THE EU TECHNOLOGY PLATFORM FOR
ZERO EMISSION FOSSIL FUEL POWER PLANTS

RECOMMENDATIONS FOR RD&D PRIORITIES WITHIN FP7 ENERGY WORK PROGRAMME 2008

IN SUPPORT OF DEPLOYMENT OF CCS IN EUROPE

FINAL DRAFT VERSION 10TH APRIL 07

ZEP TASK FORCE ON TECHNOLOGY

Recommendation for RD&D priorities within FP7 Energy Work Programme 2008

Here comes a short text giving the objectives of the TFT and the links to SRA etc.
To be completed by overall editor

Then follows - as bullets - a very concise summary of our recommendations for FP 7 Energy work Programme 2008, as follows:

TO BE COMPLTED BY OVERALL EDITOR/CO-LEADS IN FINAL DRAFT

RD&D in support of 10-12 integrated, large-scale demonstration projects across Europe:

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RD&D in support of new concepts already identified, but not validated, for demonstration by 2010-2015 and implementation beyond 2020

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Long-term exploratory R&D into advanced, innovative concepts for implementation of next-generation technology

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Table of Contents:

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1. Introduction

During 2006, the Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), outlined technology RD&D needed to implement CCS on a massive scale in Europe, and this was documented in an SRA (Strategic Research Agenda) based on expert recommendations provided by five Working Groups (WG1 – WG5)

The Key Recommendations that were formulated in the SRA (year 2006) are:

1. ***Urgently implementing 10-12 integrated, large-scale CCS demonstration projects Europe-wide. These projects shall combine CO_2 capture technologies with transportation and storage technologies***
   - 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***
   - Mobilize 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.***

To fulfil these recommendations, the ongoing CCS projects within FP6 need to be built upon and followed by several years of a wide range of RD&D activities. The SRA describes a collaborative programme of technology development for reducing the costs and risks of deployment.

Since the SRA was elaborated, the ongoing CCS projects within FP6 as well as other worldwide projects have generated more knowledge, and in the FP7 Energy Work Programme 2007 some continued RD&D actions are requested.

In addition to the ongoing FP6 projects and the RD&D actions addressed in the Energy Work Programme 2007, a range of RD&D actions on CO_2 capture technologies as well as geologic storage need to be given priority during the next few years. The European Commission has therefore requested the ZEP TF Technology to provide recommendations on such RD&D actions, to be addressed in the FP7 Energy Work Programme 2008.

The scope of this note is formulate specific RD&D topics for the FP7 Energy Work Programme 2008, based on TF Technology expert recommendations, using the ZEP SRA (year 2006) and the underlying WG1 and WG2 reports as a starting point.

The recommendations reflect the need for parallel RD&D routes to support the Key Recommendations nr 1 – 3 above, covering power plant and CO_2 capture technologies as well as CO_2 use and storage.

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The note has the following structure, with one lead author appointed for each chapter:

- CO_2 Capture
  - Post-combustion capture: Hallvard F. Svendsen, NTNU
  - Pre-combustion capture: Hans Jensen, RWE Power
  - Oxy-fuel combustion: Clas Ekström, Vattenfall Research and Development
  - Emerging and new technologies: John Chamberlain, Unión Fenosa
  - *Generic research areas to improve CCS efficiency: Guenter Scheffknecht*
- CO_2 Storage and transport
  - Aquifers: Isabelle Czernichowski-Lauriol, BRGM
  - Use and transport: Tore A. Torp, STATOIL
  - *Common issues: Niels Peter*

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Overall Editor: Clas Ekström, Vattenfall Research and Development

Co-leads of TF Technology are:

Lars Strömberg, Vattenfall
Dirk Goldschmidt, Siemens
Niels Peter Christensen, GEUS

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Complete list of TF Technology members/co-authors can be found at:

http://www.zero-emissionplatform.eu/website/taskforces/index.html

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2. Post-combustion CO_2 capture

Expected impact:
A concerted effort on the theme of Post combustion CO_2 capture should bring us to a stage where we have full insight into the advantages and limitations of both organic and inorganic, precipitating and non-precipitating absorption systems. Identifying optimal capture process designs and ways of integrating the capture systems with the power plant with respect to energy loss and environmental impact. The integration of a capture plant will be demonstrated at small industrial scale (10-15 t CO_2/h)

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Niels, Clas

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring these technologies and concepts to commercial readiness by 2020.

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Collaborative RTD projects covering the R&D areas below should be considered.

R&D area: New solvents for CO_2 capture
R&D actions (content/scope)

Demonstrate the improvements achievable with the full range of solvent systems and evaluate the environmental impact of the capture process systems.

