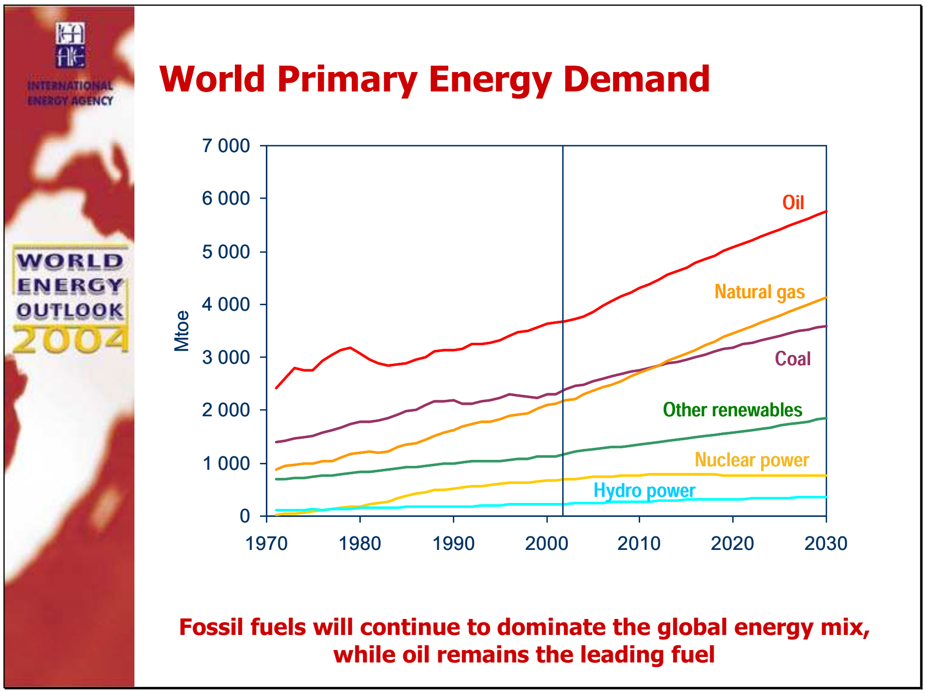
Table of Contents

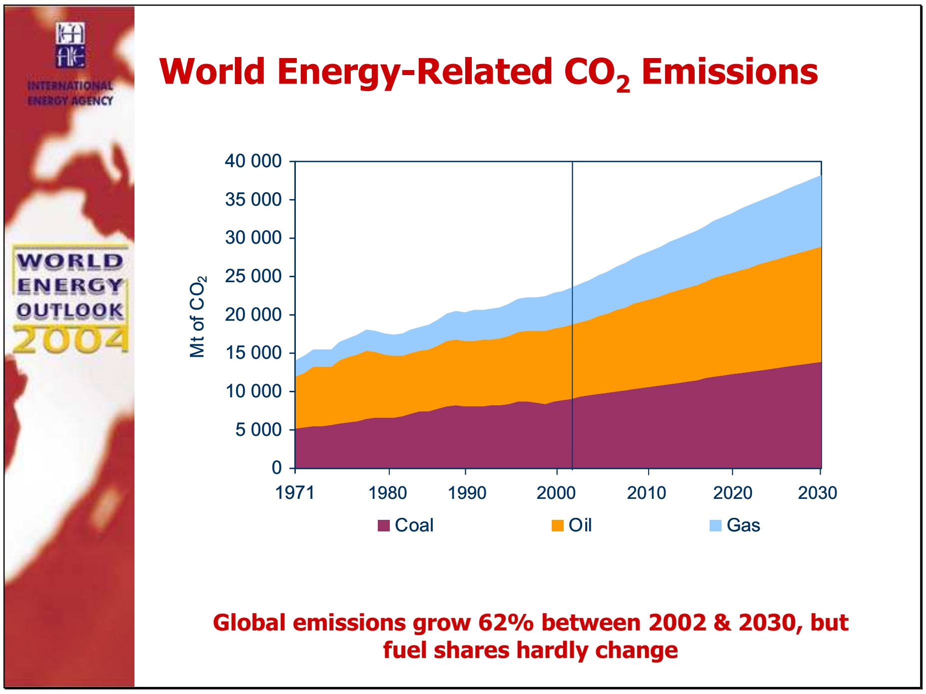
CO_2 Capture and Sequestration in the Context of Further International R&D Programmes

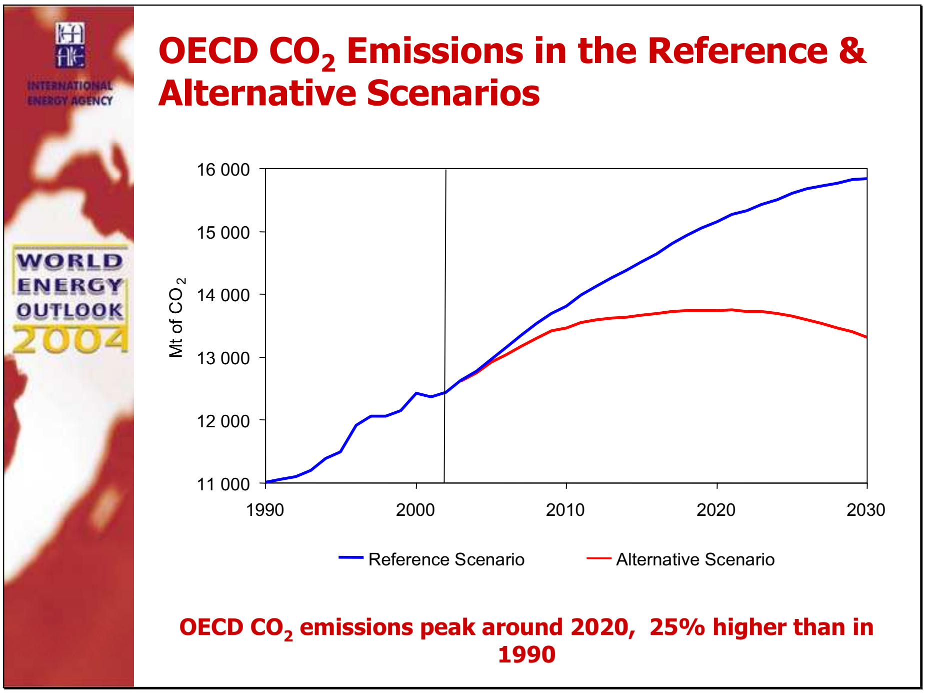
Jacek Podkanski (IEA – International Energy Agency)

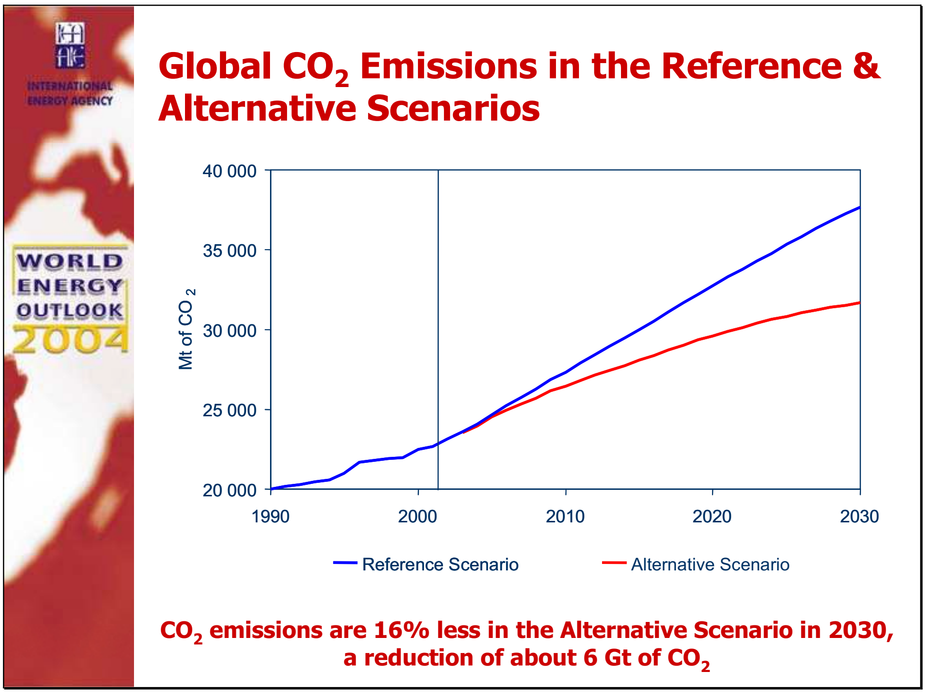
Senior Energy Technology Specialist
Energy Technology Collaboration Division

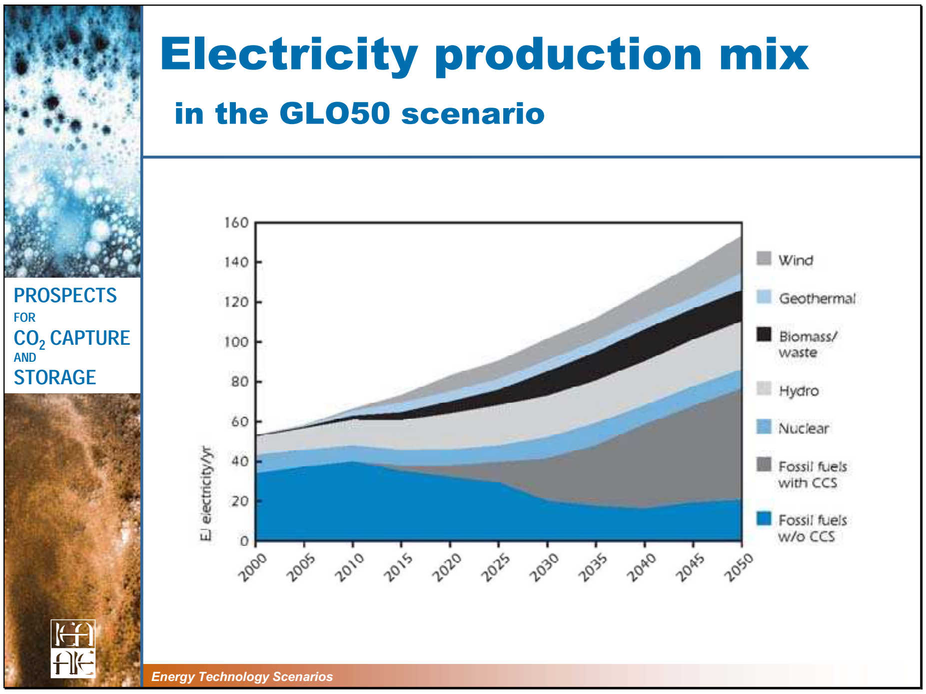


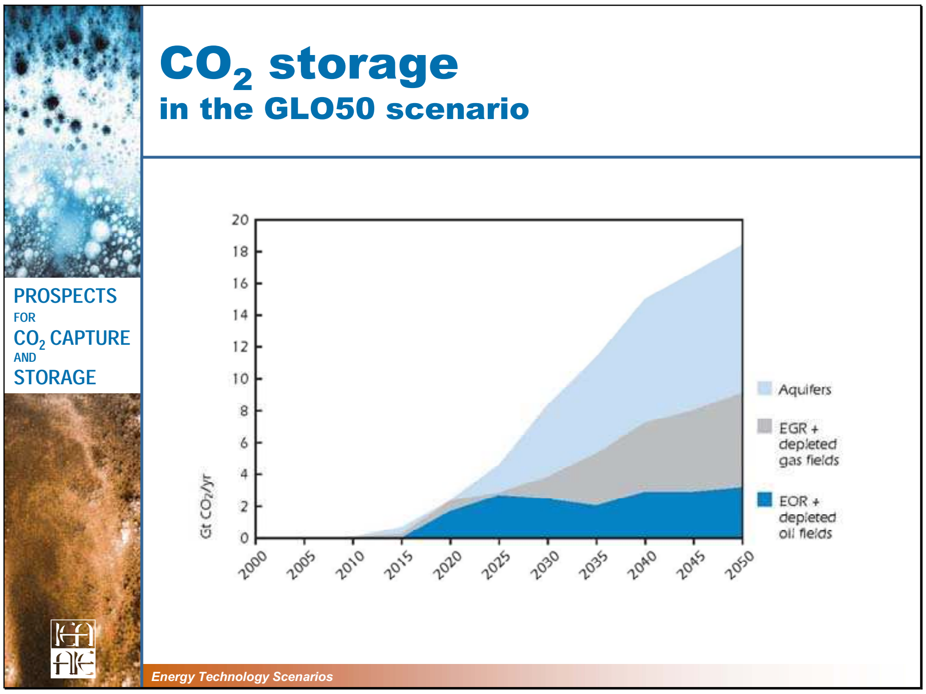

INTERNATIONAL ENERGY AGENCY
WORLD ENERGY OUTLOOK 2004
World Primary Energy Demand
Mtoe
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
1970
1980
1990
2000
2010
2020
2030
Oil
Natural gas
Coal
Other renewables
Nuclear power
Hydro power
Fossil fuels will continue to dominate the global energy mix, while oil remains the leading fuel

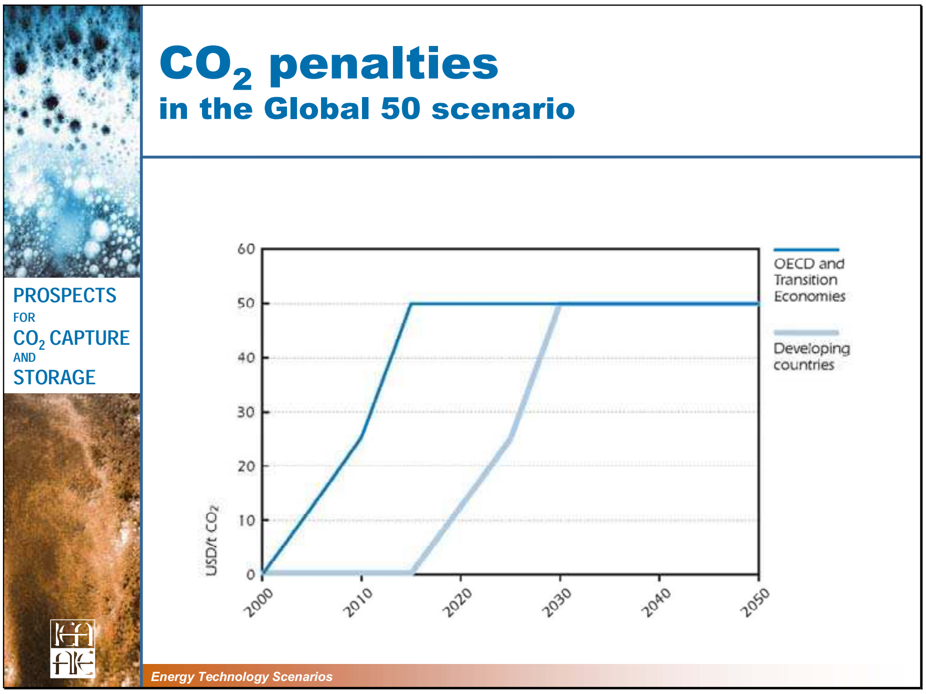

INTERNATIONAL ENERGY AGENCY
WORLD ENERGY OUTLOOK 2004
World Energy-Related CO_2 Emissions
Mt of CO_2
40 000
35 000
30 000
25 000
20 000
15 000
10 000
5 000
0
1971
1980
1990
2000
2010
2020
2030
Coal
Oil
Gas
Global emissions grow 62% between 2002 & 2030, but fuel shares hardly change

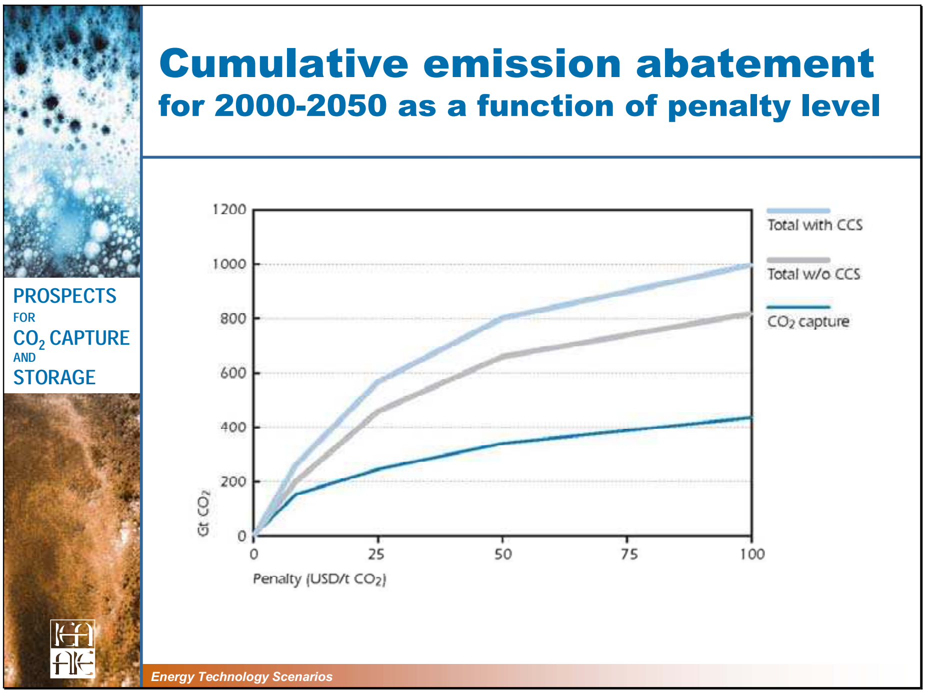

INTERNATIONAL ENERGY AGENCY
WORLD ENERGY OUTLOOK 2004
OECD CO2 Emissions in the Reference & Alternative Scenarios
16 000
15 000
14 000
13 000
12 000
11 000
Mt of CO2
1990
2000
2010
2020
2030
Reference Scenario
Alternative Scenario
OECD CO2 emissions peak around 2020, 25% higher than in 1990


INTERNATIONAL ENERGY AGENCY
WORLD ENERGY OUTLOOK 2004
Global CO2 Emissions in the Reference & Alternative Scenarios
40 000
35 000
30 000
25 000
20 000
Mt of CO2
1990
2000
2010
2020
2030
Reference Scenario
Alternative Scenario
CO2 emissions are 16% less in the Alternative Scenario in 2030, a reduction of about 6 Gt of CO2


Electricity production mix
in the GLO50 scenario
PROSPECTS FOR CO2 CAPTURE AND STORAGE
EJ electricity/yr
160
140
120
100
80
60
40
20
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Wind
Geothermal
Biomass/waste
Hydro
Nuclear
Fossil fuels with CCS
Fossil fuels w/o CCS
Energy Technology Scenarios


CO2 storage
in the GLO50 scenario
PROSPECTS FOR CO2 CAPTURE AND STORAGE
Gt CO2/yr
20
18
16
14
12
10
8
6
4
2
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Aquifers
EGR + depleted gas fields
EOR + depleted oil fields
Energy Technology Scenarios


CO2 penalties
in the Global 50 scenario
PROSPECTS
FOR
CO2 CAPTURE
AND
STORAGE
60
50
40
30
20
10
0
USD/t CO2
2000
2010
2020
2030
2040
2050
OECD and
Transition
Economies
Developing
countries
Energy Technology Scenarios

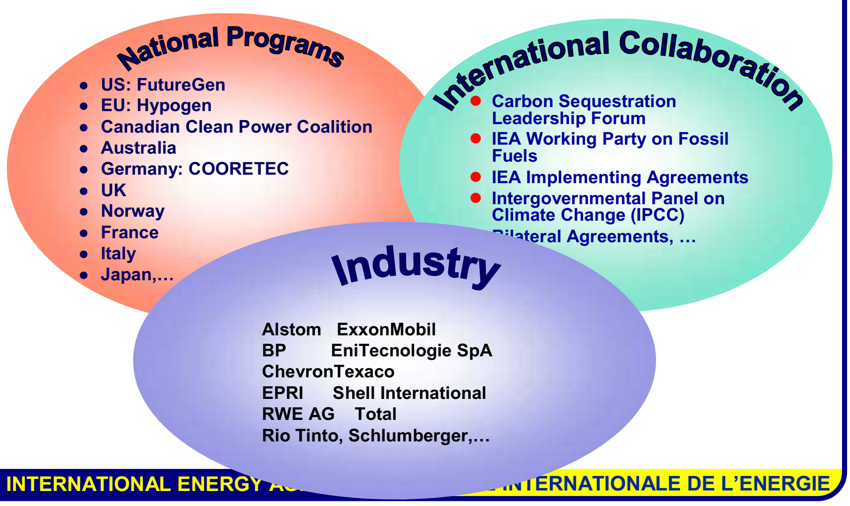

Cumulative emission abatement
for 2000-2050 as a function of penalty level
PROSPECTS
FOR
CO2 CAPTURE
AND
STORAGE
1200
1000
800
600
400
200
0
Gt CO2
0
25
50
75
100
Penalty (USD/t CO2)
Total with CCS
Total w/o CCS
CO2 capture
Energy Technology Scenarios

Challenges

- RD&D gaps
- Public awareness and acceptance
- Legal and regulatory framework
- Long-term policy framework and incentives

INTERNATIONAL ENERGY AGENCY AGENCE INTERNATIONALE DE L'ENERGIE

RD&D Public/Private Partnerships



Overview of worldwide CCS projects

CO_2 capture demonstration projects	11
CO_2 capture R&D projects	35
Geologic storage projects	26
Geologic storage R&D projects	74
Ocean storage R&D projects	9

INTERNATIONAL ENERGY AGENCY AGENCE INTERNATIONALE DE L'ENERGIE

Public awareness and acceptance

- The deployment of CCS technologies will require broad understanding and long-term commitment by numerous constituencies
- Environmental NGOs generally support RD&D work on CCS technologies
- Their main concern centres on the fact that CCS is seen and presented as a solution which would allow for the continued use of fossil-fuel resources as long as they are available

INTERNATIONAL ENERGY AGENCY AGENCE INTERNATIONALE DE L'ENERGIE

The regulatory and legal framework

- Countries should create an enabling legal and regulatory environment for national CO_2 storage projects.
- Contracting parties to international instruments should be proactive in clarifying the legal status of CO_2 storage in the marine environment, taking into consideration their objectives to stabilize CO_2 in the atmosphere.

INTERNATIONAL ENERGY AGENCY AGENCE INTERNATIONALE DE L'ENERGIE

Long-term policy framework and incentives

In addition to the acceleration of RD&D funding, countries should create a level-playing field for CCS alongside other climate change mitigation technologies. This includes ensuring that various climate change mitigation instruments, including market-oriented trading schemes, are adapted to include CCS.

INTERNATIONAL ENERGY AGENCY AGENCE INTERNATIONALE DE L'ENERGIE

CO_2 Capture and Storage – R&D Activities within the European Commission

Ángel Perez Sainz (DG RESEARCH, European Commission)

Head of Unit
Energy Conversion and Transport
Directorate General for Research

Summary

This paper describes the research strategy put in place by the Directorate General for Research of the European Commission in the field of the mitigation of CO_2 emissions. This is first placed in the general context of the Commission energy policies. This section covers the main policy actions and instruments relevant to energy policy, that is namely the climate change issue, the introduction of renewable energy sources, the security of energy supply, the promotion of energy efficiency and the opening of energy markets.

The paper then concentrates on the research policies of the Commission, mainly the European Research Area concept and its number one instrument, the Sixth Framework Programme for research and technological development, covering the years 2002 to 2006. The rational and the analysis supporting the ERA are covered, as well as the structure and the new implementation modalities of the Framework Programme.

The paper then goes into some details of past and present projects in CO_2 capture and sequestration and shows how they are organised and how they fit into the above-mentioned research policy, while contributing to the successful deployment of the Commission energy policies.

Emphasis is put on the new integrated projects and networks of excellence resulting from the first call of FP6 in this field. These new projects resulted in a tripling of the existing portfolio of research project resulting from FP5, in budget terms, and therefore in ambition.

Future perspectives, in particular in view of existing and new initiatives in the international arena, are finally outlined, addressing the need for an integrated European approach to develop and demonstrate CO_2 capture and storage technologies for the benefit of the European citizens, industry and society, within the framework of the European Initiative for Growth, aiming at 3% of GDP spent on R&D.

Introduction

Sustainable development and world-class economic competitiveness are central objectives for the European Union. These overriding needs are reflected in the European Union's research priorities in order to implement sustainable development, with energy as a key aspect. Three key strategic objectives for energy are:

- to reduce greenhouse gas and pollutant emissions,
- to secure a future sustainable and diversified energy supply, with the increased use of new and renewable energy sources
- to ensure a competitive European industry

In order to achieve an impact in the medium to long term, considerable RTD effort is required to implement a sustainable energy system with clean energy sources, carriers and conversion technologies that are economically attractive and technically robust. Within this scenario, fossil fuel use will be required to fulfil a long-term transitional role prior to the increasing introduction of new and renewable energy sources. However, if fossil fuels are to be part of this sustainable energy scenario, then near-zero emissions fossil fuel systems will be required. Accordingly, the development of CO_2 capture and sequestration systems associated with fossil fuel power plants is a key priority within the RTD Framework Programmes of the European Union (EU).

Global Environmental Policy Issues

Worldwide, there is increasing concern regarding climate change issues related to Green House Gas (GHG) emissions. It is also recognised that global issues require global responses. This approach has been reflected in the Kyoto Protocol, with many major nations agreeing to limit greenhouse gas emissions in the period up to 2012. Thus the European Union intends to decrease its GHG emissions by 8% in 2008-2012 compared to 1990 under the Kyoto Protocol. This will be achieved through a burden sharing agreement between Member States taking into account the fuel mix and situation pertaining within each State. The EU is making reasonable progress so far, although there is still uncertainty on whether a reduction by 8% will be achieved in the designated timescale. Entry into force of the Protocol is subject to the ratification by countries representing at least 55% of total CO_2 emissions. After the US withdrawal, this means that Russia should ratify and thus has in effect the future of the Protocol in its hands. The latest indications are that Russia will indeed ratify and that the protocol will consequently come into force. This will provide another incentive to initiate discussions about Post-Kyoto scenarios and agreements. The central issue in these talks will be to take on board both developed and developing countries and at the same time recognise to developing economies the right to development.

The European Climate Change Programme (ECCP) was also established to identify the most promising and cost-effective routes. With regard to the practicalities of reducing GHG emissions, this will be achieved through a combination of the more rational use of energy in all sectors together with a switch to lower carbon fuels including a greater introduction of (zero carbon) renewable energy sources. Indeed at the Johannesburg World Summit on sustainable development, it was reaffirmed that increasing the use of clean renewable energy will have multiple benefits for developed and developing countries alike, with a positive outcome likely to arise from increasing the global share of renewable energy sources. However, as is noted below, the use of fossil fuels will continue to dominate the energy mix for a variety of reasons and as such there is a need to ensure that fossil fuel systems become more energy efficient and have a less adverse environmental impact.

For fossil fuel utilisation systems, the drive will be towards near zero emission power plants and for such units the currently proposed way forward is to introduce CO_2 Capture and Sequestration techniques with the existing systems. Such techniques are not yet cost effective in the Kyoto horizon, but will be an essential component of a well-balanced energy mix in Post-Kyoto scenarios aiming at deeper cuts in emissions of the order of -50% by 2050. Thus, further RTD is worthwhile. Mitigation costs are high although they vary according to the technology to be used and even within the same technology there may be differences in costs (1), as shown in Figure 1.

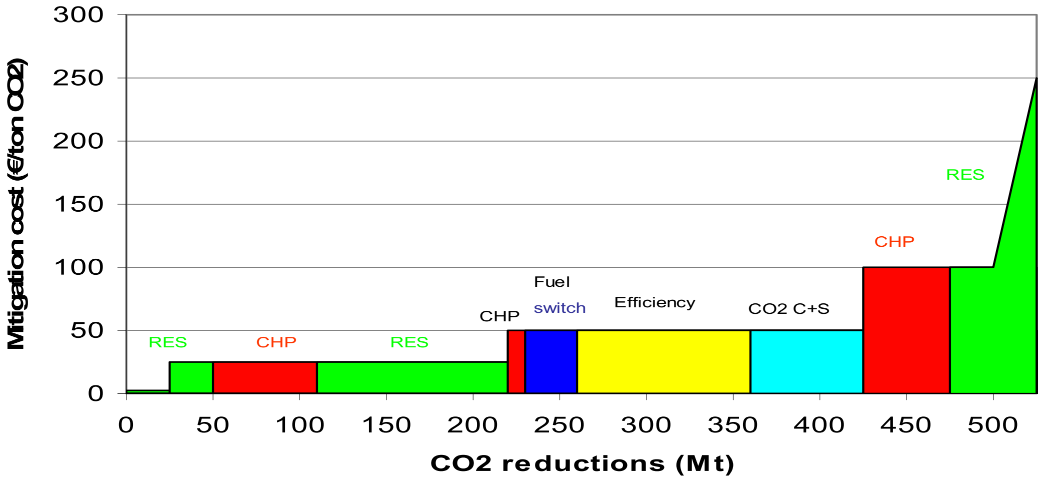


Figure 1: Cost effectiveness of CO_2 reduction technology (source: ECCP)

With regard to GHG, the European Commission has proposed that, from 2005, mandatory emissions limits are placed on all big industrial and energy intensive businesses on a continent-wide scale. There will be a EU-wide emissions trading scheme tailored to suit the Kyoto Protocol. This will draw in five industry sectors across 25 EU Member States and the three EEA States (Iceland, Lichtenstein and Norway). The scheme will cover power generation over 20 MW, including industrial installations, such as refineries, coke ovens, cement, metals, minerals and the pulp and paper industries (but not the chemicals sector) except for hazardous or municipal waste burners. A so-called "Linking Directive" will bring CDMs and Joint Initiatives credits within the emissions trading umbrella. For CO_2 capture and sequestration, it is deemed essential that the use of such technologies can receive credits in the context of these two directives. It would appear that this should be the case since neither directive refers to any particular technology while defining emissions as releases to atmosphere. However, the position needs to be clarified. Specifically in the Emission Trading Scheme, carbon capture and storage qualifies provided projects follow national guidelines, until EU-wide guidelines are developed. Such guidelines can only be heavily based on the outcome of the RTD projects which are on-going in various places. About half of the EU's total CO_2 emissions will be covered by the scheme, with 5,000 firms taking part. It will cover all greenhouse gases but only CO_2 will be traded in the first instance as it accounts for 80% of emissions in the EU. The other gases will be traded from 2008 onwards when the scheme will be extended to other sectors and chemicals will almost certainly be brought in.

International Projections and Comparisons for Energy Use

Following on from the previous point, various scenarios and projections have been made. A key study is the so called WETO Report (2), supported by the EU, which examined the world energy, technology and climate policy outlook in order to provide assistance to decision makers in defining their long term policies. Two of the key results arising from this work are as follows:

- If no specific policy initiatives and measures are taken, world CO_2 emissions are expected to double by 2030 and, with a share of 90%, fossil fuels will continue to dominate the energy system.
- As the largest growing energy demand and CO_2 emissions originate from developing countries, Europe will have to intensify its cooperation, particularly in terms of technology transfer.

The former point is shown in Figure 2, taken from the WETO study (2). Complementary work by the IEA (3) also indicates that on a global scale, coal demand for power generation is expected to double over the period to 2030, with the major increase arising within economies in transition. The IEA estimates that 4500 GW of new power plant will be required, of which coal fired plant is expected to be 40% of this with natural gas providing the very great of the remaining capacity. These projections arise from the recognition that the use of renewables can only be accelerated in the medium to long term both in developed and developing countries.

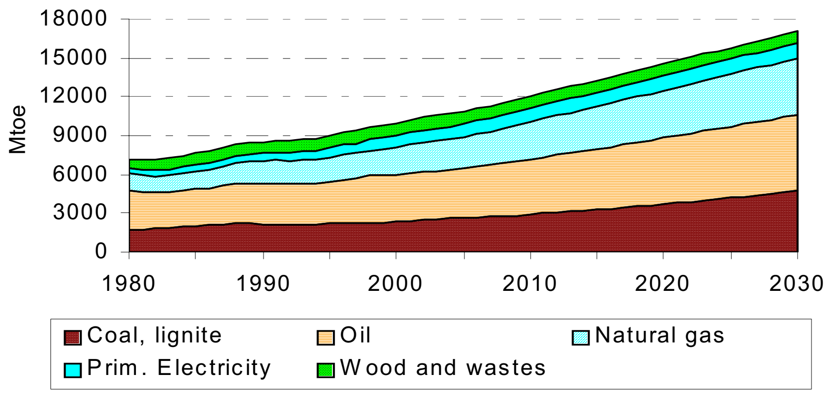


Figure 2: Scenarios and projections – fuels (source: WETO)

With regard to carbon intensity compared to GDP, the WETO report indicates that the EU is amongst the lowest, as shown in Figure 3.

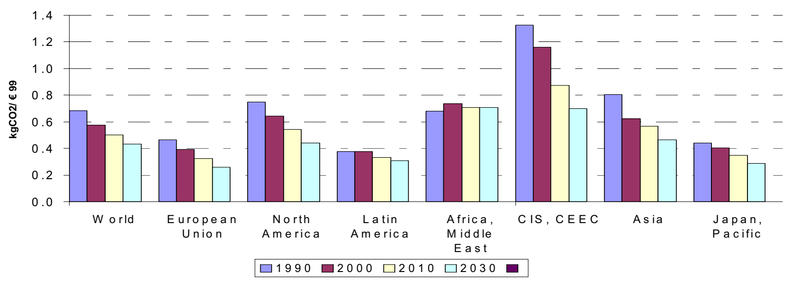


Figure 3: Scenarios and projections (source: WETO) - Carbon intensity of GDP

There are also scenarios and projections for CO_2 emissions per capita. Here, the EU is above the world average but below some other continents, as shown in Figure 4

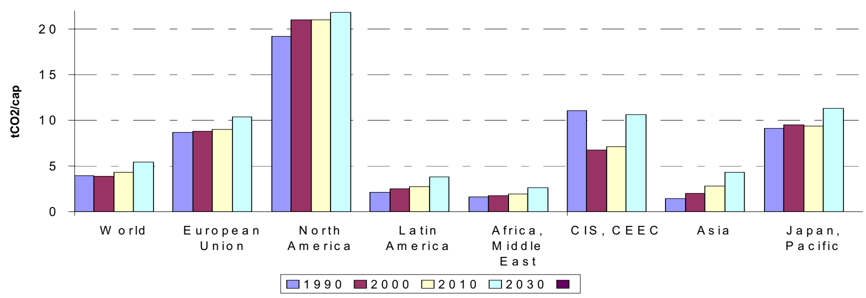


Figure 4: Scenarios and projections (source: WETO) - CO_2 emissions per capita

Key Energy Considerations within the EU

Within the European vision of energy sustainability, key issues include the need for security of energy supply and the need to ensure EU industrial competitiveness in a post Kyoto scenario. These key issues must also be reconciled with environmental protection.

Thus, in this context, within Europe, the EC Green Paper (4) identifies the need to establish a sustainable approach to energy use and management. There is a focus on ensuring diversity of supply while meeting environmental standards and limits through increased use of indigenous renewable energy sources. At the same time, the Green Paper explicitly recognises that doubling the renewables share in the energy supply quota from 6 to 12% and raising their part in electricity production from 14 to 22% is an ambitious objective. Indeed a prevailing view amongst EU energy experts is that the future energy needs of the enlarged EU will require the full range of available fuels (including renewables, nuclear, natural gas, oil and coal) to be utilised on an environmentally acceptable basis to meet the projected overall needs. Such an approach is considered sustainable as it will ensure the necessary diversity and security of supply, provided adequate environmental performance can be achieved. Consequently fossil energy usage will require advanced technologies with near zero emissions. This will mean the use of CO_2 capture and sequestration technologies integrated with the advanced fossil fuel power plant.

The other key issue is EU industrial competitiveness. EU industry needs to be placed in a position to compete globally in a post-Kyoto scenario. Since the expectation is that there will be a major upsurge in new and retrofit power station construction, based on fossil fuels (and subsequently renewables), the need is to ensure that the EU power generation and associated equipment manufacturers can remain competitive for the supply of fossil energy utilisation systems and components, both for EU markets and on a global basis. This will also help ensure a cheap and secure energy supply to all the citizens of Europe. Such systems will, in the medium to long term, need to be equipped with CO_2 capture and sequestration techniques.

In the electricity sector alone, 4500 GW of new generating plant will be required by 2030 to meet the increased demand. This represents a major market opportunity for EU industry to supply such export markets, particularly in Eastern Europe, Asia and Australasia, provided that the necessary technology has been developed and proven. Historically, EU industry has supplied close to 50% of the global market and to date has had an enhanced reputation for innovation in the development of advanced systems and components, much of which has arisen from RTD projects supported by the EU. There will be significant competition from industry in the USA and Japan, where Government support for the development of carbon management techniques is significant, with the recognition that the return on such investment is expected to come from increased export of advanced technology.

The other key point to stress is that the introduction of renewables and fossil fuels with CO_2 capture and sequestration are complementary from a timing point of view, from a generation mix point of view and to ease the penetration of hydrogen as an energy vector. This is a recognition of the fact that, at least in the first phases, most of the hydrogen will be produced from fossil fuel sources.

EU Carbon Management RTD Policy Issues

Within Europe, the challenge is to establish a sustainable energy system that will allow the preservation of equilibrium for ecosystems while also encouraging economic development. The medium to long term objective is to develop and establish new and renewable energy sources and energy vectors, such as hydrogen and electricity, which are affordable, clean and can be readily integrated into a long-term sustainable energy supply and demand structure. It is also recognised that the RTD necessary to achieve such objectives requires resources beyond the capacity of any one Member State. Indeed, the pressure of international competition necessitates an integrated European response. Work toward this goal started within the EU Fifth Framework Programme and this will be taken forward and consolidated within the Sixth Framework Programme that is now implemented.

Within this vision, it is recognised that fossil fuels will continue to be used for the foreseeable future and it is therefore imperative that cost effective solutions are required to establish near zero emissions technologies of a high environmental standard. Accordingly, the capture and sequestration of CO_2 associated with cleaner fossil fuel power plants is deemed to be an essential factor for fossil fuels to be part of the sustainable energy scenario. The approach, which is a priority topic within FP6 (2002-2006), will include both cost effective, safe and environmentally compatible disposal options together with the technology for CO_2 capture thereby enabling cleaner and more efficient fossil fuel plants (5).

There are significant costs involved in CO_2 capture and sequestration, of which capture represents 70-80% of total costs. Therefore, the primary RTD objective for the EU is to decrease the cost of capture. The target is to reduce the costs of CO_2 capture from 50-60 € down to 20-30 € per tonne of CO_2 captured, whilst aiming at achieving capture rates above 90%. Methods include pre-combustion capture (applicable to gasification systems); post-combustion capture and oxyfuels combustion.

There is also a strong need to assess both the reliability and long term stability of CO_2 sequestration in order to map geological storage potential, determine safety aspects and to build public confidence to ensure acceptability. CO_2 sequestration options of interest to the EU include geological based storage in aquifers, depleted oil and gas reservoirs (with the possibility of enhanced oil recovery) and deep un-mined coal beds (that offer the benefit of enhanced coal bed methane recovery). In addition, there are certain chemical techniques and other innovative ways that appear to be promising. At present, the EU's Sixth Framework Programme supports research on oceans and biospheric sinks such as forests and algues, but does not support the development of storage techniques in these sinks, because of the risk potential associated with the degrees of uncertainty in such techniques.

It is also recognised that while the sustainable energy economy is under development, for a transition period, hydrogen is likely to be mostly produced from fossil fuels. For fossil fuel based gasification technologies, when CO_2 is removed from the gas stream the fuel that remains is hydrogen. Thus within the FP6 RTD Programme, there is strong complementarity between the work on capture and sequestration of CO_2 from fossil fuels and another strategic priority, namely the development of new technologies for future energy carriers and converters such as hydrogen and fuel cells (5).

The Current and Proposed EU RTD Portfolio on Carbon Capture and Sequestration

The current portfolio of EU funded research projects is summarised in Table 1 for FP5.

European project acronym	Topic	Total cost (m €)	EC funding (m €)	Coordinator
AZEP	Advanced membrane cycles	9.3	3.4	Siemens
GRACE	Capture in processes	3.2	2.1	BP
GESTCO	Sequestration potential	3.8	1.9	GEUS
CO_2STORE	SACs2 follow up on land	2.4	1.2	Statoil
NASCENT	Natural storage analogues	3.3	1.9	BGS
RECOPOL	Enhanced coal bed methane	3.4	1.7	TNO
WEYBURN	Weyburn monitoring	2.2	1.2	BGS
SACS2	Monitoring of Sleipner	2.1	1.2	Statoil
CO_2NET	Thematic Network	2.1	1.4	Technology Initiatives

Table 1: The current portfolio of EU funded research projects – FP5

This indicates that the EU is contributing some 16 m€ to support nine projects, worth over 30m€ of total investment in FP5. This contains two projects on CO_2 capture, six projects covering CO_2 sequestration and sequestration monitoring and one Thematic Network. An overview of each project is given below:

AZEP

This highly innovative project is carrying out research to develop a new chemical process for the capture of CO_2 from combustion gases in power plant. The project also aims at reducing the cost of pre-combustion capture of CO_2. If successful, it will provide a process for producing an almost pure stream of liquid CO_2 for subsequent storage and as such it complements the various CO_2 sequestration projects in this area.

GRACE

Here, RTD is being undertaken on processes for the capture of CO_2 from non-power producing plants such as refineries. The aim is to produce a step change in the cost of post-combustion adsorption with amines

GESTCO

This study, involving organisations from most Member States, includes geological surveys to study and quantify the CO_2 sequestration potential in terms of sources and sinks in Europe.

CO_2STORE

The aim is to investigate four new potential sites for CO_2 reservoirs, mainly on land. It will continue to undertake reservoir simulations and study geo-chemical reactions in order to develop final-fate prediction models. This study builds on earlier activities by including new seismic observations and introducing differential seismic techniques, better suited for use on land.

NASCENT

This study is examining naturally occurring CO_2 reservoirs to establish the mechanisms that ensure retention of CO_2 over geological periods of time. The results so obtained will have a significant input into establishing the feasibility of sequestration of CO_2. In addition to organisations from the member states, there is also input from the IEA Greenhouse Gas Programme and from partners in the USA.

RECOPOL

This project is designed to provide a larger scale demonstration project of the potential for injecting CO_2 into deep coal seams for storage and in order to displace and collect coal-bed methane for subsequent use. It is being undertaken in a Polish coalfield.

WEYBURN

This project provides support for European teams monitoring the behaviour of CO_2 transported by pipeline from the USA and then used for enhanced oil recovery in the mature and well-documented Weyburn oil field in Canada. The work involves collaboration with partners from the USA and Canada.

SACS2

This project provides support for European teams monitoring the behaviour on CO_2 collected and injected into an aquifer in the North Sea. This is providing valuable data on transport rates, geophysical properties and potential leakage and/or natural sealing mechanisms.

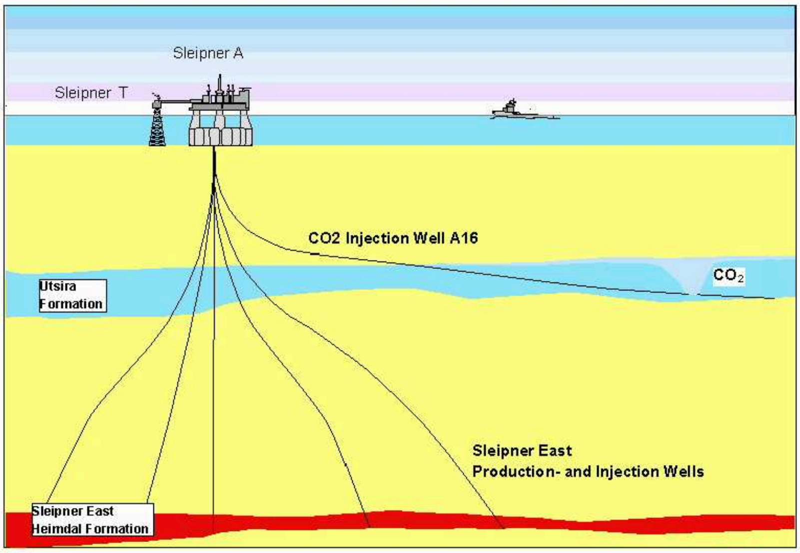


Figure 5: Sleipner – CO_2 injection into the Utsira formation – courtesy of Statoil.

