The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)

Strategic Research Agenda

Key recommendations

Experts agree that CO_2 capture and storage technology (CCS), together with improved energy conversion efficiency, is a near-term solution to reducing CO_2 emissions from fossil fuel power generation on a *massive* scale. Its *immediate* deployment is therefore vital if we are to avoid the catastrophic consequences of climate change we are facing today.

Yet despite most of the technology elements being available, CCS is still not deployed for two key reasons:

1. The costs and risks still outweigh the commercial benefits
2. The regulatory framework for CO_2 storage is not sufficiently defined.

The Strategic Research Agenda therefore describes a collaborative programme of technology development for reducing the costs and risks of deployment; while the Strategic Deployment Document outlines how we can accelerate the market for zero emission power production. To this end, the Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) recommends (under FP7):

1. ***Urgently implementing 10-12 integrated, large-scale CCS demonstration projects Europe-wide***
   - Improve the cost-effectiveness and availability of current CO_2 capture technologies; optimise energy conversion efficiency when integrated into a power plant; and bring to commercial readiness **by 2020**
   - Assess the full potential for CO_2 geological storage, demonstrate its safety to the public and understand/respond to their concerns
   - Resolve all technological uncertainties and establish a critical mass of data for exploitation in parallel R&D projects
2. ***Developing new concepts already identified, but not validated, for demonstration by 2010-2015 and implementation* beyond 2020*, e.g.***
   - Advanced new materials and combustion systems
   - Storage in onshore, deep saline aquifers and CO_2 for Enhanced Oil Recovery in the North Sea
3. ***Supporting long-term exploratory R&D into advanced, innovative concepts for implementation of next-generation technology, e.g.***
   - Innovative CO_2 capture technologies (membranes, adsorption etc.)
   - Innovative concepts for CO_2 storage
   - Simple, reliable tools for long-term modelling and monitoring of CO_2 storage
4. ***Maximising cooperation at national, European and international level***
   - Mobilise national and European funding and explore new options for launching large integrated projects, such as Joint Technology Initiatives
   - Further promote international cooperation, especially with emerging countries such as China and India.
5. ***Strengthening and accelerating R&D priorities to support the Strategic Deployment Document, informed by experience from demonstration projects and parallel R&D projects on advanced, innovative concepts.***

Contents

Foreword

Following developments in clean power generation and the priority given to 'zero emission power generation' in the Sixth Framework Programme (FP6), industrial stakeholders and the research community had several meetings in 2004 which resulted in the creation of a Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

Its brief? To identify and remove the barriers to creating highly efficient power plants with zero emissions, which would drastically reduce the environmental impact of fossil fuel use, particularly coal.

In the autumn of 2005, the Advisory Council and Coordination Group - along with the Working Groups and Mirror Group - were also established. The Technology Platform was officially launched in December and a Vision Paper was published the following May.

The Coordination Group is responsible for the Strategic Research Agenda (SRA) and the Strategic Deployment Document (SDD), and overseeing the five Working Groups. These comprise experts from industry, research and NGO[1] communities and are divided into the following areas:

i) Power Plant and CO_2 Capture Technologies
ii) CO_2 Storage and Use
iii) Infrastructure and Environment
iv) Market, Regulations and Policy
v) Communications and Public Acceptance.

Each Working Group has contributed to the SRA and SDD with a view to realising our Vision:

To enable European fossil fuel power plants to have zero CO_2 emissions by 2020.

N.B. As the Strategic Research Agenda and Strategic Deployment Document are aimed at different audiences, some of the text is duplicated in order to maintain consistency.

[1] Non-governmental organisation

1. Realising the Vision : zero emission power plants by 2020

The case for CO_2 capture and storage technology (CCS) is clear: without its urgent implementation, experts predict that CO_2 emissions will result in the average global temperature rising by anything from 1.4°C - 5.8°C between 1990 to 2100[2], thus triggering the catastrophic consequences of climate change.

Indeed, climate models established by the Intergovernmental Panel on Climate Change (IPCC) indicate that these will occur if global warming exceeds even 2ºC above the pre-industrial average. In order to avoid such a high temperature increase, it has stated categorically that global greenhouse gas (GHG) emissions must be reduced by 50% - 80% by 2050 (compared to 1990 levels).

Yet with world energy demand predicted to increase by 60% between 2002 and 2030[3], and renewable energies to make up only a third[4] of the energy mix by 2050, the immensity of the challenge becomes clear. Clearly, fossil fuels - coal, oil, gas - must remain the primary energy resource for a long time to come.

CCS could reduce CO_2 emissions in the EU by 56% by 2050
A portfolio of solutions is therefore essential, including renewable energies, improved energy efficiency and nuclear power. But that still leaves an enormous gap between global energy demand and their potential to reduce CO_2 emissions on the massive scale required. To these, we must therefore add CO_2 capture and storage (CCS) technology.

As a safe and efficient method of capturing and storing millions of tonnes of CO_2 emissions underground for thousands of years, CCS represents the bridge to a sustainable energy system.

Indeed, power plants equipped with this technology will emit less than 10% of their produced CO_2. If deployed to its full potential, it means CCS could reduce CO_2 emissions in the EU by 56% by 2050, compared to today[5].

An ambitious, but realistic goal
To this end, The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) was established in 2005. Its goal: to enable zero CO_2 emissions from European fossil fuel power plants by 2020. This will involve implementing a complete CO_2 value chain - from the capture of CO_2 at large emission sources, to its transportation to storage sites, to its storage in underground geological formations.

It is an ambitious goal, but an entirely feasible one. After all, the technology has been practised over decades – CO_2 has been separated from gaseous streams for several years in many industries. It has also been used and stored in Enhanced Oil Recovery (EOR).

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2 Intergovernmental Panel on Climate Change, "Climate Change 2001: Synthesis Report", Cambridge University Press, 2001
3 The IEA World Energy Outlook 2004
4 Shell's Long-Term Energy Scenarios
5 Bellona Paper, August 2006, http://bellona.no/artikler/notater_stangeland_solomon

But it will require substantial R&D funding if we are to accelerate its deployment on the scale now urgently required. Indeed, the future viability of CCS depends not only on fiscal incentives and a regulatory framework, but on lower CO_2 capture costs, improved plant efficiency and – above all – public support for the concept of CO_2 underground storage.

What are the main drivers for research?

a) Reduce CO_2 capture and power plant costs

If all R&D gaps are addressed, the three main CO_2 capture technologies are certainly considered capable of achieving commercial readiness by 2020. In fact, they have the potential to satisfy market demand not only in Europe, but worldwide, if global CO_2 challenges are to be met.

Their demonstration in full-scale plants is therefore of critical importance, supported by parallel R&D on key technical issues. These plants should use hard coal, lignite, gas and biomass, and cover the full range of CO_2 capture systems.

b) Demonstrate the safety of CO_2 geological storage

Experts already agree that CO_2 geological storage is both practical *and* safe. But if we are to gain public support, it must be proved beyond doubt through large-scale demonstration projects, in parallel with a R&D programme for assessing storage capacity and the behaviour of CO_2 underground.

It means building about 10-12 full-scale storage sites, in a variety of geological and geographical settings, the length and breadth of Europe. Such projects would provide a critical mass of scientific data for proving that operations, monitoring, verification, risk and mitigation can indeed be carried out in the manner acceptable to both regulators and the public.

Increasing Europe's competitive advantage

The SRA is therefore designed to provide continuity to current R&D programmes, giving the European Commission (EC) a consistent priority plan that transcends individual Framework Programmes and the industry the confidence to make a long-term commitment.

To this end, it addresses all key scientific and technical issues which could hinder Europe achieving the Vision. These must be prioritised on the basis of technical feasibility, economics and public acceptance, taking into account Europe's specific assets in R&D and industry in order to maintain – and increase - our competitive advantage.

2. Moving from small- to industrial-scale CCS projects

In line with EU energy sector priorities, EU industry - either through Member States or EC supported programmes - is already working hard at researching and validating CO_2 capture and storage technologies.

Indeed, large cooperative programmes have been launched under the 5th and 6th Framework Programmes for R&D (FP5 and FP6) and STREP[6], including AZEP, GESTCO, ENCAP, CASTOR, CO_2SINK and RECOPOL[7]. Considerable transfer and adaptation of methods and tools has also taken place from directly related fields, such as petroleum exploration and production, and geothermal operations.

CO_2 storage is already a fact
It means that several European pilot and demonstration projects have already been initiated, including:

- Sleipner, Norway - 1 mega tonnes (Mt)/year stored in the North Sea since 1996
- K12B, Netherlands - CO_2-Enhanced Gas Recovery (EGR), some hundred kilo tonnes (Kt) in the North Sea since 2004
- Ketzin, near Berlin, Germany - some 60 Kt over a few years (starting 2007)
- Snøhvit, Norwegian Sea - 0.75 Mt/y, starting 2007.

Nor are they confined to Europe: there are currently a number of larger-scale demonstrations of CO_2 geological storage already underway worldwide, including:

- Permian Basin, US - 35 Mt/y, starting 1972; over 70 projects with a total of 500 Mt/stored
- Frio Brine, Texas USA – 3.0 Kt over a short period in 2005 and 2006
- Weyburn, Saskatchewan, Canada - CO_2-EOR, 2 Mt/y since 2000
- Nagaoka, Japan - 10.4 Kt, over 1.5 years, 2004-5
- In Salah, Algeria - 1.2 Mt/y since 2004
- Gorgon, Australia, 129Mt over the life of the project, starting 2008-2010.

Some of these are "field laboratories", with the rest built on an industrial scale, operated by oil and gas companies as commercial enterprises.

CCS projects are also happening
The number of combined CO_2 capture and storage projects in Europe which have already been announced, or are underway, also demonstrates the confidence industry has in this technology, including:

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[6] Specific Targeted Research Projects

[7] AZEP (Advanced Zero Emissions Powerplant); GESTCO (Assessment of European Geological Storage Potential); ENCAP (Enhanced CO_2 Capture in Powerstations); CASTOR (CO_2 from Capture to Storage); CO_2SINK (In-situ laboratory for capture and storage of CO_2); RECOPOL (Enhanced coal bed methane)

- Shell and Statoil are planning a new 860MW natural gas fired power plant at Tjeldbergodden, Norway with CO_2 capture. CO_2 will be transported to the Draugen and Heidrun oil field and used for EOR, starting 2011.

- CO_2 capture is planned at a new natural gas fired power plant at Kårstø, Norway for use in EOR, starting 2009.

- CASTOR project under FP6: a pilot plant for CO_2 capture at the coal-fired power plant in Esbjerg, Denmark has been built by international partners – about 8 Kt/year. This is an experimental operation for post-combustion amine capture.

- BP, Southern & Scottish Energy and General Electric are engineering an industrial-scale (350MW) ZEP at Peterhead, with the CO_2 used for EOR in the Miller oil field, Scotland – storing 1.8 Mt/year CO_2, starting 2010.

- Vattenfall is building a $30MW_{th}$ coal-fired pilot boiler with CO_2 capture at Schwarze Pumpe in Germany, which is due to start operating mid-2008.

- RWE is to build a large-scale, 450MW, integrated coal gasification combined cycle (IGCC) power plant where CO_2 will be captured and stored onshore, starting 2014. It is also proposing a major CCS retrofit to a coal-fed power station at Tilbury in the UK (capture technology yet to be selected), starting 2016.

- E.ON UK are developing an IGCC power plant project with CO_2 captured and stored in the southern North Sea, off the east coast of the UK, starting 2011.

- Nuon is to demonstrate CO_2 capture at its coal gasifier plant near Limburg. It is also planning to build a new multi-fuel IGCC 1200MW power plant in Eemshaven, the Netherlands.

- Powerfuel plan to build a 900MW coal gasifier power plant with CO_2 capture (pre-combustion technology) at Hatfield colliery, UK, starting 2010.

- Progressive Energy plan to build a 800MW IGCC plant using pre-combustion technology at Teeside, UK, starting 2009.