- Continue and expand work on potential solvent systems including inorganic and precipitating systems, and identification of new improved ones
- Characterization of systems related to energy requirements; equilibrium, kinetics and thermal properties
- Determination of solvent stability and degradation rates in presence of oxygen and other pollutants and the maximum pollutant and flue gas characteristics at CO_2 scrubber inlet.
- Demonstrate energy requirement reduction and degradation rates of new systems in laboratory scale pilot plant.
- Demonstrate stability, operability and performance under long term process conditions on industrial pilot scale
- Identify the environmental and HES impact of the new capture solvents

Funding Scheme
One collaborative large scale RTD project.
Expected impact
Develop a set of significantly improved solvent systems and develop the database necessary for demonstration on industrial scale. Demonstrate one system on an industrial pilot plant scale such that small scale industrial units (40-50MW) can be set in operation in 2010-2015.

R&D area: *Development* of capture plant design and operation
R&D actions (content/scope)

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Demonstrate the improvements achievable with a range of process modifications

- Evaluate possible post combustion processes and quantify and compare the effect of a range of process improvements
- Establish operating procedures and determine possible energy requirement reductions in laboratory scale pilot plants (10-20 kg CO_2/h).
- Show the production of CO_2 at elevated pressure to reduce compression costs

- Optimize the process and equipment modifications them and demonstrate their operability and effects at industrial pilot plant scale (1-2 t CO_2/h)
- Determine energy and solvent replacement costs and plant capital cost

Funding Scheme

One collaborative large scale RTD project.

Expected impact

Identify the impact of a range of process modifications, and test the most promising ones in industrial pilot plants with a CO_2 capture capacity of 1-2 t/h. Develop the data base necessary for demonstration of these modifications by 2010-2012 and to evaluate the environmental impact of the capture processes.

R&D area CO_2 Capture plant integration *and optimisation* with power plant

Helmut Rode
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R&D actions (content/scope)

Demonstrate the availability, efficiency loss and environmental impacts of a fully integrated CO_2 capture process:

- Determine scale-up criteria and the most cost effective design for large scale capture units
- Determine the retrofit costs to fulfil inlet gas criteria, general retrofit considerations
- Studies of energy losses for different integration schemes; steam extraction, heat recuperation
- Determination of integration scheme consequences on power plant side; flue gas path, cooling water
- Demonstration of full integration with plant and measurement of energy losses
- Determine and if possible monitor the environmental impact

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Funding Scheme
One to two collaborative large scale RTD projects
Expected impact
The project(s) will show the energy impact of different integration schemes including retrofit situations. It will demonstrate the effect of a fully integrated industrial size pilot plant with regard to efficiency losses and environmental impact, and thus pave the way for small industrial size (40-50MW) demonstration in 2010-(2015).

3. Pre-combustion CO_2 capture

1. Optimise concepts as well as process components for power plants with pre-combustion CO_2 capture, and create a validated firm basis for design of integrated and large scale pre-combustion capture CCS demonstration projects with sufficient reliability to achieve market competitiveness (after allowance for EEC support of early projects).
2. Develop novel underpinning concepts in process integration, air separation, gasification, reforming, gas processing, CO_2 removal and hydrogen burning combined cycles for demonstration in safe, reliable and flexible plants by 2010-2015 and implementation beyond 2020.

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring these technologies and concepts to commercial readiness by 2020.

Collaborative RTD projects covering several of the R&D areas below should be considered.

R&D area "Full process integration and optimisation for power"

R&D actions (content/scope)

- Start-up, flexibility, load following, reliability and availability of the complex systems are important for early demonstration plants. Efficiency improvements through heat integration, process integration within units and integration across the entire power plant are important developments but not at the expense of reliability.
- Safety, especially with that related to hydrogen containment at high temperatures and pressures. Compliance codes will need to be developed.
- Scale-up of equipment and technologies taken from other processes.
- Understanding the basic heat transfer characteristics in various gas compositions for application within the gasifier, raw gas heat exchangers and gas turbine.
- Assess currently available materials and developing future materials, including ceramics, metals and coatings, for the entire plant.
- It would be helpful for all large facilities to be able to test novel technologies at smaller scales on side-streams and to incorporate basic understanding (theoretical and bench scale) in demonstration plants building on the knowledge that already exists but may not be widely known or used. Build on projects being developed at Elcogas and Nuon for side-stream shift reaction evaluation.

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Expected impact

Demonstration pre-combustion CO_2 capture power plants with availability and load following characteristics which are better than current IGCC (Integrated Gasification Combined Cycle) power plants.

Funding Scheme

Large collaborative RTD project which by its nature has opportunities for “exchange” fellowships.