CO_2NET

This is the CO_2 Thematic Network, which brings together the stakeholders in the field to facilitate the development of CO_2 capture and storage; a safe, technically feasible, socially acceptable mitigation option.

The projects listed above are supported within the Fifth RTD Framework Programme of the EU. In addition, there is funding available for this priority RTD area within FP6. The first FP6 call was published in December 2002, with a budget of 198 million € for medium to long-term energy research. Projects started in 2004 and are listed in table 2.

Project acronym	Project type	Topic
ENCAP	IP – Integrated Project	Enhanced capture of CO_2
CASTOR	IP – Integrated Project	CO_2 from capture to storage
CO_2SINK	IP – Integrated Project	In-situ laboratory for capture and sequestration of CO_2
CO_2GeoNet	NoE – Network of Excellence	Network of excellence on geological sequestration of CO_2
ISSC	STREP – Scientific Technical Research Project	Innovative in-situ CO_2 capture technology for solid fuel gasification

Table 2: RTD projects arising from the first call of FP6

The support for these projects reflects the commitment by the EU to continue to create and develop the European Research Area. A short description of each project is given below. These projects represent a total EC funding of the order of 35 m€ and a total cost of the order of 60 m€.

ENCAP

This project has been put forward by major players within the EU power industry to establish the basis for the integration of enhanced CO_2 capture techniques within fossil fuel power plant concepts.

CASTOR

This project builds on earlier work to develop effective, innovative techniques for post-combustion CO_2 capture.

CO_2SINK

This project offers the prospect of a large-scale land based detailed study of CO_2 sequestration, with the basis for an in-situ laboratory being established at the demonstration site.

CO_2GeoNet

This Network of Excellence is designed to bring together the key research institutes to rationalise and share their resources in order to create a critical mass capable of responding positively to the European challenges for geological sequestration of CO_2.

ISCC

This project will undertake RTD to develop innovative techniques for in-situ capture of CO_2 appropriate for solid fuel gasification technologies.

Future Perspectives – FP6 call in 2004

Almost all of the remaining budget of FP6 will be committed following a call for proposals which was recently published on the 8th of September 2004 with a deadline on the 8th of December 2004. Projects are likely to start in late 2005 or early 2006. The call for proposal lists the following topics in the CO_2 sector (please refer to ref. (6) for official and complete information):

- CO_2 capture and hydrogen production from gaseous fuels
- The monitoring and verification of CO_2 geological storage
- Preparing for large scale H2 production from decarbonised fossil fuels including $CO_{2\ g}$eological storage
- Advanced separation techniques
- Mapping geological CO_2 storage potential matching sources and sinks
- European co-ordination and networking activities in CO_2 capture and storage

From a longer term perspective, it is expected that CO_2 capture and storage, and indeed more broadly “near zero emission fossil fuel conversion” (to cover both electricity and hydrogen) will remain an essential component of future framework programmes.

International Cooperation and Coordination Activities

Within the EC, there is a clear recognition that the need to deal with environmental challenges requires an international approach. Accordingly the EC is involved in a wide range of international cooperation and coordination activities that complement the RTD activities that they manage directly.

Thus, the EC takes an active role in the International Energy Agency (IEA) of the OECD. It participates in the “Committee of Energy Research and Technology - CERT” and in the “Working Party on Fossil Fuels - WPFF”, with a particular role in the “Zero Emission Technologies - ZETS” strategy.

It also sponsors and participates in the IEA “Greenhouse Gas” Implementing Agreement and in the IEA “Clean Coal Centre” Implementing Agreement.

In addition, the EU, via the EC, has Science and Technology Cooperation Agreements with many countries such as Argentina, Australia, Brazil, Canada, China, India, Russia, South Africa and the USA. The EC has also signed a Memorandum of Understanding with the US Department of Energy (DoE) and is a Member of the Carbon Sequestration Leadership Forum (CSLF), which is an initiative led by the USA.

At the EU level, within the European Initiative for Growth, a number of “*quick start*” projects will probably be launched to stimulate the European economy. Among the research projects considered is HYPOGEN, a full size demonstration plant for the production of hydrogen from fossil fuels with CO_2 capture and storage. This initiative also underlines the link between CO_2 capture and storage and the future hydrogen economy.

Within the European Union, the EC is involved in the open co-ordination of Member State activities as part of the process for the creation of the European Research Area. At the policy strategy definition level, co-operation may be done through open co-ordination in which Member States voluntarily agree to coordinate amongst themselves in an informal way. With regard to structuring EU RTD work, co-ordination is carried out at the project level through STREPs, IPs, Networking and Co-ordination actions that are the instruments of the EU Framework Programmes . It may also be carried out at the Programme level through ERA-NET activities. Of relevance here is a project in an exploratory phase (FENCO) to undertake a specific support action for Fossil Energy Concerted Actions. The intention is to establish the feasibility for a subsequent co-ordination action that could create the basis for a unified approach within Europe for the development of near zero emissions technologies and carbon management strategies for fossil fuel power generation.

Conclusions

The European Union's research priorities include the need to establish sustainable development, with energy as a key aspect, while ensuring EU industrial competitiveness. The future fuel mix is expected to be diverse, thereby ensuring security of supply, and fossil fuels will be part of that mix provided that environmentally acceptable techniques can be established, with the emphasis on carbon management. Accordingly, when considering a post Kyoto scenario, the development of CO_2 capture and sequestration systems associated with fossil fuel power plants is a key priority within the RTD Framework Programmes of the EU.

There is now a significant RTD Programme that is designed to ensure both cost effective, safe and environmentally compatible disposal options together with the technology for CO_2 capture thereby enabling cleaner and more efficient fossil fuel plants. This is being undertaken by EU industry in collaboration with research institutes and universities. The involvement of EU industry is critical since they are the technology stakeholders that will subsequently have to compete in the global market place.

In addition, there is a clear recognition that the need to deal with global environmental challenges requires an international approach. Accordingly the EC is involved in a wide range of international cooperation and coordination activities that complement the RTD activities that they manage directly.

A great deal of additional information on the European Union is available on the internet.

It can be accessed through the Europa server (http://europa.eu.int).

Legal notice

Neither the European Commission, nor any person acting on behalf of the Commission is responsible for the use which might be made of the information contained in this publication. The views expressed here are those of the authors and do not necessarily reflect those of the European Commission.

References

1 European Climate Change Programme, European Commission Report June 2001.

2 World Energy, Technology and climate policy Outlook 2030, WETO. Official Publication of the EC, Report EUR 20366, Luxembourg 2003.

3 World Energy Outlook, IEA 2002

4 Towards a European Strategy for the Security of Energy Supply, COM(2000) 769 final

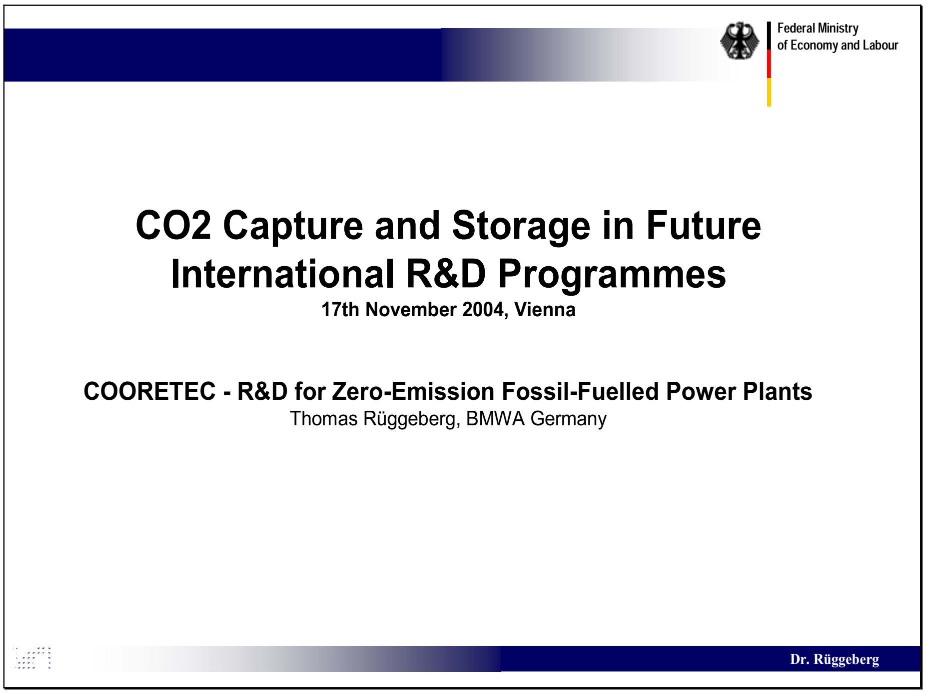
5 First call for FP6 RTD, Official Journal of the EC, 2002

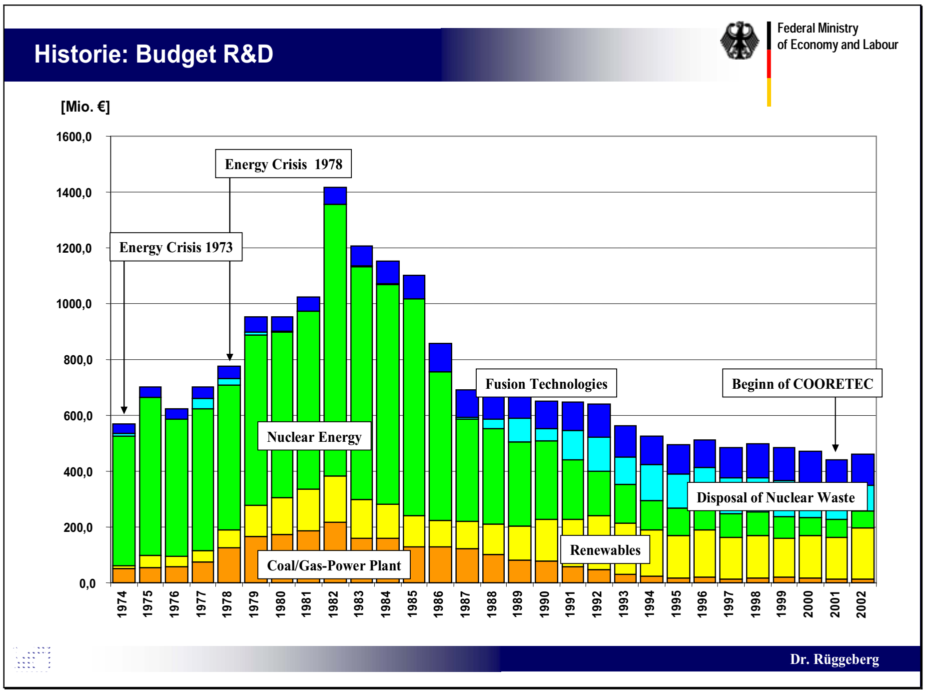
6 Third call for FP6 RTD, Official Journal, 2004, and http://fp6.cordis.lu/fp6/calls.cfm

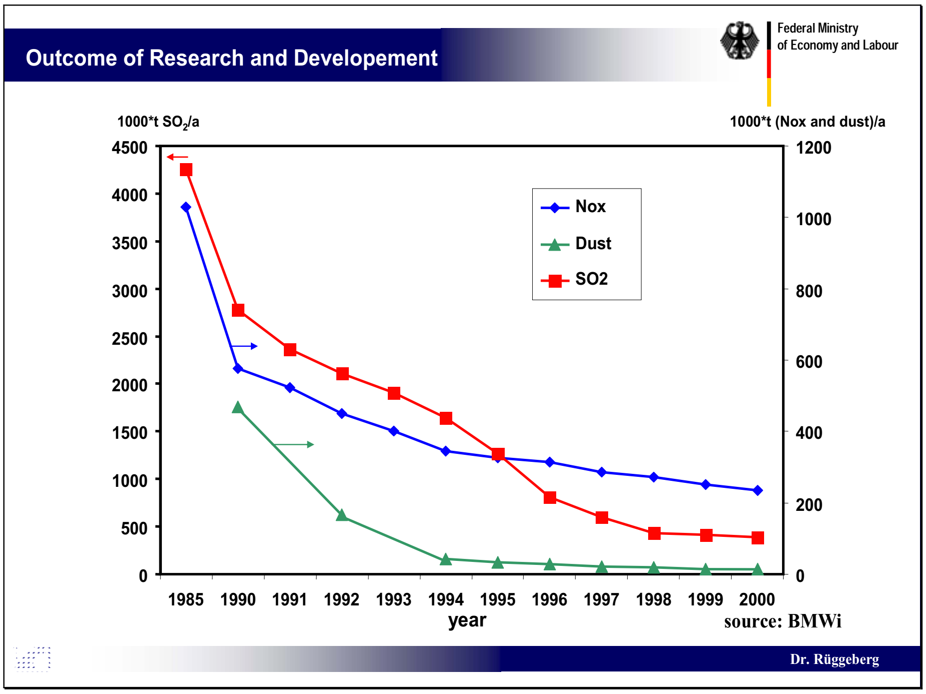
COORETEC – R&D for Zero–Emission Fossil–Fuelled Power Plants

Thomas Rüggeberg (BMWA Federal Ministry of Economics and Labour, Germany)

Ref. IXA8 – Department of Energy Research and Conversion Techniques

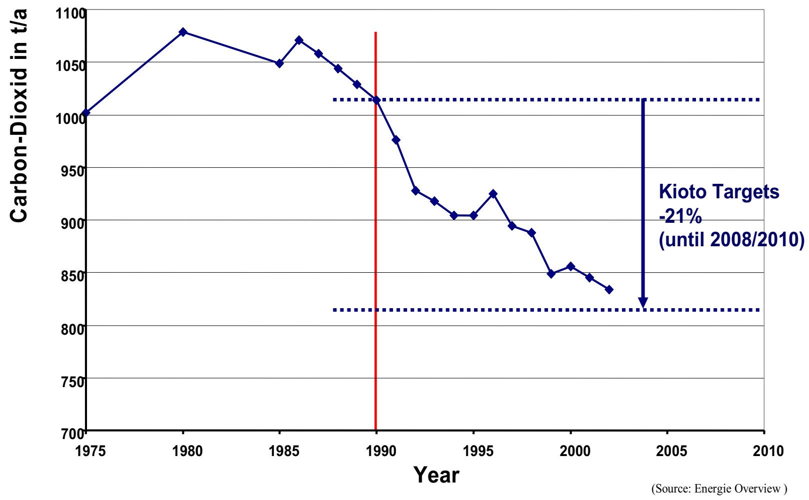



Historie: Budget R&D
Federal Ministry of Economy and Labour
[Mio. €]
1600,0
1400,0
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
Energy Crisis 1978
Energy Crisis 1973
Fusion Technologies
Beginn of COORETEC
Nuclear Energy
Disposal of Nuclear Waste
Renewables
Coal/Gas-Power Plant
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
Dr. Rüggeberg


Outcome of Research and Developement
Federal Ministry of Economy and Labour
1000*t SO2/a
1000*t (Nox and dust)/a
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1200
1000
800
600
400
200
0
Nox
Dust
SO2
1985
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
year
source: BMWi
Dr. Rüggeberg

Emissions: Carbondioxid t/a in Germany

Federal Ministry
of Economy and Labour



(Source: Energie Overview)

Dr. Rüggeberg

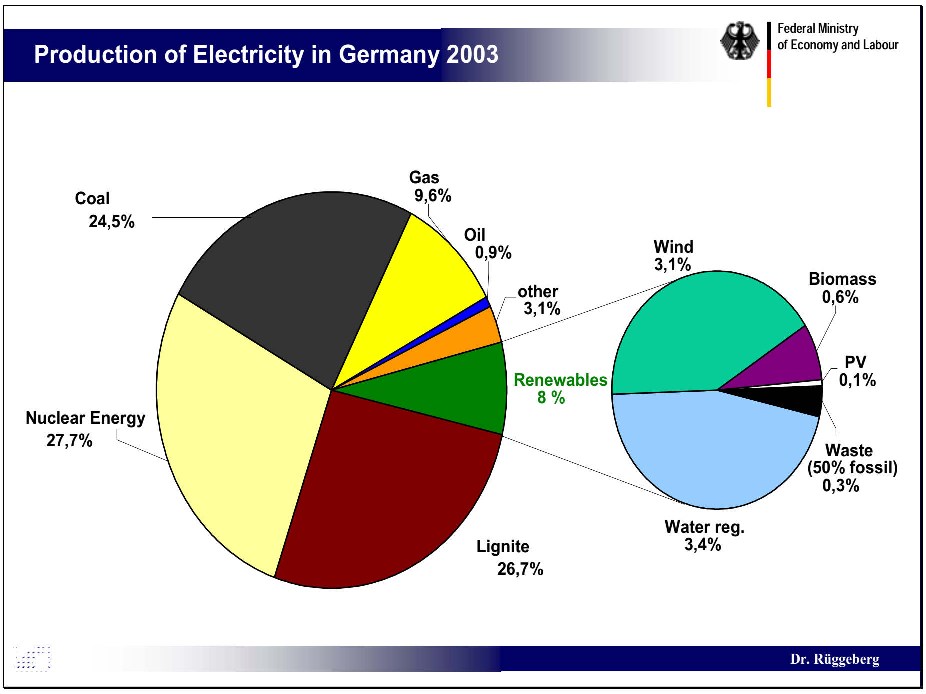
Coalition Agreement 2002

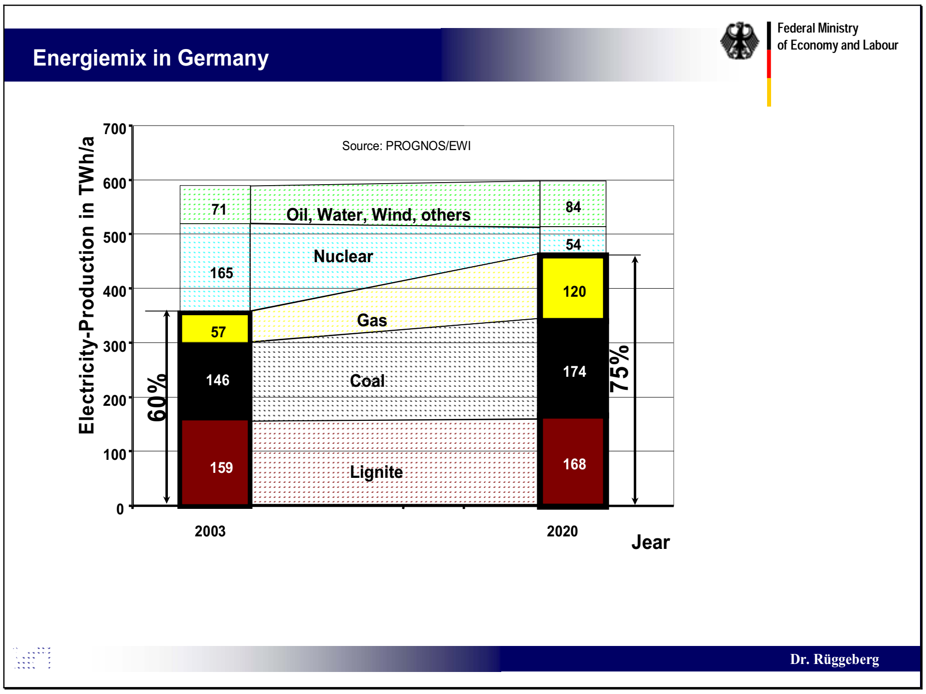
Federal Ministry
of Economy and Labour

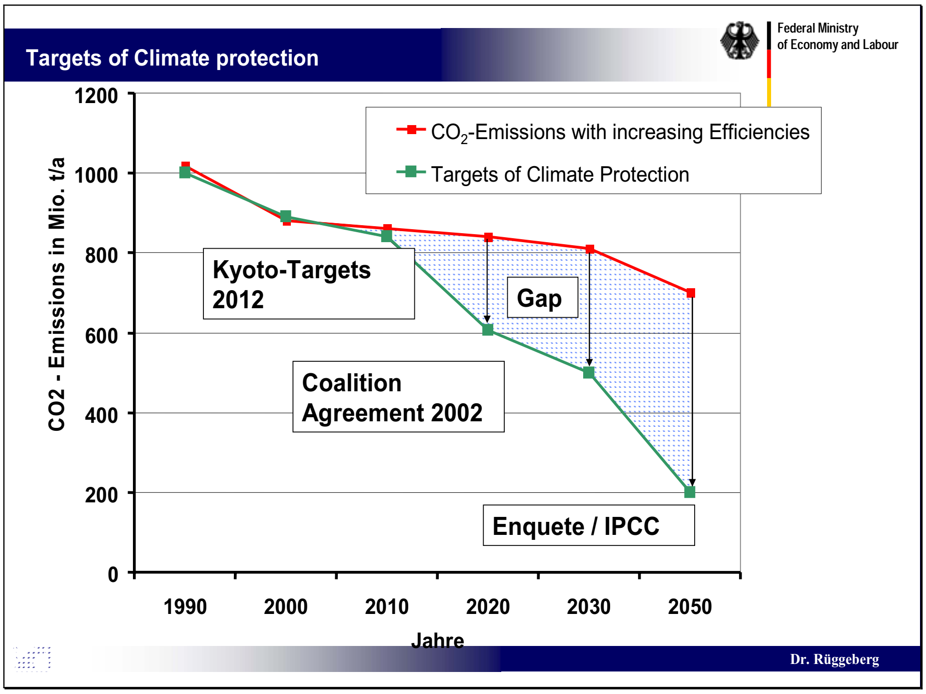
R&D

- Priority for **Renewables** and Energy saving : Doubling of Renewables till 2010.
- **Get off** Nuclear Power till 2020
- Reduce of **Greenhouse Gases** till 2020 about 40% in case that the EU reduce about 30 %

Dr. Rüggeberg


Production of Electricity in Germany 2003
Federal Ministry of Economy and Labour
Coal 24,5%
Gas 9,6%
Oil 0,9%
other 3,1%
Renewables 8 %
Nuclear Energy 27,7%
Lignite 26,7%
Wind 3,1%
Biomass 0,6%
PV 0,1%
Waste (50% fossil) 0,3%
Water reg. 3,4%
Dr. Rüggeberg


Energiemix in Germany
Federal Ministry of Economy and Labour
Source: PROGNOS/EWI
Electricity-Production in TWh/a
700
600
500
400
300
200
100
0
Oil, Water, Wind, others
Nuclear
Gas
Coal
Lignite
71
165
57
146
159
84
54
120
174
168
60%
75%
2003
2020
Jear
Dr. Rüggeberg

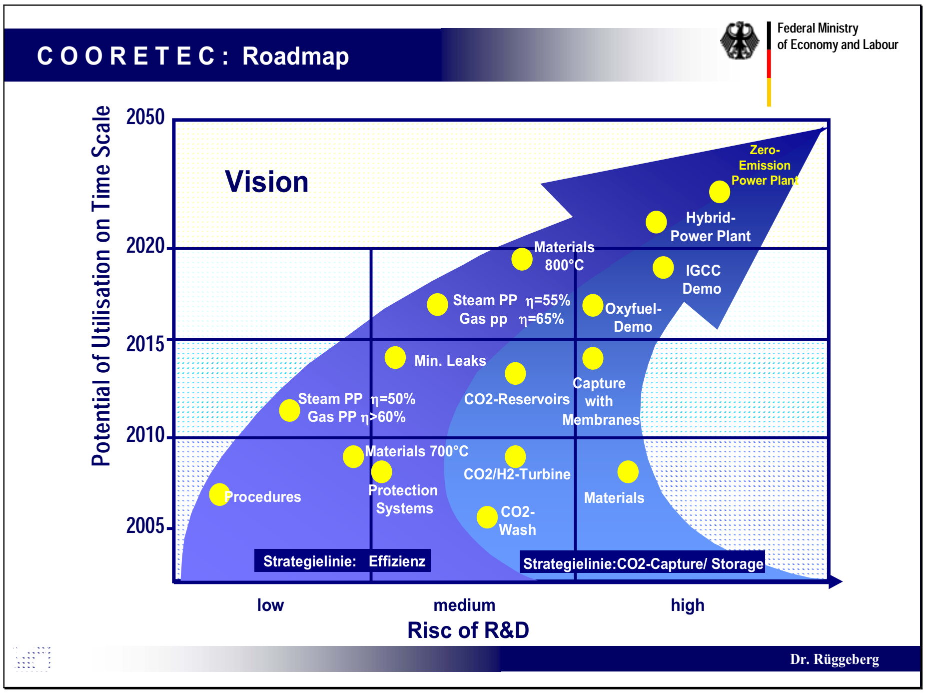


Take interim stock

Federal Ministry of Economy and Labour

1. **Potential** of Efficiency till 2020: + 15 bis 20%
   Demand of Replacement in Germany 40 GW
2. CO_2 -Reduction through **improvements of Efficiencies** : 30%
3. Improving Efficiencies makes get off **Nuclear Energy** without increasing CO2-Emissions..
4. **Kyoto Targets 2012** are available
5. More ambitioned **CO_2-Reduction-Targets** are only available with CO2-Capture and Storage Technologies.

Dr. Rüggeberg

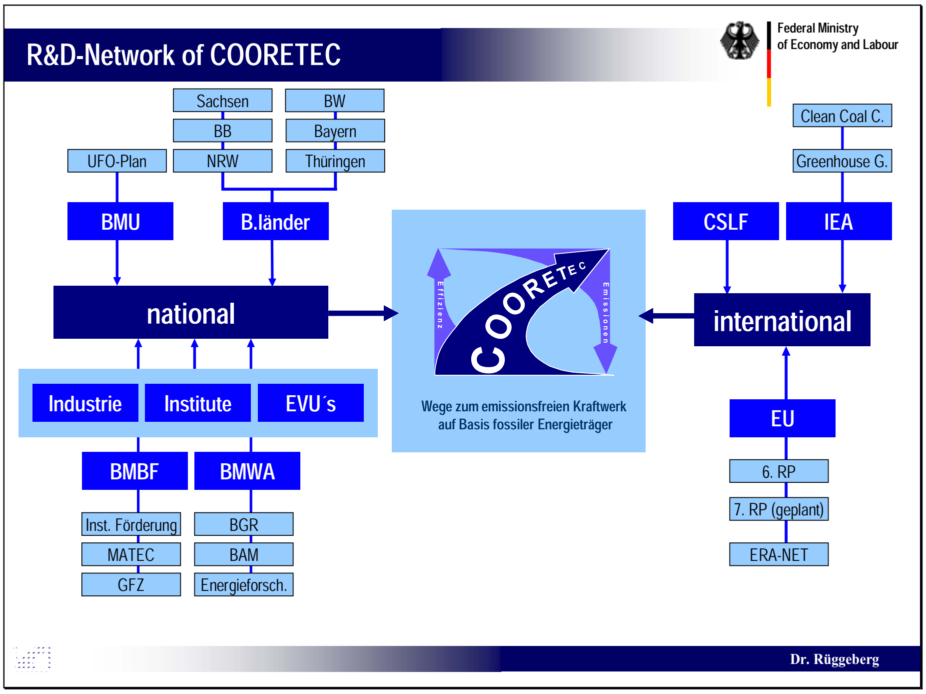


Key-Technologies

Federal Ministry of Economy and Labour

- **Oxyfuels** with decomposition of Air
  O_2 and CO_2-Membranes
  CO_2 and H_2 Turbines
- **Gasificationtechnologies** with Potential of generating new Productlinies: synthetic fuels, chemical Products, electricity, heat
- **New Materials**: nickel based steel, ceramics...
- CO_2 Capture and **Storage** Technologies
- Public **acceptance**

Dr. Rüggeberg



COORETEC: Lighthouse Projects

Federal Ministry
of Economy and Labour

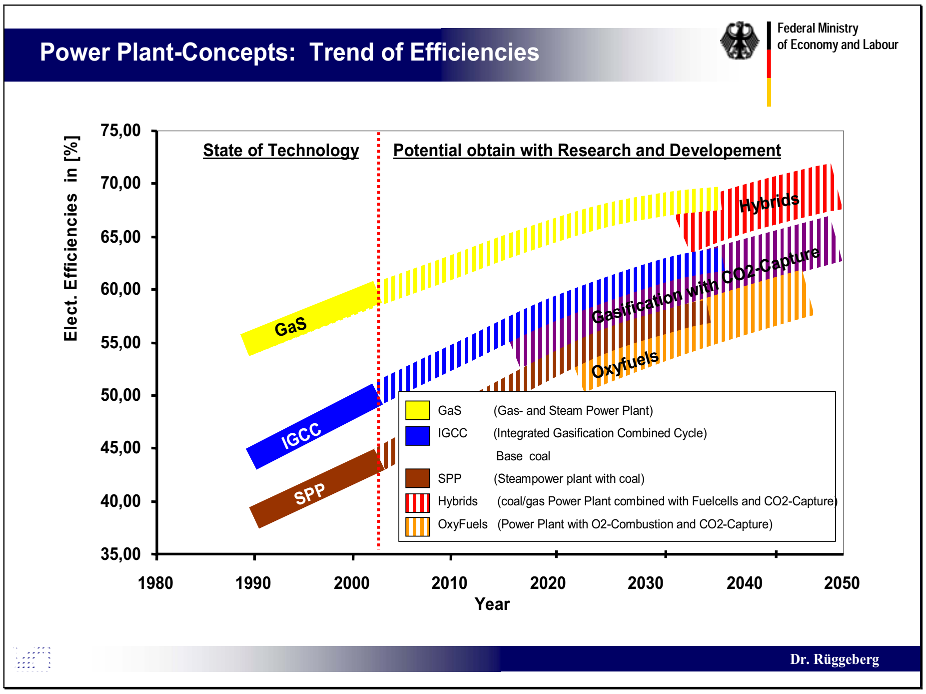
Zero - Emission -Powerplant - Technologies

- **Oxycoal** Power Plant Technology: (Post-Combustion Capture) 9 Mio. €
- **IGCC** and Gasification-technologies and (Pre-Combustion-Capture) 7 Mio. €
- **CO_2-Storage** in Ketzin: CO_2SINK 7 Mio. €

Efficiency of Turbo-components 12 Mio. €

Materials: nickel based steel, protection systems, ceramcics 6 Mio. €

Dr. Rüggeberg



Summery

Federal Ministry
of Economy and Labour

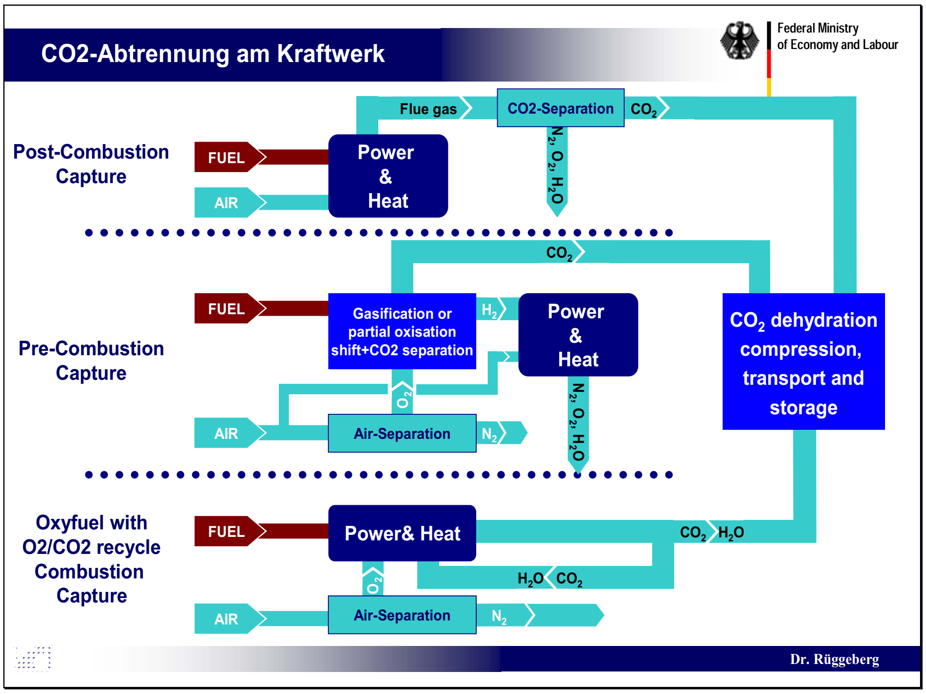
- Increasing share of gas and coal on **Energy Mix** (75% in 2020)
- **Opt out of nuclear Energy** (30% of elctricity-Production) till 2020
- Need of **Replacement**: 40 GW till 2020
- **Potencial** of increasing efficincy is limited to 20 %

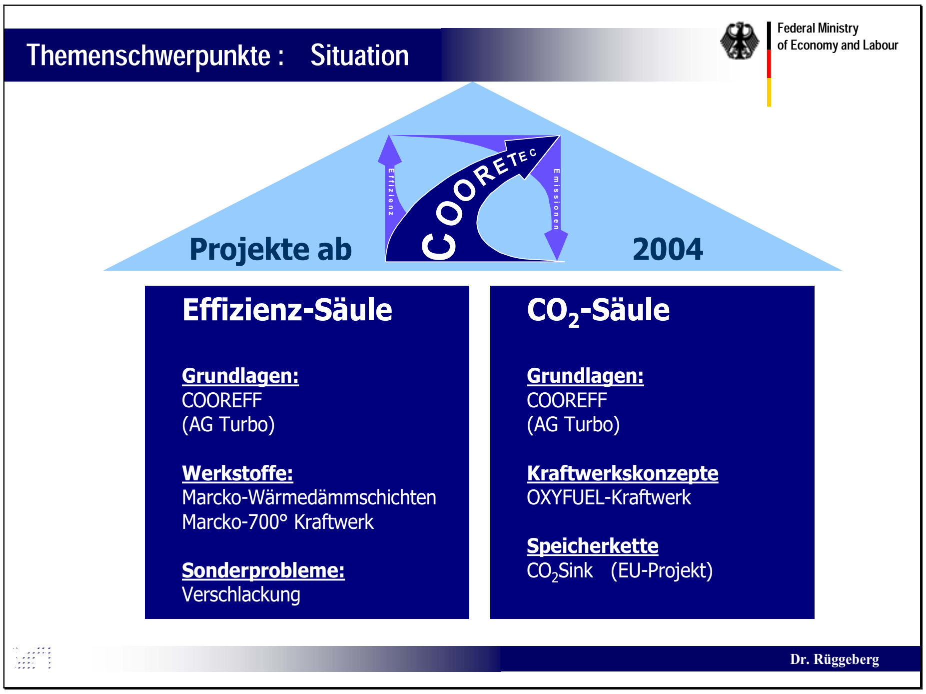
One **Purpose** of Research and Developement is to take **precautions**

COORETEC-Concept:

- Increasing **Efficiencies**: GuD 65%; DKW 55%; IGCC 58% (2020)
- Technologies for **CO2 Capture and Storage**:
- New Prozesses: Precombustion /Postcombustion - Capture
- **Hybridtechnologies**: Powerplant + Fuelcells

Dr. Rüggeberg


CO2-Abtrennung am Kraftwerk
Federal Ministry of Economy and Labour
Post-Combustion Capture
FUEL
AIR
Power & Heat
Flue gas
CO2-Separation
CO_2
N_2, O_2, H_2O
Pre-Combustion Capture
Gasification or partial oxisation shift+CO2 separation
H_2
O_2
Air-Separation
N_2
CO_2 dehydration compression, transport and storage
Oxyfuel with O2/CO2 recycle Combustion Capture
Power& Heat
CO_2 H_2O
H_2O CO_2
Dr. Rüggeberg


Themenschwerpunkte : Situation
Federal Ministry of Economy and Labour
Projekte ab
COORETEC
2004
Effizienz-Säule
Grundlagen:
COOREFF
(AG Turbo)
Werkstoffe:
Marcko-Wärmedämmschichten
Marcko-700° Kraftwerk
Sonderprobleme:
Verschlackung
CO_2-Säule
Grundlagen:
COOREFF
(AG Turbo)
Kraftwerkskonzepte
OXYFUEL-Kraftwerk
Speicherkette
CO_2Sink (EU-Projekt)
Dr. Rüggeberg

Federal Ministry of Economy and Labour

Zusammenfassung:

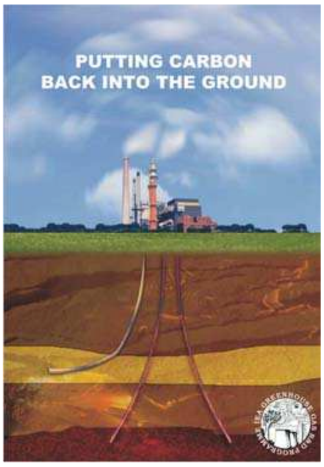
- **Weltenergiebedarf** steigt stark an (2000 GW zusätzlich bis 2020)
- Der **Anteil fossiler Energieträger** an der Stromversorgung >60%
- **Ersatzbedarf** in Deutschland ab 2010 ca. 40 GW
- Ausstieg aus der **Kernenergie** (CO_2-neutral) ist beschlossen
- **Kioto-Ziele**: -21% bis 2012 und -40%- CO_2 bis 2020
- Ziele sind nur durch **Verbesserung der Effizienz** nicht erreichbar
- **Energieforschung:** Schaffung langfristiger technischer Optionen
- **Vorsorgeprinzip:** Option der CO_2 -Abtrennung und Speicherung
- **Es bedarf:** Bündelung nationaler Kräfte
Internationale Kooperationen

Dr. Rüggeberg

CO_2 R&D Capture and Sequestration Activities from the IEA Greenhouse Gas Programme

John Topper (IEA Environmental Projects Ltd - IEA EPL, United Kingdom)

Managing Director of IEA EPL
IEA GHG (Greenhouse Gas) Project Team



This report has been produced by the IEA Greenhouse Gas R&D Programme. Whilst every effort has been made to ensure the accuracy of information contained in this report, the conclusions reached and opinions expressed do not necessarily reflect those of the IEA Greenhouse Gas R&D Programme, its supporting organisations, its Operating Agent, or the International Energy Agency, each of which disclaims liability from the contents of this report. This report has been compiled by J. Davison, P. Freund, and A. Smith.

Cover image by Cotswold Design Studio (Cheltenham, UK).

 ISBN 1 898373 28 0

INTRODUCTION

The need to reduce greenhouse gas emissions

Increasing concentrations of CO_2 and other greenhouse gases in the Earth's atmosphere are enhancing the natural greenhouse effect, leading to changes in the climate. The nature, extent and timing of these changes are uncertain but one of the main changes is expected to be a rise in the global average temperature. Figure 1 shows how the observed average temperature has already increased beyond the likely range of natural variability due to external influences such as volcanic dust and the sun's output.

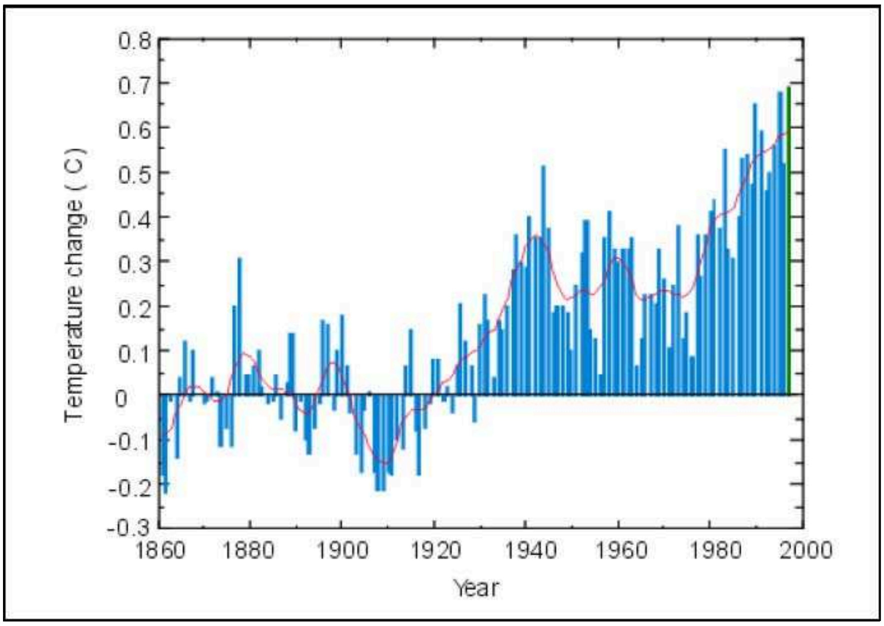


Figure 1: The observed change in global mean temperature at ground level (Courtesy of the UK Met. Office)

It is now generally accepted that limits will have to be placed on the atmospheric concentration of CO_2 and other greenhouse gases in the atmosphere. The UN Framework Convention on Climate Change (UNFCCC) is intended to address this issue. Through the Kyoto Protocol, developed countries agreed to reduce their emissions by 5.2% below 1990 levels, although this protocol has not yet been ratified. However, CO_2 levels are likely to continue increasing, so greater reductions in emissions will be needed in future – for example, emissions of CO_2 may need to be reduced by more than 60% by 2100, in order to stabilise the atmospheric concentration of CO_2 at no more than 50% above its current level.

Techniques for reducing atmospheric CO_2 levels

The main anthropogenic greenhouse gas is CO_2 - this is the subject of this report. Other greenhouse gases, such as methane and nitrous oxide, are not discussed here but opportunities for abatement of methane emissions are summarised in another report by the IEA Greenhouse Gas R&D Programme (see bibliography).

The main techniques which could be used to reduce CO_2 levels in the atmosphere are:

- Reduce the consumption of energy services
- Increase the efficiency of energy conversion or utilisation
- Switch to lower carbon content fuels, e.g. natural gas instead of coal
- Enhance the sinks for CO_2, e.g. forests, soils and the ocean, which draw-down CO_2 from the atmosphere
- Use energy sources with very low CO_2 emissions, such as renewable energy or nuclear energy
- Capture and store CO_2 from fossil fuel combustion.

The extent to which each of these techniques is used will depend on many factors, including the emission-reduction targets, costs, available energy resources, environmental impact and social factors.

Measures for reducing energy consumption and switching to low carbon fuels are cost-effective in many places today and will deliver useful reductions in emissions. Enhancing natural sinks could make a significant contribution in the short term but the capacity of the sinks is limited and carbon stored in, for example forests, is not always secure. Large reductions in emissions could be achieved by widespread switching to renewable energy or nuclear power. However the extent to which those options might be used will be influenced by factors other than just their technical performance.

Capturing CO_2 and storing it underground can be done with available technology but it has only recently been seriously considered as a potential method of reducing emissions. Its importance stems from the fact that, currently, about 85% of the world's commercial energy needs are supplied by fossil fuels. A rapid change to non-fossil energy sources, even if possible, would result in large disruption to the energy supply infrastructure, with substantial consequences for the global economy. The technology of CO_2 capture and storage would enable the world to continue to use fossil fuels but with much reduced emissions of CO_2. In view of the many uncertainties about the course of climate change, further development of CO_2 capture and storage technologies is a prudent precautionary action.

The purpose of this report is to provide an overview of the technology for capture and underground storage of CO_2. It identifies the main opportunities for capturing CO_2 and describes how this would be done in practice. Transporting and storing CO_2 is then described. Some of the factors which will influence application, including environmental impact, cost and efficiency, are presented and, finally, the future prospects for the technology are discussed.