- Total is to retrofit a 30MW boiler with CO_2 capture (oxy-fuel technology), transport and storage in Lacq plant France, starting 2008.

- SEQ International and ONS Energy are planning to build a 50MW power plant with CO_2 capture (oxy-fuel technology) for use in EOR (0.2 Mt/y), near Drachten, the Netherlands.

- In Spain, there is a co-ordinated initiative to build pilot plants in the scale of 5-10MW to explore CCS in post-combustion, pre-combustion and oxyfuel technologies.

All industrial-scale projects, however, will require Government incentives if they are to progress.

A step change is now vital
Research-driven, small-scale field laboratories, such as Ketzin, allow us to test new tools and methods with some flexibility and it is important we continue monitoring activities at these early sites in order to establish long-time series of information. Larger research projects, such as those associated with Sleipner and In Salah, on the other hand, have provided opportunities to study CO_2 on a pre-commercial scale.

However, although experience gathered from single projects has been extremely valuable, Europe's leading position within CCS remains precarious. If we are to maintain – and increase – it, a step change is now vital; and that means building 10-12[8] industrial-scale demonstration projects from which we can draw a critical mass of scientific data. These should be ready for commissioning by 2015 *at the latest* – but many will be ready before this date.

[8] Industrial-scale CCS demonstration projects need to demonstrate a diverse range of infrastructure, technologies, fuels and storage locations.

3. Lowering the cost of zero emission power generation

What is CO_2 capture?
The purpose of CO_2 capture (when efficiently integrated into a steam or gas & steam power plant) is to produce a concentrated stream that can be easily transported to a CO_2 storage site – a deep underground geological formation.

CO_2 capture applies mainly to large power plants fired with hard coal, lignite and natural gas[9]. It also applies to large, single point emission processes such as refineries, cement plants, chemical plants and steel mills that can use the same or similar technology - as well as transport infrastructure – thus increasing the efficiency of the entire CCS system. It can even apply to biomass, paving the way for net *negative* emissions, because biomass also draws CO_2 down from the atmosphere whilst it is growing.

There are three main technology options under development:

- ***Post-combustion*** systems separate CO_2 from the flue gases produced by combustion of a primary fuel (coal, natural gas, oil or biomass) in air. Can be retrofitted to existing power plants, as well as new builds.

- ***Pre-combustion*** systems process the primary fuel (natural gas or synthetic gas from coal) in a shift reaction to produce streams of CO_2 and hydrogen which can be separated. ***The hydrogen can then be used for either electricity or as a fuel - accelerating the transition to a hydrogen economy.***

- ***Oxy-fuel combustion*** systems use oxygen instead of air for combustion, producing a flue gas that is mainly H_2O and CO_2, which can be easily captured after the water vapour is condensed.

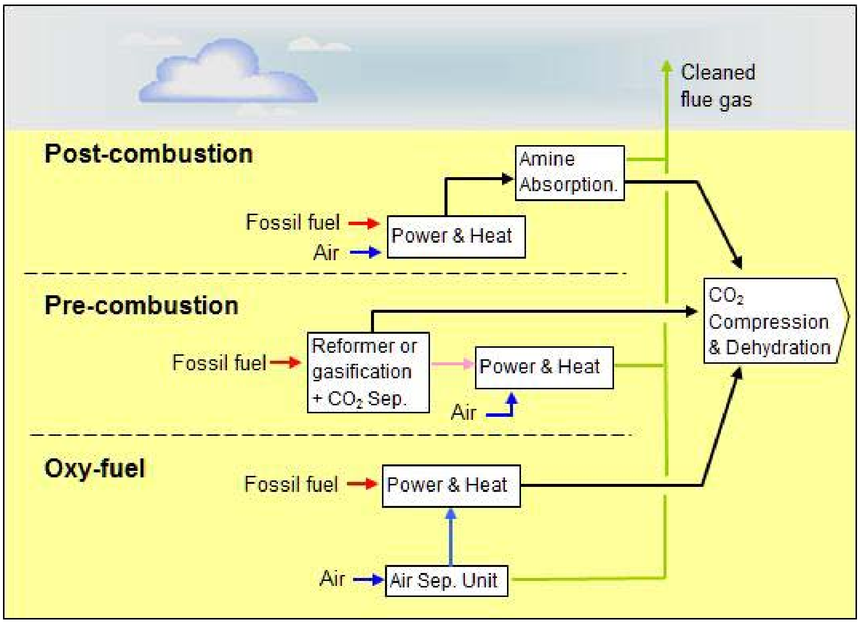

Fig. 1 - Main technology options for CO_2 capture from power plants

[9] Although several CO_2 capture technology developments for coal also apply to oil, it is not considered an economically preferred fuel for future power generation (except for niche applications).

In principle, all can be applied using commercially available equipment, but with varying degrees of system modification. Indeed, a significant scale-up will be required - 20-50 times - no power plant in the world today being equipped with capture technology on such a scale. Minimising the energy requirements for capture and improving the efficiency of energy conversion processes will also continue to be high priorities in order to minimise overall environmental impacts and cost.

This must be urgently addressed through the implementation of industrial-scale demonstration projects and associated research projects, with all technologies given equal weighting (until clear conclusions have been established).

R&D should therefore focus on reducing the costs of power generation with CO_2 capture by:

a) Further developing CO_2 capture techniques and reducing the energy consumption of oxygen production and CO_2 treatment

This is certainly considered possible. Indeed, each is considered capable - subject to substantial R&D and economies of scale - of delivering future zero emissions power at electricity prices of €45 - €55/MWh for coal and around €60/MWh for gas with CO_2 avoidance costs of €15 - €25/t CO_2 for coal and €50 - €60/t CO_2 for natural gas (calculated with current fuel prices and excluding CO_2 transport and storage costs).

Although these figures seem to put gas in a rather unfavourable light, it must be remembered that the amount of CO_2 it generates is lower per MWh, leading to much more comparable figures for the cost per MWh. In any case, if we are to achieve the massive reduction in CO_2 emissions necessary, we will need to have a portfolio of technologies, including coal and gas.

The following chart shows the expected range of avoidance costs[10] for the three main technology options which can be developed and demonstrated until 2020.

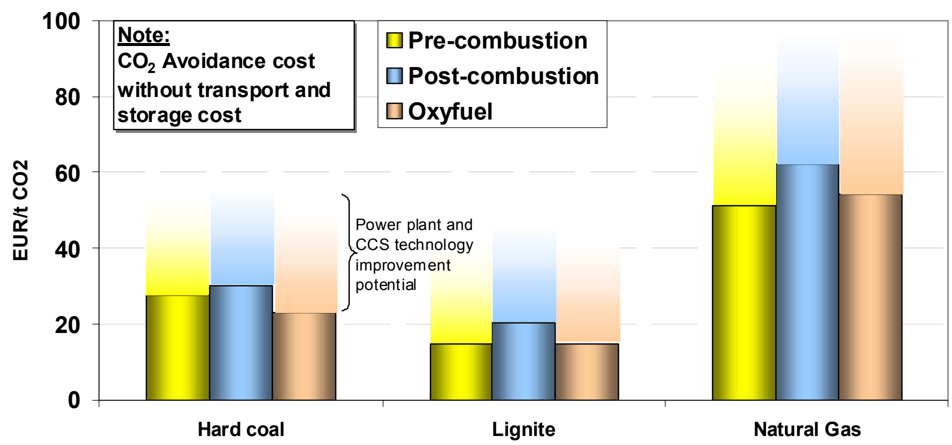

Fig. 2 – Expected avoidance costs for industrial-scale power plants in operation by 2020[11]

[10] i.e. cost of both CO_2 capture *and* that incurred to offset additional CO_2 generated through the capture process

[11] Source: Working Group 1, ZEP Technology Platform

Research should therefore aim at reducing both CAPEX[12] and OPEX[13] related to CO_2 capture plants. The main contribution to OPEX is energy required for CO_2 capture, so the cost related to energy should be minimised by optimising the energy-flow of the power plant. As plants produce heat, the overall process can also be improved by optimising the integration of electricity production, heat production and CO_2 capture.

N.B. costs are expected to fall as we gain experience from demonstration projects and advance technology development. Transport costs will be avoided altogether where ZEP plants are located above the storage location itself.

b) ***Increasing the efficiency of both CO_2 capture and the power plant in order to reduce energy consumption (which the capture process can increase)***

Increasing the efficiency of the power plant when integrated with CO_2 capture will reduce both fuel consumption *and* CO_2 emissions, reducing environmental impact, saving energy resources and lowering costs, thus improving competitive advantage.

However, when evaluating CO_2 capture technologies, it is also important to consider the following key parameters:

- Thermal efficiency
- Flexibility of plant fuel
- Exhaust gas composition
- Flexibility in handling different CO_2 sources
- Efficiency of CO_2 removal
- Size of plant, including cost and availability of area required
- Integration of CO_2 capture technologies with power plant
- Suitability for retrofit to existing power plants

i) Post-combustion technology

Current status

The good news is that post-combustion CO_2 capture technology, based on chemical absorption processes, is already proven and commercially available in the oil and gas industry, and on a moderate scale for flue gases.[14] Indeed, because of its long track record, it is the closest to large-scale commercial development, especially as it can be retrofitted to existing fossil fuelled power plants.

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[12] CAPEX – Capital Expenditure
[13] OPEX – Operational Expenditure
[14] A detailed description of the current status for CO_2 capture technology can be found in a report published by the Intergovernmental Panel on Climate Change (IPCC), "Carbon Dioxide Capture and Storage", Cambridge University Press, UK, 2005

However, a significant scale-up will be required – up to 20−50 times. Since economically viable capture is not possible with existing solvents, new ones must therefore be developed which significantly lower energy consumption.

Sulphur oxide (SO_2), nitrous oxides (NO_x) and particulates must also be reduced, as they reduce the effectiveness of the chemical absorber. Finally, there is real potential for process optimisation - new absorbers, contactors and processes are currently being researched in order to achieve the cheapest capture costs possible.

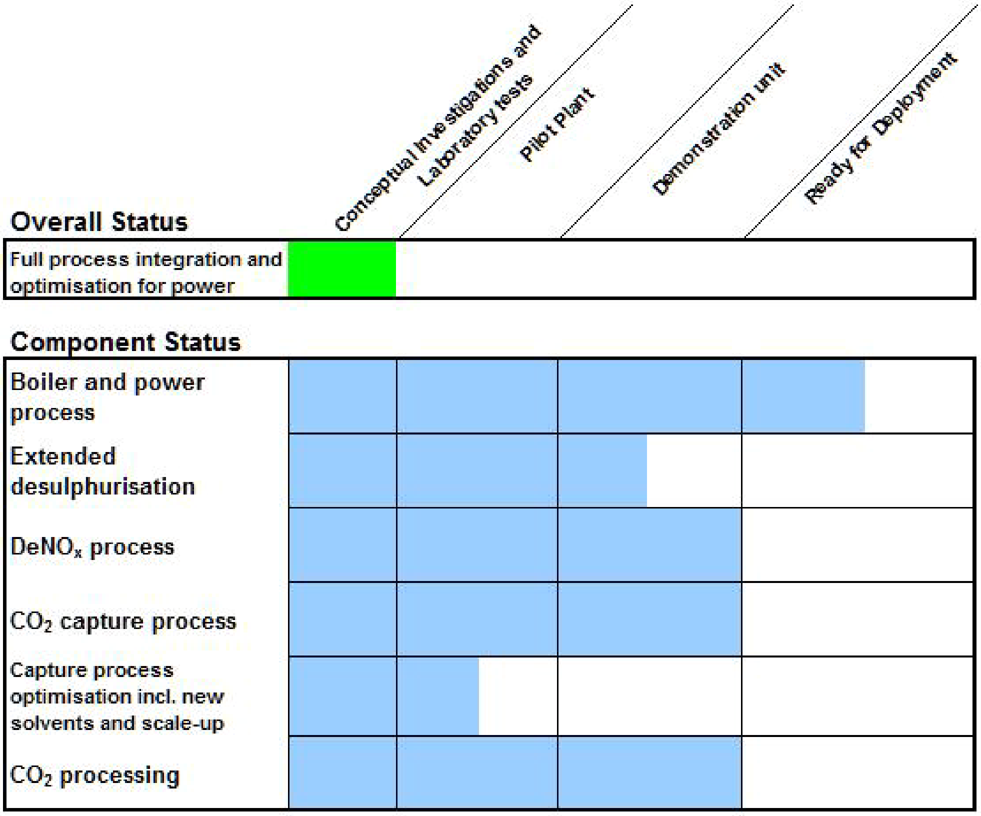

Fig. 3 - Current status of post-combustion technology

Figure 3 shows the maturity of post-combustion technology, with almost all major components commercially available. However, they are neither integrated nor optimised for CCS.

Key research issues

- Insufficient experience for power plant application on a large-scale and special requirements due to flue-gas conditions
- High energy demand/penalty for regeneration of the solvent and energy requirements for CO_2 compression
- Full process integration and optimisation for power generation
- Absorption system with high-throughput under oxygen environment is unavailable today

CO_2 capture and conditioning processes
General areas include:

- New and less energy-intensive solvents which exhibit stable performance in flue gases
- Process optimisation for large-scale plants
- New and less energy-intensive solvents which exhibit stable performance in flue gases
- Demonstrating long-term operational availability and reliability on a full-scale power plant, using relevant fuels
- Retrofittable concepts

More specifically:

- New solvents with high CO_2 loading, low regeneration energy requirement and fast reaction kinetics
- Reduction or avoidance of thermal and oxidative degradation of sorbents and losses
- Developing third generation absorbents, e.g. which avoid the use of water and are able to work at higher temperatures
- Degradation mechanisms investigation and analysis
- Methods to reduce impact of flue gas contaminants (particulates, sulphur- and nitrous oxides) on the solvent process
- Developing low-cost and compact equipment for the solvent processes
- Optimising gas path integration to reduce investment costs
- Optimising heat integration methods to limit impact on the power production process
- Improving efficiencies in capture concepts
- Conceptual studies, including power plant integration
- Process modelling and equipment modelling
- Corrosion studies
- Kinetic and mass transfer studies

Emerging technologies

- Materials research to improve the performance and lower the costs of the separating agents, such as adsorbents, membranes
- Component development, e.g. membrane modules and novel reactors addressing issues such as scale-up, methods of fabrication
- Improving the efficiency of supporting technologies, e.g. vacuum pumps and CO_2 compressors
- Process development to demonstrate technical feasibility of the process or a particular component on a small scale and/or in a realistic environment
- Laboratory-based pilot plant activities

ii) Pre-combustion technology

Current status

The idea behind pre-combustion is to remove the carbon from natural gas, oil or coal prior to combustion, leaving only hydrogen. This can then be used as fuel in power plants or fuel cells. Indeed, the gasification of solid fuels has been a well-known and industrially available technology for many years, but not widely used for power purposes in an Integrated Gasification Combined Cycle process (IGCC).

While large-scale demonstration plants exist, further research is still required, taking into account all the lessons learnt during their operation. A highly efficient hydrogen turbine is also still not yet available, optimised and developed for CCS. As with post-combustion technology, there is real potential for up-scaling and process optimisation.

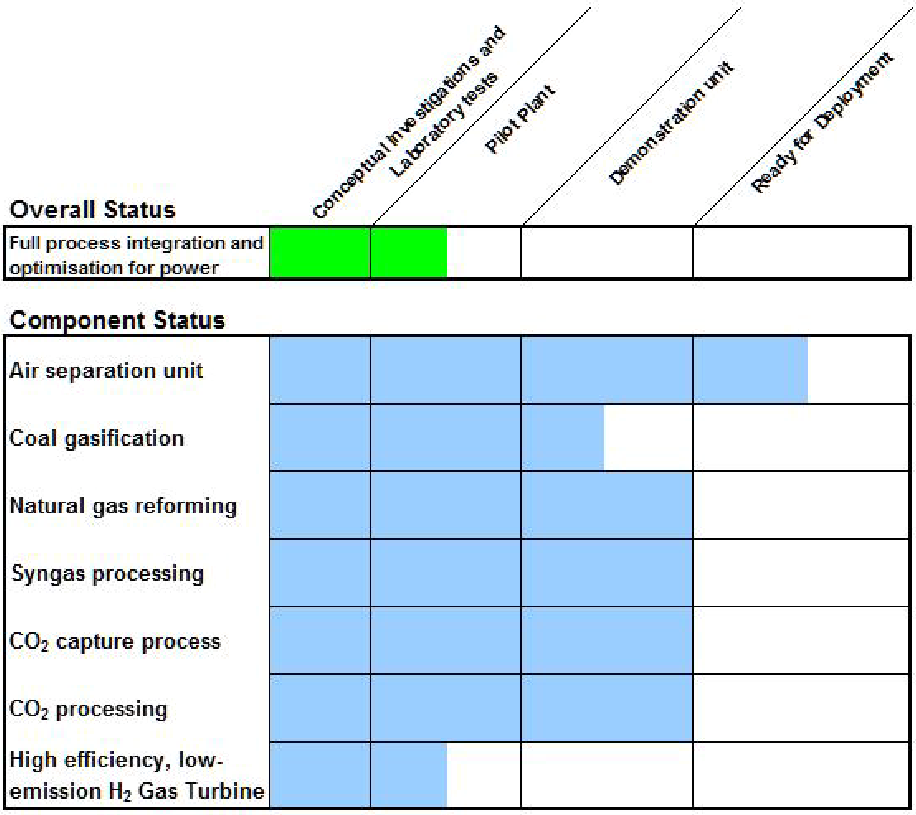

Fig. 4 - Current status of pre-combustion technology

Figure 4 shows the advanced maturity of pre-combustion technology. However, it has not been utilised for power purposes in the IGCC. The key issue is therefore to improve overall optimisation, reliability and availability in the integrated process; improve components and develop the turbomachinery.

Key research issues

- Scale-up issues in designing and developing a highly reliable industrial-scale power plant with CO_2 capture
- Scale-up of gasifiers
- Highly efficient gas turbines for hydrogen combustion
- Energy losses by shift-reaction and CO_2 capture process must be compensated
- Full process integration and optimisation for power generation

Gasification, reforming, gas cooling and cleaning

- Develop large up-scaled gasifiers with 1200-1500MW_{th} for a single train configuration, together with an effective heat recovery/quench system
- Develop improved coal feeding systems
- Improve slag and fly ash removal systems
- Develop conversion technologies with O_2 membrane production

Gas conditioning in CO_2 capture

- Further develop the shift catalyst - specifically in durability, reduction in costs and admission of high concentrations of CO
- Develop optimised solvents to separate CO_2 and H_2S. Improve selectivity and reduce investment, and operations and maintenance (O&M) costs
- Develop membranes to separate CO_2 and H_2S. Improve selectivity and reduce investment and O&M costs
- Achieve the cost-effective cryogenic separation of CO_2 and H_2
- Develop membranes for separating CO_2 and H_2
- Determine admissible specifications of impurities for CO_2 geological storage
- Develop new or improved physical or chemical solvents for gas treatment under pressure
- Remove sulphur at high temperature level on a dry basis
- Investigate CO_2 hydrates

Gas turbine and water steam cycle

- Optimise plant concepts with reduced auxiliary consumptions
- Develop 300MW+ gas turbines capable of burning H_2-rich gases with the highest efficiencies
- Further develop high temperature water steam cycles
- Optimise unit control system of the overall plant
- New cycles for higher efficiency, e.g. hybrid combining fuel cells and gas turbines

Air Separation Unit (ASU)

- Optimise process integration, depending on air extraction and N_2 dilution requirements
- Improve adsorbents for removing contaminants prior to distillation, tailored for high pressure adsorption and regeneration cycles
- Develop high efficiency packings for distillation fluids close to supercritical conditions
- Develop mixed conducting ceramic membrane technology for oxygen production
- Undertake process studies to evaluate the various schemes needed to provide oxygen at high pressure, upstream the gasifiers.

iii) Oxy-fuel combustion technology

Current status

In oxy-fuel combustion, nitrogen is removed from the air using a conventional air separation unit. The fuel is then combusted with oxygen mixed with CO_2, which is re-circulated to control the combustion temperature. This gives a flue gas consisting mainly of CO_2 and water vapour, which can then be condensed to produce a highly concentrated stream of CO_2.

Firing with pure oxygen, mixed with CO_2, is well understood on a small-scale and many industrial installations with oxygen combustion exist. However, for coal and larger-scale power processes, it is still not well-established with regard to radiation characteristics, formation of pollutants and fouling properties - and on the industrial-scale required. Using oxy-fuel technology in a steam process will also slightly alter the combustion process, while a gas turbine will need to be completely redesigned.

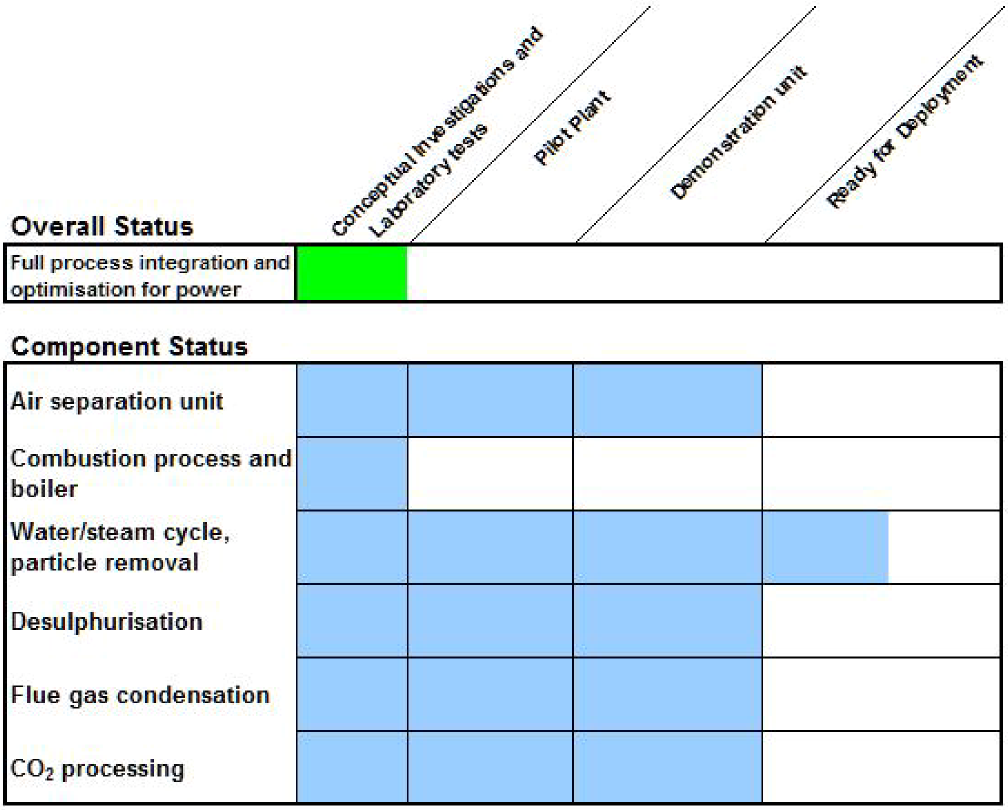

Fig. 5 - Current status of oxy-fuel combustion technology

Figure 5 illustrates the maturity of oxy-fuel combustion technology - all the major components applied to boilers exist on an industrial scale, but the process is currently only demonstrated on laboratory-sized equipment. However, all our experience shows that there is no significant difference from air combustion. The desulphurisation is also conventional, but with CO_2 instead of nitrogen as the main gas component. As with the other technologies process integration will be a major task.