IEA Greenhouse Gas R&D Programme

This report has been produced by the IEA Greenhouse Gas R&D Programme (IEA GHG). IEA GHG is an international collaboration of governments and industries from many countries, with several linked objectives:

- To identify and evaluate technologies that could be used to reduce the emissions of greenhouse gases arising from the use of fossil fuels;
- To disseminate the results of those evaluations;
- To identify targets for research, development and demonstration, and promote the appropriate work.

IEA GHG was established in 1991 and, since then, its main focus has been on capture and storage of CO_2. It has also examined a wide range of other technologies, including carbon sequestration in forests, renewable energy sources (biomass and wind energy) and methods for reducing emissions of non- CO_2 greenhouse gases. This helps to put in perspective the potential of capture and storage of CO_2.

WHERE CAN CO_2 BE CAPTURED?

Capture of CO_2 is best carried out at large point sources of emissions, such as power stations, which currently account for about a third of global CO_2 emissions. Other large point sources include oil refineries, petrochemical, fertiliser and gas processing plants, steel works and pulp and paper mills. This report will concentrate on large scale power generation but many of the points would also be applicable to the other major energy-using industries.

Capture in power generation

The main technologies used to generate power from fossil fuels are, currently, natural gas combined cycles and pulverised coal-fired steam cycles. Integrated Gasification Combined Cycles (IGCC) are also being developed, although they are generally considered to be not yet economically competitive. CO_2 capture could be incorporated in all of these types of plant. These technologies are described below. How they could be adapted to include CO_2 capture is described in the following section.

Pulverised coal-fired steam cycle

This has been the main power generation technology for more than 50 years. Pulverised coal is burned in a boiler which raises high pressure steam, which is then passed through a steam turbine, generating electricity. The efficiencies of modern coal fired power plant are around 40%. Plant with efficiencies of around 47%[1] have been built; such plant use higher steam temperatures and higher steam pressures. The key requirement in the development of higher efficiency steam cycle plant is the development of new materials (e.g. nickel and chromium alloys). Attempts are being made to develop materials for steam conditions up to 375bar/700°C, which would result in efficiencies of up to 55% at favourable Northern European coastal sites. Reaching these conditions may take up to 15 years.

An alternative to pulverised coal combustion is fluidised bed combustion. This is not discussed in detail in this report because the efficiencies, emissions and costs of fluidised bed combustion power plants are broadly similar to those of pulverised coal plants and the way in which CO_2 capture would be introduced is very similar.

[1] On a lower heating value basis – this is used throughout this report.

Figure 2: A modern coal fired power station (Courtesy of Elsam)

Natural gas combined cycle

Natural gas is burned in a gas turbine, which generates electricity. The hot exhaust gas from the gas turbine is fed to a boiler which generates steam, which is then passed through a steam turbine, generating more electricity. Natural gas combined cycles have been introduced mainly during the last 10 years, as the market for natural gas for power generation has become deregulated. World-wide, gas turbine based systems are taking well over half of the market for power plant. Large, commercial gas turbine combined cycle plant typically have thermal efficiencies of up to 56-58%. Within the next three years it is likely that efficiencies of 60% will be established as state-of-the-art and significantly higher efficiencies are expected to be achieved in future.

Figure 3: A natural gas combined cycle power station (Courtesy of PowerGen)

IGCC

In this type of plant, fuel is reacted with oxygen and steam in a gasifier to produce a fuel gas consisting mainly of carbon monoxide and hydrogen. This is then cleaned and burned to generate power in a gas turbine combined cycle. The IGCC concept enables the use of fuels such as residual oil and coal in plant with the high efficiencies of a combined cycle; it also results in very low emissions of pollutants such as sulphur dioxide. The efficiencies of IGCC plants will increase in future in line with those of gas turbine combined cycles but IGCC plants are likely to be less efficient, by about 10 percentage points, because of the energy losses associated with gasification and gas cleaning.

The components of IGCC have been developed over many years. Gasifiers were first used in Germany immediately prior to World War II and were further developed in South Africa in the early 1980s. Over 300 gasifiers are reported to be in operation but most of these are producers of synthesis gas (CO, hydrogen and CO_2 mixtures) as an intermediate stage in chemicals production. Commercial-scale coal IGCC demonstration plants have been built in the USA, Netherlands and Spain. There is also a major interest in the oil industry in gasification of refinery residues to produce electricity and/or hydrogen and three large plants are being built in Italy. IGCC has been successfully demonstrated but the capital cost needs to be reduced and the reliability and operating flexibility needs to be improved to make it widely competitive in the electricity market.

Other Opportunities for CO_2 Capture

Major energy using industries

Four major industries account for about three quarters of total industrial CO_2 emissions, equivalent to about half of the emissions from power generation (Table 1 shows data for 1994-1996). These industries may present further opportunities for capturing CO_2 for storage. Aluminium production is another major energy using industry but most of its CO_2 emissions (over 300 million tonnes/y) arise from the generation of the electricity used by this industry.

About two thirds of the CO_2 emissions from oil refineries come from fired heaters. The flue gas from these heaters is similar to the flue gas in power stations, so CO_2 could be captured using the same techniques and at broadly similar costs. About 60% of the CO_2 emitted by the iron and steel industry is in the off-gas from blast furnaces; both this and the newer direct reduction processes would be suitable applications for CO_2 capture. CO_2 emitted in the flue gases from cement production could also be captured using similar techniques. Flue gases at large point sources in other industries may also be suitable for CO_2 capture.

	CO_2 emissions Million tonnes/year
Iron and steel production	1440
Cement manufacture	1130
Oil refining	690
Petrochemicals	520
Other industry	1320
Overall industry	5100
Power generation	7660

Table 1: CO_2 emissions by major industries Sources:
IEA GHG (individual industries), OECD Environmental Data 1997 (overall), IEA World Energy Outlook 1998 (power generation).

In some other industries, for example production of hydrogen for ammonia, fertilisers and processing of natural gas, CO_2 is already being separated. Most of this CO_2 is vented to the atmosphere but it could be stored underground at little extra cost. This could provide useful opportunities to demonstrate the feasibility of CO_2 transport and storage, as well as early application as a mitigation technique. The first example of this being done on a commercial scale is the Sleipner Vest gas field in the Norwegian sector of the North Sea, where CO_2 separated from natural gas is injected into an underground saline reservoir.

Figure 4 : Oil and gas production facilities, in the Sleipner field (Courtesy of Statoil)

Energy carriers for distributed energy users

A large amount of fossil fuel is used in transport, e.g. cars or aircraft, and in small-scale heat or power production. It is not practicable to capture, collect, and store CO_2 from such sources using current technologies. Nevertheless, large reductions could be made in CO_2 emissions from these dispersed sources, through use of a carbon-free energy carrier, such as hydrogen. Hydrogen is often considered as a carrier for energy from renewable sources. However, it can also be produced from fossil fuels, using capture and storage technology to minimise release of CO_2. Production of hydrogen from fossil fuels with CO_2 storage could be an attractive transitional strategy to aid the introduction of hydrogen as an energy carrier.

HOW CAN CO_2 BE CAPTURED?

There are two basic options for capture of CO_2 in power stations: post-combustion or pre-combustion.

Post-combustion capture

CO_2 is only a small part of the flue gas stream emitted to atmosphere by a power station (Table 2). Other gases include nitrogen, oxygen and water vapour. It would be impractical to store flue gases underground because there would be insufficient storage space and because too much energy would be needed to compress the flue gas. Some method of separation is therefore required to capture the CO_2.

	CO_2 concentration in flue gas vol %, approx.)
Pulverised coal fired	14
Coal fired IGCC	9
Natural gas combined cycle	4

Table 2: CO_2 concentration in power station flue gas

CO_2 can be captured using technologies that have been developed and proved in other applications.

A variety of techniques are available - the main one in use today for separating CO_2 from flue gases or other gas streams is scrubbing the gas stream using an amine solution. After leaving the scrubber, the amine is heated to release high purity CO_2 and the CO_2 -free amine is then reused. Figure 5 is a simplified diagram of a gas turbine combined cycle power station with post-combustion capture of CO_2. Such techniques can also be applied to coal fired power stations but with some additional cleaning of the flue gases. In many respects, post-combustion capture of CO_2 is analogous to flue gas desulphurisation (FGD), which is widely used on coal- and oil-fired power stations to reduce emissions of SO2.

The low concentration of CO_2 in flue gas means that a large volume of gas has to be handled, resulting in large and expensive equipment. A further disadvantage of the low CO_2 concentration is that powerful solvents have to be used to capture CO_2 - regeneration of these solvents, to release the CO_2, requires a large amount of energy. The CO_2 concentration can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or gas turbine. If fuel is burnt in pure oxygen, the flame temperature is excessively high, so some CO_2 -rich flue gas would be recycled to the combustor to make the flame temperature similar to that in a normal combustor. The advantage of oxygen-blown combustion is that the flue gas has a CO_2 concentration of typically >90%, so only simple CO_2 purification is required. The disadvantage is that production of oxygen is expensive, both in terms of capital cost and energy consumption.

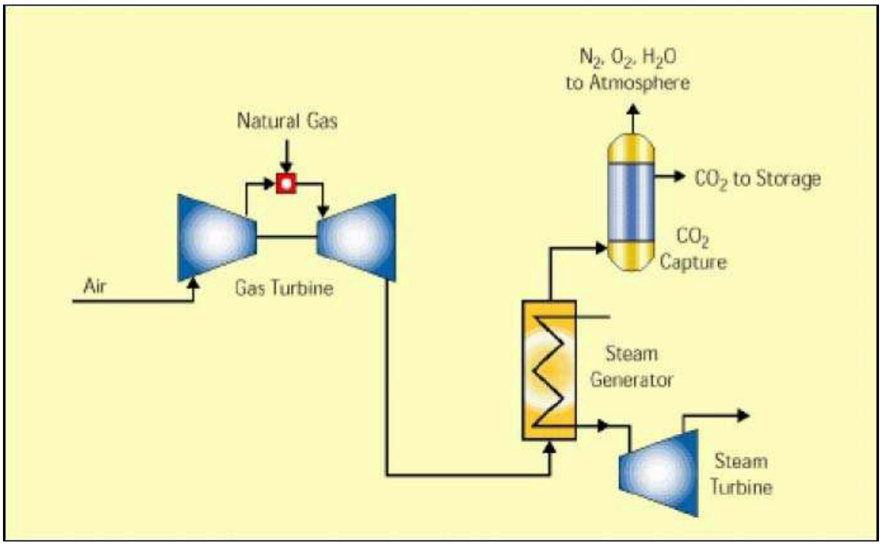


Figure 5: Gas turbine combined cycle with post-combustion capture of CO_2

Pre-combustion capture

An alternative way to increase the CO_2 concentration and partial pressure is to use pre-combustion capture. This involves reacting the fuel with oxygen and/or steam to give mainly carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is then separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process is, in principle, the same for coal, oil or natural gas. Figure 6 is a simplified diagram of a coal-fired power plant with pre-combustion capture of CO_2.

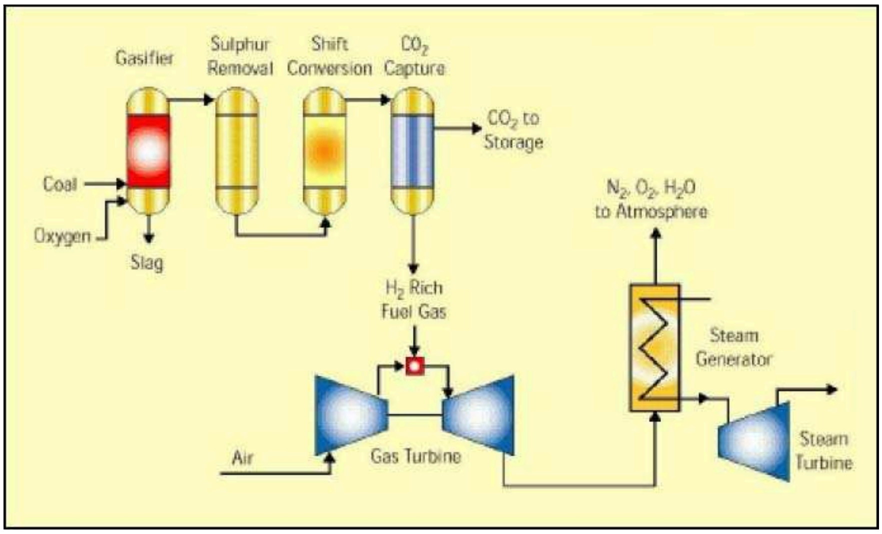


Figure 6: Coal fired IGCC with pre-combustion capture of CO_2

Although pre-combustion capture involves a more radical change to the power station design, most of the technology is already well proven in ammonia production and other industrial processes. One of the novel aspects is that the fuel gas is essentially hydrogen. It is expected that it will be possible to burn hydrogen in an existing gas turbine with little modification but this is not commercially proven technology. At least two gas turbine manufacturers are known to have undertaken tests on combustion of hydrogen-rich fuels.

The hydrogen produced in pre-combustion capture processes could, alternatively, be used to generate electricity in a fuel cell. The technology of capture and storage is therefore expected to be suitable for future as well as current power generation technologies.

CO_2 capture technologies

Solvent scrubbing

Amine scrubbing technology was established over 60 years ago in the oil and chemical industries, for removal of hydrogen sulphide and CO_2 from gas streams. Commercially, it is the most well established of the techniques available for CO_2 capture although practical experience is mainly in gas streams which are chemically reducing, the opposite of the oxidising environment of a flue gas stream. There are several facilities in which amines are used to capture CO_2 from flue gas streams today, one example being the Warrior Run coal fired power station in the USA, shown in Figure 7, where 150 t/d of CO_2 is captured.

Figure 7: CO_2 capture plant at Warrior Run power station, Cumberland, USA (Courtesy of AES)

Mono-ethanolamine (MEA) is a widely used type of amine for CO_2 capture. CO_2 recovery rates of 98% and product purity in excess of 99% can be achieved. There are, however, questions about its rate of degradation in the oxidising environment of a flue gas and the amount of energy required for regeneration. Improved solvents could reduce energy requirements by as much as 40% compared to conventional MEA solvents. There is considerable interest in the use of sterically-hindered amines which are claimed to have good absorption and desorption characteristics.

The conditions for CO_2 separation in pre-combustion capture processes will be quite different from those in post-combustion capture. For example, in a coal IGCC process, modified for capture, the CO_2 concentration would be about 35-40% at a pressure of 20 bar or more. In that case, physical solvents, such as Selexol®, could be used for pre-combustion capture of CO_2, with the advantage that the CO_2 can be released mainly by depressurisation, thereby avoiding the high heat consumption of amine scrubbing processes. However, depressurisation of the solvent still results in a significant energy penalty. Physical solvent scrubbing of CO_2 is well established, e.g. in ammonia production.

Cryogenics

CO_2 can be separated from other gases by cooling and condensation. Cryogenic separation is widely used commercially for streams that already have high CO_2 concentrations (typically >90%) but it is not used for more dilute CO_2 streams. A major disadvantage of cryogenic separation of CO_2 is the amount of energy required to provide the refrigeration necessary for the process, particularly for dilute gas streams. Another disadvantage is that some components, such as water, have to be removed before the gas stream is cooled, to avoid blockages. Cryogenic separation has the advantage that it enables direct production of liquid CO_2, which is needed for certain transport options, such as transport by ship. Cryogenics would normally only be applied to high concentration, high pressure gases, such as in pre-combustion capture processes or oxygen fired combustion.

Membranes

Gas separation membranes allow one component in a gas stream to pass through faster than the others. There are many different types of gas separation membrane, including porous inorganic membranes, palladium membranes, polymeric membranes and zeolites. Membranes cannot usually achieve high degrees of separation, so multiple stages and/or recycle of one of the streams is necessary. This leads to increased complexity, energy consumption and costs. Several membranes with different characteristics may be required to separate high-purity CO_2. Solvent assisted membranes are being developed to combine the best features of membranes and solvent scrubbing. Much development is required before membranes could be used on a large scale for capture in power stations.

Adsorption

Solid adsorbents, such as zeolites and activated carbon, can be used to separate CO_2 from gas mixtures. In pressure swing adsorption (PSA), the gas mixture flows through a packed bed of adsorbent at elevated pressure until the concentration of the desired gas approaches equilibrium. The bed is regenerated by reducing the pressure. In temperature swing adsorption (TSA), the adsorbent is regenerated by raising its temperature. PSA and TSA are commercially practiced methods of gas separation and are used to some extent in hydrogen production and in removal of CO_2 from natural gas. Adsorption is not yet considered attractive for large-scale separation of CO_2 from flue gas because the capacity and CO_2 selectivity of available adsorbents is low. However, it may be successful in combination with another capture technology.

TRANSPORT OF CO_2

After capture, CO_2 would be transported to the storage site. CO_2 is largely inert and easily handled and it is already transported in high pressure pipelines. About 90 million tonnes/year of CO_2 is currently transported by pipeline in the USA. The longest pipeline at present is the Sheep Mountain pipeline, which is 656 km long. If CO_2 capture and storage became widely used, pipeline grids such as those used for natural gas distribution would probably be built, to improve operating flexibility and provide economies of scale.

Ships would be used for long distance transport of CO_2. Although CO_2 is not transported by ship at present, tankers similar to those currently used for liquefied petroleum gas (LPG), shown in Figure 8, could be used.

Figure 8: An LPG tanker - CO_2 could be transported in a similar way (Courtesy of Mitsubishi Heavy Industries Ltd.)

At high concentrations, CO_2 is an asphyxiant and, because it is heavier than air, it will tend to collect in depressions. The risks of problems due to pipe leakage are very small but, to minimise risks, CO_2 pipelines could be routed away from large centres of population. Some intermediate storage of CO_2 will be needed to cope with variability in supply, transport and storage, particularly if CO_2 is transported by ship. Other potentially hazardous gases such as natural gas, ethylene and LPG are already stored, with very few problems. The same safety considerations would need to be applied to intermediate storage of CO_2.

It is typically cheaper to pipe CO_2 than to transmit electricity. It would therefore be cheaper to locate power stations close to electricity demand and transport the CO_2 as necessary to the storage site. However, if transport of CO_2 is a major concern, power stations could be built close to the storage sites.

UNDERGROUND STORAGE OF CO_2

For CO_2 storage to be an effective way of avoiding climate change, the CO_2 must be stored for several hundreds or thousands of years. CO_2 storage also needs to have low environmental impact, low cost and conform to national and international laws. The main options for storing CO_2 underground are in depleted oil and gas reservoirs, deep saline reservoirs and unminable coal seams, as shown in Figure 9. Storage of CO_2 in the deep ocean has also been proposed; this is summarised in another report by IEA GHG (see bibliography)

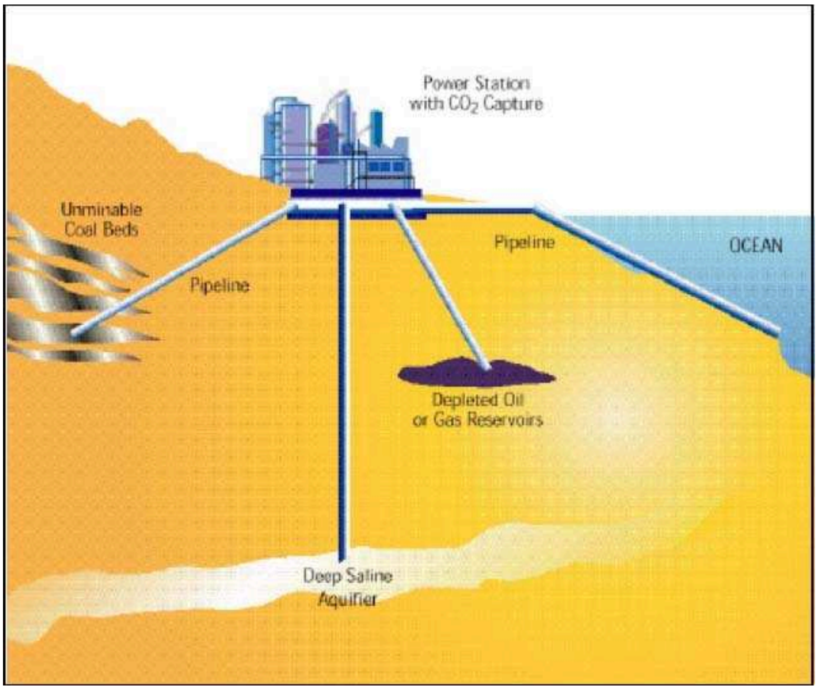


Figure 9: Options for storage of CO_2

Depleted oil and gas reservoirs

Oil and gas reservoirs consist of porous rocks covered by impermeable cap rock, which is often dome shaped. Following more than a century of intensive petroleum exploitation, thousands of oil and gas fields are approaching the ends of their economically productive lives. Some of these depleted fields could act as effective storage sites for CO_2.

Depleted oil and gas fields have a number of attractive features as CO_2 storage reservoirs:

- Exploration costs would be small
- The reservoirs are proven traps, known to have held liquids and gases for millions of years
- The reservoirs have well known geology
- There is potential to re-use some parts of the hydrocarbon production equipment to transport and inject the CO_2.

In most oil fields only a portion of the original oil in place is recovered using standard petroleum extraction methods. CO_2 injected into suitable, depleted oil reservoirs can enhance oil recovery by typically 10-15% of the original oil in place in the reservoir. This is an established technique, called CO_2 -EOR (enhanced oil recovery), which is illustrated in Figure 10. The additional oil production could, in certain circumstances, more than offset the cost of CO_2 capture and injection.

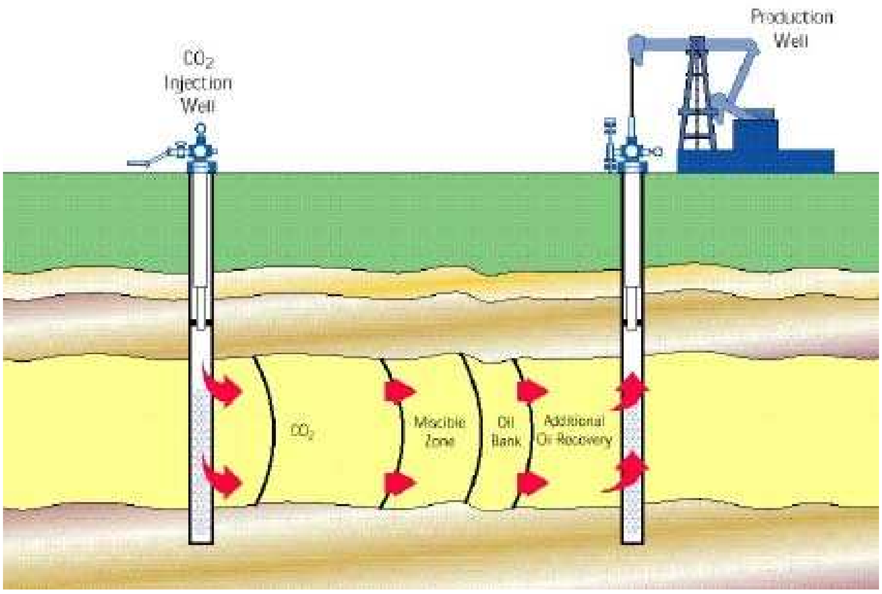


Figure 10: CO_2 enhanced oil recovery

About 33 million t/y of CO_2 is already used at more than 74 EOR projects in the USA - most of this CO_2 is extracted from natural reservoirs but some is captured, as described above, from natural gas plants and ammonia production. A further 6 million t/y of CO_2 has been injected as part of a large CO_2 -EOR project in Turkey. An example of a CO_2 -EOR scheme using anthropogenic CO_2 is the Weyburn project in Canada. CO_2 captured in a large coal gasification project in North Dakota, USA is to be transported 200 miles by pipeline and injected into the Weyburn field in Saskatchewan. Initially 5 000 tonnes per day of CO_2 will be injected. An international research project, organised through the IEA Greenhouse Gas R&D Programme, will aim to determine how effective this CO_2 storage will be over the long term.

Depleted natural gas fields are also feasible sites for CO_2 storage. Underground storage in natural reservoirs has been an integral part of the natural gas industry for many decades. Natural gas is routinely injected into, stored and withdrawn from hundreds of underground storage fields. Some depleted gas fields could be adapted easily for storage of CO_2.

Figure 11: Weyburn CO_2 EOR project (Courtesy of Saskatchewan Energy and Mines)

There will need to be some changes in current practice in order to make use of depleted oil and gas reservoirs for CO_2 storage. For example, operational procedures for EOR with CO_2 storage may differ significantly from current EOR schemes. Transfer of ownership of a depleted field from the licensed operator to a storage operator is, as yet, an untried procedure. Also, abandoned fields will still contain oil and gas resources, which potentially have economic value if oil prices were to rise enough or new EOR technologies were developed in future. All of these aspects will be need to be addressed in order to make use of depleted oil and gas fields for CO_2 storage.

Deep saline reservoirs

There are many underground, water-filled strata (aquifers) that could potentially be used to store CO_2. The aquifers that would be used for CO_2 storage are deep underground, contain saline water and are unsuitable for supplying potable water. CO_2 would partially dissolve in the water in the aquifer and in some formations it would slowly react with minerals to form carbonates, which would lock up the CO_2 essentially permanently. Suitable aquifers would have a cap rock of low permeability to minimise CO_2 leakage. Injection of CO_2 into deep saline reservoirs would use techniques similar to those for disused oil and gas fields.

Nearly a million tonnes per year of CO_2 is already being injected into a deep saline reservoir under the Norwegian sector of the North Sea in conjunction with gas production from the Sleipner Vest gas field. When this injection began in 1996 it marked the first instance of CO_2 being stored in a geological formation because of climate change considerations.

CO_2 removed from a natural gas stream, which would normally be discharged to the atmosphere, is being stored underground. The storage reservoir is the Utsira formation, which is a sand formation extending under a large area of the North Sea at a depth of about 800m. The flows of CO_2 injected at Sleipner are being monitored and modelled as part of an international project established by Statoil with the IEA Greenhouse Gas R&D Programme. This work should help in the design and operation of future CO_2 injection projects.

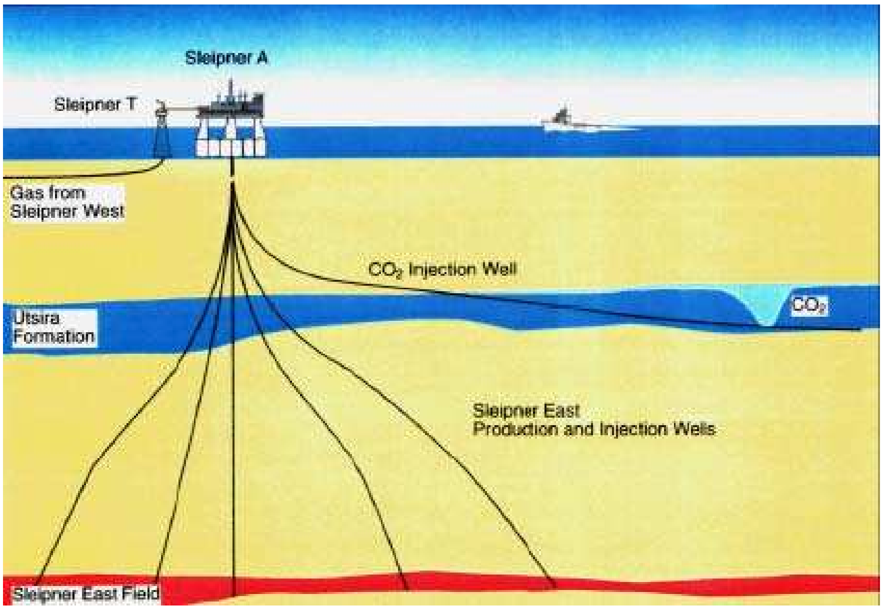


Figure 12: CO_2 injection into the Utsira deep saline reservoir (Courtesy of Statoil)

Unminable coal seams

Another potential storage medium is unminable coal. CO_2 can be injected into suitable coal seams where it will be adsorbed onto the coal, locking it up permanently provided the coal is never mined. Moreover, it preferentially displaces methane that exists in the coal. Methane is already extracted from coal seams by depressurisation but this typically recovers only about 50% of the gas in place. Injection of CO_2 enables more methane to be extracted, while at the same time sequestering CO_2. Coal can adsorb about twice as much CO_2 by volume as methane, so even if the recovered methane is burned and the resulting CO_2 is reinjected, the coal bed can still provide net storage of CO_2.

A substantial amount of coal bed methane is already produced in the USA and elsewhere but, so far, there is only one CO_2 -enhanced coal bed methane project, the Allison Unit in New Mexico, USA. Over 100 000 tonnes of CO_2 has been injected at this unit over a three year period.

A field test of enhanced coal bed methane (ECBM) production using CO_2 and nitrogen mixtures is being carried out by the Alberta Research Council under an international project facilitated by the IEA Greenhouse Gas R&D Programme. The combined approach may offer more attractive means of recovering methane and storing CO_2.

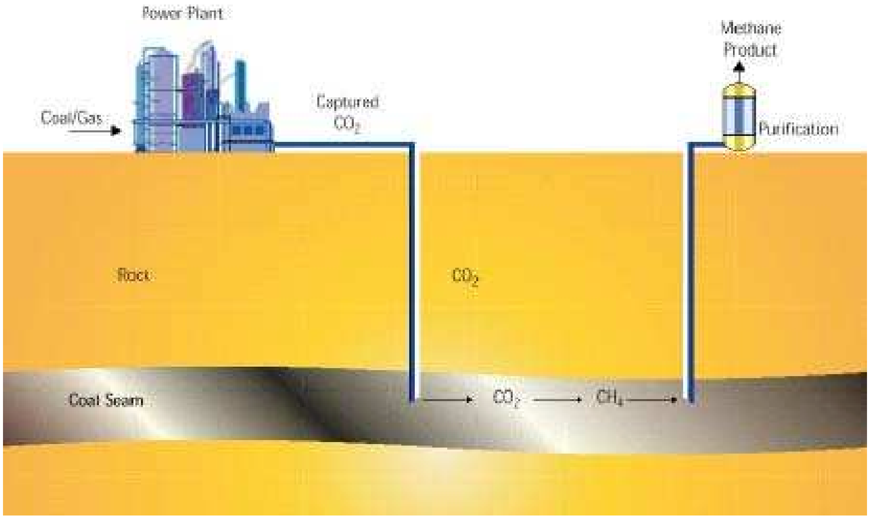


Figure 13: CO_2 enhanced coal bed methane production

Other storage options

There are various other ways of potentially storing CO_2 but none has been found to be economically competitive against the options described above. Underground caverns, such as mined salt domes, could be created to store CO_2. Such caverns are used for short term storage of natural gas and certain industrial gases but the quantities of CO_2 that would need to be stored are very much larger. Solid CO_2 (dry ice) could also be stored in a repository, surrounded by thermal insulation to minimise heat transfer and loss of CO_2 gas.

Another option is to react CO_2 with naturally occurring minerals, such as magnesium silicate, to produce carbonates that could be stored permanently. However, the mass of mineral that would need to be quarried and stored would be substantially more than the mass of CO_2 and costs would be much higher than for storage in oil and gas reservoirs, aquifers and coal seams. An advantage of this option is that the CO_2 would be locked-up for extremely long timescales. However, a better way to achieve this end may be to inject CO_2 into underground reservoirs that contain minerals that will react with CO_2.

Storage capacities

The global potentials for underground CO_2 storage, estimated by the IEA Greenhouse Gas R&D Programme, are shown in Table 3. These numbers may be compared with projected total emissions between 2000 and 2050, according to a "business as usual" scenario (the IPCC's IS92a projection), which shows that this technique could have a substantial impact on CO_2 emissions.

Storage option	Global capacity	
	Gt CO_2	% of emissions to 2050
Depleted oil and gas fields	920	45
Deep saline reservoirs	400 - 10 000	20-500
Unminable coal measures	>15	>1

Table 3: Natural reservoirs suitable for storage of CO_2

The estimates for deep saline reservoirs were made in the early 1990s. More recent estimates suggest the capacity for storage in geological reservoirs in North West Europe alone could be as much as 800 Gt CO_2 (most of this is in deep saline reservoirs). Further research is required to assess the potential storage capacity of deep saline reservoirs.

ENVIRONMENTAL IMPACTS

Much of the technology for transportation and storage of gases is established and in use today. Large quantities of CO_2 are routinely transported in pipelines and tankers. CO_2 is injected underground in many EOR projects. Underground storage of natural gas, an analogous technique, is widely practised. This gives confidence that the new concept of underground storage for sequestration of CO_2 can be done in a safe and reliable manner.

Nevertheless, because CO_2 is an asphyxiant and heavier than air, there may be concerns about the safety of underground storage - either possible slow leakage or sudden large-scale emission resulting from seismic activity. Slow leakage of CO_2 is unlikely to give cause for safety concerns unless the gas is inadvertently trapped. The risk of sudden large-scale release of CO_2 would have to be avoided in the same ways as for other gases, such as by avoiding unsuitable sites. It is also important that CO_2 remains in the underground stores for a long enough time to minimise climate change. Oil and gas fields have remained secure for millions of years but there is a possibility that drilling and extraction of oil and gas may disrupt the integrity of the cap. Chemical interactions between injected CO_2 and underground minerals would have the beneficial effect of permanently sequestering CO_2 but there is a possibility that interactions could impact the integrity of the cap rock. Deep saline reservoirs are generally less well characterised than oil and gas reservoirs due to their lack of commercial importance to date. More information is needed to calibrate their ability to contain CO_2 for the necessary timescales.

Solvents used to capture CO_2 gradually degrade in use and so there need to be suitable procedures for destruction/disposal. There may also be some solvent carry-over in the flue gas stream. Both of these factors will be minimised for cost reasons, as well as to reduce potential environmental impacts. It has been suggested that the CO_2 capture at a 500 MW gas-fired power station could produce about 2 000 tonnes/year of sludge from decomposed amines, and about 10 tonnes/year of carry-over in the flue gas. However, these quantities are speculative and are the subject of further evaluation.

Possible legal and political obstacles to storage of CO_2 will need to be addressed. For example, the London Convention may in some circumstances limit the opportunities for storage of CO_2 under the sea bed. However, storage of CO_2 to mitigate climate change was not considered at the time the Convention was agreed.

VERIFICATION OF CO_2 STORAGE

If CO_2 storage were to be used as a basis for emissions trading or to meet national commitments on emissions reduction, it would be necessary to verify the quantities of CO_2 stored. Verification is also a significant challenge for other carbon storage options, such as forestry and enhanced storage in soils.

For CO_2 capture, the flows of gas would be measured as a normal part of the chemical engineering of the process; technology already exists to do this and additional costs would be small. Capture of flue gases can be measured with great accuracy and at low cost. Also, with transport of CO_2, pipelines already carry CO_2 across the USA on a commercial scale, with large quantities of CO_2 monitored accurately in real time using equipment that is available now at low cost. Similar measurements would be used to monitor CO_2 injected into geological reservoirs.

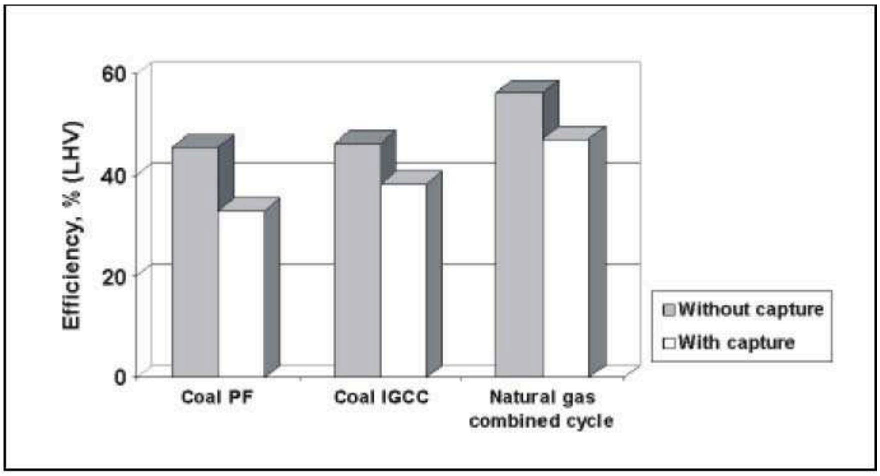
Major oil and gas companies and their contractors have the technology to track gas flows in underground reservoirs using seismic, well logging, and reservoir simulation tools. These technologies are being successfully applied in EOR projects and in the North Sea. Logging technology would be most easily applied in reservoirs where there are also production wells (e.g. oil production). The application to, and effectiveness of, seismic technology for tracking stored CO_2 in underground reservoirs is showing promise, but further development of the technique is required. Tracking will need to be accurate over much longer periods of time for CO_2 storage compared to EOR, where slow leakage is not a major concern.

PERFORMANCE AND COSTS

Power generation efficiency and emissions

The IEA Greenhouse Gas R&D Programme has recently completed a study on the performance and cost of new 500 MWe (nominal) gas and coal fired power plants with and without CO_2 capture. Power stations with post-combustion capture using amine scrubbing, and pre-combustion capture using Selexol® physical solvent scrubbing were assessed. The coal IGCC uses pre-combustion capture and the pulverised coal and natural gas combined cycle plants use post-combustion capture (the efficiency and emissions would be very similar for a natural gas combined cycle with pre-combustion capture). Compression of the CO_2 to a pressure of 110 bar for transportation to storage is included.

The efficiencies and emissions of power stations with and without CO_2 capture are shown in Figures 14 and 15.



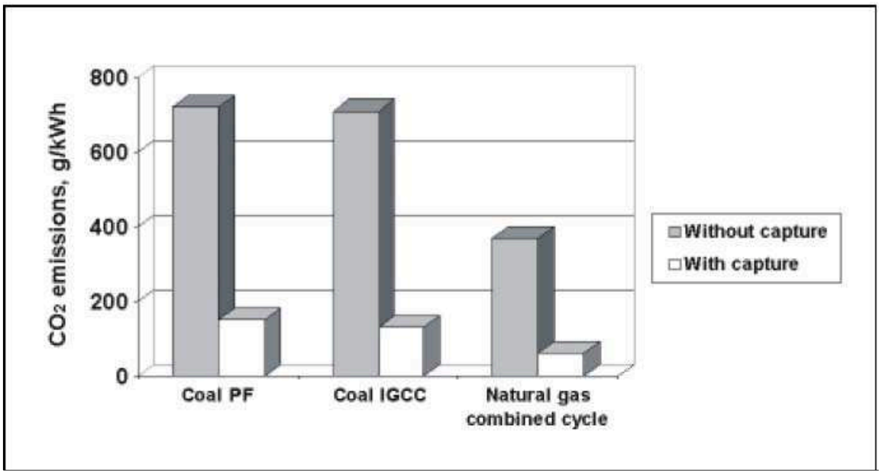


Figure 14: Power generation efficiencies and Figure 15: Power station CO_2 emissions

CO_2 capture reduces the emissions of CO_2 per unit of electricity by about 80%. The generating efficiency decreases by 8-13 percentage points. The reduction in efficiency is less in the gas fired plant than in the pulverised coal plant, mainly because less CO_2 has to be captured and compressed per unit of electricity produced. The efficiency penalty for CO_2 capture is lower in the IGCC plant than in the pulverised coal plant, because less energy is needed for regeneration of the CO_2 capture solvent .

Power generation costs

Capital and operating costs of power stations with and without CO_2 capture were estimated to an accuracy of ±25%. Adding CO_2 capture approximately doubles the capital cost of a natural gas combined cycle plant. CO_2 capture increases the capital cost of a pulverised coal plant by 80% and an IGCC plant by 50%, although even with CO_2 capture the IGCC plant is still more expensive than the pulverised coal plant.

The costs of transport and storage of compressed CO_2 is expected to be low compared to the costs of capture and compression. The IEA Greenhouse Gas R&D Programme, has estimated that storage in deep saline reservoirs and in depleted oil and gas fields would cost \$1-3/t CO_2, excluding the cost of CO_2 transport. In some cases injection of CO_2 e.g. in enhanced oil recovery or enhanced production of coal bed methane, will generate an income which can partially offset the cost of capture and storage. Local conditions will dictate how far the CO_2 has to be transported from where it is produced to where it is stored. The cost of pipeline transport is estimated to be ~\$1-3/t CO_2 for 100km distance.

Cost of electricity

Costs of electricity generation with and without CO_2 capture and storage at a range of fuel prices are shown in Figure 16. The costs are calculated assuming a 10% discount rate, base load operation and a CO_2 transport and storage cost of \$8/t CO_2 stored.

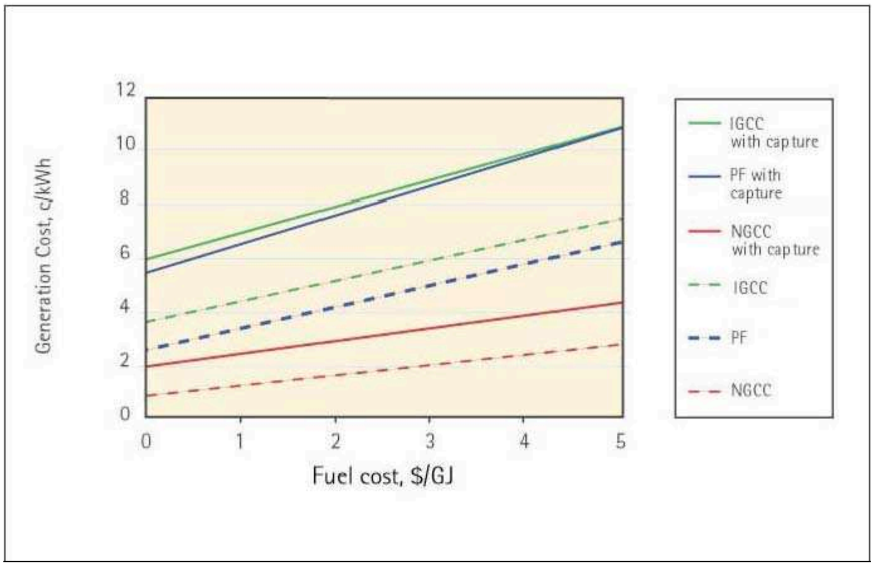


Figure 16: Costs of electricity generation with and without capture and storage

CO_2 capture and storage increases the cost of gas fired electricity generation by about 1.5 c/kWh, or 60%. Post-combustion CO_2 capture and storage increases the cost of electricity generation in a pulverised coal plant by about 3 c/kWh or 90%. The cost of electricity from an IGCC with pre-combustion capture is roughly the same as from a pulverised coal plant with post combustion capture. In percentage terms, the increase in cost of electricity to the final consumer would be less because of the added costs of distribution and sales

Cost of avoiding CO_2 *emissions*

The cost of avoiding CO_2 emissions at a range of fuel costs is shown in Figure 17 (the cost is assessed relative to a similar plant without capture).

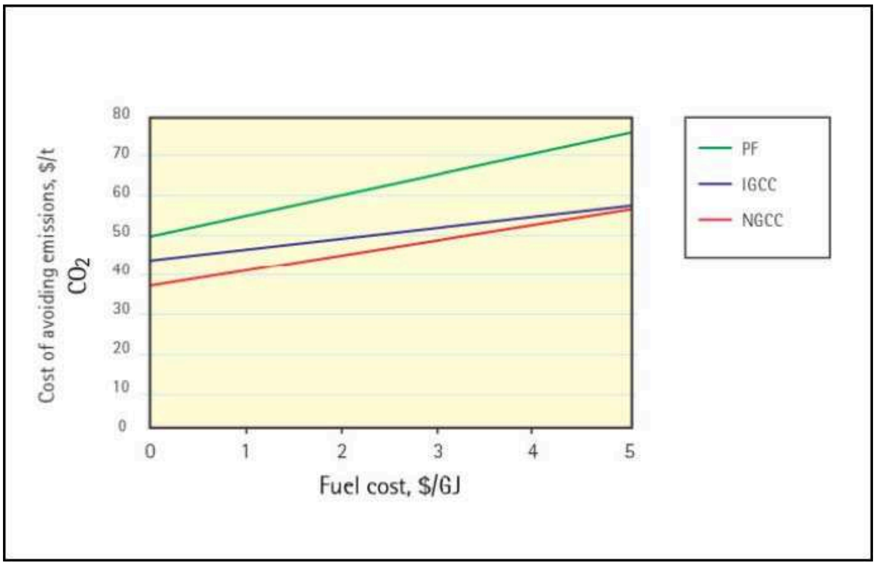


Figure 17: Costs of avoiding CO_2 emissions

The overall cost is around $40-60/t CO_2 emissions avoided and is broadly similar for coal and gas fired power plants. The quantity of CO_2 emissions avoided is less than the quantity captured, because the energy consumed during capture results in additional CO_2 production. The cost per tonne of CO_2 captured would therefore be lower than the cost per tonne of emissions avoided.