Research issues

- No commercial gas- or coal-fired power plants currently exist which operate under oxy-fuel conditions
- Only tests being performed are in laboratory-scale rigs and experimental boilers up to a size of a few MW_{th}
- There are uncertainties as to what are acceptable impurities in the CO_2 rich flue gas
- CO_2 rich flue gas treatment is not yet developed

Developing and implementing oxy-fuel combustion for boilers

- Laboratory research into combustion, heat transfer, formation of pollutants, ash compositions, slagging, fouling and corrosivity of flue gases. For circulating fluidised bed (CFB), also bed material behaviour and in-situ sulphur removal
- Develop design tools for scale-up, based on research results
- Pilot plant tests (10s of MW_{th}) of full oxy-fuel pulverised fuel (PF) process and oxy-fuel CFB
- Large-scale demonstrations (100s of MW_{th}) of complete oxy-fuel PF and oxy-fuel CFB power plants
- Oxy-fuel combustion for CFB boilers: specific design and scale-up issues include strong heat extraction to solid bed material circulation loop

Emerging technologies

- Oxy-fuel gas turbines and combined cycles - establish a sound engineering basis for these turbines through basic R&D, possibly with some pilots within the next 5 years
- Development and implementation of Chemical Looping Combustion (CLC):
    - Benefit from proximity to CFB boiler technology in development and scale-up
    - Create a portfolio of oxygen carriers suitable for various fuels and conditions, based on laboratory research and evaluations
    - CLC for solid fuels - further work on fuel reactor and carbon stripper design
    - CLC combined with gas turbines - develop particle separation at high temperatures, with low pressure drops and low cut-off size
    - Focus on material development (0-5 years), practical reactor studies (0-5 years), pilots (5-10 years) and demonstrations (10-15 years)
- R&D on emerging technologies, including lower flue gas recycle in oxy-fuel PF boilers, CFBs and new large-scale oxygen production concepts, using ceramic transport membranes or ceramic autothermal recovery (CAR) technology

- General R&D as basis for new oxy-fuel based systems, i.e. high temperature steam cycles (up to 1000–1200˚C, gas turbine derived technology); high temperature heat exchangers; condenser operation and heat transfer characteristics for high CO_2 content mixtures; dynamics of power cycles with high degree of integration; cost-effective membrane modules; and combustion in near surface conditions (membranes)

Material selection and R&D

- Investigate long-term operational properties of materials for flue gas environment in oxy-fuel processes, including testing new advanced materials expected to be used in future Ultra Critical Code (USC) 700°C power plants. Research materials for both coal-fired boilers and gas turbine application

CO_2 capture, compression and conditioning process for oxy-fuel combustion

- Develop flue gas cleaning technologies for implementation in the CO_2-compression train
- Optimise CO_2 processing and compression system to remove inert gases from the CO_2-product
- Establish themophysical properties of high concentration CO_2-mixtures
- Improve the efficiency of CO_2 compressors and scale-up

Air separation unit (ASU)

In addition to R&D actions for pre-combustion capture:

- Further increase in the single-phase and two-phase cryogenic heat-exchangers to reduce power consumption due to pressure drops and temperature differences
- Develop very large air compressors, potentially of the adiabatic type, to lower the cost of these units and develop new integration possibilities within the heat system of the power plants

Increasing power plant efficiency

CO_2 capture requires a lot of energy and decreases efficiency significantly. A drastic increase in energy conversion efficiency of steam and gas turbine combined cycle power plants is therefore necessary to avoid the increased use of limited primary energy sources.

Clean coal technology, in particular, needs to improve plant efficiency, reliability and costs substantially through RD&D of clean coal and other solid fuel conversion technologies which produce secondary energy carriers (including hydrogen) and liquid or gaseous fuels.

Steam power plants - achieve over 50% efficiency

- Develop and qualify new materials for high-temperature-loaded areas in steam generators, piping, valves and turbine for 700°C+
- Research component adapted design and integrity concepts

- Develop new protective coatings
- Improve welding methods, cost-cutting measures for manufacturing and certification, safeguarding of properties, manufacturing large components and measures for detecting defects and flaws
- Investigate corrosion under oxy-coal atmosphere
- Develop novel steam turbine designs with steam cooling, ceramic coatings, improved clearance control, new sealings and improved aerodynamics
- Improve water/steam cycles
- Enhance design tools and codes in order to calculate heat transfer, aerodynamics and components
- Conduct experimental validation and rig tests as required for successful implementation

Gas turbine plants - achieve over 63% efficiency

- Harmonise optimisation of gas turbines, steam turbines, generators and boilers, while reducing losses in auxiliary equipment
- Improve aerodynamic performance, materials and cooling systems. Design ultra high-strength materials for gas turbine rotors, production technology for large components, assessment methods for material properties and new materials for blades of low density
- Develop thermomechanical models and simulation tools for evaluating material properties
- Research high temperature coating systems
- Improve rubbing, sealing and combustion systems
- Investigate low-emission technology
- Achieve longer lifetime, combined with cost-efficient operation
- Enhance lifetime modelling
- Fuel flexibility (different natural gas compositions, syngases, H_2-rich gases and low heating value fuels, such as bio-fuels and industrial gases)

Cross-sectional themes for gas turbine and steam power plants

- Higher plant output by advanced components
- Improve materials, aerodynamic and thermodynamic performance, cooling systems and Instrumentation & Control systems
- Fuel processing and multi-fuel capacity
- Achieve reliability > 98%, availability > 95%
- Improve part-load efficiency

Action plan

Post-combustion technology

- **Improve efficiencies in capture processes**
- **Research new solvents, with improved degradation characteristics**
- **Optimise plant concepts to minimise internal energy consumption**

Pre-combustion technology

- **Scale-up and demonstrate coal gasification technology to 1500MW_{th}**
- **Develop plant concept and optimise for lower energy consumption**
- **Use hydrogen in high efficiency and low emission gas turbines, optimised for hydrogen combustion**
- **Improve gas conditioning for CO_2 separation**
- **Optimise air separation units**

Oxy-fuel technology

- **Develop and demonstrate large-scale boiler technology for coal in oxygen/CO_2 environment**
- **Research and develop oxy-fuel combustion for CLC based on CFB boiler technology**
- **Research oxy-fuel gas turbines and combined cycles**
- **Optimise air separation units**

Improving plant efficiency

- ***Steam power plants*: achieve efficiency of 50% by designing novel steam turbines and further developing boiler technology for steam parameters of 700°C+**
- ***Gas turbine power plants*: achieve efficiency of 63%. Gas turbine must be significantly developed for highest gas inlet temperatures (1300°C+)**
- **Undertake experimental validation, large-scale rig tests and demonstration for both steam and gas turbine plants**

4. Demonstrating the safety of CO_2 geological storage

Experts already agree that storing CO_2 underground should pose no health, safety or environmental hazard - either over the short- or long-term. Indeed, CO_2 is comparatively benign – it will neither burn nor explode and is even found in human breath!

Nevertheless, public perception may differ and R&D aims not only at filling gaps in our knowledge, but proving unequivocally that CO_2 geological storage is both safe and desirable. The first time this will be tested will be when energy companies apply for national permits to build CCS, estimated to be 2010-15.

We therefore need to implement 10-12 large-scale storage demonstration sites as soon as possible, in a variety of geographical and geological settings, the length and breadth of Europe. These will have a lead-time of 5-10 years and an operational lifetime of 30 years or more.

No shortage of CO_2 storage options is anticipated
There is certainly no shortage of suitable storage options in the multiple billion tonnes range. How much of that potential can actually be utilised will be closely linked to the research and demonstration activities carried out over the next few years.

CO_2 can be stored using a variety of different mechanisms (single free phase, dissolved in water, absorbed on surfaces, trapped by relative permeability and fixed in minerals), with several options for underground storage. Storage in the deep oceans is not considered an option for Europe. International work on defining methods and standards for geological storage capacity assessments has already begun and as a leading player in CCS, Europe has a key role to play.

The relative order-of-magnitude potential of the various storage methods may be expressed, very simply, as follows:

1000	Deep saline aquifer storage (porous rocks)
100	Oil/gas field use and storage
10	Deep unmineable coal bed use and storage
1	Mineral sequestration

Deep saline aquifers (or formations) have the largest storage potential globally, but are the least well explored and researched as, up till now, they have not had any economic potential. We therefore need to build a more comprehensive dataset of their geological characteristics through considerable research and larger-scale injection projects.

For example, the Utsira is a large, regional deep saline aquifer which has been used by Statoil since 1996 to store CO_2 removed from gas production. At over 400 km by 50-100 km, it is over 26,000 km^2 and capable of storing up to 600 billion tonnes of

CO_2[15]. To put this into perspective, this is equivalent to all the CO_2 emissions from all the power stations in Europe for the next 600 years!

The GESTCO and GeoCapacity[16] projects (under FP5 and FP6) have already begun the task of identifying regional deep saline aquifers that are accessible to large CO_2 emissions sources, both on land and close to the shore.

Although we believe these formations hold the most promise, we need to demonstrate storage in a variety of types and settings in order to realise the full potential of this medium. It means exploring as many countries as possible, especially those with few hydrocarbon deposits and less knowledge of deep geology, in order to include them in our evaluations.

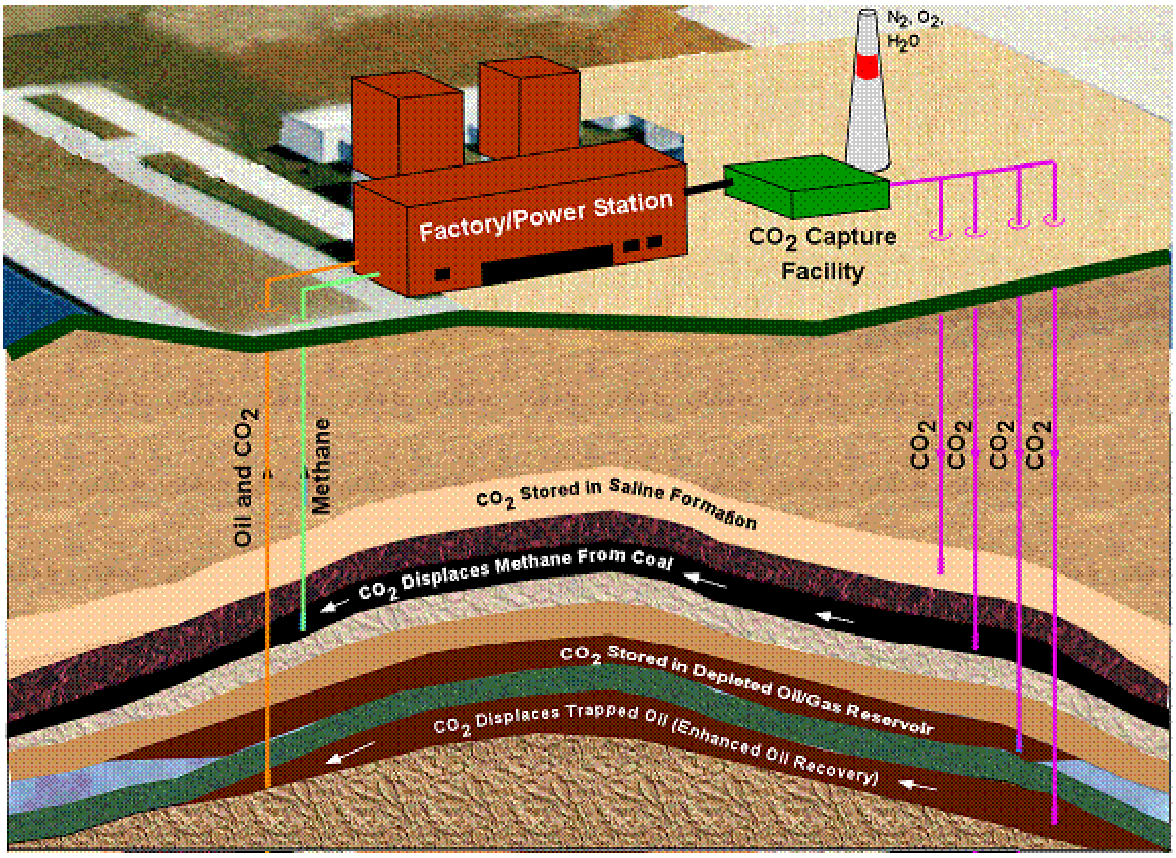

Fig. 6 shows the wide variety of options for CO_2 underground storage available

Maximising early commercial opportunities
One way to kick-start the development of CO_2 infrastructure is to identify niche markets where the cost and income are at acceptable levels, e.g. where CO_2 is given a commercial value. This will motivate stakeholders to act on a commercial basis, even without proper framework conditions.

Use of CO_2 in ***Enhanced Oil Recovery*** (EOR) is a perfect example of this. Not only is the geology well understood and existing infrastructure potentially recyclable, there

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[15] See IEA Greenhouse gas website: http://www.ieagreen.org.uk and Sleipner CO_2 project reports

[16] Both GESTCO and GeoCapacity are assessing the capacity for CO_2 geological storage in Europe.

is even the opportunity to increase revenue if the CO_2 can be used to increase hydrocarbon production. Indeed, when used in this way, CCS could contribute to improved energy security for Europe through increasing oil and gas production rates, as well as the overall recovery of reserves. EOR may also be combined with the storage of even more CO_2 after the commercial life of the fields ends (it will need to be adapted for permanent storage).

The best opportunities for EOR in Europe are in the North Sea and the use of anthropogenic CO_2 for this purpose would constitute a normal hydrocarbon operation. However, *we only have a short time window of about 10 years.* Indeed, if infrastructure is not established soon, there is a danger that oil fields[17] will be closed down without realising the potential of CO_2 for EOR. Given that opportunities for EOR in Europe are limited onshore, a considerable number of deep saline aquifers must be identified and tested as demonstration sites.

It will be easier to gain public support for injecting CO_2 into an offshore oil reservoir than on land, close to where people are living. Such projects can then be used as examples of safe and cost-effective CO_2 storage.

Although in the experimental stages, ***Enhanced Gas Recovery*** (EGR) and ***Enhanced Coalbed Methane Recovery*** (ECBM) are also promising technologies for CCS that would further increase European fossil fuel resources. The geological aspects of the main European coal basins are, in most cases, quite well-known and ECBM could lead to the development of Coalbed Methane Recovery projects that have not yet taken place in Europe.

Indeed, many Member States also have methane-bearing coal basins on which operations could be carried out. It could also give the EU a competitive advantage when working with countries such as India or China who not only have extensive coal reserves, but a great need for technological expertise. The main disadvantages are a) lower capacities compared to deep saline aquifers b) most European coal basins are placed in fractured areas, with risks of leakage and a higher complexity of field studies.

Depleted oil and gas fields, too, are attractive because the geology is well understood and the existing infrastructure recyclable. Other options, although limited, include ***deep unmineable coal beds***, which could be quite important in some coal provinces. ***Mineral sequestration***, which consists of trapping CO_2 by reacting with basic rock material, is still at an exploratory stage.

Although ***using CO_2 in industrial processes and products*** (e.g. agriculture greenhouses, urea fertiliser production and chemicals) will have no lasting impact on mitigating climate change, it could also contribute to kick-starting the CO_2 infrastructure by providing CO_2 for early storage demonstration activities.

[17] Especially major offshore oilfields in the North and Norwegian Seas

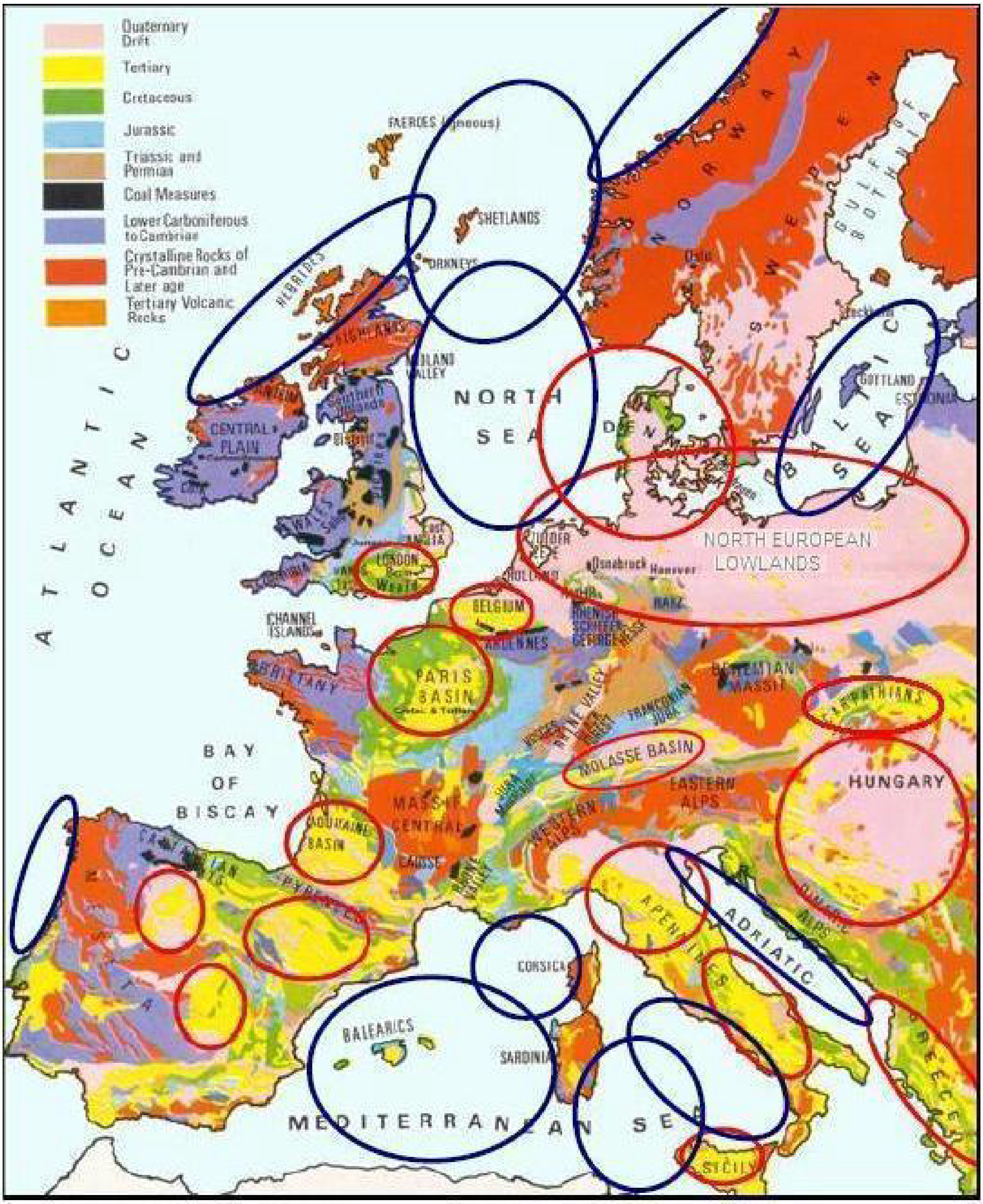

Fig. 7 shows major on- and offshore sedimentary basins in Europe which are possible storage sites. Cost analyses must be performed to identify the most cost-effective.

Modified after Kirkaldy, 1967

Research issues

Storage of CO_2 in the subsurface has many similarities to that of natural gas, particularly when it takes place in deep saline aquifer or hydrocarbon structures, such as domes or anticlines. However, it differs in two key ways: a) residence time and b) CO_2 dissolved in the formation water forms an acid, which may alter reservoir and cap rocks, as well as equipment. For any geological formation, research is therefore needed to ensure that CO_2 can be stored safely for a long period of time and to the standard required by CO_2 suppliers.

Assessing storage capacity
There is currently a lack of hard data on storage capacity, requiring a tool for predicting spatial reservoir characteristics. Probably the best way to fill gaps and evaluate potential storage capacity is to start with well-characterised deep saline aquifers and establish clear qualifying and quantifying criteria. Research should focus on:

- Establishing standards for improving the assessment of storage capacity
- Analysing and assessing capacity for storage, relative to geology and trapping mechanisms

Proving the trapping concept
Research is needed to prove the trapping concept in a wide range of geological settings:

- Understand physical, chemical and biological processes in the subsurface involving CO_2.
- Through laboratory work, identify expected fluid–rock interactions at variable fluid chemistry, using variable percentages of CO_2 saturation in water and for different rock types (*i.e.* mineralogy). Also verify different in-situ geological conditions, including different pressure and temperature conditions.
- Undertake field case studies on rock-fluid interactions from reservoirs in which CO_2 has been injected.
- Undertake pilot projects to explore seal integrity for injecting large amounts of CO_2 (up to 12 million tonnes CO_2/year) into multi-well storage systems in different geological settings.
- Systematically develop dynamic models of CO_2 over time (free and saturated) and migration for all geological settings with potential for CO_2 storage.
- Study constraints on the fate of CO_2 from geophysical and geochemical monitoring.
- Study cap rock integrity, seal classification and prediction of seal characteristics (up-scaling of seal characteristics remains a scientific challenge.) Establish a comprehensive shale database.
- Up-scale experimental data (e.g. gas breakthrough experiments) with CO_2 for low permeable samples.

- Develop tools for predicting spatial reservoir properties, coupled to the burial history.

- Study glacial influence and other late tectonic movement of the sedimentary strata – vital for evaluating the overburden integrity.

Modelling the storage reservoir
Modelling is used to characterise storage performance in terms of injectivity, capacity, containment and quantitative estimation of potential leakage:

- Design field and well systems for positioning injection and production wells and monitoring systems.

- Determine the evolution of CO_2 stored underground for long periods, *i.e.* from operational phase (lasting decades/centuries), to thousands of years. Describe all possible migration paths – both from the reservoir perspective, as well as surrounding and adjacent areas.

- New models must account for the main mechanisms for CO_2 propagation, both during operation and long-term storage.

- Build a detailed, static geological model of the entire site in order to predict accurately the short- and long-term safety and reliability of CO_2 geological storage. Calibrate parameters by dynamic modelling from dedicated laboratory and field test data or history matching.

- Model long-term transport processes through clay-rich sediments and other cap rocks.

- Undertake geochemical modelling of reactions and transport of species, including reaction kinetics and the impact of CO_2 injection (i.e. the porosity change) on the lower section of the cap rock.

- Model the coupled phenomena of chemical reactions, caprock permeability, mechanical properties, and geochemical factors.

- 3D modelling of reservoirs lacks suitable solutions for some clastic reservoir types (e.g. for modelling deep-sea fan sediments), as well as for carbonates with complex porosity systems. The development of up-scaling tools for architectural systems of different depositional systems is therefore strongly recommended.

- The complex structure and behaviour of faults makes modelling difficult. More knowledge on faults is required and stochastic modelling as a supplement to deterministic modelling is needed. Geomechanical modelling should be included in determining fault slip tendency. Two key questions relating to faults are the influence of CO_2 on the strength properties of faults apart from chemical reactions and the possible effect of differential CO_2 injection pressure.

Investigating CO_2 thermodynamics
Existing fluid flow simulation tools and models developed for oil and gas production have already been used successfully to predict the short-term flow behaviour of CO_2 (e.g. Sleipner/Utsira aquifer). However, in order to better represent CO_2 properties, improved simulation tools are required, especially in mixtures with impurities:

- New tools to cover short-term detailed processes simultaneously at the reservoir scale (e.g. CO_2 dissolution in the salt water), as well as long-term, large-scale hydrological processes in the overburden.
- New improved models to include reactions of CO_2 with rock - of major importance in the longer-term.
- New simulation tools to be multi-phase and multi-component fluid flow models, including relative permeabilities, capillary pressures and thermodynamics. Heat and mass transfer between fluids should be taken into account by the transport model.
- Improve long-term predictions with coupled models that address several parallel phenomena, with geochemistry, geomechanics and multi-phase flows accounted for.
- Assess the impact of impurities injected with the CO_2 (*i.e.* O_2, N_2, NO_x, SO_x, CO, H_2S, etc) on fluid properties and geochemical reactions.