Other industries

As indicated above, CO_2 is already separated during some petrochemical and gas purification processes. The cost of capturing and storing this CO_2 would be low, as it would only have to be pressurised and in some cases some minor impurities removed. This suggests that such plant may offer opportunities for early action and some projects have already been proposed. CO_2 could also be captured in other major energy using industries, as discussed earlier. Costs per tonne of CO_2 are expected to be broadly similar to those of power plants.

Future cost trends

As with most new technologies, costs of CO_2 capture and storage are expected to decrease when they are applied on a large scale and technical improvements are made. The analogous situation occurred with FGD. Capital costs of FGD plants have decreased by about 75% since they were first introduced on a large scale around 1970. FGD was originally regarded as an excessively expensive addition to power stations but is now usually regarded as a relatively modest addition, fully justified by the environmental benefits.

FUTURE PROSPECTS

Market opportunities

Markets for CO_2 capture and storage technology will depend on future energy demand, the degree of CO_2 emission-abatement required and its relative attractiveness compared with other abatement options. The main application for capture and storage in the long term would be power generation but, near term, there may be opportunities for emission reduction from other sources. Although these may not have the potential global benefit of the power sector, they would be less costly to build. Application in projects which can generate some offsetting income is also expected to be attractive, especially near term.

About 100 GWe per year of new fossil fuel fired power plant is currently being ordered worldwide, 70% of which is gas fired. The market for power plant is likely to grow at 2-3% for the foreseeable future. A substantial proportion of new power plant could potentially include CO_2 capture and storage. Retrofitting to existing plants is feasible but would require large modifications, necessitating a long operating life to recover the capital investment. Major energy using industries are another major potential application for capture and storage and adoption of this technology to produce energy carriers such as hydrogen could open up much of the rest of the energy market to deep reductions in CO_2 emissions.

Research and development needs

The technology for capture and storage of CO_2 is already available, the main barriers to wider use being the energy penalty, cost of capture and the need to prove the reliability of storage and the integration of technologies at the required scale. This indicates areas of immediate priority for further development. Some specific topics are outlined below.

CO_2 capture:

The near-term priority is to reduce the penalty of using CO_2 capture in power plant. In the case of absorption technology there is scope for the development of improved solvents, starting at the laboratory scale and leading to use in commercial scale plants. Investigation of improved separation processes would also be justified, e.g. membranes, cryogenic separation, improved heat recovery to compensate for losses introduced by CO_2 capture, and novel concepts such as different methods of separating oxygen, enriched oxygen combustion or a combined reactor/membrane separator for the decarbonisation of fuel gases.

In the long-term, international agreement to reduce CO_2 emissions would likely alter the nature of the world's energy systems; for example, it might accelerate the introduction of a hydrogen-based energy system. Initial distribution of hydrogen produced by decarbonising fossil fuels would provide a practicable 'bridge' to an energy system based primarily on non-fossil sources.

CO_2 storage:

The main requirement for research is to establish storage as an environmentally acceptable solution to the threat of climate change. The security of storage in a variety of applications needs to be demonstrated. Storage is less expensive than capture, so research to reduce costs is not a high priority.

Work under European and US programmes has identified and quantified potential underground stores but there is considerable need for more information on potential storage sites. Refinement of techniques to monitor CO_2 in underground strata will take place as part of the Sleipner and Weyburn projects and other programmes. Research to assess the long-term interaction of CO_2 with potential host rocks will be done in the laboratory. Before land-based schemes could be adopted (the only existing scheme is under the North Sea), their safety and public acceptability would need to be established.

Other matters:

It is important to involve a wide range of interest groups in considering the environmental and social issues related to many new technologies, including CO_2 capture and storage. The views of environmental non-governmental organisations (ENGOs), industry, government agencies, lawyers and others are needed, as well as those of scientists and researchers, to identify areas of concern and agree the main research needs.

There are significant advantages in many cases if R&D is undertaken by international co-operation. These opportunities also apply to potential demonstration projects where the need to focus limited resources and the high costs make international co-operation highly desirable.

Formal recognition of CO_2 capture and storage within the UNFCCC would contribute to faster development and take-up

CONCLUSIONS

Large reductions in emissions of CO_2 to the atmosphere are likely to be needed to avoid major climate change. Capture and storage of CO_2, in combination with other CO_2 abatement techniques, could enable these large reductions to be achieved with least impact on the global energy infrastructure and the economy.

Capture and storage is particularly well suited to use in central power generation and many energy-intensive industrial processes. CO_2 capture and storage technology also provides a means of introducing hydrogen as an energy carrier for distributed and mobile energy users.

CO_2 can be captured using available technology. Potential stores for CO_2, e.g. natural underground reservoirs, have sufficient capacity for many years' emissions.

The environmental side-effects of CO_2 capture and storage are mostly quite small.

For power stations, the cost of capture and storage is about $50/t of CO_2 avoided. This compares favourably with the cost of many other options considered for achieving large reductions in emissions. Use of this technique would allow continued provision of large-scale energy supplies using the established energy infrastructure.

There is considerable scope for new ideas to reduce energy consumption and costs of CO_2 capture and storage which would accelerate the development and introduction of this technology.

BIBLIOGRAPHY

Department of Trade and Industry (UK), *Gasification of Solid and Liquid Fuels for Power Generation*, report TSR 008, Dec. 1998

Department of Trade and Industry (UK), *Supercritical Steam Cycles for Power Generation Applications*, report TSR 009, Jan. 1999

Durie R, Paulson C, Smith A and Williams D, Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies, CSIRO (Australia) publications, 2000

Eliasson B, Riemer P W F and Wokaun A (editors), Greenhouse Gas Control Technologies, Proceedings of the 4th International Conference, Elsevier Science Ltd., Oxford 1999

Herzog H, Eliasson B and Kaarstad O, *Capturing Greenhouse Gases*, Scientific American, Feb. 2000, 54-61

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995 -The Science of Climate Change*, Cambridge University Press, 1996

International Energy Agency, *Key World Energy Statistics*, 1999 edition.

IEA Greenhouse Gas R&D Programme, Transport & Environmental Aspects of Carbon Dioxide Sequestration, 1995, ISBN 1 898373 22 1

IEA Greenhouse Gas R&D Programme, *Abatement of Methane Emissions*, June 1998, ISBN 1 898 373 16 7

IEA Greenhouse Gas R&D Programme, *Ocean Storage of* CO_2, Feb. 1999, ISBN 1 898 373 25 6

IEA Greenhouse Gas R&D Programme, The Reduction of Greenhouse Gas Emissions from the Cement Industry, report PH3/7, May 1999

IEA Greenhouse Gas R&D Programme, The Reduction of Greenhouse Gas Emissions from the Oil Refining and Petrochemical Industry, report PH3/8, June 1999

IEA Greenhouse Gas R&D Programme, *Leading Options for the Capture of* CO_2 *Emissions at Power Stations*, report PH3/14, Feb. 2000 Stevens S and Gale J, *Geologic* CO_2 *Sequestration*, Oil and Gas Journal, 15 May 2000, 40-4

CO_2 Sinks in Oil/Gas Fields & Aquifers: Technologies, Challenges & Potentials

Zoltán Heinemann & Claudia Scharf (University of Leoben, Austria)

Zoltán Heinemann is Professor for Reservoir Engineering and Director of the Petroleum Engineering Study Programmes

Claudia Scharf is Scientific Assistant at the Petroleum Department

Short Summary

The importance of capturing CO_2 and storing it underground stems from the fact that 85% of the world's commercial energy needs are supplied by fossil fuels. Apart from atmospheric removal of CO_2 by forestry measures with very limited potential, disposal in deep oceans and geological formations (salt cavern, coal bed, oil or gas reservoir and aquifer) could be considered for large-scale sequestration.

CO_2 injection has been used as a commercial process for enhanced oil recovery (EOR) since the 1950's. Thus, the technologies for transporting CO_2 in pipelines, injecting as well as producing and handling gas and oil containing CO_2 are matured including the safety and environmental questions.

The geological disposal of 1 ton CO_2 requires approximately 1.5 m^3 pore volume. In a first approach the storage capacities of exploited oil and gas reservoirs can be calculated based on the cumulative oil, gas and water production, subtracting the volume of injected water. The CO_2 can be injected until the initial pressures of the reservoirs are restored. By using the entire volume, 400 MM t of CO_2 could be stored in Austria. The comparable number worldwide is 325.000 MM t of CO_2. Supplementary volumes for 5 MM t in Austria and 12.000 MM t worldwide will be created yearly by hydrocarbon production. Until ultimate recovery of oil and gas, 510 MM t of CO_2 storage capacity will be available in Austria and 1,000,000 MM t in the world. These numbers can give a rough estimation of the magnitude but due to local factors and economical conditions the effective capacities can be considerably different.

Taking only the largest 11 oil and 13 gas reservoirs existing in Austria into account, and assuming that the initial pressure could be restored and the invaded water could be completely displaced, theoretically 465 MM t CO_2 storage capacity is available. This number is close to the 510 MM t ultimate capacity mentioned above. 430 MM t are located in the Vienna Basin in fields operated by OMV AG. The remaining part is in the so-called Molasse, operated by RAG AG. Not all of these reservoirs can be recommended though, especially not from beginning. At first those reservoirs should be considered which are geologically isolated from other units and which are only penetrated by a limited number of wells.

In 2003, the author examined the mentioned oil and gas reservoirs and selected six potential candidates. All of them are still in production, which is very convenient, because wells and facilities become available for a CO_2 sink. The time in which they could be converted for CO_2 storage must be determined concisely, taking also into consideration the interest of oil and gas production. A realistic time point would range between 2010 and 2025.

It is difficult to give a, exact, reliable cost estimation without designing the facilities and the operations in detail. However, the price of the disposal can be estimated to range between 11 and 12.5 €/t, including a pipeline length of 30km.

The only known aquifer which could be considered for CO_2 injection is the Aderklaa Conglomerate in the Vienna Basin, which is very well known due to the petroleum exploration and production. The central part of the conglomerate is closed by faults and is directly connected both to the largest oil reservoir (16. Torton horizon) and to the largest gas reservoir (Zwerndorf) in Austria. At least 10 MM t CO_2 could be injected before the initial pressure would be restored. Supplementary storage capacity for up to 1 Gt. CO_2 could be created, by water production for thermal usage.

Introduction

The importance of capturing CO_2 and storing it underground stems from the fact that 85% of the world's commercial energy needs are supplied by fossil fuels. Apart from atmospheric removal of CO_2 by forestry measures with very limited potential, sinks in deep oceans and in geological formations could be considered for large scale sequestration. For both storage types only pure CO_2 with negligible impurities can be used. The CO_2 will be comprised, transported and injected at 100-120 bar. At this stage CO_2 is a supercritical fluid, with properties similar to a liquid, which can be easily pumped and injected.

The ocean is the largest natural sink for CO_2. For depths greater than 3000 m, the density of CO_2 is higher than that of seawater, thereby the CO_2 sinks deeper and forms plumes or hydrates at the bottom. However, the environmental effects of disposing of CO_2 in oceans are not well known.

A geological formation can mean salt cavern, coal bed, oil or gas reservoir and aquifer. Salt caverns and coal beds are also underground storages but from a technological point of view they are fundamentally different to hydrocarbon fields and aquifers. Salt caverns were used for underground storage of oil, oil derivate, natural gas and compressed air and the technology has been already developed. A single salt cavern can have a volume of up to $5*10^5$ m^3 and can store fluids at a pressure of up to 80% of the fracturing threshold. Unfortunately, the associated costs are too high to be considered for CO_2 disposal. CO_2 has a high affinity with coal. Injecting CO_2 into coal beds that are too deep or uneconomic for coal mining presents a two-fold advantage. Firstly, CO_2 is sequestrated by adsorption on the coal matrix. Secondly, methane is produced which, although also a greenhouse gas, can be used instead of coal as a much cleaner fuel. This technology is already used in the San Juan basin to enhance methane recovery, but it is far from being regarded as an established technology. The main drawbacks are the low permeabilities of the coal and the normally complex geological conditions, especially in Western Europe.

The purpose of this paper is to provide an overview of the technology for transporting and storing CO_2 in hydrocarbon fields and aquifers and to estimate the storage capacities in general and especially in Austria. At the end of the paper suggestions will be made for national efforts as a possible contribution to the international R&D programs.

CO_2 Sequestration

CO_2 is a color- and odorless gas at ambient temperature and atmospheric pressure. Its critical temperature and pressure are 31.1°C and 7.38 Mpa (73.8 bar). Above this temperature and pressure it is a supercritical fluid with properties similar to a liquid. Assuming a geothermal gradient of 3°C/100 m and hydrostatic formation pressure, the CO_2 will be in a liquid-like state in the entire injection system (wellhead, injection well and formation) for all depths above approximately 900m. Below 1500 m the CO_2 phase density is nearby constant at 680 kg/m^3 and as such always lighter than the formation water (brine). Generally, 1 ton CO_2 requires 1.5 m^3 pore volume to be stored. The CO_2 phase segregates by gravitation, migrates to the top of the formation and will be trapped if a closure exists. The existence of natural CO_2 deposits shows that it can be stored safely over geological time periods. Water-free CO_2 is non-corrosive and the interaction between CO_2 and the rock is not worth mentioning in this relation.

CO_2 injection has been used as a commercial process for enhanced oil recovery (EOR) since the 1950's. Recently 71 of such projects were reported worldwide. Currently about 20 Mill.t/y are injected into 4500 wells, producing 180-200.000 bbl of oil /d (30.000 m^3/d). The location and the movement of the CO_2 phase within the formation can be monitored by geophysical methods (seismic). The technologies for transporting CO_2 in pipelines, injecting and also producing and handling of gas and oil containing CO_2 are matured including the safety and environmental questions. Therefore CO_2 sequestration in geological formations is rather a political and economical question than a technical one. Where, when and which kind of formation should be used can only be answered after thorough investigation of local conditions.

Oil reservoirs, natural gas reservoirs and aquifers need to be considered separately for two reasons: (1) the actual disposal processes would be quite different, and (2) the three options fall under different regulatory agencies in most of the countries. In the cases of gas reservoirs and aquifers CO_2 is considered as waste, whilst in oil reservoirs it is considered an agent to increase recovery. The economics of disposal in oil reservoirs are more favorable than the disposal in gas reservoirs because of the by-product oil credits. Also, regulatory restrictions relating to CO_2 purity are apt to be more stringent for gas reservoirs and aquifers than for oil reservoirs.

In a first approach the storage capacities of exploited oil and gas reservoirs can be calculated based on the cumulative oil, gas and water production, where the volume of injected water must be subtracted. The CO_2 can be injected until the initial pressures of the reservoirs are restored. By using the entire volume, 400 MM t of CO_2 could be stored in Austria. The comparable number worldwide is 325.000 MM t of CO_2. Supplementary volume for 5 MM t in Austria and 12.000 MM t worldwide will be created yearly by hydrocarbon production. Until ultimate recovery of oil and gas, 510 MM t of CO_2 storage capacity will be available in Austria and 1,000,000 MM t in the world. These numbers can give a rough estimation of the magnitude but due to local factors and economical conditions the effective capacities can be considerably different. Some negative but also some positive circumstances should be considered here: Many reservoirs are too small to justify the construction of pipelines and injection facilities. The encroached water probably cannot be completely displaced, causing a volume reduction of up to 40%. On the other hand side, a reservoir pressure 20 % above the initial one could increase the storage capacity.

Enhanced Oil Recovery

For better understanding, this section provides some basic background knowledge on the state-of-the-art of enhanced recovery processes and technologies:

To date, CO_2 injection projects have focused on oil with densities between 29 and 48 ^{o}API (855 to 711 kg/m^3) and reservoir depths from 760 to 3700 m. Within the U.S., CO_2 -EOR operations are centered in the Permian and Rocky Mountain basins (Texas, New Mexico and Colorado). Current use of CO_2 is limited by the costs and the availability of CO_2. Taber et al.[1]estimate that more than 80% of the oil reservoirs worldwide might be suitable for CO_2 injection, based upon oil-recovery criteria alone. Moreover, the process is widely applicable to both sandstone and carbonate formations with a variety of permeability and thickness of hydrocarbon bearing zones. The major factors limiting CO_2 injection as an oil recovery process have been the availability of CO_2 and the costs to build pipelines to carry CO_2 into oil producing regions. If substantial additional quantities of CO_2 are made available due to sequestration efforts, significant CO_2 EOR oil could be exploited from operating oil reservoirs.

On the other hand there is a race between EOR application and resource abandonment. The technology advancement and change of economic conditions could be too late for most of the fields, which are potentially CO_2 EOR candidates. If a field is already abandoned, the reactivating for CO_2 flooding will not be possible. An aggressive and focused R&D and technology transfer effort on improved recovery technologies needs to be undertaken in order to capitalize on the massive remaining oil resources in the U.S.[2]. This statement is certainly also valid under Austrian conditions.

CO_2 flooding processes can be classified as immiscible or miscible[3, 4].

1. Miscible CO_2 flood

   CO_2 and crude oils are not miscible upon first contact in the reservoir. Miscibility will be achieved by a so-called multiple contact. At high pressure CO_2 is very soluble in crude oils and the intermediate components vaporize into the CO_2 gas phase. If the pressure is high enough then the interfacial tension between the two phases becomes very low, assuring efficient displacement of the oil by the gas phase. The residual oil saturation at this stage is 4-8% compared to 20-30% by water displacement. The pressure that results in drastic reduction of the residual oil is termed the “minimum miscibility pressure” (MMP). Correlations have been developed for MMP vs. the API gravity (crude oil density), the molecular weight of the C_{5+}-fraction and the reservoir temperature. Such relationships were published by Yellig and Metcalf[5], Bailey at al.[6], Heller and Taber[7], and Orr and Silva[8]. These correlations can be used for pre-screening of reservoirs for CO_2 EOR application but they do not replace laboratory investigations. It should be considered that most of the measurements and correlation were made for U.S. fields. However, if the oil

differs significantly from the types of crudes of the Permian basin, and this will be the case for the Vienna Basin, then laboratory tests will be unavoidable. Furthermore, EOS based fluid characterization methods usually fail in prediction of MMP. Recently, methods for MMP calculation were published but no evidence exists relating to their applicability[9, 10]. Generally, the MMP should be determined by laboratory slim tube tests.
The laboratory investigation of phase behavior for crude oil and CO_2 systems is long and drawn-out. A comprehensive summary based on all publications before 1981 is given by Sayegh and McCaffery[11]. They conclude that instead of determining a full phase diagram by static single contact tests, the more simple extraction experiment and laboratory displacement tests are recommended[12, 13, 14].

2. Immiscible CO_2 flood

   The recovery mechanism in immiscible processes involves the increase of the net oil volume through swelling, reduction of the oil viscosity, and a decrease in the interfacial tension, long before the MMP is achieved. In the U.S.A. a single project is characterized as immiscible15 but probably a considerable part of the “miscible” projects also operate under immiscible conditions. Nevertheless, if the miscibility is given under average process parameters, it will not be valid for every part of the reservoir. Doleshall et al.16 investigated CO_2 displacement under immiscible conditions using a 1 m long and 25 mm diameter laboratory model. They used unconsolidated reservoir sandstone and live reservoir oil. The additional oil recovery was 12-16% of the original oil in place (OOIP) after hydrocarbon gas displacement and 8-12% after water displacement. The additional CO_2 oil recovery was related to the result of conventional water displacement. They concluded that it is impossible to find general relationships between oil and rock properties, displacing gas composition, operation conditions and the additional oil recovery. The parameters influencing the effectiveness of immiscible CO_2 flood must be individually determined for each project.

   Immiscible CO_2 flooding is normally uneconomic due to the moderate increase of recovery compared to a conventional water flood. This situation will be changed if low cost CO_2 becomes available or to a greater extent if underground CO_2 disposal becomes a business issue.

3. The WAG process

   Conventional gas injection processes often include water injection as well. Such schemes are called WAG (water alternating gas) injection, and there are a number of variations commonly used. In one version alternate slugs of water and gas are injected. In another, gas is injected continuously until significant breakthrough occurs. At that point WAG injection begins. The possible benefits of WAG injection arise from two sources. Firstly, and usually most importantly, gravity forces cause the water and gas to sweep different portions of the pores space. Generally, gas invades the upper portion of the reservoir more efficiently while water invades the lower portion more effectively. Secondly, the presence of water can reduce the mobility of the gas, thereby reducing gas cycling.

   The advantages of a WAG process compared with continuous CO_2 injection are not clearly testified. The main problem is that any WAG scheme strongly depends on the distribution of permeability as well as factors that determine the impact of gravity segregation (i.e., fluid densities, viscosities and reservoir flow rates). In addition, the performance of a WAG scheme can strongly depend on the details of the flow behavior of the oil, gas and water as reflected by the two- and three-phase relative permeability. One argument for the WAG process could be that water injection increases the sweep efficiency of the CO_2, leading to a greater portion of the pore volume being invaded. However, the higher sweep efficiency can be achieved more effectively using suitable injection schemes rather than by alternating water injection.

The costs of purchased CO_2 in the Permian basin (Texas) were reduced by half during the last 20 years. For this reason the economic advantage of the WAG process was reduced, consequently the operators increased the size of the CO_2 slug and reduced the amount of injected water. More and more operators changed to continuous CO_2 injection. This simplifies the operations, eliminates corrosion problems in injection wells and reduces the operational costs.

Disposal in Depleted Oil Reservoirs

Considerable costs of the oil recovery are the purchase costs of the injected CO_2, therefore, strong reservoir engineering design effort has gone into reducing the total amount of CO_2 required to recover each ton of oil. If, on the other hand, the objective of the CO_2 injection is to increase the amount of CO_2 left behind at the end of the recovery process, the approach to the design questions changes. Until now very few investigations were made in this direction. In this section it will be discussed how CO_2 utilization might be increased, primarily based on the work of Jessen at al.[17].

They declared that “of course, sequencing of gas, water and WAG injection across a large field can offer significant opportunities for increased gas storage.” This statement is not acceptable because it contradicts fundamental physical facts. The major part of the CO_2 will be stored in the free gas phase and not dissolved in the oil and water. Furthermore, the amount of CO_2 dissolved in the water is negligible compared to that in the gas phase. If free water is present within the oil leg the volume of free gas is reduced, consequently the CO_2 storage capacity will also be reduced. The only realistic argument for WAG is the possible reduction of CO_2 consummation per unit of incremental oil and the reduction of the residual amount of CO_2 in the reservoir after displacement. Thereby, it is possible to reduce the cost of EOR oil but it is a clear contra indication to the CO_2 sequestration projects.

Aquifers underlie many oil fields, a fact that suggests less conventional schemes for CO_2 storage. CO_2 could be injected into the aquifer instead of into the oil zone above. Injection deep in the aquifer would be less prone to cycling, and could also displace oil trapped in the vertical capillary transition zone.

The specific reservoir situation will determine whether aquifer injection makes sense, but it should be investigated because aquifer volumes can be large. Finally, there will be some point in the economic life of an oil field at which the cost of operating the producing wells is unattractively high for the given oil production. However, it would be possible to continue CO_2 injection after the oil production ceases.

The slow gravity drainage of the remaining oil might also allow periodic production of some additional oil in specific reservoir situations.

Disposal in Depleted Gas Reservoirs

No CO_2 disposal project was reported in the literature so far. The process to be applied is very similar or even identical with the underground gas storage or other gas injection operations, therefore its feasibility is not questionable in any respect.

Disposal in Aquifers

Theoretically, CO_2 could be stored at shallow depths. At this pressure the density of CO_2 gas is low and to be able to store significant amounts of CO_2 a huge pore volume would be necessary. Furthermore, most of the shallow onshore aquifers are already used for potable water supply. It may be possible to store CO_2 as liquid below the critical temperature (31.1°C), which corresponds to a depth less than 700 m below the surface. However, then it would be necessary to overpressure the host formation, requiring a completely sealed formation.

Deep aquifers contain fossil, high salinity water that is not fit for industrial and agricultural use or for human consumption. Such aquifers are already used for the injection of hazardous liquid waste. In most of the sedimentary basins the geothermal gradient is 25-35°C/km and the pressure is hydrostatic 100-105 bar/km. At about a depth of 800 m or more the free CO_2 would be in the supercritical stage. Its density would vary between 440 and 740 kg/m^3. Therefore, on the one hand a relatively large amount of CO_2 can be stored within the available pore space but on the other hand the CO_2 would migrate under its own buoyancy, back to the surface of the Earth, at least in terms of thousands of years. Therefore, deep underground storage requires a seal above the host formation, which would prevent the vertical CO_2 migration. This could be clay, shale or other rock, which would be impermeable to CO_2 within this time frame.

Three concepts exist for CO_2 disposal into aquifers:

a) Disposal into closed aquifer systems.
b) Disposal into conventional traps, which were not filled by hydrocarbons during the geological time.
c) Disposal in aquifers, which are not laterally confined.

Case (a): Injecting fluid into a closed system where the only space available for CO_2 storage is the compression of the rock matrix and the pore water. It was estimated that by 100 bar pressure increase not more than 2% of the pore volume could be occupied by CO_2. The transient pressure increase around the injection wells and the subsequent relaxation will depend on the permeability and the injection rate. Supplementary storage capacity can be created by production water, simultaneously.

Case (b): An open aquifer system will not be overpressured. The higher pressure around the wells will decline after termination of the operation and theoretically it could return to the initial pressure. The formation water will be displaced, which will migrate towards the ground surface or the seabed. This might not be a problem offshore, because the salinity of the formation water near to the seabed is similar to the seawater. However, onshore, it might cause a rise in the salinity of the groundwater, and a rise in the water table.

In case (c) CO_2 will not be trapped, but it will move slowly along a long flowpath, coming in contact with uncarbonated formation water and reactive minerals. If the flowpath is long enough, the CO_2 might completely dissolve in the water or become fixed by mineral reactions before it has reached the formation margin[18]. Theoretical investigations showed that under realistic assumptions thousands of years are necessary to reach the aquifer boundary. Furthermore, very little CO_2 will escape because most of the CO_2 is dissolved in the aquifer[19]. This investigation suggests that injection should take place offshore, far from shore, so that there would be no possibility of affecting the terrestrial environment[20].

The Sleipner field [21, 22] is located in the Norwegian sector of the North Sea and contains 202 Gsm^3 rich gas. The CO_2 content of the gas varies between 4 to 9.5%. The field produces at a plateau rate of 20.5 Msm^3 sales gas per day, under the Troll Gas Sales Agreements. The maximum allowed CO_2 in sales gas is 2.5% and therefore, the CO_2 must be removed at the field. Approximately one million metric ton of CO_2 per year is injected into the Utsira sandstone formation in a depth of 800 m. The thickness of the formation varies between 150 to 250 m, the porosity is between 35 and 40%, the permeability between 1 to 8 Darcy. The Ustira sand is overlaid by thick Hordaland shale. The formation is not confined laterally. The CO_2 is injected at the bottom of the sand, rises under its own buoyancy to the caprock and spreads out laterally.

Austrian Oil and Gas Fields

Taking only the largest 11 oil and 13 gas reservoirs into account, and assuming that the initial pressure could be restored and the invaded water could be completely displaced, theoretically 465 MM t CO_2 storage capacity is available. This number is close to the 510 MM t ultimate capacity mentioned above. 430 MM t are located in the Vienna Basin in fields operated by OMV AG. The remaining part is near Linz, in the so-called Molasse, operated by RAG AG. Not all of these reservoirs can be recommended though, especially not from beginning. At first those reservoirs should be considered which are geologically isolated from other units and which are only penetrated by a limited number of wells, which are possibly completed using corrosion free steel or could be re-completed in this way. In 2003, the author examined the mentioned oil and gas reservoirs and selected six potential candidates. They are given below in sequence of the suitability:

1. Schönkirchen Tief (OMV) - Oil reservoir
2. Höflein (OMV) - Gascondensate reservoir
3. Schönkirchen Übertief (OMV) - Sour-gas reservoir
4. Reyersdorfer Dolomit (OMV) - Sour-gas with oilrim
5. Atzbach-Schwanenstadt (RAG) - Gas reservoir
6. Voitsdorf (RAG) - Oil reservoir

All of them are still in production, which is very convenient, because wells and facilities become available for a CO_2 sink. The time in which they could be converted for CO_2 storage must be determined concisely, taking also into consideration the interest of oil and gas production. A realistic time point would range between 2010 and 2025.

To get an idea about the capital and operational costs we assumed an emitter of yearly 1.5 MM t CO_2 (corresponding a caloric power station having a yearly average output of 425 MW), situated within a 20 km distance from Schönkirchen-Baumgarten. The total investment would be 92 MM €. The 30 km pipeline system would cost 42 MM €, the compressor station 15 MM €, the injection system including one new injection well 35 MM €. The annuity for 15 years and 4.5 % interest will be 6 €/t. The operational costs are easier to estimate based on the analogy to existing gas storage and water disposal operations and probably they would not exceed 4 €/t (published values are between 4 and 6 €/t). These numbers do not contain profit. Also counting for that, the price of the disposal will be around 11 €/t. Sensitivity analysis showed an uncertainty interval of $^{+}/-$ 10 %.

In Upper Austria a storage for 1 MM t/y over a 15 years interval could be created in the region of Atzbach-Schwanenstadt-Voitsdorf (corresponding to a caloric power station having a yearly average output of 425 MW) with a disposal price of 12.5 €/t. At both locations a 30 km pipeline was considered. The CO_2 could be transported over hundreds of kilometers as well causing supplementary cost of 0.03 €/km per ton.

It is not possible to give a more reliable cost estimation without designing the facilities and the operations in detail. Note also, that the specific costs are not proportional to the yearly quantity, the specific costs increase by reducing it. Also an uneven output could increase the costs considerably. The calculated specific costs fit well to those published by May and Turkovic[24] (12.3 €/t) for Baden-Württemberg, but a direct comparison, lacking detailed information, is not possible.

Possibility for Aquifer Storages

Due to the geological situation in Austria most of the aquifers contain potable water with direct connection to the atmosphere or the water is used or could potentially be used for balneologic purposes. Closed aquifer lenses naturally exist in all sediment basins but they are small and therefore unsuitable for CO_2 disposal. The only known geological body, which could be considered, is the Aderklaa Conglomerate in the Vienna Basin, which is very well known due to the petroleum exploration and production. The central part of the conglomerate is closed by faults and is directly connected both to the largest oil reservoir (16. Torton horizon) and to the largest gas reservoir (Zwerndorf) in Austria. Due to the oil and gas production the conglomerate pressure uniformly dropped by 20 bars. The average salinity of the formation is 10 g/l and therefore not usable. The pore volume of the unit is 15.10^9 m^3 in magnitude. This conglomerate could be used for CO_2 disposal. At least 10 MM t CO_2 could be injected before the initial pressure would be restored. Supplementary storage capacity for up to 1 Gt. CO_2 could be created, by water production for thermal usage. Thus, the water should be injected into other formations or conducted into rivers, which would create severe public discussions, however.

The easiest solution would be to pump the water into the Danube River. The water flow rate of the Danube at medium water level is 1.920 m^3/s. The salinity varies between 10 and 30 ppm and is relatively constant along the river. A yearly rate of 10 MM m^3, corresponding to a 5MM CO_2 disposal, would increase the salinity of the Danube water by less than 2 ppm (0.00165 g/l). According to actual regulations, the guideline values for potable water for sodium are 20 ppm, for chloride 25 ppm, which leads to approximately 40 ppm for NaCl.

Conclusion and Recommendations

1. The Austrian oil industry posses all geo-scientific and technical knowledge necessary for safe and cost-effective disposal of CO_2. The numerous underground gas storage operations qualify both OMV and RAG. Beyond that, the following past experiences should be mentioned:
    - Successful CO_2 injection by RAG
    - Successful CO_2 injection in field Hochleiten by OMV 2004
    - Sour gas production and processing from the fields:
        - Höflein
        - Schönkirchen-Übertief and Reyersdorfer Dolomit
    - Water sink in Aderklaaer Conglomerate,
    - Development of a complex simulation software SURE, suitable for CO_2 sequestration projects by HOT (Leoben) since 1992.
    - Offering an 8 months project on "Knowledge Transfer Program" for planning and modeling compositional operations, including CO_2 sinks, by the Montanuniversität Leoben, 2004-2005.
    - At this time two doctorate works are conducted at the Montanuniversität (2003-2006).
2. A national research project on the topic should be initiated involving all relevant companies and institutions (universities, governmental organizations…) where the possibilities for CO_2 sequestration in Austria are thoroughly investigated. At least two pilot applications should be conducted, one for an oil reservoir and the other for an aquifer.

References

[1] Taber, J.J., Martin, F.D. and Seright, R.S.: "EOR Screening Criteria Revisited," SPE/DOE paper 35385, SPE Res.Eng.,Aug, 189-205, 1997.

[2] Brashear, J.P., Biglarbigi, K. and Ray, R.M.: "Improved Oil Recovery in the United States: The race Between Thechnology Advancement and Resource Abandonment," SPE/DOE 27778, paper presented at the SPE/DOE Ninth Symposium on Improved Oil Recovery held in Tulsa, OK. 17-20 April 1994.

[3] Martin, F.D. and Taber J.J.: SPE 23564

[4] Martin, F.D. and Taber, J.J.: "Carbon Dioxide Flooding," JPT April 1992, 396-400.

[5] Yelling, W.F. and Metcalf, R.S.: "Determination and Prediction of the CO_2 minimum Miscibility Pressure," JPT (Jan, 1980) 160-68.

[6] Bailey, R.E., et al.: "Enhanced Oil Recovery, Natl.Petroleum Council, Washington, DC (June 1984).

[7] Heller, J.P. and Taber, J.J.: "Influence of Reservoir Depth on EOR by CO_2 Flooding," SPE 15001, paper presented at the 1986 SPE Permian Basin Oil and Gas Recivery Conference, Midland, 13-14 March 1986.

[8] Orr, F.M.Jr. and Silva, M.K.: " Effect of Oil Composition on Minimum Miscibility Pressure - Part 2: Correlation," SPERE (nov. 1987) 479-91.

[9] Moritis, G.: "2002 worldwide EOR survey," Oil&Gas J. Apr.15,2002. 43-47,71-83. Jessen, K., Michelsen, M.L. and Stenby, E.H.: Global Approch for Calculation of Minimum Miscibility Pressure," Fluid Phase Equilibria 153, pages 1998.

[10] Wang,Y. and Orr, F.M.Jr.: "Calculation of Minimum Miscibility Pressure," J.Pet.Science and Engineering, 27, pages 151-164, 2000.

[11] Sayegh, S.G. and McCaffery, F.G.: "Laboratory Testing Procedures for Miscible Floods," Enhanced Oil Recovery (editor Fayers,F.J.), Elsevier, Amsterdam, 1981, pages 285-298.

[12] Lindeberg, E. and Holt, T.: "EOR by Miscible CO_2 Injection in the North Sea," SPE/DOE 27767, paper presented at the SPE/DOE Ninth Symposium on Improved Oil Recovery held in Tulsa, OK. 17-20 April 1994.

[13] Mayn, V.: " A Novel Devise for CO_2 Flooding," Enhanced Oil Recovery (editor Fayers,F.J.), Elsevier, Amsterdam, 1981, pages 467-482.

[14] Skillerne de Bristowe, B.J.: "The Use of Slim Tube Displacement Experiments in the Assessment of Miscible Gas Projects," Enhanced Oil Recovery (editor Fayers,F.J.), Elsevier, Amsterdam, 1981, pages 467-482.

[15] Moritis, G.: "2002 worldwide EOR survey," Oil&Gas J. Apr.15,2002. 43-47,71-83. Jessen, K., Michelsen, M.L. and Stenby, E.H.: Global Approch for Calculation of Minimum Miscibility Pressure," Fluid Phase Equilibria 153, pages 1998.

[16] Doleschall, S. at al.: Complex Study of CO_2 Flooding in Hungary," Enhanced Oil Recovery (editor Fayers,F.J.), Elsevier, Amsterdam, 1981, pages 299-312.

[17] Jessen, K. *at al*: "Increasing CO_2 Storage in Oil Recovery", Internal paper, Dep.of Petroleum Engineering, Stanford University, CA 94305

[18] Brinks, J. and John Fanchi, J.: "Geologic Sequestration: Modelling and Monitoring Injected CO_2," SPE 66749, paper presented at the 2001 SPE/EPA/DOE Exploration and Production Enviromental Conference held in San Antonio, 26-28 February 2001.

[19] Lindeberg, E.: "Escape of CO_2 from large horizontal aquifers confined only by a cap seal. Paper presented at the conference "Greenhouse Gases: Mitigation Options", London, August 1995.

[20] Holloway,S., Heederik, J.P., van der Meer, L.G.H., Czernichowski-Lauriol, I., Harrison, R., Lindeberg,E., Summerfield, I.R., Rochelle,C., Schwarzkopf, T., Kaarstad, O. and Berger, B.: "The Underground Disposal of Carbon Dioxide, Summary Report," European Communities, Non-Nuclear Energy R&D Programme JOULE II., British Geological Survey, Keyworth, Nottingham,UK, 1996.

[21] Kongsjorden, H., Karstad,O. and Torp, T.A.: "Saline Aquifer Storage of Carbon Dioxide in the Sleipner Project," Waste Management, Vol.17, No.5/6, 303-308, 1997.

[22] Baklid, A. and Korbol, R.: "Sleipner Vest CO_2 Disposal, CO_2 Injection into a Shallow Underground Aquifer," SPE 36600, paper presented at the 1996 SPE Annual Conference and Exhibition held in Denver, CO. 6-9 October 1996.

[24] May, F. and Turkovic, R.: "Minderung von Treibhausgas-Emissionen durch CO_2-Spicherung in Tiefen Aquiferen," Z.Angw.Geol. (1/2003).

"The authors would like to thank OMV and RAG for providing necessary reservoir data as well as VEÖ (Verband der Elektrizitätsunternehmen Österreich) for collaboration and commission of a study on this topic."

Assessing a European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion - GESTCO Project

Franz May (Bundesanstalt für Geowissenschaften und Rohstoffe - BGR, Germany)

Co-Ordinator of CO_2-storage related activities and projects within BGR

Short Summary

GESTCO was a three-year EU supported project carried out by the Geological Surveys of 8 European countries (Norway, Denmark, The United Kingdom, France, Belgium, The Netherlands, Germany, and Greece), ECOFYS and some subcontracted companies. The project started in the year 2000 and it was co-funded by a consortium of industrial and-users. The project partners have produced:

- Twenty-eight technical reports,
- a Geographical Information System (GIS) containing information about industrial CO_2 sources, transport infrastructure, and underground storage potential, and
- a Decission Support System (DSS), to evaluate the economics of CO_2 capture, transport, and storage, within the geographical context laid down in the GIS.

The main research and development activities and project results are described in the extended summary:

Extended Summary

The GESTCO project was initiated by European Geological Surveys in 1998. The three-year project and started in March 2000. Participants of the project were the Danmark og Grønlands Geologiske Undersøgelse (GEUS), British Geological Survey (BGS), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Bureau Recherches Geologiques et Minieres (BRGM), Ecofys, Geological Survey of Belgium (GSB), the Greek Institute for Geology and Mineral Exploration (IGME), Norges Geologiske Undersøgelse (NGU) and the Netherlands Institute of Applied Geoscience (NITG-TNO). Contributions to the project were made also by Vito Engineering (Belgium), Public Power Corporation of Greece, Compagnie Francaise de Geothermale (CFG), Danish Oil and Natural Gas Company (DONG), CE-Transform (Netherlands) and the Tyndal Centre (UK). The project formed part of the European Union 5th Framework Programme for Research and Development and was 50% funded by the Programme. The following organisations also contributed to the project, either financially or by contributing data: BP, Danish Energy Authority, Gaz de France, IEA Greenhouse Gas R&D Programme, Norsk Hydro, Norwegian Petroleum Directorate, Shell, Statoil, TotalFinaElf, UK Department of Trade and Industry, Vattenfall, BEB (now Exxon Mobile Production Germany).

The primary goal of the project was to determine whether the geological storage of carbon dioxide captured at large industrial plants is a viable method of reducing greenhouse gas emissions capable of widespread application in Europe. This was established by a series of case studies that evaluated the CO_2 storage potential of saline aquifers, geothermal reservoirs, coal seams and oil and gas reservoirs. The case study approach was used because it meant that currently available largely theoretical generic information had to be applied to real geological situations. This resulted in more rigorous identification of the important issues, which will enable any necessary further research or development to be better focused. Secondary goals of the GESTCO project were to establish a CO_2 storage GIS for Europe and a Decision Support System (DSS) to serve as an economic analysis tool for CO_2 storage in Europe. The main project tasks and results are briefly summarized in the following chapters.

Inventory of major industrial sources of CO_2 in the participating countries

In 1990, the Kyoto Agreement basis year, EU-15 CO_2 emissions were about 3324 million tonnes. The EU Kyoto commitment is an 8% reduction of greenhouse gas emissions to be achieved between 2008 and 2012. To fulfil this first modest target, an annual reduction of some 334 million tonnes of CO_2 is required.

Major industrial sources of CO_2 emitting more than 100 kt/a in the participating countries were identified and compiled into a database (> 20 kt/a for Norway). In almost all countries, the major sources of CO_2 are power plants, integrated steel plants, refineries/petrochemical complexes and cement works. In Norway however, many of the major sources of CO_2 are generators at offshore oil and gas fields. The location and details of the sources of CO_2 have been compiled in a GIS linked data base. In many countries, a relatively small number of industrial point sources account for a significant proportion of the total CO_2 emissions. For example, in the UK the 20 largest sources produce about 132 million tonnes CO_2, almost 24% of the UK total annual emission of 558 million tonnes (2000 data). This indicates that a significant reduction in total national emissions could be achieved by adapting a relatively small number of plants for CO_2 capture and storage.

CO_2 Storage in oil and gas fields

Although the potential storage capacity of deep saline aquifers is many times greater than that of hydrocarbon structures, there are some distinct advantages of using depleted hydrocarbon fields as storage sites:

- The hydrocarbon fields have proved their capability to retain fluids and gases, in many cases for millions of years.
- The reservoir is well understood due to the intensive data gathering prior to and during the producing life of the field.
- Infrastructure for the production and transport of fluids and gases is already in place. With all necessary workovers and modifications, this infrastructure might be partly re-used to deliver and inject CO_2 for storage in such fields.

- The natural-gas industry has routinely used depleted gas fields for the underground storage of natural gas (UGS).
- The oil industry has routinely, but nearly exclusively confined to North America, used CO_2 injection for enhanced oil recovery (EOR). In some cases, the benefits of incremental oil production could more than offset the costs of CO_2 capture and injection.
- In many gas fields, production of gas occurs mainly because the natural gas pressure found in the untapped reservoir is much greater than atmospheric pressure so gas flows to surface via the production wells and the reservoir pressure is gradually depleted (this is known as depletion drive). Even though the gas pressure in the pore space is depleted, in some fields little or no water flows into the pore spaces of the reservoir rock (there is low water drive) and although there may be some compaction of the reservoir rock as a result of the lowering of fluid pressure within it, the combined effect of water inflow and compaction may only reduce the reservoir pore volume occupied by low pressure gas by a few percent. At least some of the major gas fields in the southern North Sea are of the depletion drive type. Gas production from these fields has created a significant volume of low pressure gas-filled pore space in the field which subsequently can be filled with CO_2.