Designing new monitoring tools
Much of the technology needed for monitoring the geological storage of CO_2 can be adapted from hydrocarbon exploration and development activities, at least as a first-generation approach. However, second-generation solutions are also required, including the development of new monitoring tools:

- Tool response functions should be based on fluid and rock properties and able to characterise measurement resolution, accuracy and sensitivity to changes in CO_2 saturation.
- Include multi-measurements and model-based interpretation in order to monitor CO_2 displacement and CO_2 in place.
- Develop methodologies for calibrating simulation models, e.g. by history matching.
- Use detailed tool response models calibrated on laboratory experiments to interpret measured data. Compare actual with predicted measurements to improve predictive models.
- Develop borehole seismic measurements in order to link surface seismic with other well measurements, focusing on accurate tiltmeters or satellite-based ground elevation measurement techniques (i.e. Synthetic Aperture Radar (SAR) interferometry). Micro-seismicity will also image re-activated faults planes. Interference testing and tracer injection could complement this by providing information about changes in fault transmissibility.

Understanding wellbore integrity over the long-term:

- Characterise the completion component (casing, cement) degradation and leakage routes
- Characterise interfaces of formation-cement and cement-casing in terms of hydraulic isolation
- Quantitatively estimate leaks from integrity measurements
- Monitor wells after closure (plugs) and estimate fault transmissibility
- Optimise the monitoring system with regard to storage performance, risk control and monitoring cost.

Detecting and mitigating leaks, and tracking CO_2 in the reservoir:

- Improve the measurement of fault-pathfinder trace gas concentration and fluxes to help detect potential leakage routes, before and during CO_2 injection
- Develop methods and technologies for mitigating leaks in the unlikely event that they occur
- Define the measurement grid that will provide comprehensive coverage of an area that can be affected by a leak
- Identify the correct and widespread use of tracers added to the injected CO_2 to differentiate anthropogenic input from the natural one
- Improve standards for the comparison and cross-use of different soil gas and infrared (IR) remote sensing (or eddy covariance) techniques in the same site
- Evaluate precisely geogas uprising velocity from the soil
- Develop the ability to monitor precursors of large seismic hazards, especially in background-induced micro-seismicity
- In order to benefit from synergies, use and analyse multiple measurement techniques together. Both local direct measurements (sampling) and global, indirect measurements (seismic) should be addressed
- Establish a field laboratory for studying CO_2 migration in the overburden - this could also be used to calibrate models and study specific processes.

Ensuring new monitoring programmes also:

- Control storage operation performance with respect to capacity, injectivity and containments
- Control risks associated with leakage, including the contamination of shallower formations, releases on surface and corrective action
- Estimate the evolution of the performance and risks as reliably as possible

- Establish a guide for performance and risk analysis, accounting for all potential leakage pathways
- Control the displacement and distribution of the CO_2 in the reservoir
- Benchmark the distribution of CO_2 and the behaviour of contaminants.

Action plan

- **Run R&D programmes in parallel with CO_2 storage demonstration projects as large-scale research facilities. Gather experimental data for developing proper modelling and monitoring tools, together with knowledge and methods on trapping, modelling, rock and fluid properties, monitoring, stability/integrity and CO_2 mobility.**
- **Continue monitoring R&D activities at existing European storage sites (Ketzin, Recopol, K12B, Sleipner, In Salah, Snøhvit) in order to establish long-time series of data and link to new demonstration projects in FP7.**
- **Establish a European leakage laboratory site(s) in order to study leaks and their consequences in a controlled environment (a pressing need not likely to be addressed without a strong initiative at EU level.)**
- **Further assess European potential for CO_2 storage in deep saline aquifers and additional data required to mature them. Define site criteria for a range of EU-wide demonstration projects.**
- **Undertake urgent field studies on CO_2 for EOR - especially in the North Sea - in order to identify potential depleting or depleted oil fields. Perform infrastructure and field studies to identify the optimal linking of potential CO_2 sources and oil/gas fields where EOR/EGR is an option.**
- **Identify locations and structures where ECBM can be utilised. Clarify the real CO_2 adsorption capacity of coal at different depths, permeability and other parameters vital for capacity estimations.**
- **Map, with a higher level of accuracy, the geological storage capacities of Europe in a variety of geological settings and trapping mechanisms. Improve methods for capacity assessment and contribute to the establishment of international standards.**
- **Investigate innovative concepts for CO_2 storage and establish links to other relevant industries which generate large amounts of CO_2, e.g. steel, cement, fertiliser.**

5. Enhancing CO_2 transportation

Building on years of experience
The transportation of CO_2 is already well understood – it has been shipped regionally in small liquid quantities for the last 15 years and a 4,000 km onshore network has been in operation in the US for the past 30 years; while in Europe, at the Snøhvit Liquefied Natural Gas (LNG) processing facility in the Norwegian Sea, a pipeline to an offshore CO_2 storage site is due to start operating in 2007.

There is also extensive knowledge of the liquid propane gas (LPG) and LNG industries upon which we can draw. Indeed, experience in hydrocarbon pipeline transportation can be transferred directly to CO_2 transport. However, while there are very few major research gaps regarding CO_2 transportation, it can certainly be enhanced to Europe's competitive advantage.

What are the options?
In general, pipelines are used for large volumes over shorter distances, while ships can be used for smaller volumes over long distances; trains and trucks are rarely used. Nevertheless, the best transport system will vary according to individual CCS infrastructure projects, according to:

- CO_2 volume
- Distance between source and storage location
- Geography and geology of the route taken
- Costs

Pipeline options include CO_2 in gas and supercritical phase (above critical pressure). Most of the CO_2 pipelines in the world today are high pressure, supercritical phase lines, being the most economic method of moving CO_2 over long distances. CO_2 transport by ship will be in liquid form.

With many potential storage sites both onshore and offshore in Europe, new studies (together with ongoing studies, such as the EU GeoCapacity project) are therefore required to determine the best infrastructure routing, aimed at minimising costs and the environmental footprint. Experience from the natural gas industry could be a good starting point.

Europe's dense population means that CO_2 transport routes onshore must be carefully planned, with urban areas avoided if possible, as for hydrocarbon and chemical pipelines. Extensive use of pipeline modelling and gas modelling dispersion technology will therefore be essential. Special care must also be taken with offshore pipelines to ensure that they are laid in sufficiently stable areas (a regulatory requirement for all offshore pipelines in Europe today).

Research issues

Materials

The corrosive behaviour of CO_2 when wet is well known, but further research is necessary to determine how variations in temperature, flow rate, gas stream composition and pH influence the corrosion on different materials. This is particularly important when storing other acid gases emitted by large combustion plants together with the CO_2.

- Identify and solve all issues related to the corrosive properties of CO_2, e.g. design equipment process systems capable of dealing with the corrosive atmosphere, using technology transfer studies as the basis for research.

- Study the interaction of CO_2, water, oxygen, heavy metals, particulates and other acid gases, as well as varying levels of different impurities.

- Ensure pipe material requirements are adequate for all likely conditions, e.g. offshore applications, unstable geology, large temperature variations and consistently cold or hot environments.

- Research advanced joining technologies to ensure against leakage. (Supercritical phase CO_2 pipelines can experience propagating/longitudinal failure due to the stored energy if CO_2 is suddenly exposed to atmospheric conditions.)

- Study circumferential cracks or joining locations (due to external bending loads) in order to predict, with great precision, the formation of these cracks; determine critical situations for a guillotine-break; and improve design methods.

- Improve sealing options for pipelines and ships through both research and technology transfer. Transport systems for CO_2 include pumps, valves and flanges that have seals to prevent leakage. Seals are typically manufactured out of specialised polymers that can resist the corrosive effect of CO_2 and its tendency to permeate any porous material under high pressure and temperature.

Pipelines

- Validate any differences between transportation of hydrocarbons via offshore pipeline and that of CO_2. (Technology and experience is available from the US for onshore CO_2 pipelines).

- Define and optimise methodologies for underwater CO_2 pipeline tie-in technology, from both a safety and a cost perspective - critical for installing offshore CO_2 pipelines.

- Develop accurate and verifiable monitoring systems in order to detect potential infrastructure leakages (as an adjunct to today's state-of-the-art systems used in all modern pipeline control centres).

Ships

- Optimise the efficiency of terminal storage, with particular emphasis on total systems design, construction and safety, including load port and off load port applications.

- Identify the best storage medium (at lowest cost) and any environmental impacts where CO_2 might escape during trans-shipment, either between ship and intermediate storage (rock caverns or large tanks); directly to final storage facility; or from ship into a pipeline interface location for onward transmission.

- Ensure refrigerated CO_2 can be safely, environmentally and economically transhipped and mixed into a pipeline that carries super-critical CO_2. (This has both onshore and offshore implications).

- Develop optimal materials (stainless steel) for building CO_2 ships capable of moving large volumes of CO_2 and resisting its corrosive behaviour.

Action plan

- **By 2008, establish the most efficient transport routes, based on new studies linking sources to storage locations.**

- **By 2008, identify the most cost-effective projects for linking sources to storage locations (based on total volume, distance to storage site and volume CO_2 to be stored) in order to reduce CO_2 emissions by the volume required.**

- **Ensure all pipeline, ship and equipment materials, metallurgy and seal technologies are sufficiently advanced to meet safety and environmental requirements for transport systems.**

6. Resolving environmental issues

Our primary goal is obviously to capture and store the greatest amount of CO_2 possible. Environmental assessment frameworks for the capture, transportation and storage of CO_2 must therefore be established.

Zero tolerance for CO_2 leakages

Major acute or chronic leakages are neither acceptable nor expected. Indeed, ***in storage sites that are well-sited, operated and monitored, leakages simply should not happen at any significant level.*** However, in the unlikely event that they do, sophisticated monitoring and remediation techniques, based on those already well proven in the oil and gas industries, should be able to correct them immediately.

Some ***CO_2 capture*** processes and materials produce solid and liquid wastes, e.g. solvent scrubbing processes produce degraded solvent wastes which would be incinerated or disposed of by other means. However, both the CO_2 capture and transport elements of the CCS chain are already covered by well-established frameworks for permission and organisational processes. There is therefore no immediate need for either research or new legislation on environmental issues.

As for ***CO_2 storage***, the main risk of leakage to the atmosphere is due to wells, faults and seals. Although the best corrective actions are still under discussion, experience in the oil and gas industries can be directly transferred to CCS, including:

- Natural and industrial analogue case studies
- Laboratory tests on borehole cement chemical stability in contact with CO_2 rich brine
- Numerical and analytical tools
- Geochemical monitoring and test sites.

As CO_2 is an asphyxiant and heavier than air, there may be concerns about the safety of CO_2 infrastructure, either due to possible slow leakage, or sudden large-scale emission resulting from ruptures. Slow leakage of CO_2 is unlikely to cause safety concerns unless it is inadvertently trapped.

Local risk factors include the population inhaling a possible "surplus" of CO_2; alteration of the groundwater chemistry; and impact on terrestrial vegetation and animal population (for onshore leakage) and on marine life (for offshore leakage).

CO_2 - a commodity or by-product, but *not* a waste

CO_2 has been handled successfully for decades and any risks implied with its use can be – and have been - effectively managed or mitigated. In fact, many existing post-combustion capture plants already produce high purity CO_2 for use in the food industry and other industries.

Even though the probability of leakage is very low, it is important to understand the hazards should exposures occur. The physiological and toxicological responses to elevated CO_2 concentrations are already relatively well understood: naturally occurring releases of CO_2 (e.g. by volcanism) provide a good basis for empirical data describing the CO_2 fluxes into the shallow subsurface and CO_2 concentrations in the ambient air.

Research issues

Although much environmental research has been done in the area of CO_2 ground contamination[18], further studies should be undertaken. ***The main challenge lies in defining regulations for mitigating CO_2 leakages, should they occur.***

This means developing tools for estimating the spatial and temporal distribution of CO_2 fluxes and predicting ambient CO_2 concentration resulting from a given CO_2 exposure. Dispersion modelling is therefore required in all geographical areas - especially sub-sea environments and dense urban areas - to establish any detrimental effects as a result of catastrophic leaks.

Available impact studies should also be reviewed, and incremental studies performed, to identify potential impacts on surface and near-surface ground contamination, as well as human safety. These require the support of dispersion models to predict the effects of accidental CO_2 releases and determine appropriate methods for the controlled release of significant volumes of CO_2 for operational reasons.

The impact of escaped CO_2 on terrestrial and marine ecosystems should be determined, including models of escape profiles and calculations of CO_2 concentrations in the air, ground and water, due to possible leakage.

We also need to better understand the health effect of CO_2 on humans, animals and plants in order to reassure the public and design a regulatory system which addresses the key issues (without over-regulating).

Finally, for offshore storage, safety regime modifications must be validated and design research performed to ensure all CO_2 lines in service can meet safety standards for offshore use. In oil and gas applications, safety requirements may dictate a rapid depressurisation of all systems during emergencies.

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[18] See studies performed by the British Geological Society (www.bgs.ac.uk) and International Energy Agency (www.iea.org)

Action plan

- **Conduct studies on the entire infrastructure chain - including CO_2 capture plants, onshore and offshore pipelines, ships, storage sites and process equipment - to assess any risk of leakage.**
- **Undertake sub-sea dispersion modelling to determine any detrimental effects as a result of catastrophic sub-sea pipeline leaks.**
- **Model possible escape profiles and calculate CO_2 concentrations in the air or ocean water.**
- **Determine impact of CO_2 leakages on terrestrial and marine ecosystems.**
- **Establish systems for mitigating actions should leakages occur as part of the regulatory framework.**

7. Gaining the support of the public

Gaining public – and political – support is vital if CCS is to receive the funding, incentives and State Aid guidelines it now urgently requires. Understanding public concerns and attitudes towards climate change and CCS is therefore key to its successful implementation. As it is a complex and relatively unknown technology, it is essential that high quality research continues the work of social studies on the public's perception of CCS.

How do experts, stakeholders and the public perceive CCS?
It means understanding the:

- Perception of risk from CCS, with reference to previous research on the social perception of risky technologies and their contribution to climate change

- Perceived benefits of the technology

- Existing level of knowledge

- Role of media in framing public perceptions

- Differences between public, stakeholder and expert perceptions. Understanding those of experts, politicians, media and NGOs may offer a broader understanding of the social perception of CCS. Particular attention should be paid to possible regulator(s), as their role it is not yet clearly defined.

- Differences in perception across European countries using a high quality measurement tool and time series analysis.

- Reactions to the local siting of onshore reservoirs. In many countries, the best CO_2 storage sites are onshore, which could generate concerns from local communities. (Here, the attitude toward CCS of local people may differ from that of the general public.)

- Potential for CCS within the broader debate over energy and climate change policy at national and EU levels, particularly with respect to nuclear power and renewable energy.

- How opinion-leaders use information on public attitudes to shape their views and policies.

- CCS will also need to be attractive to major emerging economies, such as China and India, who will see much of the growth in GHG emissions over the coming century. It is therefore also important to understand how it might be perceived in these markets (as the case of Monsanto's efforts to introduce GMOs[19] in India illustrates).

[19] Genetically modified organisms

How can we build public trust?
Research needs to be undertaken to find out how best we can build trust, including understanding:

- The level of trust in institutions, environmental organisations, industry and the media, as well as amongst regulators and scientists, as reliable sources of information

- How successful organisations build trust - and how it can be lost

- The relationship between trustworthy sources and the formation of public opinions

- How public support can be built up through dialogue, joint efforts and partnerships - and what forms of public engagement erode support

Developing a risk communication strategy
Developing a risk communication strategy is key to stimulating a public debate about CCS, but is a delicate task, as emotional and ethical elements are involved. Research questions include:

- How important is the background and reputation of the communicator?

- What tools have been used successfully to convey complex information?

- What mental models develop around CCS and how do views of climate change and other technologies influence them?

Adapting in-depth research tools
In order to gain a deeper understanding of the public perception of CCS, we need to research/develop quantitative and qualitative methodologies, including participatory approaches, by:

- Understanding how pseudo-opinions can be distinguished from more robust representations

- Distinguishing between the reliability of alternative survey instruments (open-ended versus closed-form questionnaires, internet, phone and face-to-face interviews)

- Investigating how framing can affect the way that information is presented and processed

- Drawing extensively from work being done in the study of public attitudes towards problems of science and technology, environment and risk.

Action Plan

- **Use demonstration projects to engage with the public and better understand their concerns.**
- **Research/adapt in-depth socio-economic research tools in order to gain a deeper understanding of the public perception of CCS.**
- **Assess research actions required to improve the public perception of CCS (e.g. safety).**
- **Link research activities closely to deployment issues, as defined in the Strategic Deployment Document.**

8. Looking ahead to 2020

Given the urgency of the situation, deployment of CCS must begin with the implementation of the most promising technologies available today. Indeed, considerable advances have already been made, or are currently ongoing, which have enabled the fast development of first-generation CCS technologies over a relatively short period, e.g. in adapting methods and tools from related areas, such as oil and gas production.

Clearly, full-scale demonstration projects will be vital for gathering large amounts of basic scientific data. This will enable us to prove and document that operations, monitoring, verification, risk and mitigation, permitting etc can indeed be carried out in a manner acceptable to both regulators and the public.

However, as the application of CCS grows and the industry opens up to more players, many new technologies may become available which have not yet been identified. Indeed, if next-generation technology is to be ready for implementation by 2020, longer-term exploratory research into advanced, innovative concepts must begin *now*.

Urgent research into next-generation technology is required
It is therefore vital that basic research in diverse areas is not overshadowed or omitted from the research agenda in the short- to mid-term. After all, current technologies are only available as a result of research carried out in previous decades.

As the research community grows, the number of solutions is bound to increase and some of these could be radically new. These could include areas such as nanotechnology, new thermodynamic cycles, biotechnology, new materials, new chemistry sensors and monitoring systems.

As totally new ideas are expected to occur during the period covered by the FP7, it is therefore essential that R&D projects should include areas which do not yet hold the greatest promise, but where new research could accelerate development, e.g. within ECBM, CO_2 mineral sequestration, or the use of CO_2 in manufacturing processes.

Building up expertise in key knowledge areas
All of this, of course, requires the expertise of European research teams in which training and education will have a very important role to play. It means strengthening leading edge science and technology areas such as combustion, materials, separation processes, underground storage, numerical modelling, signal treatment for storage monitoring etc. It specifically includes:

- ***Combustion science***
  Innovative combustion technologies (H_2-burners, oxy-fuel combustion, flameless and catalytic combustion, fluidised beds and heterogenic reaction systems) are vital to most CO_2 capture schemes, requiring innovative equipment and simulation design methods.

- ***Thermodynamics***
  The entire CCS process includes multiple thermodynamic processes, requiring a basic knowledge of process integration, optimisation and the development of

new turbomachinery. However, more advanced technologies also combine thermodynamics with chemical engineering to form innovative concepts, such as chemical looping technology, new separation technologies and new machinery for energy conversion.

- ***Computer-aided modelling***
  The only way to establish a basic knowledge of large-scale processes and chemical/physical mechanisms available is through experimental research, combined with computational fluid dynamics (CFD) modelling. Such models have yet to be developed and tools need to be refined.

- ***Materials***
  Further research is needed into highly allied steels metallurgy, coatings and alternative materials (ceramics, composite materials etc) which can withstand high temperatures, high pressures and corrosion from flue gases. This is also essential for CO_2 transportation infrastructures.

- ***Turbomachinery***
  A key area is the integration of new materials, combustion technologies, new cooling concepts and new aerodynamic designs for turbomachinery. This includes large-scale development and testing, before these concepts can be applied in a ZEP. The development and improvement of CO_2 compression on a large-scale is also important.

- ***Separations***
  Innovative separation technologies based on new membranes, sorbents or solvents can lead to very significant reductions in CO_2 capture cost. CO_2 separation is the first application, but innovative methods for separating O_2 from air may also have a very important impact on pre-combustion and oxy-fuel combustion technologies. Alternative capture technologies which incorporate a separation device in a reactor (e.g. membrane or sorption enhanced reactors for hydrogen production with CO_2 capture) may also lead to potential breakthroughs.

- ***Geological reservoir modelling***
  Advanced modelling and simulation tools are needed to assess the behaviour, security and long-term integrity of CO_2 stored underground and its interactions with its surroundings.

- ***Storage monitoring***
  Monitoring based on the transmission of different physical and chemical signals makes it possible to control the behaviour of the storage system at different stages of operation. This requires innovative tools that are both simple and reliable, and progress is expected in the area of physical emitters and sensors, as well as signal analysis methods.

- ***Storage standards***
  As with a number of other natural resources (e.g. petroleum, minerals etc), standards are required for the assessment of storage capacity (reserves) and performance (amount, permanence etc).

Maximising EU and international co-operation
Achieving the Vision will require strong cooperation from all stakeholders in order to optimise resources, avoid duplication and maximise synergies. The ZEP Technology Platform will obviously play a key role in promoting strong cooperation at a European level - between power and utilities, oil and gas companies, equipment manufacturers and R&D centres.

Ensuring Europe maintains its competitive edge may also require a dedicated programme, such as a Joint Technology Initiative (JTI), in order to accelerate the development and demonstration of innovative technologies on a large-scale. Certainly, such demonstration projects must have clear access protocols so that a wide variety of institutions can collaborate and share their knowledge.

FENCO: the power of partnership

FENCO ERA-NET was established in 2005 by 12 Member States as a pan-European initiative designed to strengthen European research skills in CCS technology and our ability to compete in world markets. It aims to achieve this by co-ordinating national agencies and governments, and improving the co-operation between national RTD programmes. The project will run from 2005-2009.

This is already happening: the EC is not only co-ordinating Member State activities through the European Research Area (e.g. FENCO ERA-NET initiative[20]), but playing an active role in many global initiatives, e.g. the Committee of Energy Research and Technology (CERT) and the Working Party on Fossil Fuels (WPFF) of the International Energy Agency (IEA) and the Carbon Sequestration Leadership Forum (CSLF), which involves 22 countries worldwide. It also sponsors and participates in the IEA "Greenhouse Gas" and "Clean Coal Centre" Implementing Agreements.

As importantly, the EU has Science and Technology Cooperation Agreements with many countries, such as Argentina, Australia, Brazil, Canada, China, India, Russia, South Africa and the US. Indeed, the role of emerging countries such as China, India and Brazil will be vital to curbing future CO_2 emissions and cooperation must be further encouraged. The EU-China Memorandum of Understanding on near-zero emission power through CCS and the COACH[21] project are a good start, but we cannot afford to be complacent.

Clearly, many technical aspects of CCS are suitable for international co-operation. Others, however, such as intellectual property rights, make co-operation on CO_2 capture more complex than for CO_2 storage.

Making the link

[20]Fossil Energy Coalition
[21]Co-operation Action within CCS EU-China

It is just as important to link up with other related European Technology Platforms and initiatives in order to leverage synergies and maximise all opportunities in sustainable energy:

- ***Materials***: the successful implementation of ZEP is highly dependent on the development and demonstration of advanced materials which can withstand the high temperatures and aggressive environments the new plant will be operating under. It is therefore imperative that Materials R&D runs in parallel with ZEP through collaboration with European Platforms on Advanced Materials (EuMaT) and Steels (ESTEP).