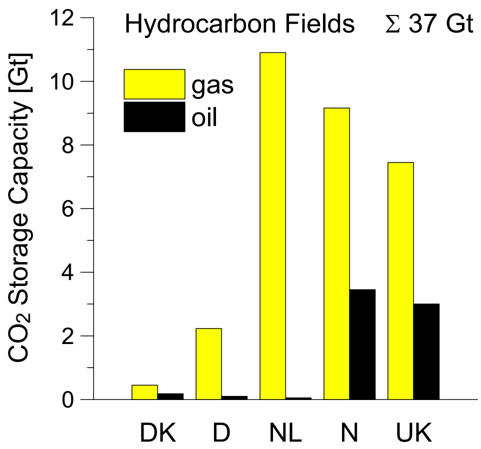


Figure 1: Potential CO_2 storage capacity in oil and gas fields of selected European countries.

The totals include all gas fields with ultimately recoverable reserves (URR) >2 x 109 standard m³ and all oil fields with URR >1 x 106 m³.

The CO_2 storage potential of the hydrocarbon fields of Denmark, Greece, Germany, the Netherlands, Norway, and the UK was investigated. Based on the 1:1 volumetric replacement of recoverable reserves of oil and gas by CO_2, the storage potential of the oil and gas fields in these countries is shown in Figure 1.

The assumption of 1:1 volumetric replacement is theoretical approximation of realistic storage capacity of the fields. In gas fields it assumes that there is no residual gas saturation, no water influx into the field, no compaction of the reservoir rock and 100% CO_2 sweep efficiency, no displacement of Formation water out of traps and no storage in the aquifer surrounding hydrocarbon traps. For oil fields is has been assumed that storage operations would commence only after oil production has ceased. Any EOR potential would be part of the oil production operation and CO_2 consumption/storage from such activities would thus be in addition to the potential estimated in this study.

- It is not known how much of this potential storage capacity is actually likely to be deployed for CO_2 storage. This is largely a question of economics, potential conflicts of use, public acceptance and safety and security of storage:
- Firstly, all of the potential CO_2 storage capacity in oil and gas fields in Denmark, Norway, Greece and the UK lies offshore. In practice there may well be only a relatively short window of opportunity to exploit the storage capacity of the offshore fields. Once the production infrastructure has been removed the opportunity may be

lost because the costs of installing new field infrastructure may be prohibitive. Furthermore, much of the UK storage capacity in oil and gas fields lies in the northern and central North Sea – at very long distances from most European point sources. CO_2-tankers are presently seen as the most promising option to transport CO_2 to offshore fields in the North Sea.

- Secondly, onshore (and some offshore) fields may have an alternative use - as natural gas storage facilities. Most of the potential storage capacity in the Netherlands (68.5% or 7512 million tonnes) lies in the Groningen field. It is not known whether this will have an alternative use. This giant field is, however, expected to produce natural gas for several decades to come.
- Thirdly, in the long term, even the gas fields with depletion drive will presumably suffer significant water encroachment and will lose some of their CO_2 storage potential.
- Finally, concerns about safety and security of storage in depleted fields need to be considered. However, the success of natural gas storage facilities in disused gas fields suggests that leakage should not be an insuperable problem providing wells can be effectively sealed for the necessary very long time frame.

The main geological barriers to utilisation of the oil and gas fields for CO_2 storage was perceived to be the possibility of leakage through disused wells or through new migration paths created because of damages to the cap rock as a result of production operations.

CO_2 Storage in aquifers, including geothermal aquifers

The CO_2 storage potential of selected saline aquifers in and surrounding the Southern North Sea was investigated in nine case studies. Some of these studies, e.g. the studies of Danish and Norwegian aquifers, confirmed that there is significant potential to store CO_2 in selected saline aquifers. Others, e.g. the study of the Bunter Sandstone Formation in the UK sector of the southern North Sea, indicate that further detailed work is required before significant storage capacity can be confirmed. In particular it is necessary to reduce uncertainties regarding storage structure integrity and the volumes of CO_2 that could be injected without unacceptable pressure rise. Identified storage capacity is summarised in Table 1. Note that in most cases these figures apply to selected areas only of the participating countries.

The studies of aquifers in Belgium, the Paris Basin of France, onshore eastern England, and the Netherlands onshore suggest that at best there are only niche opportunities for CO_2 storage underground in these areas.

The studies of geothermal aquifers concluded that there were no significant advantages in injecting CO_2 in the return well of a geothermal doublet. The rate of injection was too low to be of interest for significant CO_2 sequestration and the volumes of CO_2 which possibly could be stored would be marginal. High well re-completion cost and would be an additional obstacle. It was thus concluded that storage of CO_2 in conjunction with geothermal plants, from a volumetric point of view, would be of little overall importance, but could be of interest as a local option.

Case study area	**CO_2 storage capacity (Gt)**	**Comments**
UK sector, southern North Sea	Up to 14.7	Detailed study of integrity and injectivity of individual storage structures in the Bunter Sandstone Fm required to firm up potential
Selected onshore & near shore aquifers, Denmark	16	Study focused on 11 individual storage structures (structural traps) in the onshore area
Onshore Germany	20 ± 8	Capacity mainly located within the North German basin. Extrapolated from regional studies.
Offshore Norway, structural traps	13	Estimated potential of >286 Gt if storage is not in conventional traps for buoyant fluids
Netherlands entire onshore and offshore area	1.6	Extrapolated from a limited set of evaluated traps
Greece, entire onshore and offshore area	2.2	
Campine Basin, Belgium	0.1	Potential conflict of interest with natural gas storage
Paris Basin, Buntsandstein to Dogger aquifers	0.66	Selected aquifers are located in the Paris Basin. They are used for geothermal heat production.

Table 1: CO_2 storage capacity of selected aquifers in participating countries

CO_2 Storage in coal seams, coal mines and other mines and man-made cavities

The storage of CO_2 in deep unminable coal seams is considered possible because CO_2 has an affinity to be adsorbed onto the macerals of coal. This affinity is greater than that of the methane (coalbed methane) that commonly occurs in nature adsorbed onto coal. Thus it may prove possible to use CO_2 to enhance coalbed methane production from coal seams whilst at the same time sequestering CO_2. In theory, at least twice as much CO_2 would be sequestered in the coal seams as would be liberated to the atmosphere by burning the produced methane. Because the CO_2 would be adsorbed onto the coal it would be stored in a more stable way than if it was a free gas in the pore spaces of a conventional sandstone or carbonate reservoir rock.

The development of CO_2-enhanced coalbed methane production (ECBM) technology is at an early stage and technical uncertainty remains. For example, the injection of CO_2 into coal seams is dependent on the presence of sufficient permeability in the seams. A figure of >1 Millidarcy permeability has been suggested as a minimum requirement for economic (ECBM) production. The in situ permeability of the Carboniferous coal seams of Europe is thought to be generally low and in many areas possibly too low for ECBM. This theory is supported e.g. by the absence throughout Europe of economically viable coalbed methane production from virgin coal seams, despite the abundant evidence of high seam methane content in many coalfields.

40The theoretical potential for storage of CO_2 in coal mines varies across the participating countries. However, much of the abandoned mine galleries are too shallow for the storage of high-density CO_2 under pressure.

The case-study of the potential to store CO_2 in the Campine coal basin in Belgium indicates that 432 million tonnes of CO_2 could be stored, associated with ECBM production. In Belgium the main uncertainty is the sealing capability of the overlying Chalk strata under overpressure. A case-study of the Belgian Beringen-Zolder-Houthalen collieries shows that sequestration in these coal mines is a viable option. At an injection rate of 0.3 to 0.5 Mt/a, storage could last for about 25 years. These are considerable contributions, approximately 3 to 6 % of the mitigation required to reach the Kyoto-target of Belgium, relative to the 1990 emission level.

In Germany and the UK there is abundant evidence of gas leakage to the ground surface in the major coal mining areas. This alone would prevent the storage of CO_2 in the mines in these countries because of the risk of asphyxiation if the CO_2 leaked into the built environment. Within the last years for most of the abandoned mines in the Ruhr area concessions for mine gas production have been granted. This, and also ongoing mining in the interconnected pits, would be in conflict with CO_2 storage. In the UK, the natural recovery of water levels in the workings to the level of the local water table or any drainage soughs installed in the mines gradually drives out any free gas retained in the coal mines at the end of coal production. This would preclude the storage of free CO_2 in the mines although it might be possible to cause CO_2 to be adsorbed onto the residual coal in seams surrounding the extracted seam(s).

It might be possible to store free CO_2 in certain salt mines. However, a case-study of German salt mines indicated that these generally have other uses of abandoned underground cavities that may be considered to have higher priority, e.g. storage of toxic or various levels of radioactive waste. Though it might be possible to store relatively small volumes of CO_2 in solution-mined salt caverns the disposal of brines from the cavern solution would create other local environmental problems.

Safety and security of storage and potential conflicts of use

The case-studies of safety, conflicts of use, and legal aspects of storage in Germany indicate that these subjects are dependent on the inter-relationships between geological, societal, technical and economic factors affecting CO_2 storage underground. For example, the legal issues and the degree of public acceptance will affect the planning and regulatory requirements, which in turn will affect the economics of storage. Human intrusion, either accidental or deliberate, for example the destruction of wellheads as an act of war as has already occurred in oil fields, is likely to be a major consideration.

The case-study of safety and security of storage in Germany indicates that the injection of CO_2 onshore in Germany may be subject to mining law and water legislation. The federal water framework law (Wasserhaushaltsgesetz) prohibits injection or storage of substances that could cause negative alterations of groundwater properties. From the legal point of view saline brines in deep aquifers are groundwater. Thus, by analogy with the case of aquifer storage of natural gas, there is the necessity to comply with both. , and obey the rights of land owners affected by the proposed storage. Because of the risk of leakage, the injection process has to be monitored and has to be controllable, and long term liability may need to be accepted by the state. Considerable experience exists in a number of the countries regarding abandonment of mines.

The storage of CO_2 in abandoned salt mines in Germany is subject to conflicts of use with storage of waste. The storage of CO_2 in gas fields is subject to conflicts of use with the seasonal storage of natural gas. According to federal mining law, deep saline aquifers are deposits of geothermal energy and brines, which may be used for table water production, in spas, or as a source of base material for the chemical industry. The mining law is intended to give protection to resources, and may give priority to uses other than CO_2 storage. Furthermore, in North Germany natural gas is stored in aquifers at four locations. Thus, the down-dip catchment area of these existing storage structures cannot be used for CO_2 injection.

CO_2 sequestration activities on the land surface are - at least temporarily - in conflict with land use. Pipelines, injection and monitoring wells and surface installations may not be allowed within groundwater protection zones, protected natural reserves, and waste deposits. It may also be difficult to obtain permissions from property owners in urban, military, and industrial areas to build or operate surface infrastructure. Also, considerable parts of the land surface will not be available or will be difficult to use in both densely populated and rural areas. Areas of ecological importance cover large parts of northern Germany. Activities in these areas are either affected by various degrees of restrictions or they have a declared preferential use.

The <u>case-study of security of storage in the Bunter Sandstone of the UK sector of the southern North Sea</u> indicated that potential security of storage issues associated with the injection of CO_2 into a closed structure (e.g. a dome) developed in a reservoir rock are as follows:

Geochemical issues:
- Corrosion of the reservoir rock matrix by CO_2/water mixtures, leading to the compaction or collapse of the formation and thus to the development of cracks and new migration paths through the cap rock.
- Precipitation of minerals within the reservoir rock could mean that the pressures required for the given injection rates could exceed safe pore fluid pressure.
- Dissolution of cap rock minerals by carbonic acid, leading to its collapse or failure as a seal.
- Dehydration of the cap rock could induce shrinkage and create pathways for CO_2 through it.
- Transport of dissolved CO_2 out of the structure by natural or induced pore fluid flow.

Pore fluid pressure issues:
- Fracturing of the cap rock, due to increased pore fluid pressures in the reservoir.
- The opening up of pre-existing but closed migration paths (e.g. faults) through the cap rock, caused by increased pore fluid pressures during injection.
- Gas pressure in the CO_2 accumulation exceeding the capillary entry pressure of the overlying cap rocks, resulting in CO_2 transport through the cap rock.

Well issues:
- Escape of CO_2 via poorly sealed pre-existing wells or by failure of the injection well.
- Escape of CO_2 due to corrosion of cement or steel in wells penetrating the storage structure or cement holding the borehole casing to the surrounding rock.

CO_2–ECBM; There is very little practical experience of injecting CO_2 into coal seams and very little realistic knowledge of the practical safety and security issues. The major issues may be:

- Poor understanding of the physics and chemistry of $CO_2/CH_4/N_2$ adsorption and desorption.
- The potential for CO_2 emissions, e.g. via hydraulic fractures induced in the coal seams to increase injectivity, faults or mining-induced cracks in the Coal Measures strata.
- Potential emission of CH_4 which is a much more powerful greenhouse gas than CO_2.
- Sterilisation of a potential energy resource. Any attempt to mine or gasify the coal in situ after CO_2 storage would most likely lead to the release of CO_2.

Other issues:

- The presence of unidentified migration paths through the cap rock.
- Escape of CO_2 via a spill point at the base of the closed structure, e.g. due to underestimated viscous fingering or incorrect mapping of structural closure.
- Displacement of highly saline brines from the storage location.

Various geotechnical risks to proper storage performance are envisaged. Providing adequate characterisation of the storage site is undertaken before injection starts, the most important concerns are (1) that there may be unidentified migration paths out of the structure and (2) concerns related to injectivity, in particular the potential for undesirable rapid pore fluid pressure rises to occur in the reservoir. Among the latter, there is a risk that unidentified permeability barriers may occur within the reservoir, effectively dividing it into compartments or reducing its permeability on the macro-scale. This could result in the threshold reservoir pressure being reached very early and the possible failure of the project. It might also result in the opening of pre-existing faults. The best way to resolve this question would be by injection tests into the reservoir rock.

There is a risk that salt will be precipitated and fill the pore space near the well as a result of water dissolving into the dry CO_2 injected down the well. This could possibly be remediated by injecting fresh water that would dissolve the salt cement. However, large quantities of fresh water are not easily available offshore.

Issues relating to pre-existing wells may also be important. The highly saline pore water in the Bunter Sandstone is likely to be made more aggressive towards steel, and certainly more aggressive towards cement, by the addition of CO_2. However, at present very little is known, and nothing has been published, about the state of casings or cement plugs and bonds in the exploration and production wells in the southern North Sea, even though some have been in place for nearly 40 years. It is recommended that a materials selection study to identify suitable cements and borehole casings for CO_2 injection wells be undertaken.

The CO_2 storage GIS

The objective for the GESTCO GIS was to produce a Geographical Information System (GIS) that would incorporate the wide range of data provided by the project partners and allow meaningful access to the data. The GIS allows users to simultaneously view one or more layers of data including the location of the CO_2 sources and possible CO_2 sinks. It also enables the user to perform extensive on screen analysis on all the available data.

Geoscientific datasets included in the GIS comprise: location of potential aquifer storage sites, designated injection points in aquifers, hydrocarbon field locations and hydrocarbon field injection points, coal mines, coal fields and potential coal field injection points as well as the locations of the CO_2 sources, existing pipelines and pipeline terminals. Many other datasets have also been provided to enhance the capabilities and information held within the GIS, for example geological, tectonic zone and ecosystem data.

Many case studies have been carried out for the project and the data from these has been included in the GIS. As this data has been provided in many different formats and is specific to particular case studies this data has not been merged into single datasets as with the general GIS datasets. There are many maps and diagrams that have been provided for the case studies, as it is highly useful to be able to view such maps, diagrams and seismic profiles, from within the GIS, hyperlinks have been set up. This enables the user to click on a feature with the hyperlink tool and view any maps or documentation associated to the feature.

The GESTCO Decision Support System

The Decision Support System (DSS) consists of a GIS front end, covering Europe and populated for the participating countries, and underlying Excel calculation modules. The GIS front end enables the operator to select a source of CO_2 and a potential sink for that CO_2. This is combined with a routine that calculates the best transport route for the CO_2, using a cost grid of geographic factors such as topography, urbanisation, river crossings, the location of existing pipeline routes and pipeline landing points. The Excel calculation routine allows the operator to calculate the costs of CO_2 separation, compression, transport and injection into the subsurface.

The CO_2 sources in the Gestco GIS consist of existing, real sources of CO_2. This has a profound effect on analysis of the capture and storage costs associated with these plants, which by definition, require retrofitting for CO_2 capture. Clearly this may not always be the most effective method of capture, but, the user can modify the database and add items according to his needs.

The economical evaluation comprises:

- calculation of the cost of capture for all sources in the GESTCO source database
- uncertainty and sensitivity analyses of the four sequestration system elements, i.e. capture, compression, transport, and storage of carbon dioxide.
- case studies using the GESTCO-DSS application for specific sequestration systems in the countries participating in the GESTCO project. The exemplary case studies are based on existing carbon dioxide sources and real reservoirs that are suitable candidates for the storage of the captured CO_2 (see below).

Capture Cost Analysis

For over 350 power supply installations in the eight European GESTCO countries the carbon dioxide capture costs were determined using the GESTCO-DSS. The capture costs include all costs to separate the carbon dioxide from the energy conversion process and exclude compression, transport and storage costs. The cost calculations are performed using the default parameter values in the GESTCO-DSS. The average costs in this study amounts to about 25 to 52 euro per Mg of CO_2 avoided for the power installations. Often capture costs are quoted between 15 and 40 euro per Mg CO_2 avoided. However, it should be taken into account that the following circumstances of the CO_2 capturing differ from other studies and which influence significantly the results of the cost calculations:

- The analysed plants are all existing plants; retrofitting old plants is more costly than constructing new plants with capture facilities. On average, investment costs might be about 30% lower for new installations. Also the integration of the capture process can be done more efficient in new plants than in existing plants.
- The operational time per year (the load factor) of the plants are relatively low compared to other studies. In the cost calculations, the operational time is assumed to be the same as the load factor without the capture installation. The load factor is taken from the source database inventory. In practise, however, it would be more realistic that installations with capture installation will increase their load factor and reduce in that way the avoidance costs. An average load of 8000 hours per year instead of the actual load factor will decrease the capture costs by about 25% compared to the load factor in current existing installations.
- In the database, many relatively small plants are included. Generally, cost calculations are performed for power plants with a size of at least 500 MW_e. Capture costs per tonne of CO_2 avoided are significantly higher at smaller plants than at larger ones.

The average calculated costs for coal-fired power plants are considerably lower than for natural gas-fired plants. This can largely be explained by the fact that the average operational time of natural gas plants (often equipped with gas turbines) are considerably lower than for coal-fired power plants. Also the average size of coal-fired power plants is much larger than natural gas-fired power plants.

The calculated capture costs of pre-combustion technologies are on average over 60% higher than the post-combustion technology. This can be explained by the fact that currently almost no integrated coal gasifier combined cycles (IGCC) are installed. This type of power plant is relatively attractive to apply the pre-combustion method. Pre-combustion at existing boiler/steam-turbine installations on the other hand is relatively expensive and not recommendable. The average capture costs for new IGCC plants with high load factors will therefore be considerably lower and will amount to about 20 to 25 euro per Mg CO_2 avoided.

The capture cost analysis has been performed for the industrial CO_2 sources listed in the database alike. In total about 230 Mt of carbon dioxide can be avoided at average costs of about 26 €/t of CO_2 avoided. About 13 Mt can be captured from industrial installations against avoidance costs of about 1 €/t of CO_2 avoided. The low-cost opportunities can mainly be found at hydrogen and ammonia production facilities (Figure 2). Sensitivity studies using Monte-Carlo simulations have been performed to assess uncertainties in the cost calculations and to identify the most influential cost parameters, both for power plants and industrial sources.

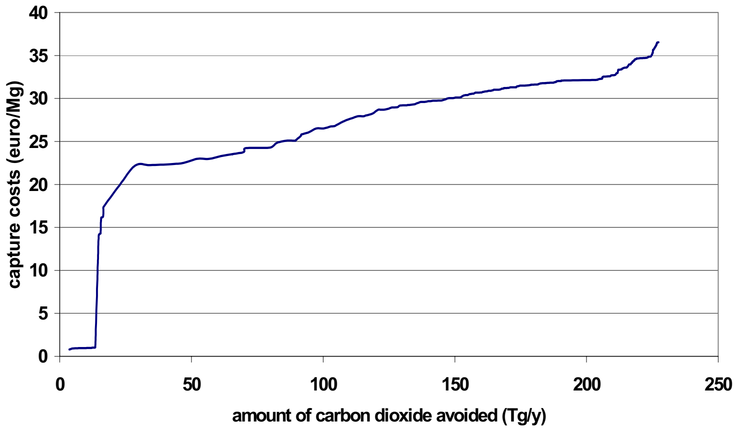


Figure 2: Cost curve for carbon dioxide capture costs for industrial installations in the GESTCO source data-base using the post-combustion method based on amine technology

CO_2 sequestration case studies

In the GESTCO project the geological surveys of the participating countries designed and evaluated seventeen carbon dioxide sequestration case studies. Numerical simulations were performed to investigate questions of storage capacity and efficiency, CO_2 movement within the reservoirs, or its ability to pass though cap rocks in long time scales. These detailed case specific studies yielded additional information to the more general considerations e.g. about regional storage capacity. Geochemical simulations were performed for some of cases in order to predict possible geochemical reactions that might cause geotechnical problems during the injection period, or could influence long-term storage safety. The economical evaluation of the case studies was carried out using the GESTCO-DSS.

The smallest project (an ammonia plant) avoids about 0.018 Mt/a of CO_2, while the largest projects (power plants) avoid 6 to 8 Mt/a of CO_2. The case study projects were primarily chosen on readily available data on sources and storage reservoirs and to a lesser extend to presumed financial suitability. All the projects described in the case studies deal with existing plants, which are more expensive to equip with carbon dioxide capture than newly built plants. Six industrial plants (of which three plants with pure streams and three plants with diluted streams of carbon dioxide) and eleven power plants are evaluated. For the storage, fourteen cases comprise aquifers while three cases are oil and/or gas fields (without enhanced oil recovery).

The highest total costs amount to about 100 €/t of CO_2 avoided. These costs are calculated for relatively small systems running 40% or less of the time. The lowest costs of 14 €/t of CO_2 avoided is found for an ammonia plant with a pure stream of carbon dioxide. The ammonia plant is located nearby a suitable storage reservoir. The lowest costs for a power plant case study are obtained for a large coal-fired power plant (1528 MW_e) in Denmark. The total avoidance costs amount to 32 €/t of CO_2 avoided, of which 2/3 is required for the capture process.

Analysis of Public Outreach and Recommendation for Future Activities

The compilation and analysis of public outreach studies and events held to date yielded some common positions of public concern and interest that have to be addressed when proposing the future implementation of CO_2 capture and storage technology:

- Ocean storage is not likely to be accepted in Europe – NGO's and the public have demonstrated deep seated objections to this approach.
- Carbon storage must be evaluated in the context of other carbon mitigation options and as part of broader debate of energy policy; it should not be considered in isolation.
- Investment in the development of Carbon Capture and Storage (CCS) technology must not be at the expense of other emission mitigation options, such as renewable energy technologies and energy efficiency improvements.
- Even the more sceptical stakeholders may view CCS more positively if its role is identified as part of a bridging strategy towards a more truly decarbonised energy infrastructure.
- Government signals are required before industry can proceed with the technology.
- The debate about the desirability of CCS is really about the long term use of fossil fuels - maintaining this is used either as an argument in its favour (for example, to address concerns over energy security, diversity of supply, and maintenance of the existing energy sector) or an argument against the approach (e.g. that the sooner we give up the fossil fuel 'habit', the better).

There remains a widespread attitude activities described in this report are about ways of promoting or “selling” the technology. Thus outreach activities should recognise, that the need for genuine participation of the public remains in addressing questions such as whether we want CCS to play a role, what form it should take, how much storage is necessary, how it should be funded, other conditions that need to be met - all in the context of broader energy / climate policies.

For CO_2 storage to become an important mitigation technology, a number of further activities would be advisable:

- Extend mapping of capacity and quality of the European geological storage potential.
- Assessment and inventorying of new power requirements and existing emission sources, particularly in the new and coming EU member states.
- Further research into safety and security aspects of storage, reducing geological and engineering uncertainties is needed, and, wherever possible, doing this in conjunction with demonstration of the technology and including public outreach and acceptance.
- Building European technical standards for CO_2 capture and storage operations, including monitoring requirements and targeted research into the prediction of chemical reactions and fluid behaviour over very long time spans.
- Provide scientific and technical input for national and EU legislation concerning CCS

CO_2 Sub-Surface Risk Management & Mitigation

Kamel Bennaceur (Schlumberger, United Kingdom)

General Manager for CO_2 and Subsurface

Public and regulatory acceptance of long-term CO_2 storage as a safe solution for emissions control requires the development of a risk management methodology, and in particular for the sub-surface where the potential of leakage exists. The Oil & Gas industry has adapted or developed for its applications a number of risk management methodologies. They range from task and process, to project qualitative and quantitative risk analysis. Because of the complexity and the interconnection of the various elements of a quantitative risk analysis, including static and dynamic models, solutions for integrated workflows that reduce both processing time and iterations, are presented. The issues related to wellbore and seal integrity, which have been identified by several industry reports as one of, or even, the most critical leakage risk. A methodology has been developed to test cementing systems under simulated conditions of exposure to super-critical cement. It also allows protocols for accelerated ageing testing, which allow an improved understanding of the cement behavior over 100-s of years. Wellbore evaluation techniques, including 3-dimensional cement imaging are then discussed.

Schlumberger Involvement in CO_2 Capture & Storage

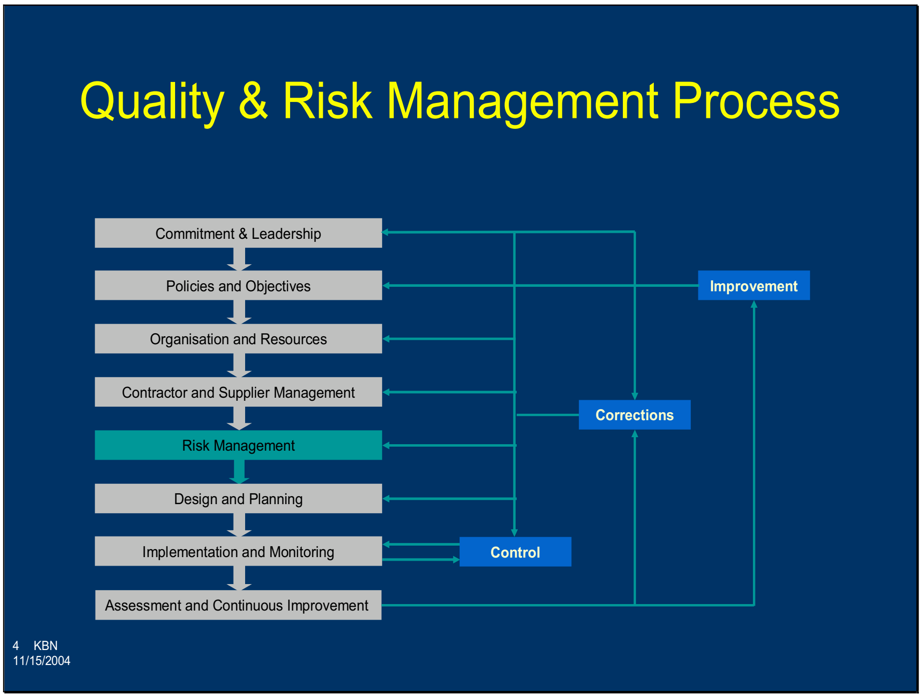
- Provision of:
  - Geological & Geophysical Solutions
  - Reservoir Simulation & Production Optimization
  - Wellbore & Reservoir Monitoring
  - Wellbore Construction, Isolation & Completion
  - Information & Knowledge Management Solutions
  - Real-time Automation: Production & Injection Management
  - Project Management
- Involved in almost all anthropogenic CO2 projects

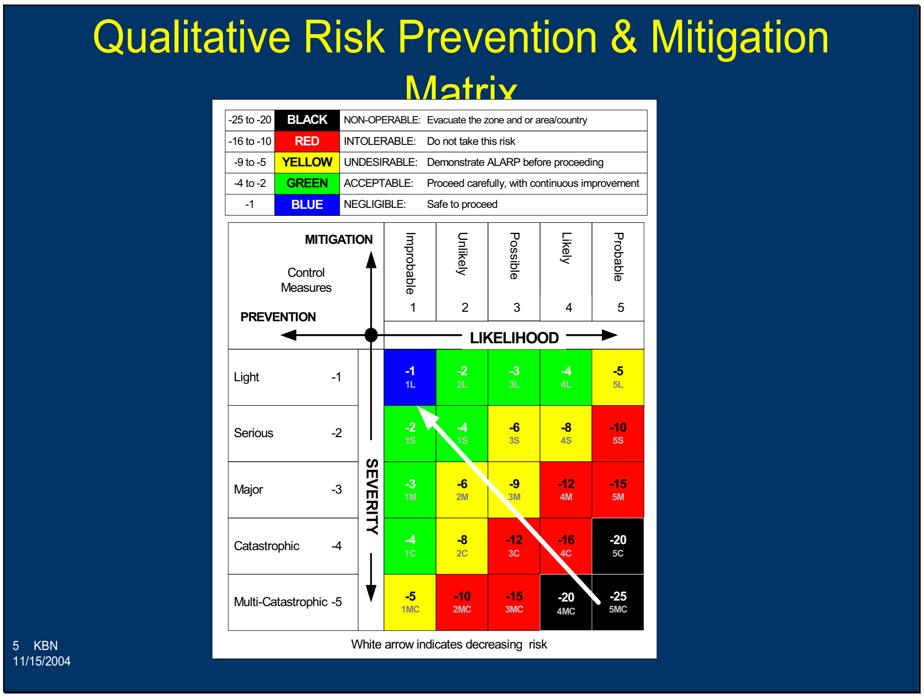
2 KBN
11/15/2004

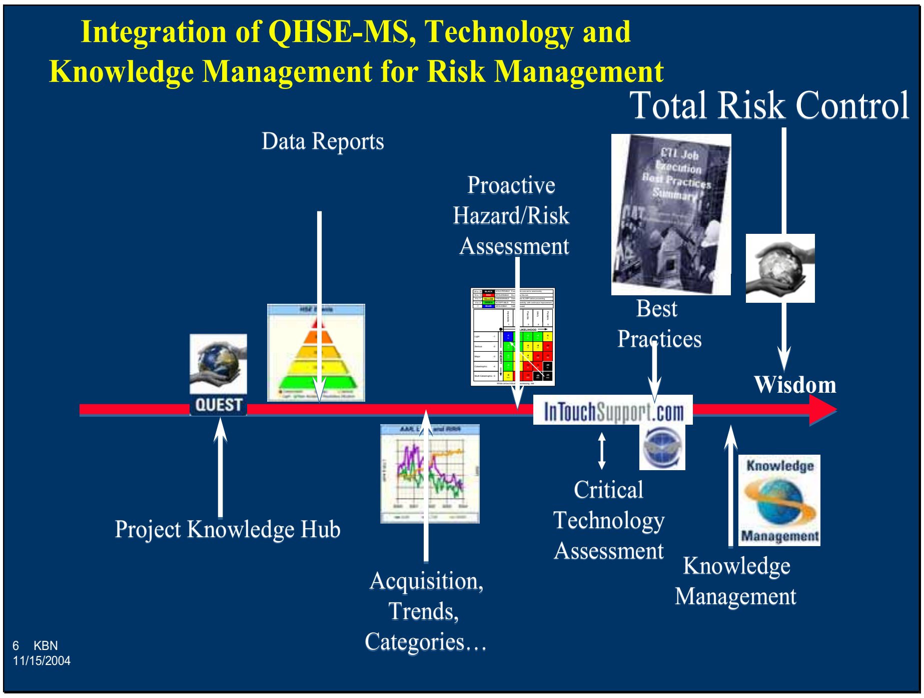
Sub-Surface Management for CO_2

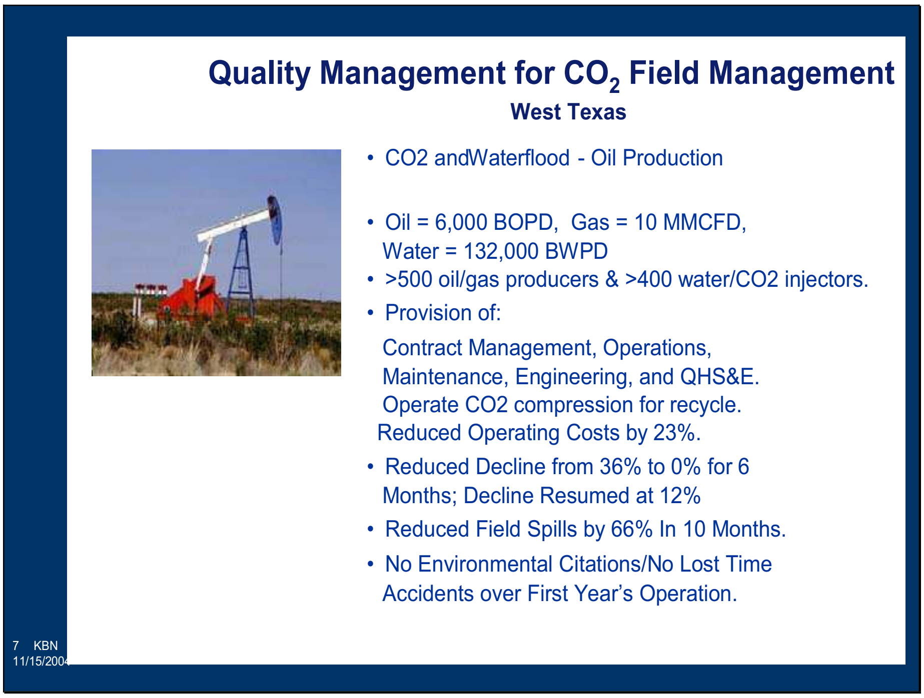
- Evaluation of Potential Storage Sites
- Uncertainty Assessment & Value of Information Analysis
- Static Model(s) and Prediction from Dynamic Simulation (ranges of outcomes)
- Integrated Well Construction & Formation Evaluation
- Sub-surface Monitoring (near wellbore and across wellbores)
- Resulting Actions:
  - Maintenance, Remediation
  - Update of Static & Dynamic Simulation

3 KBN
11/15/2004


Quality & Risk Management Process
Commitment & Leadership
Policies and Objectives
Organisation and Resources
Contractor and Supplier Management
Risk Management
Design and Planning
Implementation and Monitoring
Assessment and Continuous Improvement
Improvement
Corrections
Control
4 KBN
11/15/2004


Qualitative Risk Prevention & Mitigation Matrix
-25 to -20 BLACK NON-OPERABLE: Evacuate the zone and or area/country
-16 to -10 RED INTOLERABLE: Do not take this risk
-9 to -5 YELLOW UNDESIRABLE: Demonstrate ALARP before proceeding
-4 to -2 GREEN ACCEPTABLE: Proceed carefully, with continuous improvement
-1 BLUE NEGLIGIBLE: Safe to proceed
MITIGATION
Control Measures
PREVENTION
Improbable 1
Unlikely 2
Possible 3
Likely 4
Probable 5
LIKELIHOOD
SEVERITY
Light -1
Serious -2
Major -3
Catastrophic -4
Multi-Catastrophic -5
-1 1L
-2 2L
-3 3L
-4 4L
-5 5L
-2 1S
-4 1S
-6 3S
-8 4S
-10 5S
-3 1M
-6 2M
-9 3M
-12 4M
-15 5M
-4 1C
-8 2C
-12 3C
-16 4C
-20 5C
-5 1MC
-10 2MC
-15 3MC
-20 4MC
-25 5MC
White arrow indicates decreasing risk
5 KBN
11/15/2004


Integration of QHSE-MS, Technology and
Knowledge Management for Risk Management
Total Risk Control
Data Reports
Proactive
Hazard/Risk
Assessment
Best
Practices
Wisdom
QUEST
InTouchSupport.com
Knowledge
Management
Project Knowledge Hub
Critical
Technology
Assessment
Knowledge
Management
Acquisition,
Trends,
Categories…
6 KBN
11/15/2004


Quality Management for CO_2 Field Management
West Texas
• CO2 andWaterflood - Oil Production
• Oil = 6,000 BOPD, Gas = 10 MMCFD,
Water = 132,000 BWPD
• >500 oil/gas producers & >400 water/CO2 injectors.
• Provision of:
Contract Management, Operations,
Maintenance, Engineering, and QHS&E.
Operate CO2 compression for recycle.
Reduced Operating Costs by 23%.
• Reduced Decline from 36% to 0% for 6
Months; Decline Resumed at 12%
• Reduced Field Spills by 66% In 10 Months.
• No Environmental Citations/No Lost Time
Accidents over First Year's Operation.
7 KBN
11/15/2004

Challenges in CO_2 Sub-Surface Storage

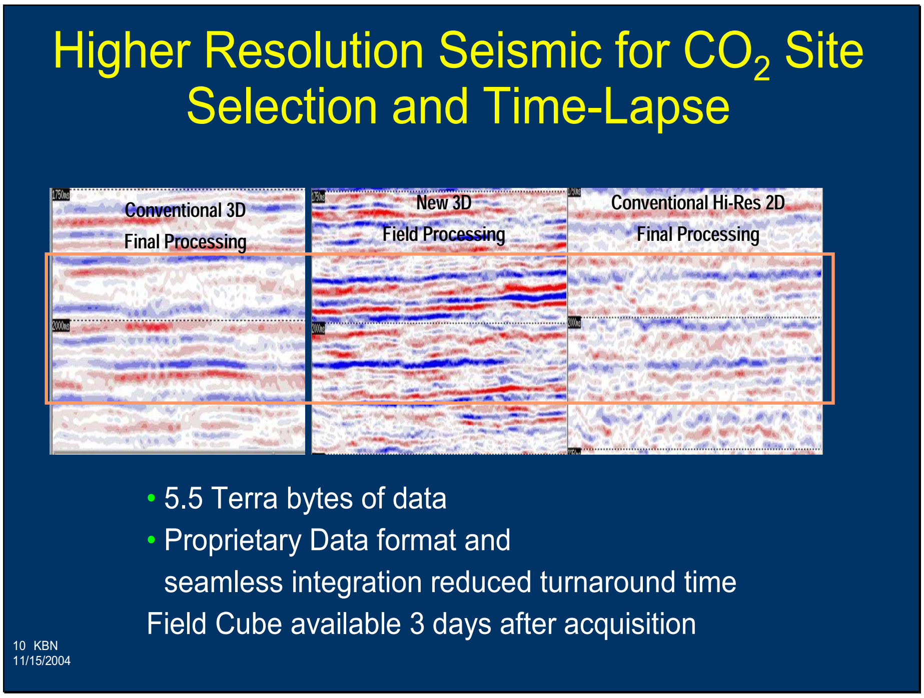
- Technology & Process Gaps
  - Long-Term (100s->1000s of years) Assurance
  - Lack of Standard Industry Processes
  - Sub-surface characterization: a shared model for static and dynamic formation modeling
  - Integrated Teams Workflows
  - Rapid processing of static and dynamic models
  - Cost-effective permanent monitoring
  - Wellbore Integrity (often overlooked)
  - Modeling of Interaction between CO_2 and Formation

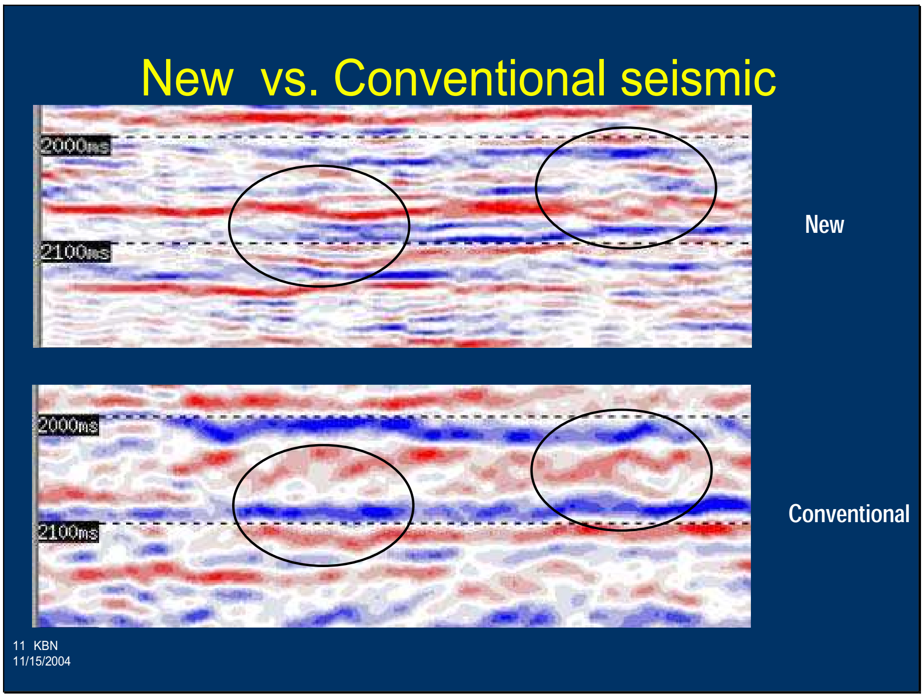
8 KBN
11/15/2004

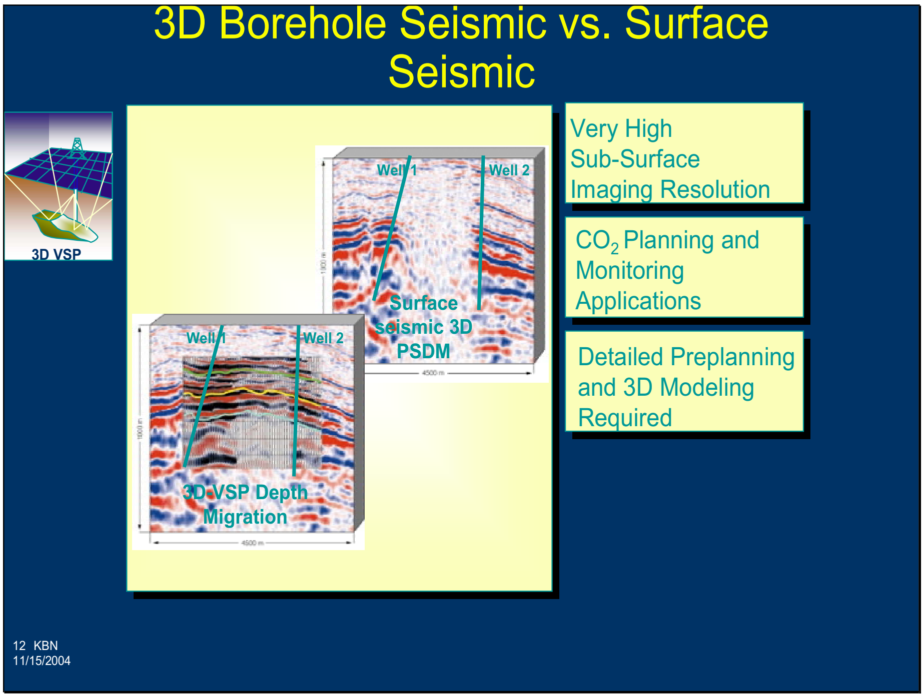
Challenges in Monitoring

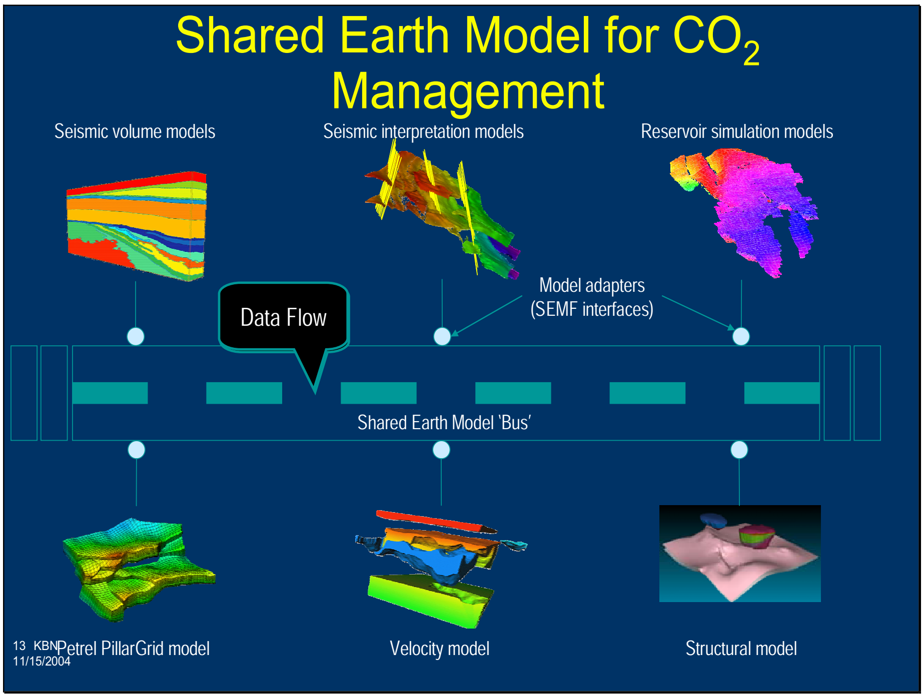
- Time-Lapse Seismic (Surface, X-wellbore)
  - Resolution
  - Processing time: Need for AI-based inversion tools
- X-wellbore electrical & electro-magnetic tools
- Wellbore measurements (producers, injectors, monitoring wells)
  - Layer measurements (downhole sampling …)
  - Distributed Measurements (fiber optics …)

9 KBN
11/15/2004

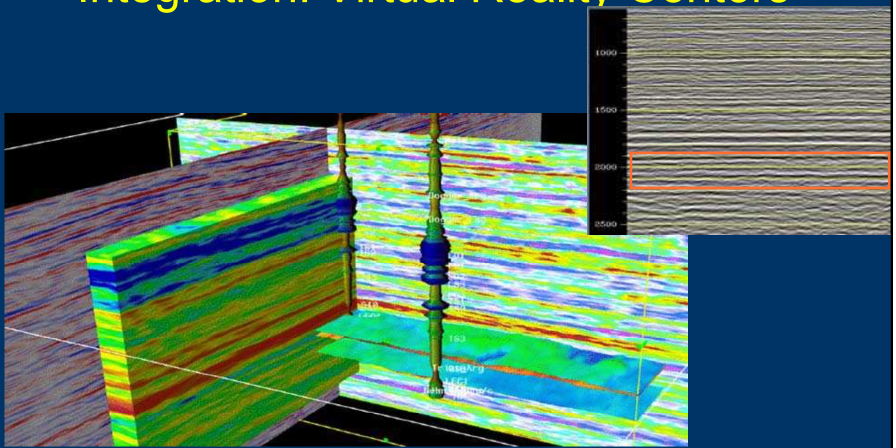

Higher Resolution Seismic for CO2 Site Selection and Time-Lapse
Conventional 3D Final Processing
New 3D Field Processing
Conventional Hi-Res 2D Final Processing
• 5.5 Terra bytes of data
• Proprietary Data format and seamless integration reduced turnaround time
Field Cube available 3 days after acquisition
10 KBN
11/15/2004


New vs. Conventional seismic
2000ms
2100ms
New
2000ms
2100ms
Conventional
11 KBN
11/15/2004


3D Borehole Seismic vs. Surface Seismic
3D VSP
Well 1
Well 2
Surface seismic 3D PSDM
Well 1
Well 2
3D VSP Depth Migration
Very High Sub-Surface Imaging Resolution
CO_2 Planning and Monitoring Applications
Detailed Preplanning and 3D Modeling Required
12 KBN
11/15/2004


Shared Earth Model for CO_2 Management
Seismic volume models
Seismic interpretation models
Reservoir simulation models
Data Flow
Model adapters
(SEMF interfaces)
Shared Earth Model 'Bus'
Petrel PillarGrid model
Velocity model
Structural model
13 KBN
11/15/2004

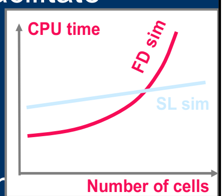
Improved Visualization & Team Integration: Virtual Reality Centers



14 KBN
11/15/2004

Challenges of CO_2 Simulation
Impact of Uncertainties/Heterogeneities

- Formation vertical and lateral heterogeneities play a significant role in CO2 movement
- Current finite-difference grid-cell models are slow to perform multi-scenarios analysis due to computational requirements
- Streamline methods being developed to facilitate Monte-Carlo simulations of CO2 injection
  - Speed-up factor by orders of magnitude
  - Need to include capillary forces



- Industry/Academia efforts could be combir

15 KBN
11/15/2004

Wellbore Integrity & Flow Assurance

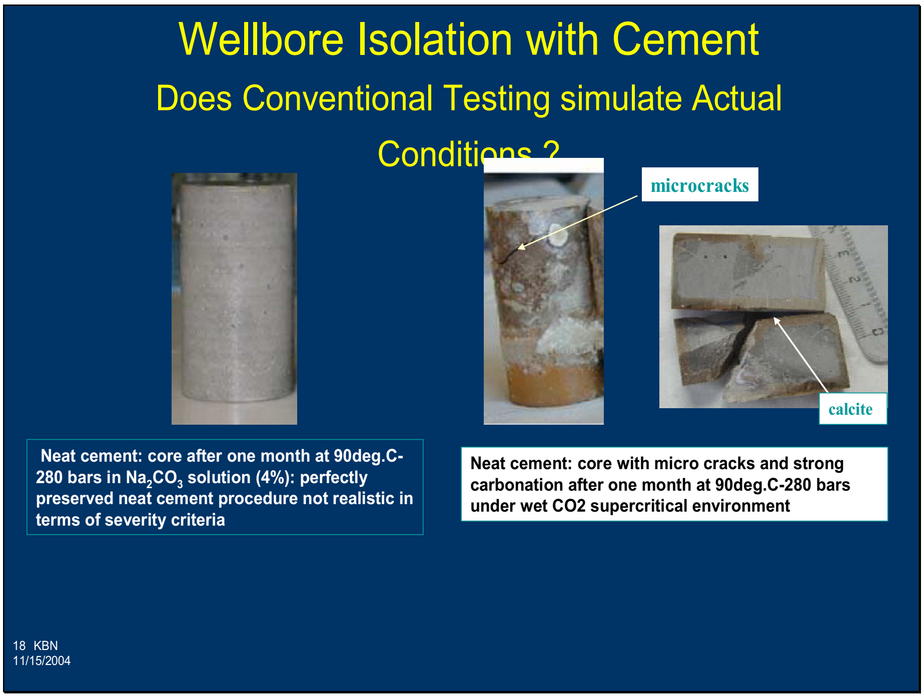
- Current cementing practices (API-RP, Class 1 & 2 wells) do not address long-term storage requirements, hence a significant risk of leakage
- Monitoring of cement integrity during the life of the well, and subsequent repairs
- Need to optimize metallurgy composition to minimize subsequent intervention

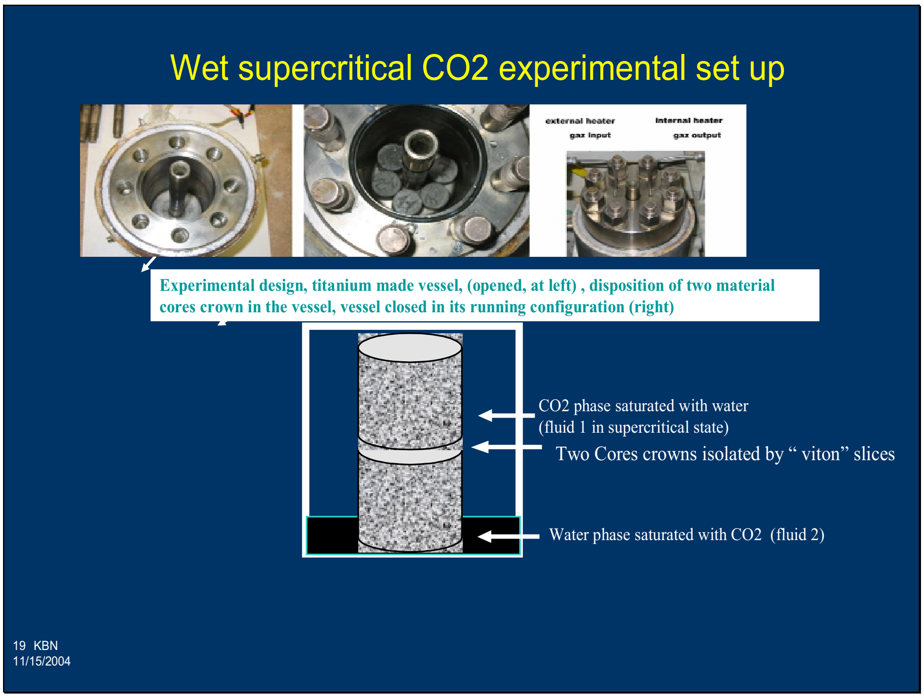
16 KBN
11/15/2004

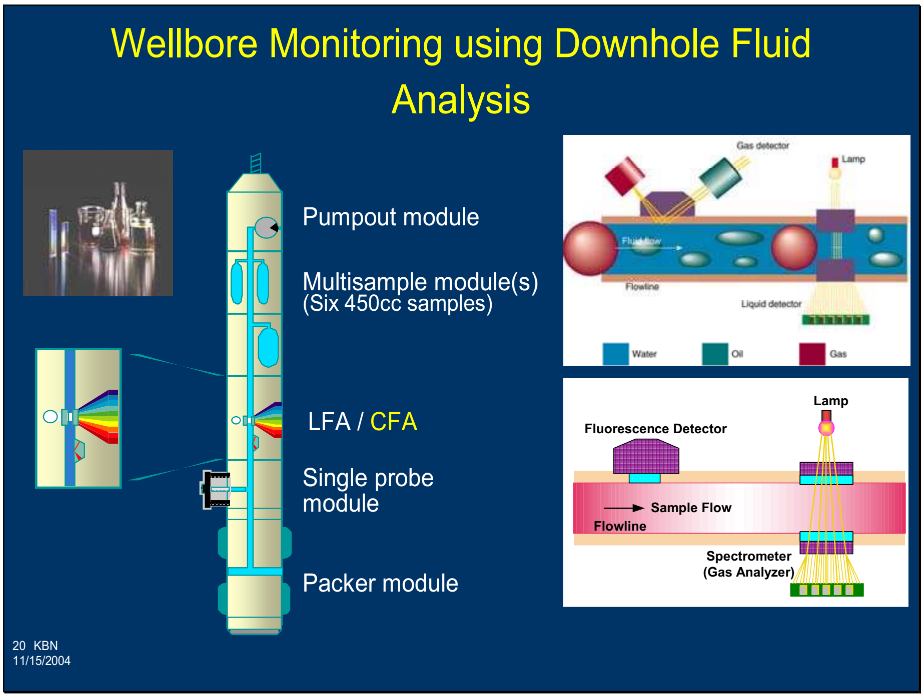
Largest Risk from Analogues

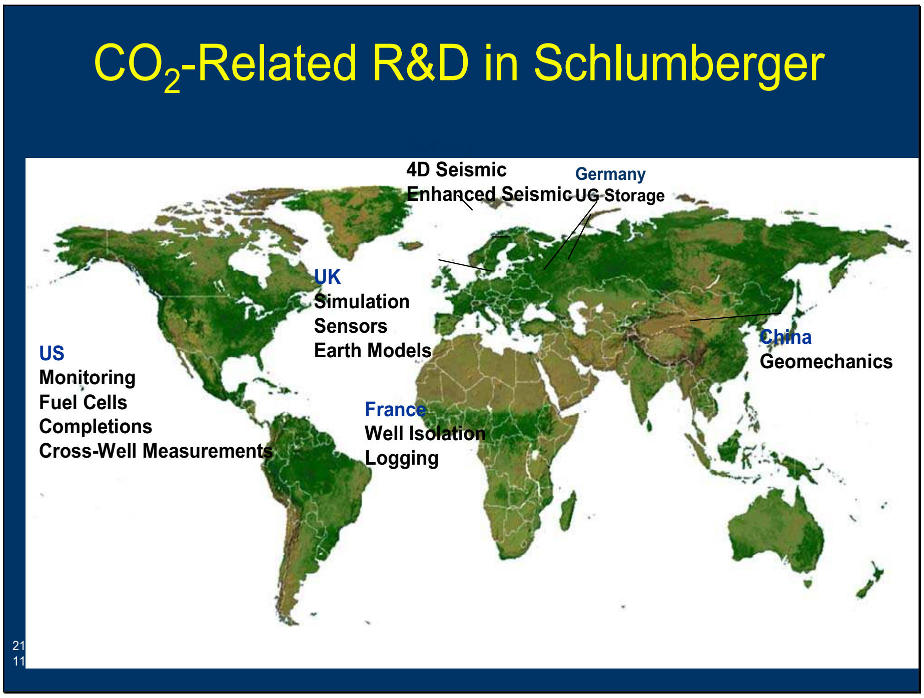
- W. Heidug (Shell)
  - Biggest risk from CO2 Storage due to:
    - Leakage through poor quality or injection well completions
    - Leakage up abandoned wells
    - Leakage due to inadequate caprock characterization

17 KBN
11/15/2004


Wellbore Isolation with Cement
Does Conventional Testing simulate Actual Conditions ?
microcracks
calcite
Neat cement: core after one month at 90deg.C-280 bars in Na_2CO_3 solution (4%): perfectly preserved neat cement procedure not realistic in terms of severity criteria
Neat cement: core with micro cracks and strong carbonation after one month at 90deg.C-280 bars under wet CO2 supercritical environment
18 KBN
11/15/2004


Wet supercritical CO2 experimental set up
external heater
gaz input
internal heater
gaz output
Experimental design, titanium made vessel, (opened, at left) , disposition of two material cores crown in the vessel, vessel closed in its running configuration (right)
CO2 phase saturated with water
(fluid 1 in supercritical state)
Two Cores crowns isolated by " viton" slices
Water phase saturated with CO2 (fluid 2)
19 KBN
11/15/2004


Wellbore Monitoring using Downhole Fluid Analysis
Pumpout module
Multisample module(s)
(Six 450cc samples)
LFA / CFA
Single probe module
Packer module
Gas detector
Lamp
Flowline
Liquid detector
Water
Oil
Gas
Fluorescence Detector
Lamp
Sample Flow
Flowline
Spectrometer
(Gas Analyzer)
20 KBN
11/15/2004


CO_2-Related R&D in Schlumberger
4D Seismic
Enhanced Seismic
Germany
UG Storage
UK
Simulation
Sensors
Earth Models
US
Monitoring
Fuel Cells
Completions
Cross-Well Measurements
France
Well Isolation
Logging
China
Geomechanics

Recommendations

- In order to mitigate risks, Industry needs to:
  – Develop comprehensive G&G databases and use common Earth Models
  – Standardize integrated static and dynamic workflows
  – Develop improved understanding of geochemical interactions
  – Incorporate such models in more-efficient reservoir simulation models
  – Use enhanced resolution surface seismic techniques

22 KBN
11/15/2004

Continued….

Recommendations

– Expand use of x-wellbore measurements
– Cooperate on development of chemical sensors and other wellbore measurements
– Develop standard testing procedures for injectors and producers
– Develop a standard methodology for wellbore isolation (cementing)
– Share experiences and lessons learned

23 KBN
11/15/2004

CO_2 Capture, Storage, and EOR: A Promising Technology

Laura Atkins (OPEC)

Energy Technology Analyist
Energy Studies Department

Short Summary

Carbon dioxide capture and storage (CCS) is a promising technology given its potential to achieve cost-effective reductions in CO_2 emissions, in particular from large stationary sources. In the case of CO_2 storage in depleting oil reservoirs, it could contribute to an increase of oil reserves. In recognition of the significance of this technology and the requisite policies and financing mechanisms, OPEC and the World Petroleum Congress jointly sponsored a workshop in Vienna on 8^{th} – 9^{th} June, 2004 on CCS, CO_2 for Enhanced Oil Recovery, and gas flaring reduction. The workshop convened experts from OPEC Member Countries, government agencies, research institutions, and the oil industry to assess the state of the art of the technologies, share experiences, and discuss various issues related to the future development and deployment of these technologies as a means of bringing added value to oil and gas operations in oil producing countries while presenting a proactive response to environmental concerns.

This paper summarizes key findings and conclusions from the workshop. CCS could enable the continued use of fossil energy resources for several decades while providing sufficient reductions in CO_2 emissions. Despite many successful industrial cases, more research and development is, however, necessary to improve processes and reduce costs. In addition, appropriate financing mechanisms and incentives should be developed. The paper summarizes the current state of the technology and major R&D programmes. The Clean Development Mechanism and its role in furthering CO_2 sequestration and gas flaring reduction projects is reviewed. Activities of OPEC Member Countries in both CCS and gas flaring reduction are highlighted.

1

CO_2 Capture and Storage: A Promising Technology

Laura Atkins
Energy Technology Analyst
OPEC Secretariat

CO_2 Capture and Sequestration in Future International R&D Programmes
Vienna
November 17, 2004

2

Introduction

- Fossil energy is expected to remain the predominant source of energy to meet growing world demand
  - Fossil fuels have been a driving force behind economic development
  - Over 1.6 billion people in the world today have no access to electricity and modern fuels and over 2 billion don't have modern fuels for cooking and heating
  - Provision of modern energy, including fossil energy, is necessary to achieve Millennium Goal of poverty reduction
- Impact of GHG emissions on climate change has not yet gained wide undisputable scientific acceptance. However, the precautionary principle is often invoked.
- Technologies must continue to be developed to reduce GHG emissions from energy use.
- Sustainable development → Balance between economic growth, social progress, and environmental protection.

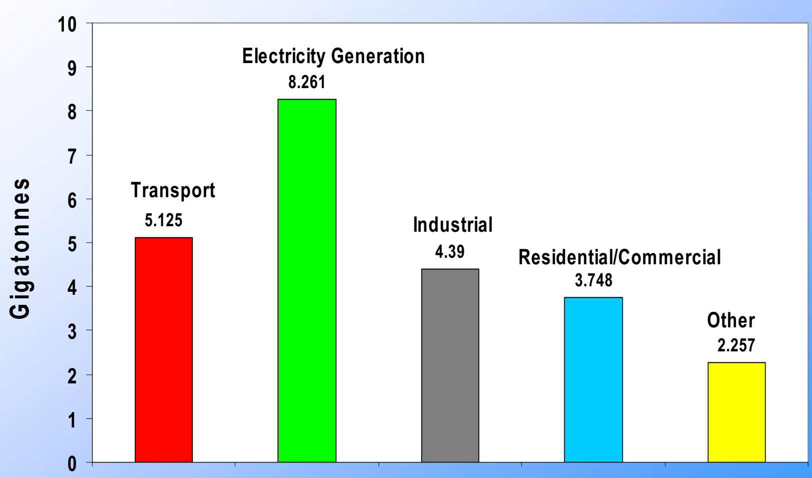
3

Benefits of Carbon Dioxide Capture and Storage

- At present and for the foreseeable future, there are few economically viable substitutes for fossil fuels
- CO_2 Capture and Storage (CCS) has the potential to make huge reductions in emissions of CO_2 from stationary sources such as fossil fuel-fired power plants and industrial plants.
- Stationary sources contribute over 50% of global CO_2 emissions
- CCS could provide 70% of the GHG emissions reductions necessary for stabilization of atmospheric CO_2 concentration in the medium to long term
- CO_2 storage in oil reservoirs can substantially increase oil production and recovery through an enhanced oil recovery (EOR) process.

4

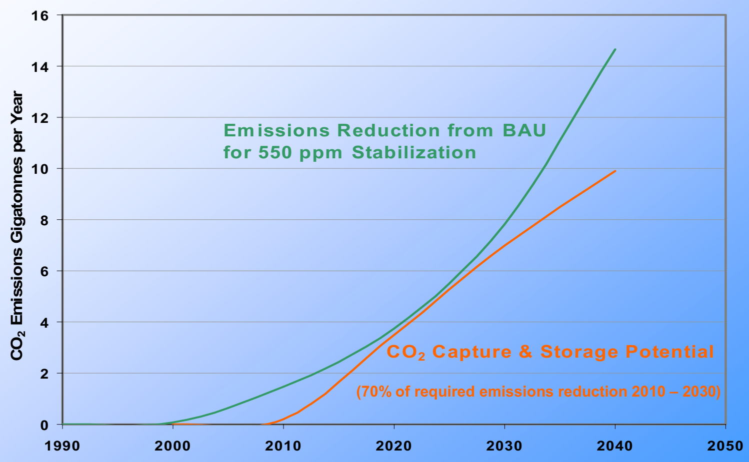
Global CO_2 Emissions by Sector in 2000



Source: World Energy, Technology, and Climate Policy Outlook, European Commission, 2003

5

CO_2 Capture and Storage
Potential Contribution to Atmospheric Stabilization



Sources: Dolf Gielen, IEA/EET Working Paper, "The Future Role of CO2 Capture and Storage: Results of the IEA-ETP Model, 2003;
EU World Energy, Technology, and Climate Policy Outlook, 2003;
IPCC Greenhouse gas emissions scenarios.

6

OPEC/WPC Workshop On CO_2 Capture, Storage and EOR; and Gas Flaring Reduction

- **OPEC and the World Petroleum Congress see carbon dioxide and storage as a promising technology**
- **Workshop convened experts to discuss technology, current applications, future potential, and areas for cooperation**
- **19 presentations were made plus round table discussions at the end of each day, including:**
  - **CCS technology state-of-the-art and R&D programmes**
  - **Case studies on CO_2 storage in saline aquifers and CO_2 EOR**
  - **Policy, legal, and financing aspects of CCS and gas flaring reduction**
  - **Gas flaring reduction initiatives**
- **OPEC Member Countries activities highlighted**

7

CO_2 Capture & Storage Challenges

- The cost of CO_2 capture needs to be further reduced
  - Technologies have been available for years to remove CO_2 from sales gas streams, but these are costly
  - If installed at a power plant, efficiency is reduced
- Issues related to geologic storage require more research
  - Technical issues related to monitoring, verification of storage and leak remediation
  - Legal aspects related to liability and long term ownership of storage sites
- Absence of commercial incentives
- Public awareness must be increased
- These are being addressed by various R&D programmes

8

CO_2 Capture and Storage State of the Technology (1)

- Capture is the largest component of the cost of CCS
  - Power plant post-combustion capture costs $40 to $100 per tonne of avoided emissions
  - More concentrated CO_2 is less costly to capture but the technology is immature
    - Processes such as pre-combustion de-carbonization and oxygen burning promise to reduce costs
- R&D is expected to bring down the costs of all methods of capture. Three major programmes:
  - CO_2 Capture Project
  - IEA Greenhouse Gas Reduction Programme
  - US DOE carbon sequestration R&D

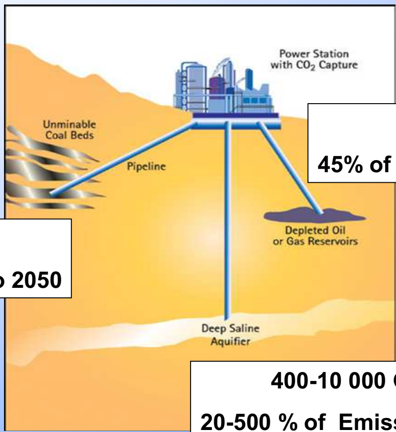
9

CO_2 Capture and Storage
State of the Technology (2)

- **Transportation and injection of CO_2 is relatively low cost**
  - **CO_2 has been transported by pipeline for many years in North America**
  - **CO_2 can be shipped in low pressure LPG vessels**
  - **Infrastructure requirements for large scale CO_2 capture and transport to geologic storage sites could be substantial**
- **For storage in geologic formations, monitoring, verification and long term storage are being addressed through technology development and demonstration projects**
- **However; the potential is huge**

10

Global Geological Storage Potential



920 Gt CO_2
45% of Emissions to 2050

40 Gt CO_2
<2% of Emissions to 2050

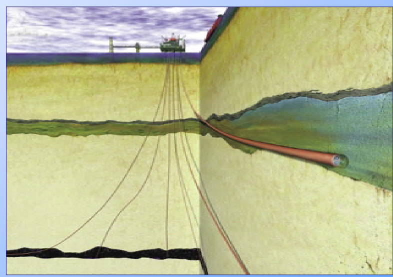
400-10 000 Gt CO_2
20-500 % of Emissions to 2050

Comparative potentials at storage costs of up to $20/t CO_2

Source: John Topper, IEA Greenhouse Gas Reduction Programme, presentation to the OPEC/WPC workshop 8th June 2004

11

Sleipner West Gas Field (1)

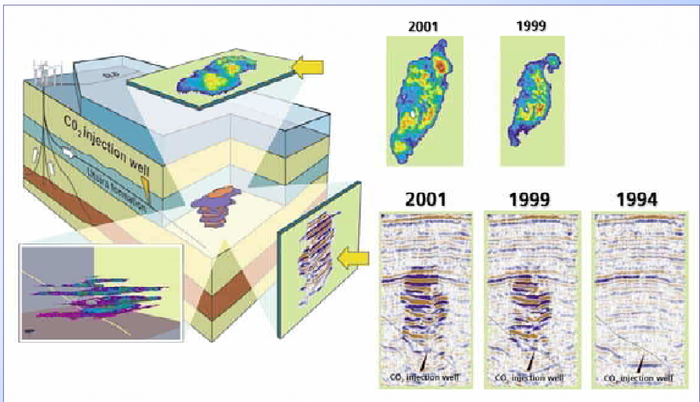


- Natural gas contains 4 to 9.5% CO_2
- Sales gas must contain less than 2.5%
- Large-scale offshore CO_2 capture
- Cost of injection facilities and well - \$80 million
- One million tonnes per year injected into the Utsira Formation

Source: Mr. O. Kaarstad, Statoil, presentation to the OPEC/ WPC workshop June 8, 2004

12

SLEIPNER WEST GAS FIELD (2)



Major R&D Results:

- EU-supported monitoring project (SACS)
- 3D Seismic indicates CO_2 is being contained in the reservoir
- Modeling studies used to predict future performance

Source: Mr. O. Kaarstad, Statoil, presentation to the OPEC/WPC workshop June 8, 2004

13

In Salah Gas Project, Algeria

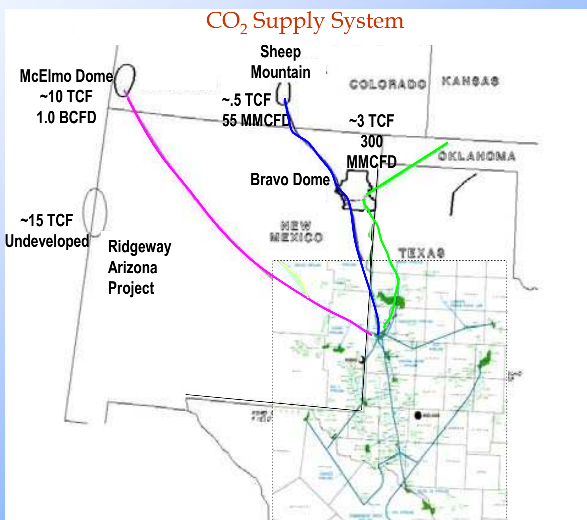
- Joint venture between Sonatrach (SH) and British Petroleum (BP).
  - Objective: Exploration, Appraisal, Development and Joint Marketing of gas produced from 7 fields of the region after its treatment.
- The gas is treated by an Ethanol - Amine solution
- The CO_2 is rejected by two amine regeneration trains
- The CO_2 is compressed through 4 compression stages up to a max of 200 bars
- The CO_2 is injected into the Krechba aquifer
  - 60 mmsdfd <=> 1.15 million tons/year
  - 20 million tons of CO2 re-injected during the life of the project

Source: Ms. N. Boudjemaa, P.E., Sonatrach, presentation to the OPEC/ WPC workshop June 8, 2004.

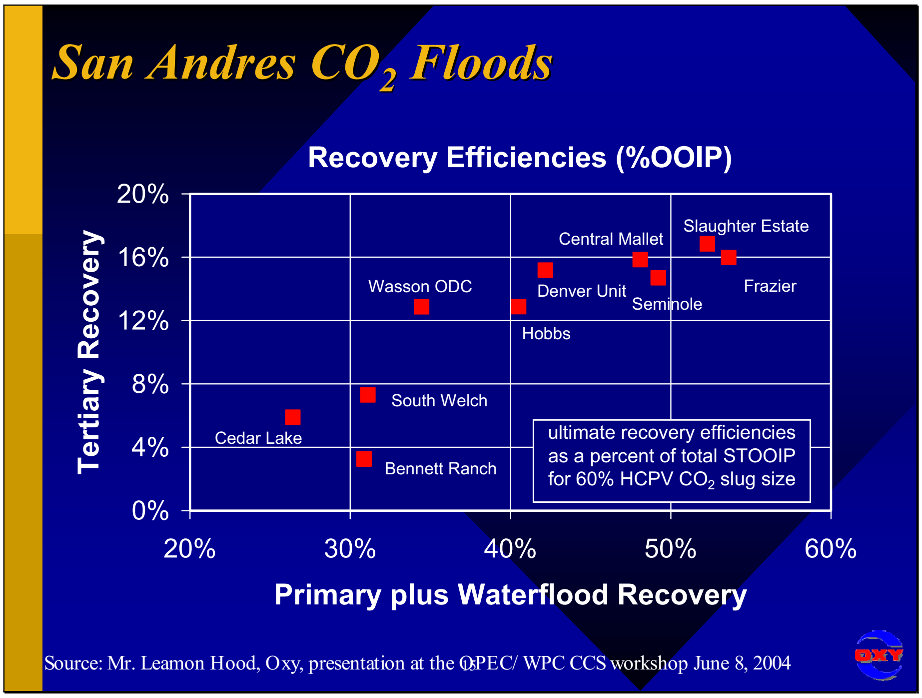
14

West Texas Permian Basin CO_2 EOR Projects

- CO_2 EOR projects have been in place for 30 years, using natural sources
- About 1500 million ft^3 per day injected (42.4 million m^3/ day)
- More than 50 active floods which contribute 20% of regional production.



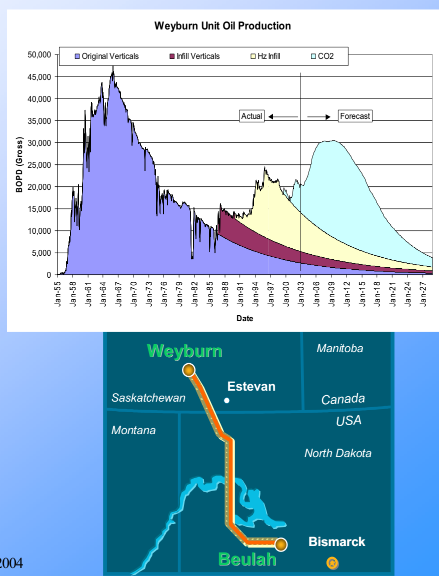
Source: Mr. Leamon Hood, Oxy, presentation at the OPEC/ WPC workshop on CCS, June 8, 2004



16

Weyburn CO_2 EOR Demonstration Project
Saskatchewan, Canada

- The CO_2 is a purchased by-product from the Dakota Gasification Company's synthetic fuel plant in Beulah, North Dakota, USA
- CO_2 is transported through a 320-km pipeline to Weyburn.
- CO_2 injection into Phase 1A started
- September 15, 2000
  - 98 BCF (2776 M m^3) CO_2 injected as of February 2004
  - Current CO_2 purchase is 105 mmscfd
  - 25 mmscfd of associated gas and CO_2 being recycled
- Incremental oil production 9000 bbl/ day out of 22,000 bbl/ day



Source: Dr. M. Wilson, Petroleum Technology Research Center, Saskatchewan, Canada, presentation to the OPEC/ WPC workshop June 8, 2004

17

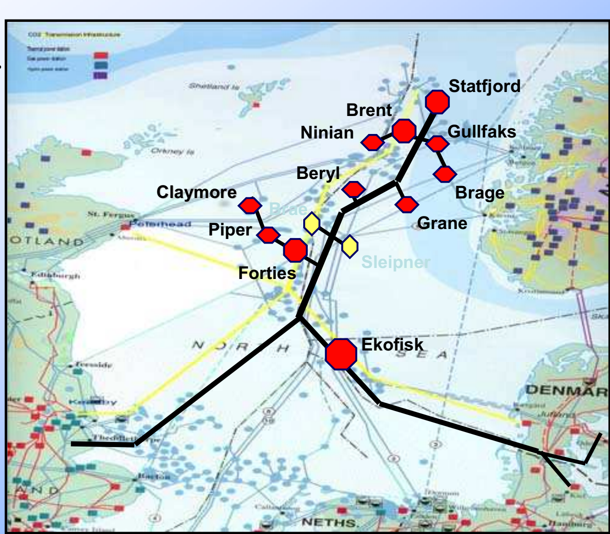
CO_2 EOR Potential

- 126 gigatonnes of CO_2 storage in EOR Projects (IEA estimate)
  - Includes major basins in N. America, Europe, Middle East, Western Siberia
  - More potential if Africa, Latin America, and Asia are included
- Win-win scenario of increasing oil supplies while storing large quantities of CO_2
- EOR can provide financial incentive for early implementation of CO_2 capture technologies, thus helping to bring down the costs
- Revenue from EOR can help support infrastructure investments necessary to transport CO_2 to other geologic storage sites

18

Possible North Sea CO_2 Infrastructure

- 30 – 40 million t/ year CO_2 stored from power stations and factories around N. Sea basin
- 100 million bbl/ year incremental oil
- Field life extended for 10 – 30 years



Source: Hugh Sharman, consultant, presentation to the OPEC/ WPC workshop June 8, 2004.

19

Carbon Capture and Storage Financing and Policy Issues

- Supportive policies should be enacted and a legal framework developed
- Financial incentives for CCS are necessary
- The Clean Development Mechanism could facilitate early implementation of CCS in developing countries, if
  - It could accommodate large scale projects
  - It would recognize additionality and GHG reduction benefits of CCS

20

Gas Flaring Reduction

- Global gas venting and flaring is around 100 bcm/ year
- The fraction of gas that is flared has been greatly reduced over the last 20 years
- Individual governments and companies have had successes in reducing flared gas, and significant investments in reduction projects are continuing.
- The World Bank Gas Flaring Reduction Initiative supports national governments' efforts to reduce flaring
  - Helps commercialize small gas volumes
  - Facilitates cooperation on gas infrastructure and markets
  - Promotes use of gas for poverty alleviation

21

Gas Flaring Reduction
Algeria Example

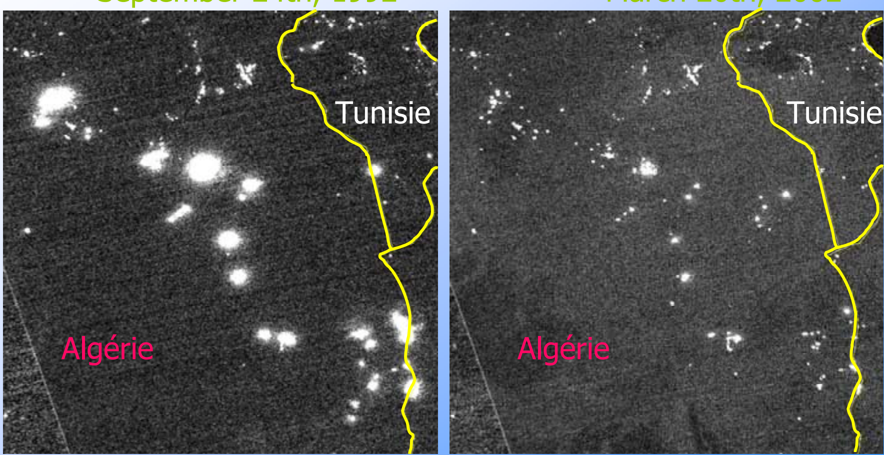
- Invested over $660 million to reduce gas flaring
- While volumes of produced associated gases have practically quadrupled the 33 last years, the rate of flaring of associated gas decreased from 80% in 1970 to 11% in 2003.
- Less than 1% of the of dry (non-associated) gas is flared.
- In terms of total associated and dry natural gas, the flaring rate is less than 3%.
- Medium-term objective is to recover 93% of produced associated gas by 2007 and 100% by 2010.
- $200 million has been allocated to additional gas flaring reduction projects.

Source: Dr. Rabah Nadir Allouani, Sonatrach, presentation to the OPEC/ WPC Workshop 9th June, 2004.

22

Satellite Observation Showing Net Reduction of Flaring

September 24th, 1992 | March 20th, 2002



Source : DMSP-OLS Observations of Gas Flares, Dr. Rabah Nadir Allouani, Sonatrach, presentation to the OPEC/ WPC Workshop 9th June, 2004.

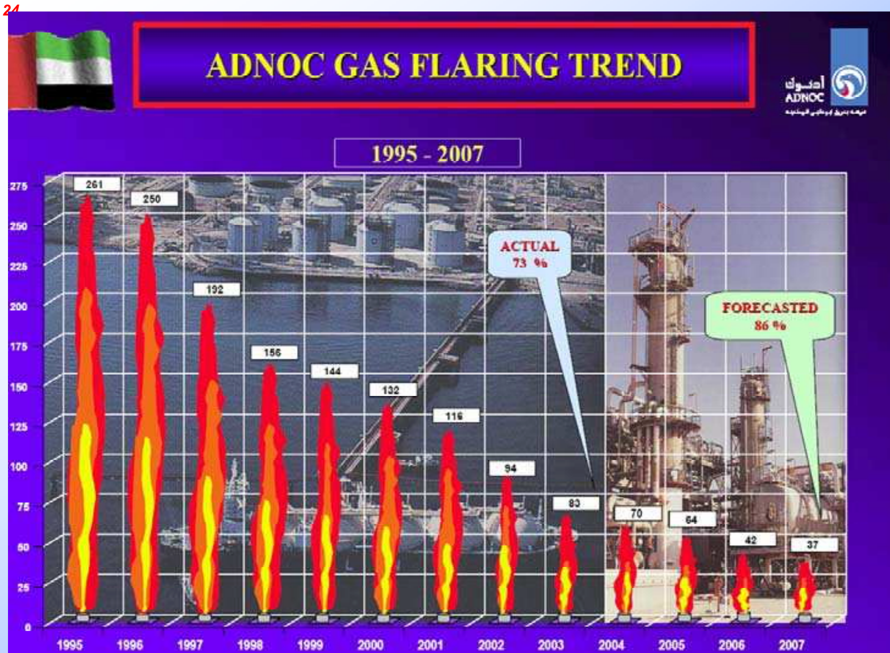
23

Gas Flaring Reduction
Abu Dhabi Example

- Abu Dhabi rapidly reduced gas flaring after 1977 from 4000 mmfcd to < 500 mmcfd in the early 1980s, to < 300 mmcfd in the mid-1990s
- Since 1995 many new projects have been implemented to reduce flaring from 270 mmcfd to 70 mmfcd today. This is only about 1% of the more than 6000 mmcfd gas production today
  - Reduced the number of flares
  - Re-injection of gas into oil reservoirs
  - Plants modified to recover gas
  - Zero flaring technology installed in some locations
- Flaring will be reduced to 30 mmcfd by 2007
- Goal is zero flaring

Source: Mr. Ihab Othman Tarmoon, ADNOC, presentation to the OPEC/ WPC workshop 9th June 2004.

24



Source: Mr. Ihab Othamn Tarmoon, ADNOC, presentation to the OPEC/ WPC workshop June 9, 2004

25

Gas Flaring Reduction
Nigeria Example

- **Over 40% of associated gas is flared**
  - **Down from 70% in 1996**
  - **The flared volume is enough to meet the electricity needs of sub-Saharan Africa**
- **Main challenge is limited domestic demand**
  - **Slow economic growth; underdeveloped local market**
  - **Lack of pipeline infrastructure**
- **Even so, domestic gas utilization has increased from 50 mmcfd in 2000 to 1000 mmcfd today.**
- **Gas gathering systems and use of associated gas to supply part of LNG feed are planned**
- **Policy is to eliminate gas flaring by 2008**

Source: Mr. Abiodun Ibikunle, NNPC, presentation to the OPEC/ WPC workshop 9th June, 2004.

26

Okpai Independent Power Project Overview

Category of the Project	Gas Flaring Reduction
Partners (Equity)	NNPC (60%) - NAOC (20%) -CONOCO PHILLIPS (20%)
Investments	~ $400 million USD
Start-up	January 2005
Project life	20 years + 5 years (possible extension)
GHG reductions	1.8 million tonnes CO_2 per annum

Will be submitted as a CDM Project

Source: Mr. Vito Caruso, Eni, presentation to the OPEC/ WPC workshop 9th June, 2004.