- ***Hydrogen & Fuel Cells*** and related initiatives (e.g. the Dynamis project, Hypogen): when CO_2 is removed from the gas stream in fossil fuel-based gasification, the fuel that remains is hydrogen, which could accelerate the transition to a hydrogen economy.

- ***Sustainable Chemistry***: promotes sustainable chemistry, industrial biotechnology and chemical engineering development, including using recycled CO_2 for producing chemicals and products.

- ***Biofuels*** and other Platforms, such as Plants for the Future: co-firing biomass may also be an attractive option for power plants, as CO_2 pre-combustion technology is very similar to that used to produce syngas from biomass.

- ***Sustainable Mineral Development***: concerning the mining and extraction of minerals along with coal, oil and natural gas.

Action plan

- **Consider establishing a European Joint Technology Initiative in order to accelerate R&D and improve competitive edge.**

- **Encourage further opportunities for international collaborative projects within the FP7.**

- **Establish links with related EU Technology Platforms and initiatives.**

- **Undertake a benchmarking comparison between European and other international programmes.**

- **Assess the competitiveness of the European industry (strengths and weaknesses) in order to prioritise new developments.**

9. Conclusion

The urgent deployment of CCS is not only desirable, it is vital if we are to prevent the catastrophic consequences of climate change to which we are rapidly heading. However, although CO_2 capture technologies are widely known and, in some cases, well-established, none are ready for implementation on the industrial-scale required.

It is therefore essential that Europe commits to a comprehensive and fully-coordinated research agenda in order to:

a) Bring current CO_2 capture technologies (together with improved power plant efficiency) to commercial readiness by 2020

b) Develop new concepts for implementation beyond this date.

This should be achieved through demonstration in 10-12 industrial-scale power plants, supported by parallel R&D on key technical issues in order to reduce costs and optimise performance.

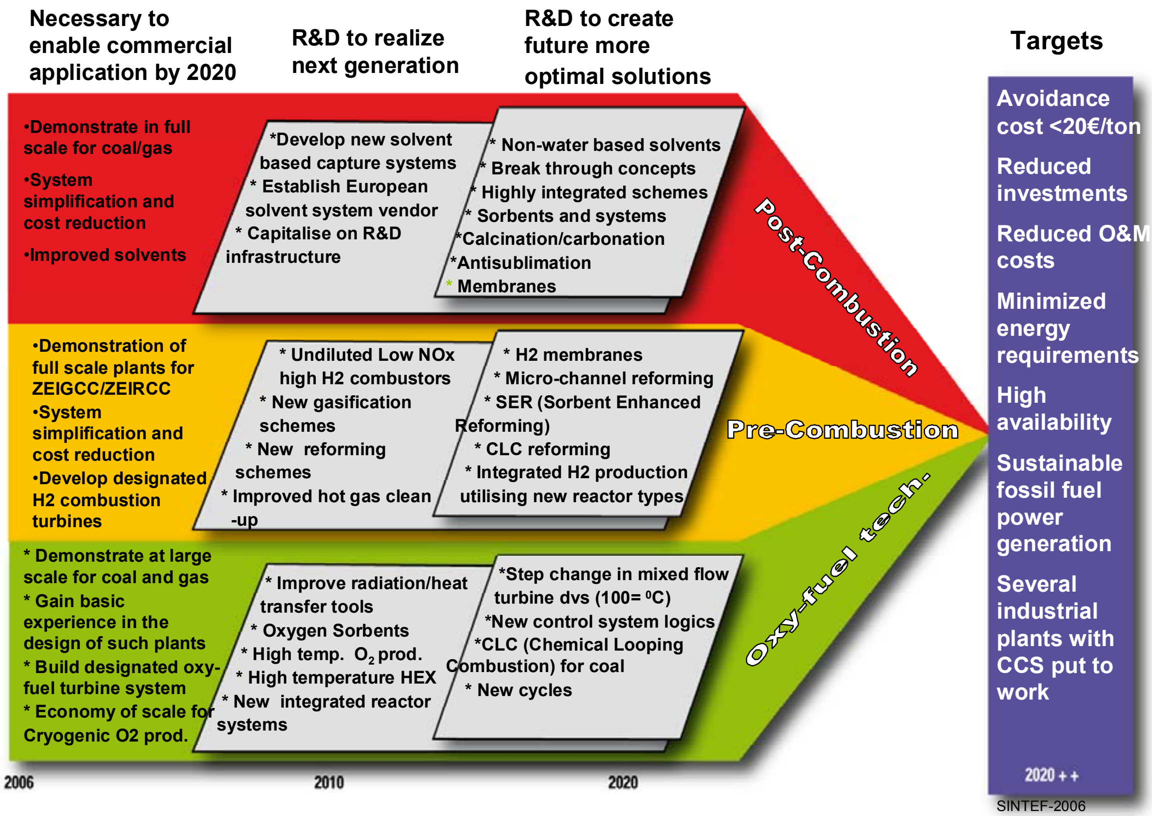

Fig. 8 shows a roadmap of R&D needs for the three main CO_2 capture technologies in order to achieve zero emission power plants by 2020

This should be integrated simultaneously with large-scale CO_2 storage projects in a variety of geographical and geological settings throughout Europe. The data resulting from such operations will not only be exploited through associated R&D programmes, but prove conclusively the safety and feasibility of CO_2 underground storage. It should therefore dovetail with in-depth research on current perceptions of CCS and the most effective means of gaining public support.

In parallel, and exploiting all the data provided by such large-scale demonstrations, longer-term research is vital in order to prepare for potential breakthroughs which will establish ZEPs as standard practice for the future.

All R&D priorities should be aligned with targets outlined in the Strategic Deployment Document.

R&D roadmap for zero emission plants by 2020 and beyond

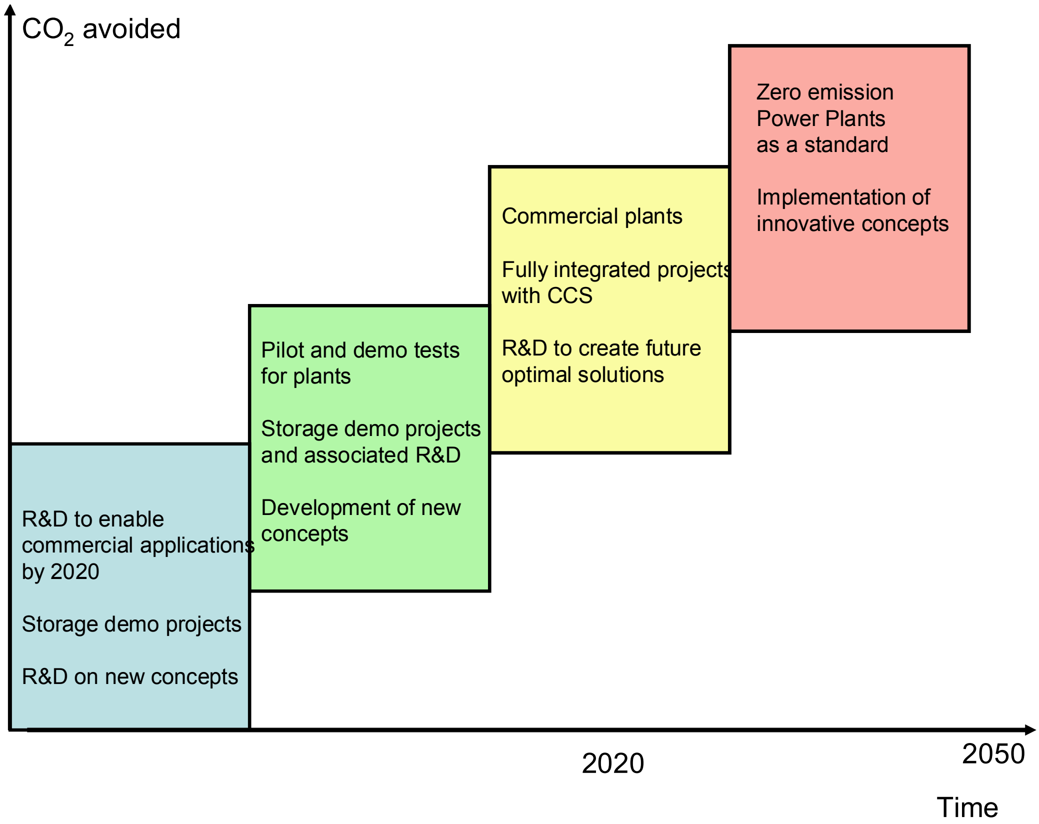

Fig. 9 shows the roadmap required not only to achieve the Vision for 2020, but prepare for future potential breakthroughs by 2050 via longer-term research

- **Introduce the need for 10-12 CO_2 capture and storage demonstration projects in the FP7 in order to optimise the integration of all systems and processes.**

- **Define R&D projects using experimental data from demonstration projects in order to develop and validate new tools (e.g. modelling tools for CO_2 storage).**

- **Promote R&D activities which enhance the technological assets of the European industry in order to improve competitiveness edge.**

- **Introduce new options for launching integrated projects, such as Joint Technology Initiatives.**

- **Define specific roadmaps for launching innovative concepts - even if commercial implementation is long-term, planning has to start now.**

- **Establish development tools for testing innovative processes or storage facilities. These could include specific sites dedicated to the investigation of innovative technologies, e.g. pilot plants for CO_2 capture, leakage laboratories etc.**

- **Support the establishment of networks in key technology and scientific areas (e.g. combustion science, thermodynamics, materials, fluid mechanics, separations, geoscience). Organise meetings and promote knowledge transfer between European research centres and joint access to common tools.**

- **Develop an information kit for training scientists and engineers in zero emission power plant technology.**

Glossary

ASU	Air Separation Unit
ATR	Autothermal Reforming
AZEP	Advanced Zero Emissions Powerplant
CAR	Ceramic Autothermal Recovery
CASTOR	Capture and Geological Storage of CO_2
CCS	Carbon Capture and Storage
CERT	Committee of Energy Research and Technology
CFB	Circulating Fluidised Bed
CFD	Computational Fluid Dynamics
CLC	Chemical Looping Combustion
COACH	Co-operation Action within CCS EU-China
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2SINK	In-Situ Laboratory for Capture and Storage of CO_2
CSLF	Carbon Sequestration Leadership Forum
$DeNO_x$	NO_x reduction process
EC	European Commission
ECBM	Enhanced Coalbed Methane Recovery
EGR	Enhanced Gas Recovery
ENCAP	Enhanced CO_2 Capture in Powerstations (FP6)
EOR	Enhanced Oil Recovery
ESTEP	European Steel Technology Platform
EU	European Union
EuMat	European Technology Platform on Advanced Engineering Materials and Technologies
FP5	Fifth Framework Programme
FP6	Sixth Framework Programme
FP7	Seventh Framework Programme
GESTCO	Geological Storage of CO_2 Project
GHG	Greenhouse Gas
GMOs	Genetically Modified Organisms
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulphide

IEA	International Energy Agency
IGCC	Integrated Coal Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
JTI	Joint Technology Initiative
kt	Kilo tonne
LNG	Liquefied Natural Gas
LPG	Liquid Propane Gas
Mt	Mega tonne
MW	Mega Watts
MWh	Mega Watt hour
N_2	Nitrogen
NO_x	Nitrous Oxides
O&M	Operation and Maintenance
O_2	Oxygen
RECOPOL	Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland
NGO	Non-Governmental Organisation
PF	Pulverised Fuel
RD&D	Research, Development and Demonstration
SAR	Synthetic Aperture Radar
SDD	Strategic Deployment Document
SO_2	Suphur Dioxide
SO_x	Sulphur Oxides
SRA	Strategic Research Agenda
STREP	Specific Targeted Research Project
t	Tonne
WPFF	Working Party on Fossil Fuels
ZEP	Zero Emission Fossil Fuel Power Plant/European Technology Platform for Zero Emission Fossil Fuel Power Plants

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For more detailed information, please see reports published by the Working Groups of the ZEP Technology Platform on the website of the European Commission (see page 4).

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