27

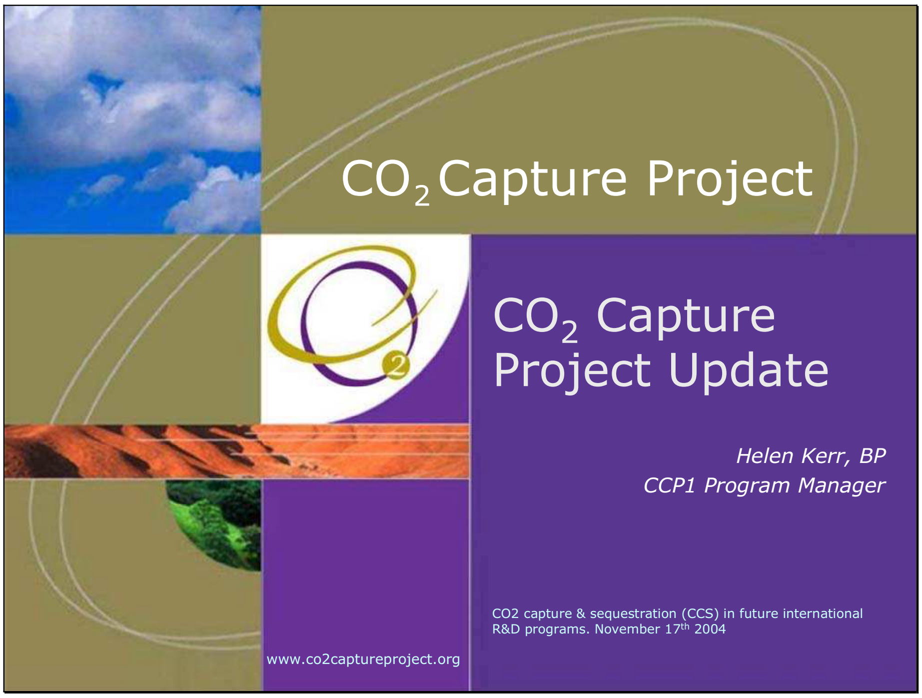
Conclusions

- CCS has enormous potential to reduce CO_2 emissions.
- CCS is one of the lowest cost near to medium term options in terms of cost per tonne of avoided emissions, and costs will be further reduced through R&D.
- CCS would allow people to continue to benefit from the use of fossil fuels.
- CO_2 enhanced oil recovery can increase oil reserves and extend plateau production in mature oil fields while storing CO_2.
- Reduction or elimination of gas flaring can contribute to GHG reductions while bringing modern energy supplies to under-developed regions of the world.
- CCS, CO_2 EOR, and gas flaring reduction projects should be:
  - Eligible for financial support, including CDM
  - Supported by appropriate legal and policy frameworks

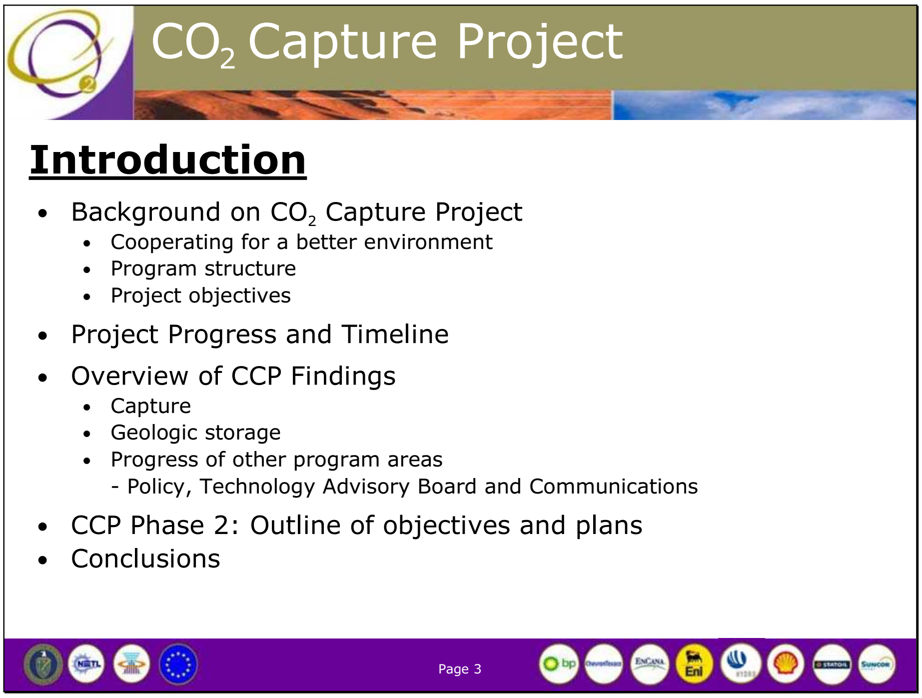
Results of the CO_2 Capture Project

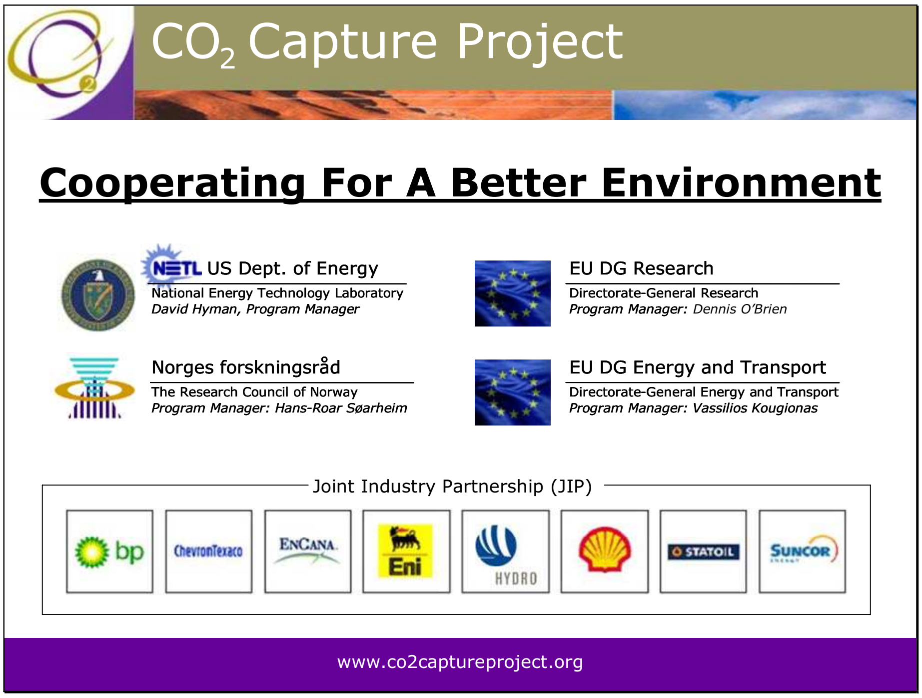
Helen Kerr (BP, United Kingdom)

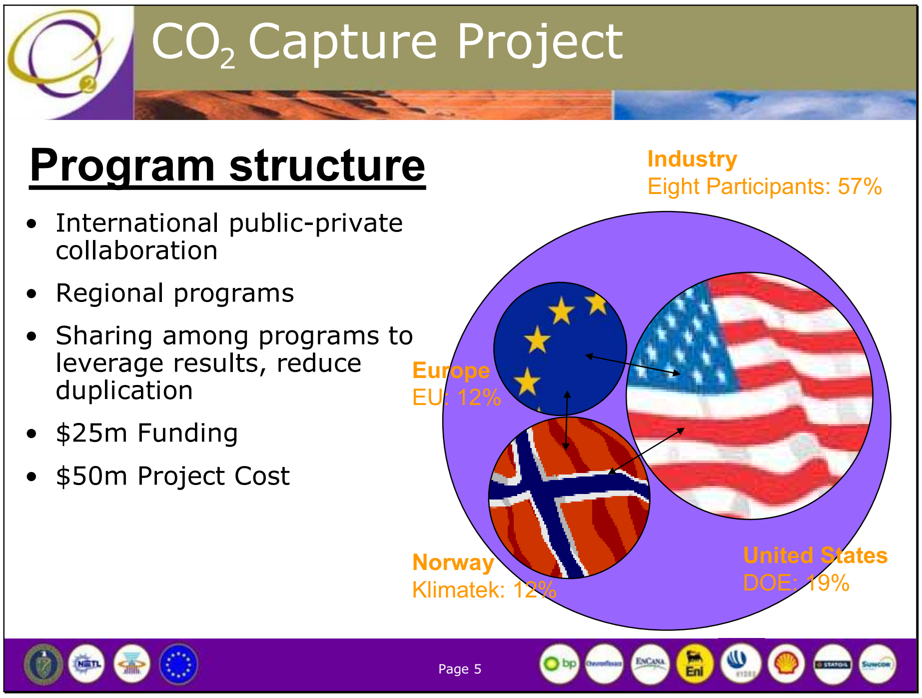
Programme Manager for the multinational joint industry project – CO_2 Capture Project or CCP based in Washington DC Group Environmental Technology

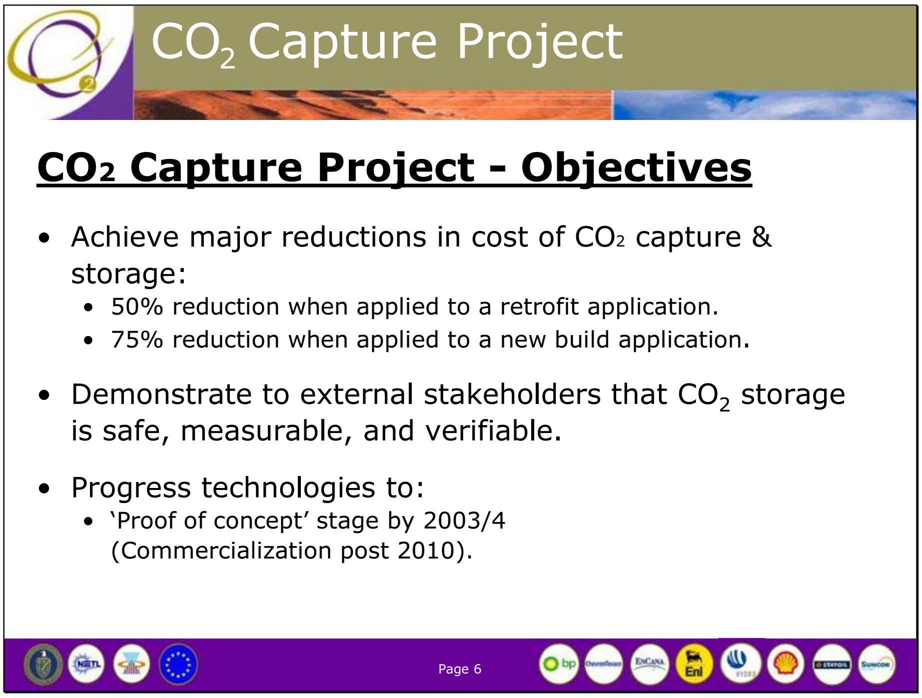



CO_2 Capture Project
This study and presentation was prepared with the support of the U.S. Department of Energy under Award No. DE-FC-26-01NT41145 and any opinions, findings, conclusions or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.
Norges forskningsråd
The Research Council of Norway
This study and presentation was prepared with the support of the Research Council of Norway.
This study and presentation was prepared with the support of the European Union.
Page 2

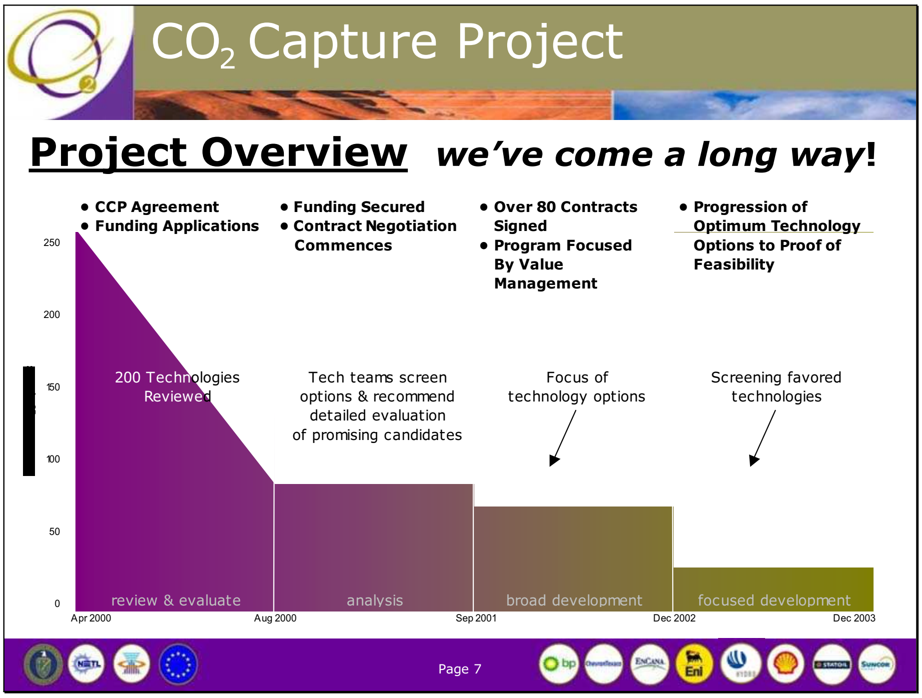

CO_2 Capture Project
Introduction
Background on CO_2 Capture Project
Cooperating for a better environment
Program structure
Project objectives
Project Progress and Timeline
Overview of CCP Findings
Capture
Geologic storage
Progress of other program areas
- Policy, Technology Advisory Board and Communications
CCP Phase 2: Outline of objectives and plans
Conclusions
Page 3


CO2 Capture Project
Cooperating For A Better Environment
US Dept. of Energy
National Energy Technology Laboratory
David Hyman, Program Manager
EU DG Research
Directorate-General Research
Program Manager: Dennis O'Brien
Norges forskningsråd
The Research Council of Norway
Program Manager: Hans-Roar Søarheim
EU DG Energy and Transport
Directorate-General Energy and Transport
Program Manager: Vassilios Kougionas
Joint Industry Partnership (JIP)
www.co2captureproject.org


CO2 Capture Project
Program structure
• International public-private collaboration
• Regional programs
• Sharing among programs to leverage results, reduce duplication
• $25m Funding
• $50m Project Cost
Industry
Eight Participants: 57%
Europe
EU: 12%
Norway
Klimatek: 12%
United States
DOE: 19%
Page 5



CO2 Capture Project
CO2 Capture Project - Objectives
• Achieve major reductions in cost of CO2 capture & storage:
• 50% reduction when applied to a retrofit application.
• 75% reduction when applied to a new build application.
• Demonstrate to external stakeholders that CO2 storage is safe, measurable, and verifiable.
• Progress technologies to:
• 'Proof of concept' stage by 2003/4 (Commercialization post 2010).
Page 6



CO2 Capture Project
Project Overview we've come a long way!
• CCP Agreement
• Funding Applications
• Funding Secured
• Contract Negotiation Commences
• Over 80 Contracts Signed
• Program Focused By Value Management
• Progression of Optimum Technology Options to Proof of Feasibility
250
200
150
100
50
0
200 Technologies Reviewed
Tech teams screen options & recommend detailed evaluation of promising candidates
Focus of technology options
Screening favored technologies
review & evaluate
analysis
broad development
focused development
Apr 2000
Aug 2000
Sep 2001
Dec 2002
Dec 2003
Page 7

CO_2 Capture Project

Overview of CCP Findings

Capture

- Made significant headway in developing technology, resulting in step reduction in costs and importantly, ruled out some technologies

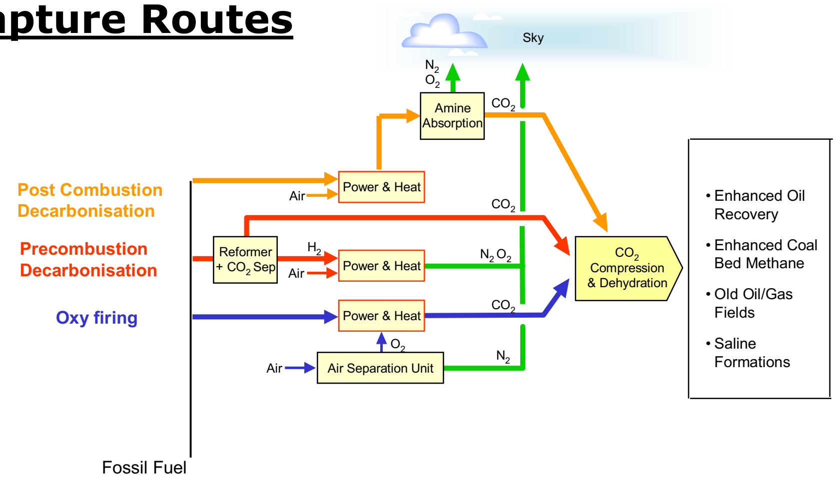
Storage

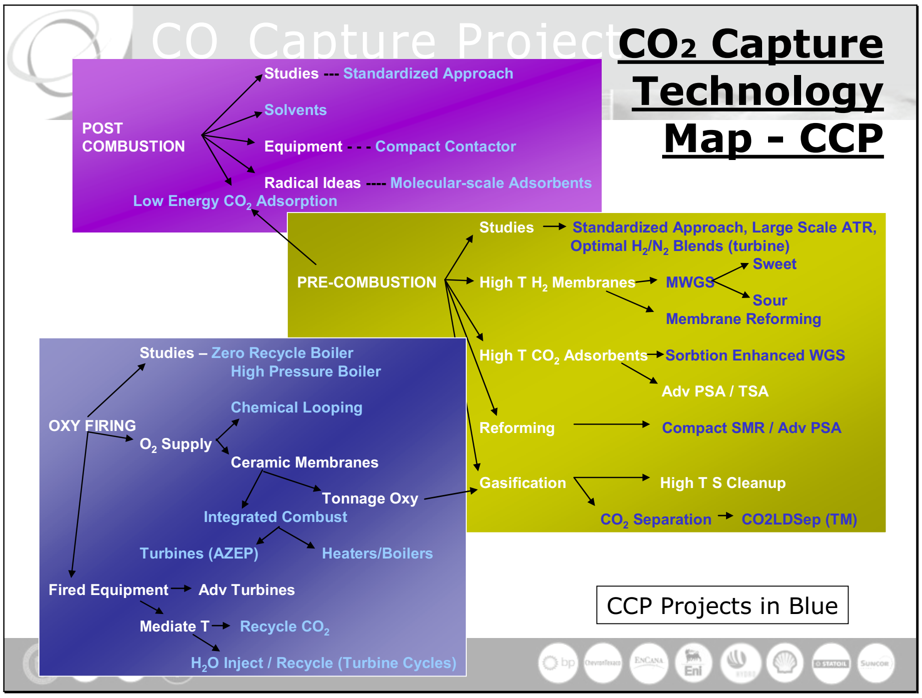
- Identified a comprehensive suite of questions we must address, to understand and demonstrate long term secure storage. Pioneered the risk based approach for site identification, operation and monitoring

Page 8

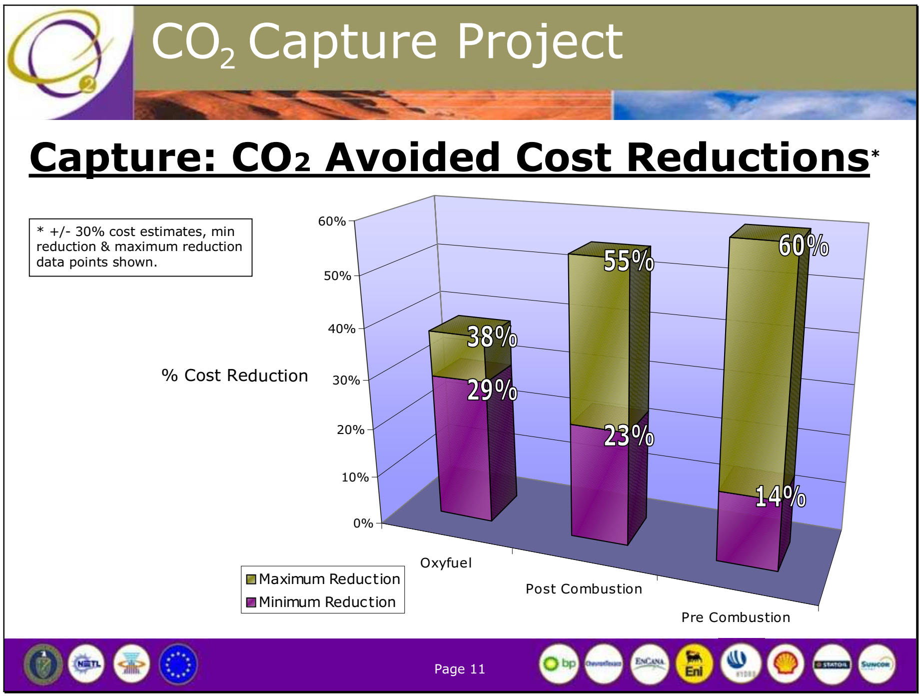
CO_2 Capture Project

Capture Routes





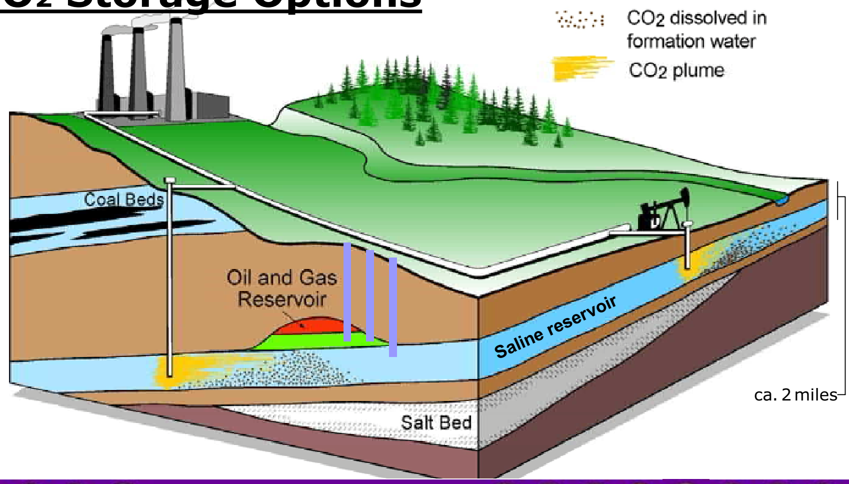
CO₂ Capture Technology Map - CCP
POST COMBUSTION
Studies --- Standardized Approach
Solvents
Equipment - - - Compact Contactor
Radical Ideas ---- Molecular-scale Adsorbents
Low Energy CO2 Adsorption
PRE-COMBUSTION
Studies
Standardized Approach, Large Scale ATR, Optimal H2/N2 Blends (turbine)
High T H2 Membranes
MWGS
Sweet
Sour
Membrane Reforming
High T CO2 Adsorbents
Sorbtion Enhanced WGS
Adv PSA / TSA
Reforming
Compact SMR / Adv PSA
Gasification
High T S Cleanup
CO2 Separation
CO2LDSep (TM)
OXY FIRING
Studies – Zero Recycle Boiler
High Pressure Boiler
Chemical Looping
O2 Supply
Ceramic Membranes
Tonnage Oxy
Integrated Combust
Turbines (AZEP)
Heaters/Boilers
Fired Equipment
Adv Turbines
Mediate T
Recycle CO2
H2O Inject / Recycle (Turbine Cycles)
CCP Projects in Blue



CO2 Capture Project
Capture: CO₂ Avoided Cost Reductions*
* +/- 30% cost estimates, min reduction & maximum reduction data points shown.
% Cost Reduction
60%
50%
40%
30%
20%
10%
0%
38%
29%
55%
23%
60%
14%
Oxyfuel
Post Combustion
Pre Combustion
Maximum Reduction
Minimum Reduction
Page 11

CO_2 Capture Project

CO_2 Storage Options



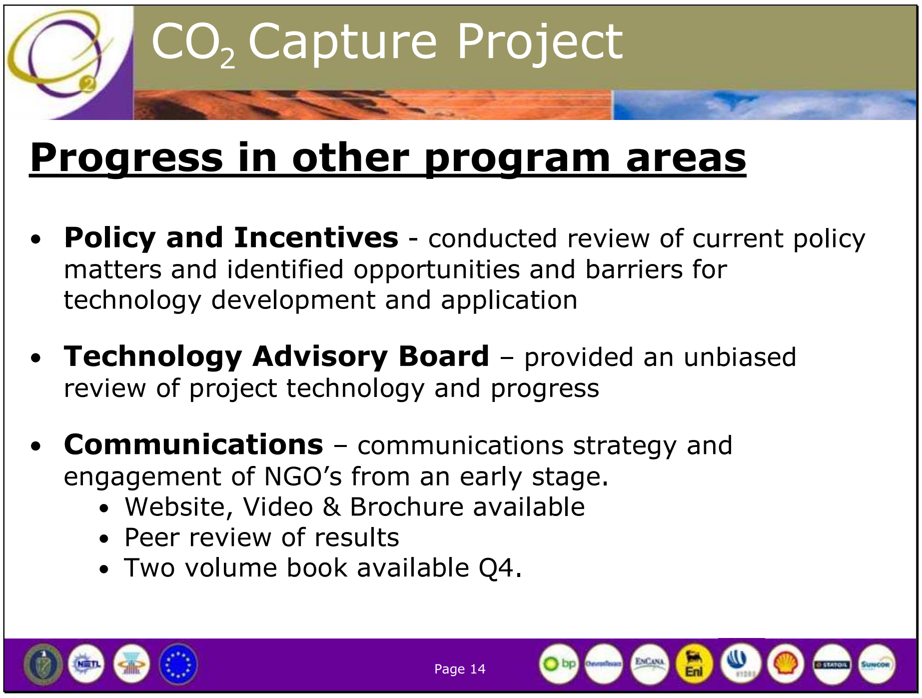
Page 12

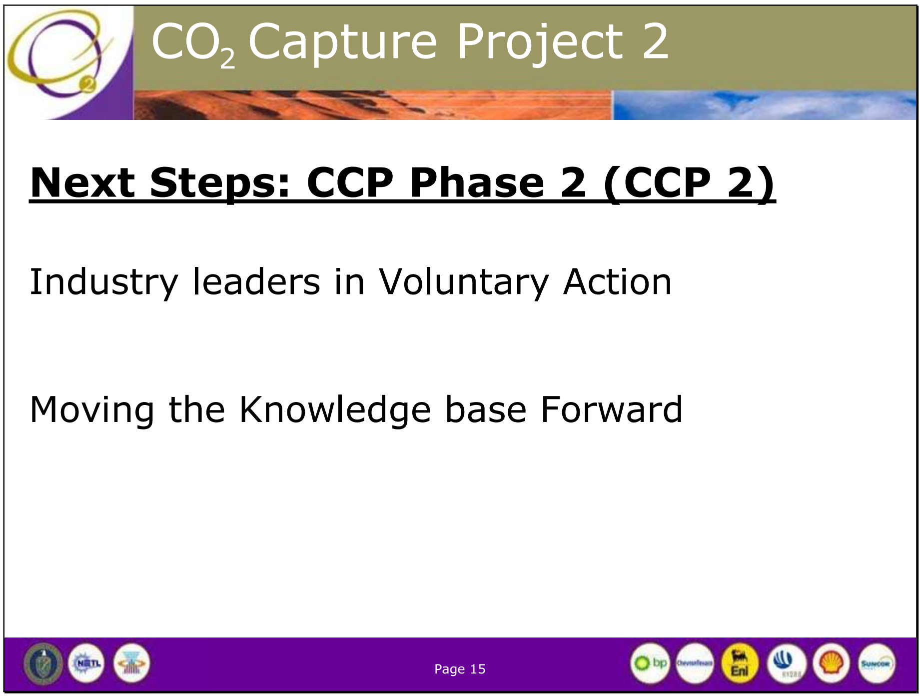
CO_2 Capture Project

Storage: Technologies Delivered

- Developed a **comprehensive understanding of the HSE risks** of, and the requirements for, secure geological storage
  - Geological formations more likely to be secure than man-made wells
  - Depleted oil & gas fields generally be more secure than saline formations
- Assembled a **large database of knowledge**, which will allow the risks associated with geological storage to be quantified and compared to other activities
- Developed an extensive repertoire of **monitoring options**, applicable to a broad range of settings
- Potential **leakage scenarios** have been mapped and matched to remediation actions

Page 13


CO_2 Capture Project
Progress in other program areas
• Policy and Incentives - conducted review of current policy matters and identified opportunities and barriers for technology development and application
• Technology Advisory Board – provided an unbiased review of project technology and progress
• Communications – communications strategy and engagement of NGO's from an early stage.
• Website, Video & Brochure available
• Peer review of results
• Two volume book available Q4.
Page 14


CO_2 Capture Project 2
Next Steps: CCP Phase 2 (CCP 2)
Industry leaders in Voluntary Action
Moving the Knowledge base Forward
Page 15

CO_2 Capture Project 2

CCP 2 (2004 – 07) Objectives

1. Further develop CO_2 capture technologies with aim to reduce cost and technical uncertainties prior to demonstration
   a. Parallel R&D, but sequential pilots
   b. Stop technology development when success achieved
2. Develop industry guidelines for secure, cost-effective CO_2 geological storage; addressing issues such as site selection, risk assessment, well integrity, monitoring, verification and abandonment
3. Establish an extended network including resources to CCP for CO_2 storage demonstrations

Page 16

CO_2 Capture Project 2

Success Factors

1. One or more capture technologies is available to pilot (with at least 50% cost reduction from 2000 baseline)
   a. Retrofit and New-build
2. Deliver a strategy for the future demonstration of at least one capture technology
3. A set of proposed industry standards for Storage, Monitoring, Verification and Abandonment
   a. Geological storage is accepted in emissions trading schemes (ie. EU ETS 2008-12)
4. A network is established for information sharing among storage demonstrations
5. >40% of CCP2 cash spend is provided by co-funders

Page 17

CO_2 Capture Project 2

4 Major Themes

1. **Capture Technology** (new/retro, pre/post/oxy, short/long term)
   i. Continued Cost reduction
   ii. Reduce technology risk around performance and cost
   iii. Balance between continuing to develop current technologies vs new technologies
   iv. Demonstration project strategy (need to decide area and technology of interest)
2. **Storage**
   i. Storage cost reduction
   ii. Storage assurance (monitoring, verification & risk assessment)
   iii. Wells
   iv. Network
3. **Industry Standards and Acceptance**
   i. Create favorable business environment for CO_2 Capture & Storage
   ii. Protocol/ Industry Standards for capture & storage
   iii. NGO's outreach and Education
   iv. Specific projects in the area of P&I to inform our companies
4. **Networking**
   i. Crosscutting

Building on experience & learning from CCP, which has identified the most promising options

Page 18

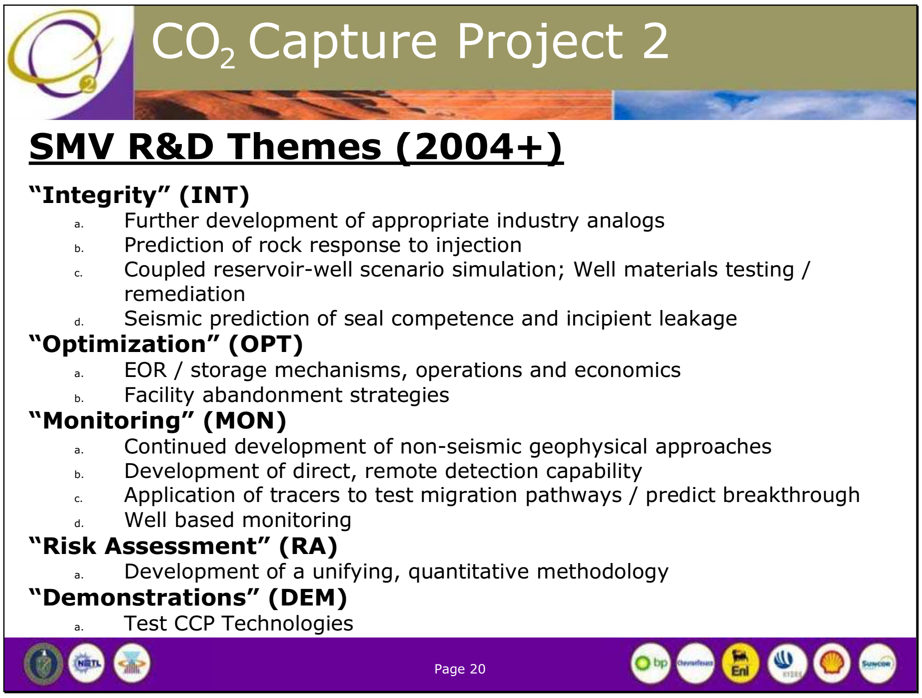
CO_2 Capture Project 2

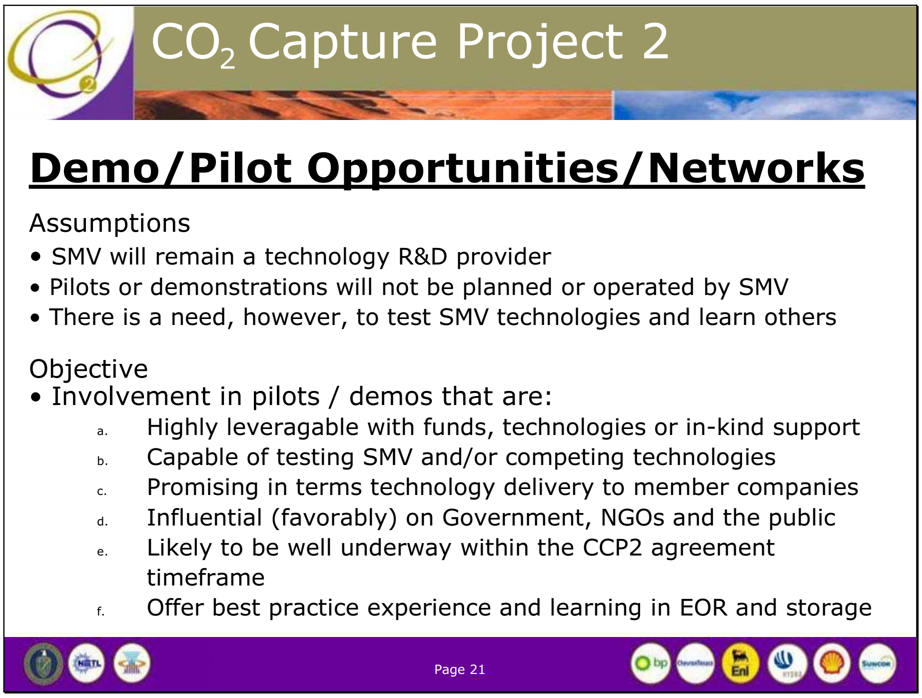
Capture Technology areas of Focus

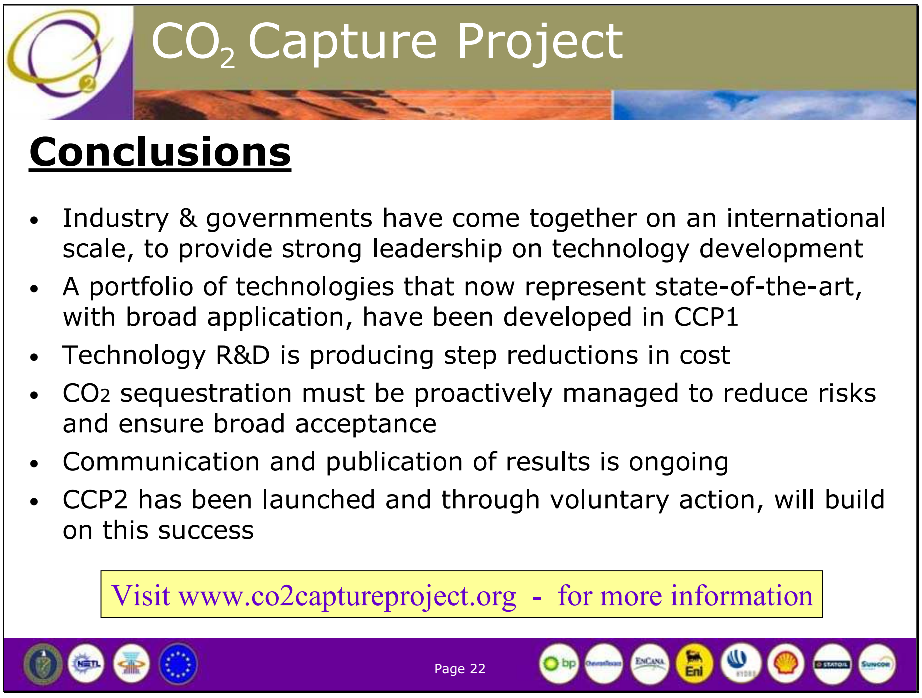
- **Post Combustion**
  - BIT
- **Pre Combustion**
  - MWGS
  - SEWGS
  - HMR
- **Chemical Looping**
- **Cost and Economic Modelling**

Focus remains on large scale combustion of fossil fuels and hydrogen with CC&S
Technology portfolio will cover retrofit and new build

Page 19


CO_2 Capture Project 2
SMV R&D Themes (2004+)
"Integrity" (INT)
a. Further development of appropriate industry analogs
b. Prediction of rock response to injection
c. Coupled reservoir-well scenario simulation; Well materials testing / remediation
d. Seismic prediction of seal competence and incipient leakage
"Optimization" (OPT)
a. EOR / storage mechanisms, operations and economics
b. Facility abandonment strategies
"Monitoring" (MON)
a. Continued development of non-seismic geophysical approaches
b. Development of direct, remote detection capability
c. Application of tracers to test migration pathways / predict breakthrough
d. Well based monitoring
"Risk Assessment" (RA)
a. Development of a unifying, quantitative methodology
"Demonstrations" (DEM)
a. Test CCP Technologies
Page 20


CO_2 Capture Project 2
Demo/Pilot Opportunities/Networks
Assumptions
• SMV will remain a technology R&D provider
• Pilots or demonstrations will not be planned or operated by SMV
• There is a need, however, to test SMV technologies and learn others
Objective
• Involvement in pilots / demos that are:
a. Highly leveragable with funds, technologies or in-kind support
b. Capable of testing SMV and/or competing technologies
c. Promising in terms technology delivery to member companies
d. Influential (favorably) on Government, NGOs and the public
e. Likely to be well underway within the CCP2 agreement timeframe
f. Offer best practice experience and learning in EOR and storage
Page 21


CO_2 Capture Project
Conclusions
• Industry & governments have come together on an international scale, to provide strong leadership on technology development
• A portfolio of technologies that now represent state-of-the-art, with broad application, have been developed in CCP1
• Technology R&D is producing step reductions in cost
• CO_2 sequestration must be proactively managed to reduce risks and ensure broad acceptance
• Communication and publication of results is ongoing
• CCP2 has been launched and through voluntary action, will build on this success
Visit www.co2captureproject.org - for more information
Page 22

The "CASTOR" Project and the CO_2 Sequestration Activities of Rohöl-Aufsuchung AG - RAG

Torsten Clemens(RAG, Austria)

Team Leader for Reservoir Engineering -
Downhole Gas/Water Separation and CO_2 Geological Storage

Summary

Austria committed to reduce greenhouse gas emissions by 13 % until 2012 compared with emissions in 1990. From 1990 to 2000, however, emissions of greenhouse gases in Austria increased by more than 3.5 %.

Reducing CO_2 emissions can be achieved by (1) increasing the efficiency of energy conversion (2) switching to fuels emitting less CO_2 (3) increasing use of renewable energy (4) CO_2 capture and storage.

To achieve the target of reducing CO_2 emissions in Austria until 2012, it will be necessary to use a number and/or combination of the above mentioned technologies. In Upper Austria, a large number of CO_2 emitting companies exist. The location of these companies and the amount of CO_2 emitted by them fits with the potential CO_2 storage capacity of RAG's fields in Upper Austria.

To evaluate the potential of CO_2 geological storage, RAG is participating in the EU project "CO_2, from Capture to Storage (CASTOR)" which has a budget of 15.8 mio €. The project is divided into three work-packages: (1) Strategy for CO_2 reduction (2) CO_2 post combustion capture (3) CO_2 storage into geological reservoirs.

In work-package (3), one of the fields which will be investigated is the Atzbach-Schwanenstadt field in Upper Austria. The scope of work includes a complete field evaluation comprising geoscientific reservoir characterisation, fluid flow experiments, reservoir simulation, geochemical and geomechanical experiments, monitoring feasibility studies and well integrity studies.

First results indicate that the field is suitable for CO_2 geological storage. However, it has to be noted that at current trading prices for CO_2, such a project is economically not attractive.

Introduction

Austria committed to reduce greenhouse gas emissions by 13 % until 2012 compared with emissions in 1990. From 1990 to 2000, however, emissions of greenhouse gases in Austria increased by more than 3.5 %.

CO_2 is one of the gases contributing to the greenhouse gas emissions. CO_2 emissions can be reduced by:

- Increasing the efficiency of energy generation
- Switching to fuels emitting less CO_2, e.g. gas instead of coal
- Increasing use of renewable energy
- CO_2 capture and storage

To achieve the target of reducing greenhouse gas emissions in Austria, it will be necessary to use a number or combination of the above mentioned technologies. In particular if deep cuts in CO_2 emissions are necessary to stabilise the CO_2 level in the atmosphere at 550 ppm, a large effort in implementing these technologies is necessary.

Costs for reducing CO_2 emissions by using different technologies vary dependent on the amount of CO_2 avoided and synergies with other processes. Wind energy requires incentives of more than 120 €/$tCO_{2\ (avoided)}$ for good locations, steeply increasing costs are incurred for poorer places. CO_2 capturing and geological storage costs are in the range of 30 €/tCO_2 – 70 €/tCO_2.

In addition to the lower cost of CO_2 capture and storage (CCS) compared with other CO_2 emission reduction technologies, CCS could also be used to generate hydrogen without producing CO_2. Hydrogen is routinely produced from fossil fuels for use in oil refineries, fertiliser generation and in other industrial processes. The cost of producing hydrogen from fossil fuels is currently substantially less costly than production of hydrogen from renewable sources which suggests this could be a transitional step on a path towards wider used of hydrogen. Generating hydrogen by the water-shift-reaction results in production of CO_2 which can be sequestered. The hydrogen could be used to reduce greenhouse gas emissions of households (e.g. using fuel cells) and the transport sector.

In the following paragraph, the specific setting of the Upper Austrian area for the use of CO_2 sequestration will be described and RAG's activities in this field are mentioned. The next paragraph gives more details concerning the CASTOR project in which RAG is participating.

RAG's CO_2 activities in Upper Austria

RAG is very successfully producing and exploring for oil and gas in Upper Austria. Also, RAG has a lot of experience in storing gas in the subsurface to account for demand and supply fluctuations of gas in summer and winter.

Cumulative oil and gas production from Upper Austria (by RAG) by end of year 2003 was more than 7.8 mio m³ oil and 17.4 billion m³ gas. The locations of the gas fields in Upper Austria are shown in Figure 1.

In 2004, RAG will produce about 700 mio m³ gas and 50,000 t oil from Upper Austria. RAG is continuously exploring for oil and gas in the concession area, in 2004, 12 exploration wells will be drilled in that region.

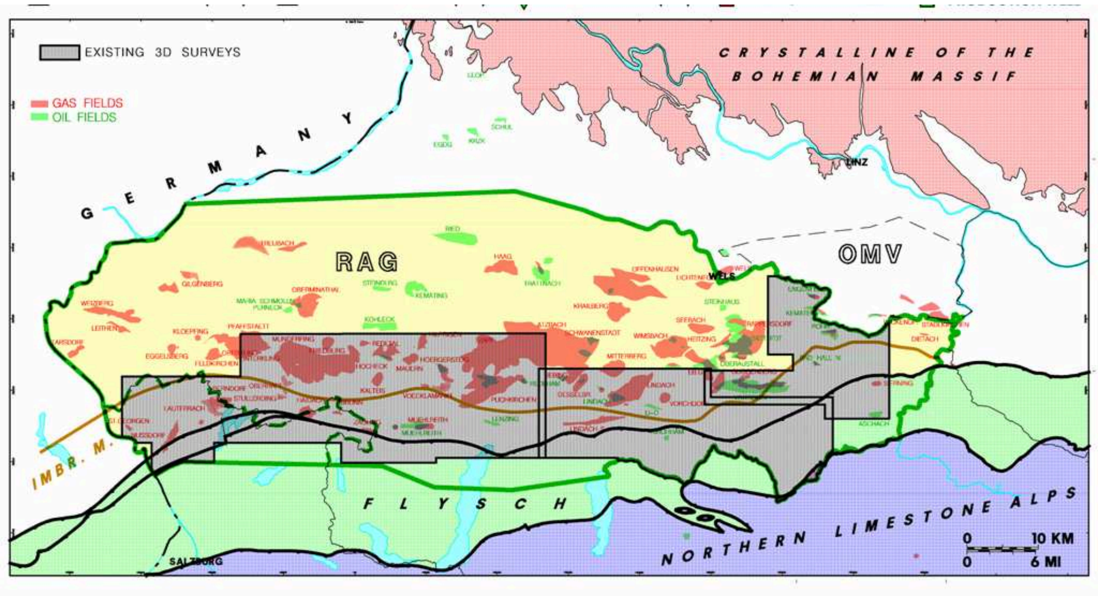


Figure 1: RAG's oil and gas fields in Upper Austria

In or close to the concession area of RAG, a large number of CO_2 emitting companies exist. The CO_2 in the exhaust gases is ranging from 3 % to 99 %. In principle, it is possible to first produce hydrocarbons and then inject CO_2 into the depleted oil and gas fields. Once the CO_2 infrastructure is generated, incremental costs for additional CO_2 sequestration projects are much lower than for the first projects. It has to be stated, however, that at current trading costs for CO_2, sequestration projects are economically not attractive.

In view of the potential of storing significant amounts of CO_2 in the subsurface and the potential increase in CO_2 trading prices, RAG decided to participate in the EU project CO_2, from Capture to Storage (CASTOR). A summary of the CASTOR project is described in the next paragraph, in the following paragraph, the CASTOR activities in Austria are detailed.

CO_2, from Capture to Storage (CASTOR) project

Introduction

The CASTOR research and development target is to enable the capture and geological storage of 10 % of the CO_2 emissions of Europe, which corresponds to about 30 % of CO_2 emitted by European power and industrial plants. To reach this goal, CASTOR aims at improving current techniques and develop, validate and generalise previously non-existent methodologies and technologies for the capture of CO_2 and its subsequent secure underground storage. The total budget of CASTOR is 15.8 mio €.

Key targets of CASTOR are:

- A major reduction in post-combustion capture costs, from 50 – 60 € down to 20 – 30 € per ton of CO_2
- To advance general acceptance of the overall concept in terms of storage performance (capacity, CO_2 residence time), storage security and environmental acceptability
- To start the development of an integrated strategy connecting capture, transport and storage options for Europe.

CASTOR activities fall into three technical sub-projects (SP):

1. Strategy for CO_2 reduction (7 % of the budget)

2. Post-combustion capture (67 % of the budget)

3. CO_2 storage performance and risk assessment studies (26 % of the budget)

In SP2 and SP3, large-scale field tests (capture facility, injection and monitoring facility) will be executed to validate the research results. In all sub-projects, innovative methods and tools will be developed, building upon the state of the art knowledge of participating organisations which are leading in the field of CO_2 capture, transport and storage.

CASTOR will make important contributions to reduce major bottlenecks that still remain in CO_2 capture and geological storage by providing:

- An improved process for capturing CO_2 in large volumes of low pressure flue gases at a much lower cost than today (development of new liquids and membranes)
- Capture validation site
- New examples of storage sites needed for achieving public acceptance
- For national and European governments there will be a clearer view on clean fossil fuels as a solution to achieve Kyoto objectives while ensuring security of energy supply for Europe
- The project will enable the research community and the industries to maintain and extend the leading position on CO_2 capture and storage

The participants in this project are listed below:

1. Institut Francais du Petrole (IFP) (Co-ordinator)
2. Statoil ASA
3. Netherlands Organisation for Applied Scientific Research (TNO)
4. Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF)
5. SINTEF Energy Research

6. SINTEF Petroleum Research
7. Norwegian University of Science and Technology (NTNU)
8. British Geological Survey (BGS)
9. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
10. Bureau de Recherches Geologiques et Minieres (BRGM)
11. Geological Survey of Denmark and Greenland (BRGM)
12. Imperial College of Science, Technology and Medicine
13. Gas de France
14. Stuttgart University
15. Vattenfall
16. ELSAM
17. ENERGIE E2
18. REPSOL
19. RWE Power
20. Public Power Corporation
21. Powergen/EON Engineering
22. ALSTOM Power
23. Istituto Nazionale di Oceangrafia e di geofisica Sperimentale
24. Mitsu Babcock
25. Siemens
26. BASF
27. GVS
28. EniTechnologie
29. Rohöl-Aufsuchung AG
30. Twente University

The project started in February 2004 and will be completed within 48 months.

In the next paragraph, the outline of the CASTOR project is shown and the different work packages are described.

Description of the work-packages

An overview of the work packages is depicted in Figure 2.

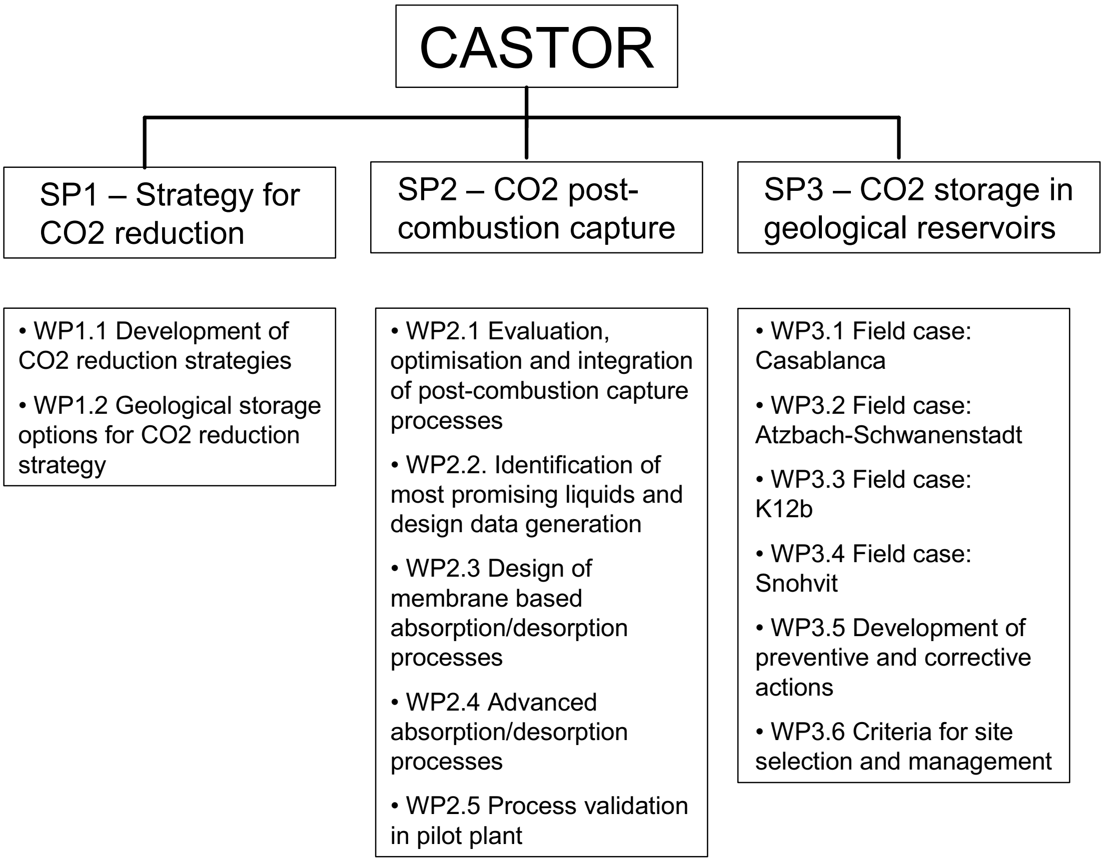


Figure 2: Overview of CASTOR work-packages

In the following sections, the work-packages are described in more detail.

SP1: Strategy for CO_2 reduction, aims to define the overall strategies required to achieve a 10 % reduction of EU CO_2 emissions and to regularly monitoring the effectiveness of the strategies (from capture to storage) from a techno-economical point of view. Research work is also focused on obtaining data on capture and geological storage capacities from Eastern Europe. At the same time, solutions will be identified for legal and public acceptance of the concept of CO_2 sequestration as a viable option for CO_2 mitigation, by developing and applying a template for exploring the public perceptions toward carbon storage. The overall impact of the project on EU countries, including candidate countries, is therefore taken into account.

SP2: CO_2 post-combustion capture, will focus on the development of new absorption liquids and innovative technologies for gas/liquid contacting (membranes) in order to provide a minimum of 90 % CO_2 recovery rate, depending of the type of fuel (it is intended to test coal, lignite and gas), with an optimised thermal energy consumption. The aim is to achieve costs per tonne of avoided CO_2 in the range of 20 € to 30 €. Reliability and efficiency of the developed post-combustion processes will be assessed at pilot plant scale. The capture pilot plant will be installed in a coal-fired power plant in Denmark operated by ELSAM.

SP3: CO_2 storage performance and risk assessment studies will develop and apply a methodology for the selection and the secure management of storage sites by improving assessment methods, defining acceptance criteria and developing a strategy for safety-focussed, cost-effective site monitoring. Items for improvements will include: The prediction of seal efficacy prior to injection, the effects of CO_2 on the seal integrity and on mechanical site stability , the leakage potential of wells and methods to improve well safety, the improvement of reaction-transport simulation models, and development of cost-effective monitoring strategy and site completion criteria. The large majority of work will be related to four sites for CO_2 storage, with a large variety of situations and characteristics:

- CO_2 injection into a depleted oilfield off-shore Spain, Mediterranean sea (Casablanca field, Repsol)
- CO_2 injection into aquifer in the Norwegian Sea (Snohvit field, Statoil)
- CO_2 injection into depleted gas field in Austria (Atzbach-Schwanenstadt field, RAG)
- CO_2 injection for enhanced gas recovery in a gas field in The Netherlands (K12b field, Gas de France)

Risk management and corrective actions studies will provide the basis for improvement of public acceptance for the CO_2 storage concept. To achieve this, public studies are needed for the understanding of the real impact of CO_2 targets such as aquifers, ecosystems and populations. Innovative procedures also have to be developed for both, preventive and corrective actions.

The next paragraph describes the activities in the work-package 3.2 “Field case: Atzbach-Schwanenstadt” in which RAG is involved in more detail.

Description of the Atzbach-Schwanenstadt work-package in CASTOR

The Atzbach-Schwanenstadt field is situated in central northern Austria, between Salzburg and Linz. This on-shore gas field is located in a depth of about 1600 m below surface. The reservoir pressure is low (11 – 30 bar), injection of CO_2 would initially require limited compression power. The reservoir consists of several sands bodies which are connected over the whole area.

Figure 3 shows the set-up of the studies performed in this work-package.

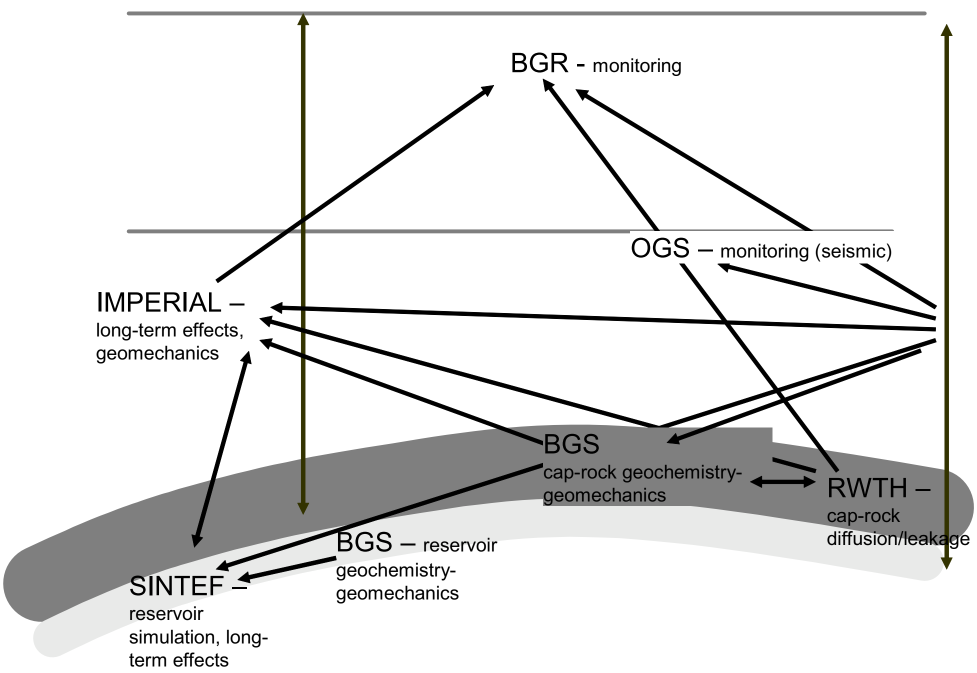


Figure 3: Set-up of the RAG part of the CASTOR project

The field study includes a complete field evaluation comprising the geology and reservoir characteristics (permeability and porosity). This part of the study is performed by SINTEF. SINTEF is also providing a geological model which is used by the other partners in the project for their contribution. British Geological Survey is investigating cap-rock and reservoir geochemistry and geomechanics by performing a number of laboratory field tests on cores from the field. RWTH Aachen is looking into cap rock capillary entry pressures for CO_2 and cap rock diffusion and flow of CO_2. Imperial college simulates long-term effects and the potential of leakage through induced fractures. Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), investigates the potential of seismic monitoring of CO_2 injected into the field and BGR looks into surface monitoring.
First results indicate that the reservoir is very suitable for CO_2 injection and that the cap-rock is sealing the reservoir very well for such a project.

Conclusions

CO_2 capture and geological storage is a viable option to contribute to reducing greenhouse gas emissions in Austria. To achieve the target of reducing greenhouse gas emissions in Austria by 13 % based on emissions of 1990, this option should be considered. Costs for CO_2 geological storage to reduce CO_2 emissions are less than 1/3 of costs for alternative electricity generation for CO_2 emission avoidance by using wind-energy.

First results from the investigations in the project CO_2, from Capture to Storage (CASTOR) indicate that RAG’s fields in Upper Austria are suitable for CO_2 geological storage. This technology offers the opportunity to create a zero-emission infrastructure integrating hydrocarbon production – electricity and hydrogen generation and industry use of hydrocarbons – CO_2 separation, transport and injection into depleted hydrocarbon fields (Figure 4).

However, it should be noted that at current trading prices of CO_2 such a project is not economically attractive.

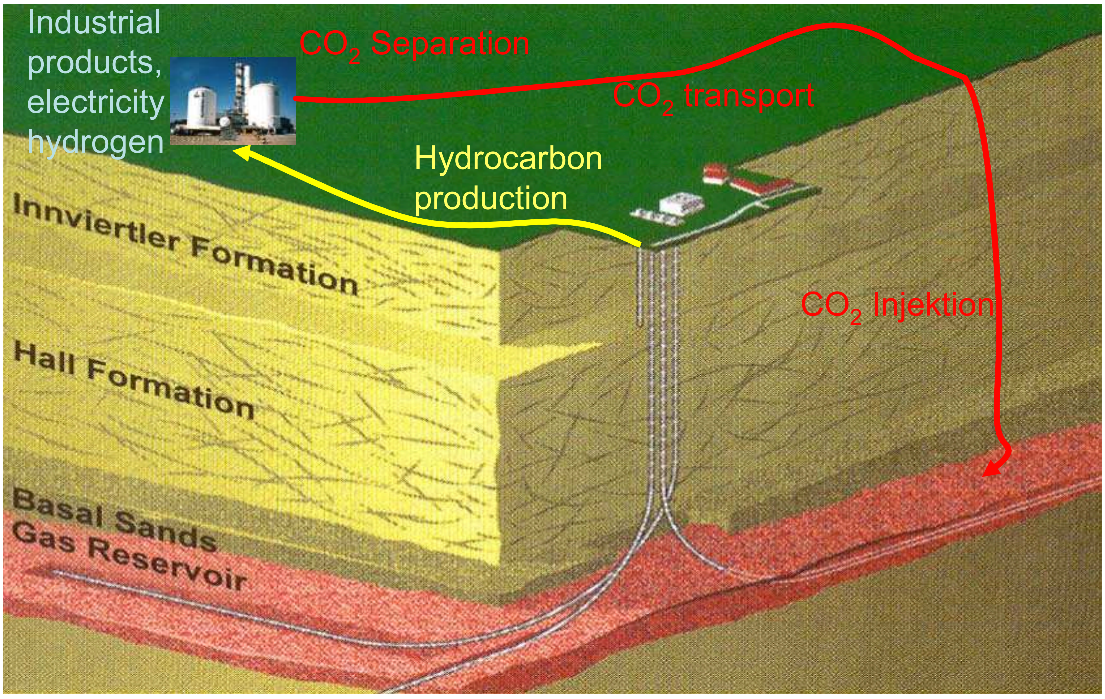


Figure 4: Generating hydrogen and electricity without CO_2 emissions by using CO_2 geological storage: Hydrocarbons are produced from subsurface reservoirs, hydrogen and electricity is produced by conventional processes, CO_2 is separated from the flue gases and injected into reservoirs.

CO_2 Capturing and Sequestration: An Emerging Business Opportunity?

Gerhard Nocker (OMV, Exploration & Production GmbH - E&P, Austria)

Assistant to Managing Director

Short Summary

It has taken a long time since the beginnings of global green house gases concerns (GHG) in 1992 (UNFCCC in Rio) and the recently signing of the Kyoto Protocol by Russia that put this set of objectives and regulation into effect.

But there are still two opponents regarding GHG globally and within the European Union. This situation creates uncertainty and resistance within the industry and prevents willingness and entrepreneurship to develop and implement solutions for GHG reduction, especially if we think about measures, which require big, long term investments. If we look at the national allocation plans (NAP's) provided so far, we also see that there is still a gap to overcome.

GHG reduction means - from an industry perspective - additional costs without any perceived value added for the customer. This is the major reason why the several available options for GHG reductions will compete primarily on costs/price. Besides that there is and will be high pressure to provide a fair global competitive arena for the industries, which will always lead to a conflict of interests.

CCS which is close to the core business of oil & gas companies has a big potential to help us to solve our problems in a mid term perspective at reasonable costs. But the oil & gas companies struggle with their non environmental image as well as with the end of pipe image of CCS. Also the high oil price may shift the focus of the oil & gas companies even more to their core business and put them into strategic dilemma regarding CCS. Do they want to act like an entrepreneur or like a follower?

The different parts of the value chain of CCS are more or less developed and used already as state of the art technology. But due to the fact that low cost is the key success factor for CCS there is still a big room for improvement. Oil & gas companies have a competitive advantage in CCS but strategic partners might help to succeed.

There are still several barriers for CCS like open or undefined legislation and related uncertainties, unclear responsibilities, unforeseen political trends and unknown price and costs scenarios. The future will show whether oil & gas companies, which are very traditional entities, are able to shift their paradigm and to open a new business for them.

OMV AUT Exploration & Production

CCS – An emerging business opportunity?

Slide Nr.1
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Move and More OMV

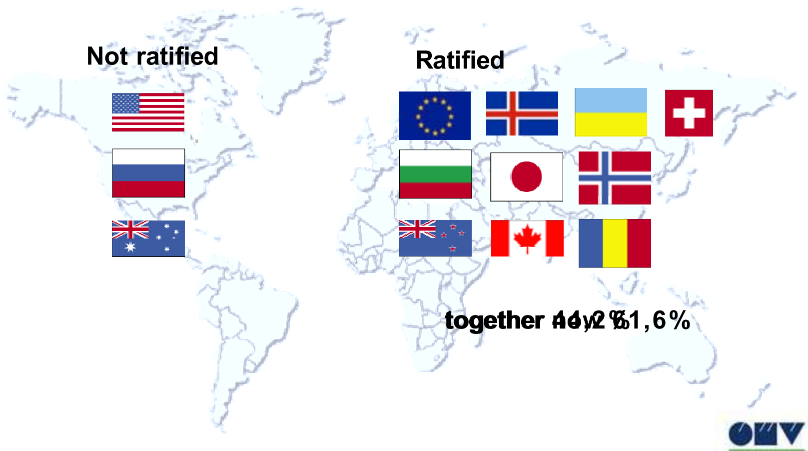
Agenda

- CO2/CCS Market
- CCS Potential
- Austrian CCS Market
- CCS Competitors
- CCS value chain
- Legal issues
- Business barriers & strategies for breakthrough

Slide Nr.2
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

CO2/CCS Market – a global one?



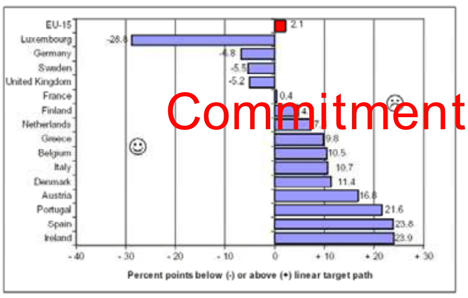
Slide Nr.3
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

The European CO2/CCS Market?

- EU15 obliged to reduce CO2 by 329 MMto (ETS-sector 143 MMto CO2)
- 1.830 MMto CO2 within ETS-sector in 2003
- Certificates for 1.790 MMto CO2 – Reduction 40 MMto CO2

Figure 2: Distance-to-target indicators (in index points = percent) for the Kyoto Protocol and burden sharing targets of EU Member States



Slide Nr.4
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

CCS Potential

storage location	global capacity [10^9 t CO2]
Depleted oil fields	100
Depleted gas fields	400
Saline aquifers	> 1.000
Coal beds	40
Total	**> 1.500**

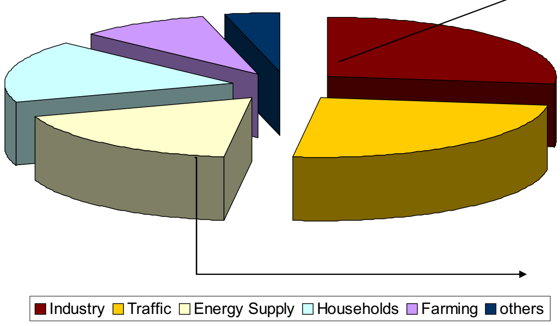
storage location	European capacity [10^9 t CO2]	
	On shore	Off shore
Depleted oil fields	0,22	5,94
Depleted gas fields	12,5	14,4
Saline aquifers	57	716
Total	**70**	**736**

Slide Nr.5
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

CCS Market Austria – Emitters & prospective Customers

CO2 Emissions in Austria [2002]



Industry

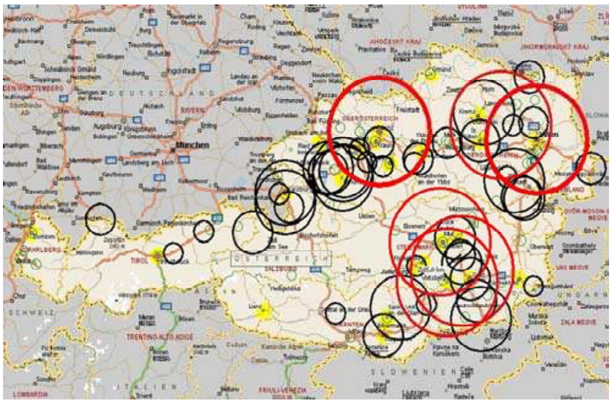
- Production & processing of ferrous metal
- Mineral industry
- Pulp & paper production

Energy supply

Slide Nr.6
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

CCS Market Austria – Emitters & prospective Customers



Industry

- Production & processing of ferrous metal
- Mineral industry
- Pulp & paper production

Energy supply

Slide Nr.6
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

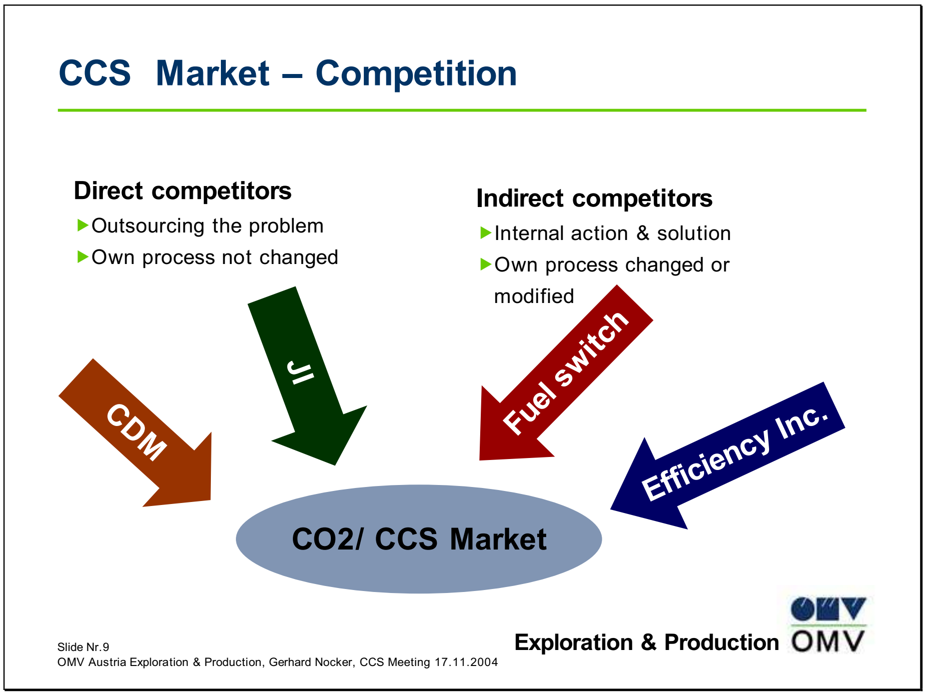
CCS Market – A business opportunity for E&P-companies?

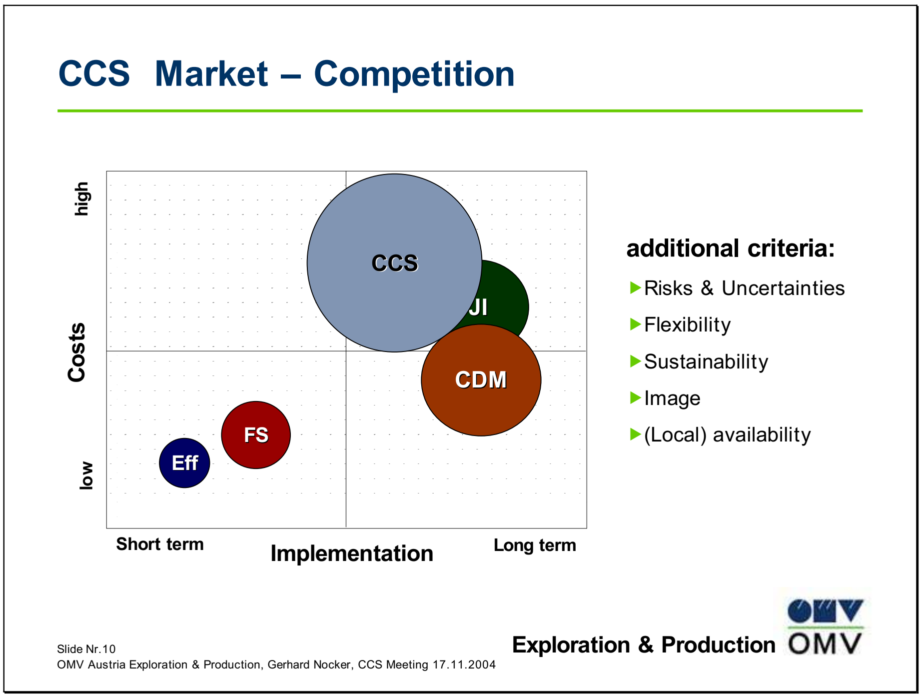
Up to now CO2-emission were free of charge, but now every ton gets a value and a market for CO2-Reduction techniques arises!

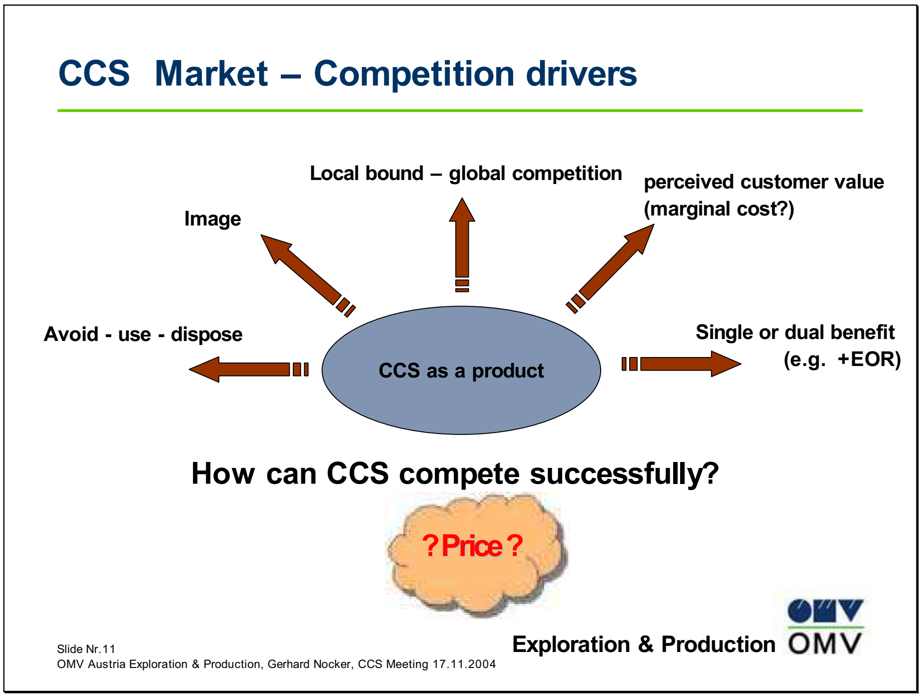
Strengths	Weaknesses
Know how & experience about storage Close to core business (existing) Infrastructure & facilities	Less knowledge about capture Locally bound Global competition
Opportunities	**Threats**
New business for mature industry Upselling potential to fuel supply Internal benefits (EOR) Positive image driver	Demand & price Legislation (e.g. approved CO2 reduction technique) Image

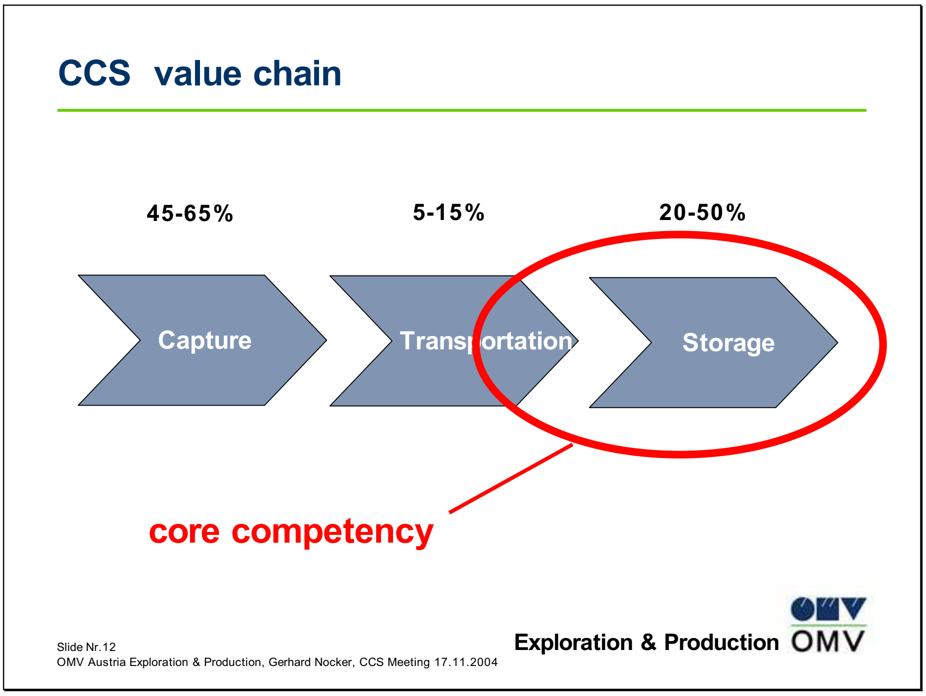
Slide Nr.8
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

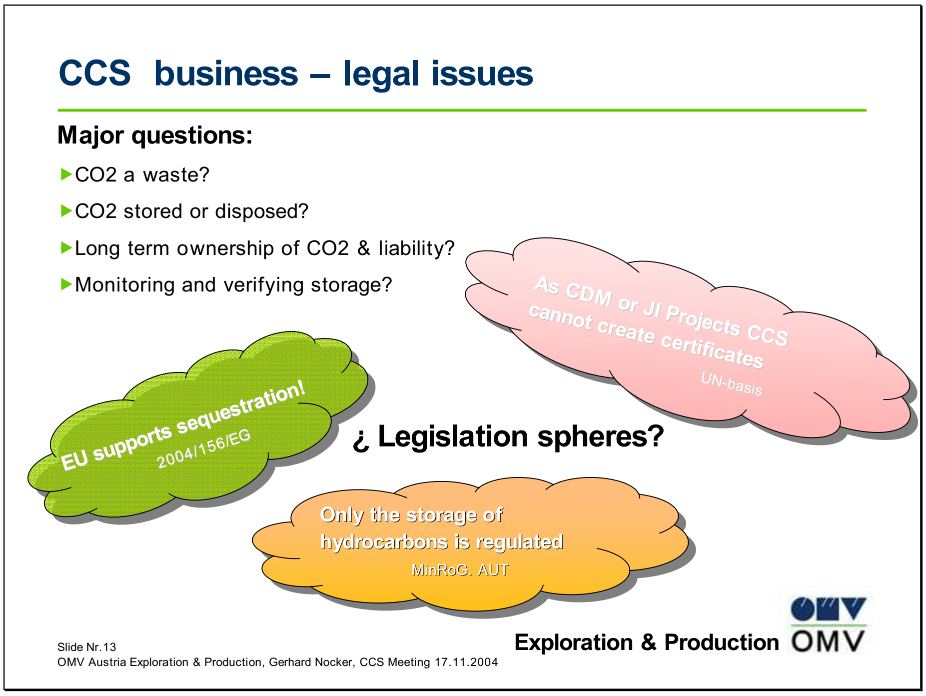
Exploration & Production OMV

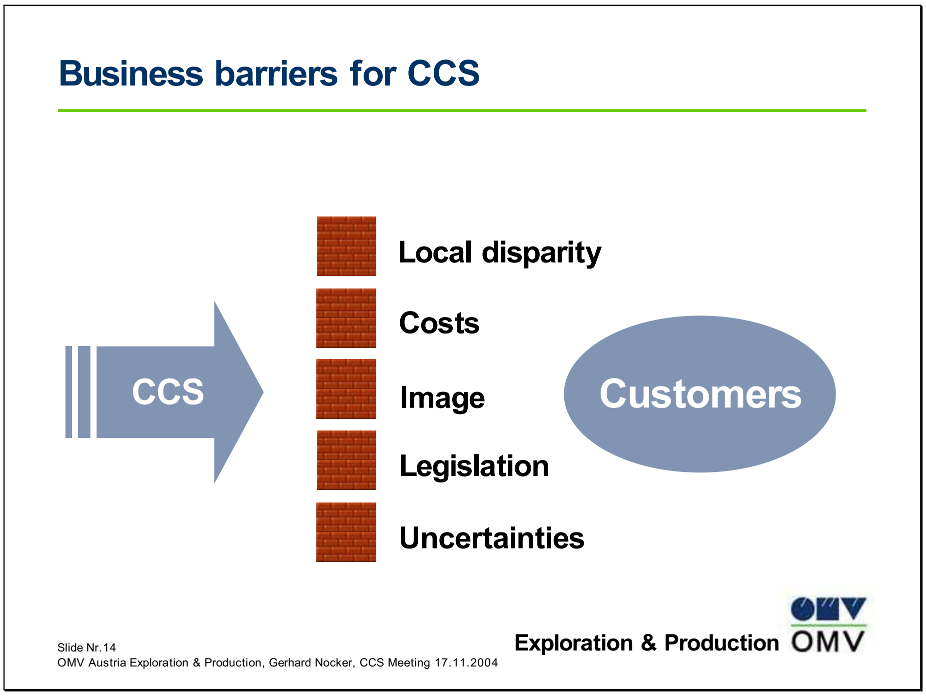

CCS Market – Competition
Direct competitors
Outsourcing the problem
Own process not changed
Indirect competitors
Internal action & solution
Own process changed or modified
JI
CDM
Fuel switch
Efficiency Inc.
CO2/ CCS Market
Slide Nr.9
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV


CCS Market – Competition
high
Costs
low
CCS
JI
CDM
FS
Eff
Short term
Implementation
Long term
additional criteria:
Risks & Uncertainties
Flexibility
Sustainability
Image
(Local) availability
Slide Nr.10
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV

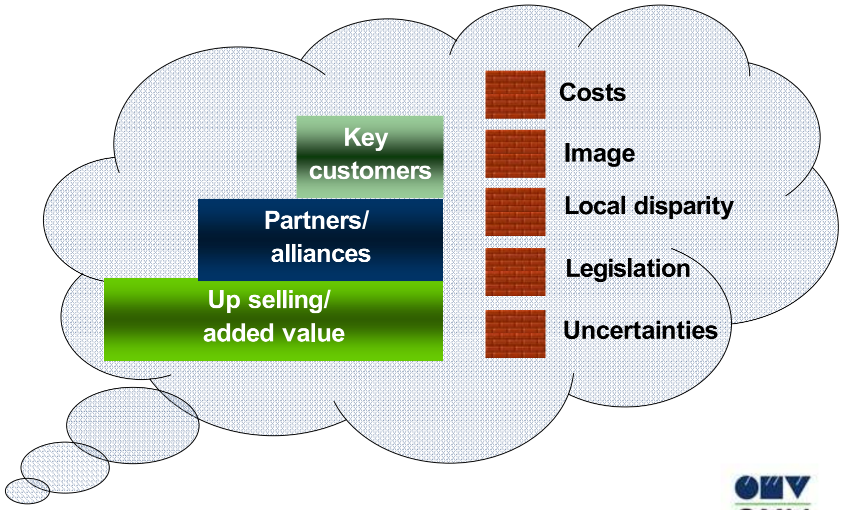

CCS Market – Competition drivers
Local bound – global competition
Image
perceived customer value
(marginal cost?)
Avoid - use - dispose
CCS as a product
Single or dual benefit
(e.g. +EOR)
How can CCS compete successfully?
? Price ?
Slide Nr.11
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV


CCS value chain
45-65%
5-15%
20-50%
Capture
Transportation
Storage
core competency
Slide Nr.12
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV


CCS business – legal issues
Major questions:
CO2 a waste?
CO2 stored or disposed?
Long term ownership of CO2 & liability?
Monitoring and verifying storage?
As CDM or JI Projects CCS cannot create certificates
UN-basis
EU supports sequestration!
2004/156/EG
¿ Legislation spheres?
Only the storage of hydrocarbons is regulated
MinRoG. AUT
Slide Nr.13
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV


Business barriers for CCS
CCS
Local disparity
Costs
Image
Legislation
Uncertainties
Customers
Slide Nr.14
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004
Exploration & Production
OMV

CCS business strategies



Slide Nr.15
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

Questions

Slide Nr.16
OMV Austria Exploration & Production, Gerhard Nocker, CCS Meeting 17.11.2004

Exploration & Production OMV

Summary

Guenter R. Simader (Austrian Energy Agency)

Head of Unit:
Energy Technologies, Systems and Market Implementation

Goals of the workshop

- Presentation of the state-of-the-art about latest European and International CCS technologies in order
  - to give orientation and guidance to international priority RTD topics
  - identify and assess future RTD potentials
- Overview about the opportunities and barriers of CCS RTD activities as possible technological option for future mitigation technology
- To support the decison makers of industrial and public sectors, scientific bodies and NGOs in their future positions and decision making

2

1st Session: International R&D Programmes and Activities - I

- IEA: CCS technologies are a serious, future CO_2 mitigation option - among others – having a significant potential for reducing GHG
  - Major challenges include RD&D gaps, public awareness and acceptance, the legal and regulatory framework, long-term policy framework and incentives
- EU vision of energy sustainability include
  - The need for the security of energy supply (incl. the full range of available fuels (incl. FF and CCS)!)
  - The need to ensure EU industrial competitiveness (global competition for the European Industry mentioned)
  - Post-Kyoto strategies to be developed incl. the full range of technological options (CCS technologies)
- EU RTD policy issues involve cost-effective FF usage in combination with zero emission technologies (incl. the whole RTD chain), a serious of FP 6 projects were presented (f. ex. Decrease of CO2 capture costs from 50-to 60 €/t to 20-30 €/t), CCS is also a priority topic in the next FP6 Call)
- EU: Clear recognition for an international approach on the issue of global environment challenges and technology development (participation in CSLF, IEA,

3

1^{st} Session: International R&D Programmes and Activities - II

- COORETEC – R&D for Zero-Emission Fossil-Fuelled Power Plants, 2-phase programme (incl. CCS in the 2^{nd} phase)
  - Replacement capacity in Germany till 2020: 40 GW
    Potential of increasing power plant efficiency: + 15 – 20 %
  - Clear roadmap shown and key technologies to be developed
- IEA GHG Program
  - Confirmation of portfolio approach in order to decrease GHG emissions (with CCS as priority topic)
  - Major studies on covering the whole portfolio of CCS technologies, latest results were mentioned that indicate a clear cost decrease in CO_2 capture technologies
  - CCS is priority topic in the greenhouse gas programme
  - New R&D networks will be set up covering risk assessment and monitoring of CO_2 storage
  - Role of international collaboration for future RTD developments outlined (participation of Austria?)

4

2^{nd} Session: CCS Projects and Activities: Key Messages - I

- CO_2 Sinks in oil/gas fields and aquifers (Prof. Heinemann)
  - Overview of world-wide CO2 storage activities and programs (presently over 70 projects)
  - Since 1950 EOR is an established technology
  - Austria: theoretical CO_2 storage volume in 11 oil/13 gas fields ~ 465 MM t (final: 510 MM t)
    - Vienna Basin (OMV): 430 MM t; Molasse (RAG): 35 MM t
    - Cost estimation (incl. 30 km pipeline): 11 – 12,5 €/t
    - Suggestion for a national CCS research project involving all major stake holders!
- GESTCO Project – Geological "detailed" storage surveys incl. 8 European countries (f. ex. storage capacity in hydrocarbon fields = 37 Gt)
  - Development of a CO_2 storage GIS (matching sources and sinks) and Decision Support System (DSS) to evaluate the economics of CSS
- Schlumberger: Identification of challenges and risks of CO_2 subsurface storage, options concerning state-of-the-art technological and simulation models for monitoring procedures (conc. risk assessment, risk prevention for gradual or sudden release of CO_2 from a particular formation), virtual reality centers for improved "on-time" visualisation of stored CO_2

5

3rd Session: CCS Projects and Activities Key Messages - II

ENERGIE VERWERTUNGSAGENTUR

- **OPEC (Ms. Laura Atkins)**
  - CO_2 storage in depleting oil gas fields can significantly contribute to an increase of oil reserves (EOR = win/win situation)
  - Description of geological storage potentials in general and with specific examples in particular (Sleipner, In-Salah, West Texas Permian Basin, Weyburn, etc.)
  - Analysing the financing and policy issues (CDM could facilitate early implementation of CCS in developing countries) incl. gas flaring reduction initiatives
- **CO_2 Capture Project Update (Ms. Helen Kerr, BP)**
  - Joint industrial partnership in order to reduce costs of CCS technologies (several projects - over 100 contracts! - involving key technologies performed by key industries)
  - Perform successful demonstration projects (incl. proof of concept, risk assessment studies, etc.), but still unsolved questions (f. ex. cap rock stability, storage stability in saline aquifers, etc.)
  - Demonstration to external stakeholders that CCS is safe, measurable, and verifiable (f. ex. develop industry guidelines, etc.)

6

3rd Session: CCS Projects and Activities Key Messages - III

ENERGIE VERWERTUNGSAGENTUR

- **CASTOR Project – RAG**
  - Reduce the costs of post-combustion capture technologies (in coal-fired power plants, f. ex. Elsam in Denmark (cost goals: 20 to 30 €/t)
  - So far, field evaluations of Atzbach-Schwanenstadt field in Upper Austria (depth: 1600 m, reservoir pressure: 11 – 30 bar) achieve positive results, however present CO_2 prices do not justify CCS investments at this stage.
- **OMV: CCS an emerging business opportunity?**
  - Consideration/analysis of the CCS market in Austria (SWOT analysis, competing technologies to CSS, ...)
  - Core competency is in the storage (not in capture and transportation technologies)
  - Major remaining questions: CO2 a waste? CO2 stored or disposed? Long-term ownership of CO2 and liability issues? Long-term Monitoring and verification issues?
  - Major business barriers exist (costs, legislation, image, uncertainties, etc.)

7

Summary

- CCS is a priority topic within the present and future(!) European and International RTD programmes and industrial activities
- Analysis by leading energy experts show a huge storage potential for CO_2
- A number of demonstration projects are presently carried-out to gain experience in practicability and other issues (f. ex. cap rock stability, CO_2 leakage, etc.)
- International collaborations (beside of national and industrial activities) may be characterised as essential to spur the development and implementation process (development of Post-Kyoto technologies necessary)
- Major uncertainties still exist in the policy and legal frameworks (liability, etc.)
- Major barriers were shown concerning the development/-implementation of CCS as business opportunity for companies (f. ex. absence of commercial incentives)

8

ENERGY SYSTEMS of Tomorrow

Title graphics: courtesy of CO2CRC

www.NachhaltigWirtschaften.at

bmvit An Initiative by the Austrian Federal Ministry for Transport, Innovation und Technology