R&D area "Coal gasification, natural gas reformer and syngas cooler”

R&D actions (content/scope)

- *Modelling, of gasification and natural gas reformer, validation verification*

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- Scale-up to 1200 to 1500 MWt in a single train
- Effective heat recovery /quench
- Improved coal feeding, ash control and ash removal
- This part of the package covers gasification or fuel reforming coupled to water gas shift modification of gas composition. It is applicable to a wide range of solid, liquid and gaseous fuels.

- Priority issues for development of the gasifier or partial oxidation equipment include fuel feeding to required stability and properties for the "burners" or reactor. Reactor scale-up, raw gas cooling, the cost and operability of raw gas coolers and ash issues within and on extraction from this stage are key to the economic performance of the first fuel conversion stage in the plant.

Expected impact

Reliable gasifiers and reformers as part of a lower cost pre-combustion CO_2 capture power plant.

Funding Scheme
Medium collaborative RTD project

R&D area "Syngas processing, CO_2 capture and CO_2 processing"
R&D actions (content/scope)

- Catalyst development including resistance to inhibition by syngas composition

- There is currently only one accepted option for the conversion of carbon containing gases in the raw gas, which is the catalytic water gas shift reaction. There are multiple options for the removal of CO_2; these vary from removal of CO_2 only after the completion of the shift reaction, through to close integration of all the chemical and physical stages in order to avoid equilibrium limitations. Work is required on optimisation of the shift stage, the catalysts and integration of the water gas shift with CO_2 separation and other gas (e.g. sulphur compound) removal. Separation of sulphur and CO_2 removal processes is key, and various solvents for these tasks should be characterised.

- CO_2 compression
- *Separation and P*urification; adaptation and optimisation for pre-combustion capture (CO_2 streams separated from syngases)
- *Link to RTD projects on Aquifer CO2 storage concerning CO_2 codes and specifications for use and storage, including geological characterisation and chemistry, transport materials compatibility and other infrastructure limitations, as well as legal, environmental, monitoring and maintenance issues of storage*
- Continuing development in CO_2 compression, purification and relevant codes

Expected impact
Pre-combustion capture of CO_2 with minimum impact on plant efficiency, minimal reagent use and a product acceptable to the CO_2 transmission and storage infrastructure.
Funding Scheme
Medium collaborative RTD project

R&D area "High efficiency, low emission H_2 gas turbines and combined cycles"
R&D actions (content/scope)
- Hydrogen-burning gas turbines (both diluted and up to 100% hydrogen content). The key areas of burner stability and emissions should be developed with theoretical studies, laboratory tests and full condition demonstrations. Catalytic, flameless and other novel GT combustion approaches should also be examined and heat recovery steam generators developed to match the gas turbines..
- High temperature material behaviour with various gas compositions.
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- Start-up and load following of advanced gas turbines and combined cycles for syngases and H_2 rich gases.
- *Fuel flexibility…..*
- *Diagnostics…*
- *Advanced cooling shemes*

Expected impact

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Safe reliable gas turbines burning the low carbon content gas. Prepare the ground for zero emission technologies with fuel flexibility such as for syngas and H_2-rich gases

Funding Scheme

medium to Large collaborative RDT projects

Develop novel underpinning concepts for demonstration by 2010-2015 and implementation beyond 2020

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Medium scale collaborative RTD projects covering several of the R&D areas below should be considered.

R&D area "Coal gasification, natural gas reformer and syngas cooler"

R&D actions (content/scope)

- Continued scale-up.
- Continued optimisation of heat recovery and/or quench
- Improved coal feeding, ash control and ash removal
- Reliability improvement

Expected impact

Improvements to efficiency, reliability, response rates or capital cost.

R&D area "High efficiency, low emission H2 gas turbines"

R&D actions (content/scope)

- Further development of gas turbines and combined cycles for higher reliability and efficiency in various operational regimes

Expected impact

Improvement to economic, environmental and sustainability characteristics

Support long-term exploratory R&D in advanced, innovative concepts for implementation of next-generation technology

Medium scale collaborative RTD projects to further optimise those concepts to be commercially ready by 2020. In ***particular***

- Optimisation of the components and systems for steady-state, part load and load following regimes with high reliability and safety systems and standards.
- Incorporation of the most advanced materials and cooling technologies in key parts of the plant.
- Introduction of new materials, constructional techniques and plant equipment designs
- CO_2 compression and purification including links to CO_2 storage projects.
- Maximising the fuel flexibility of gas turbines for stable operation with gases from hydrogen to methane as well as various syngas compositions in order to maximise flexibility in operation of other plant components.

4. Oxy-fuel combustion

Expected impact:

The RTD actions add to ongoing projects in order to optimise the complete power plant concepts as well as process components, and create validated firm basis for design of large scale demonstrations (100s of MW_{th}) of complete oxy-fuel boiler power plants, including compression and conditioning of captured CO_2. Construction and operation of such large scale demonstration plants can then form the basis for commercial readiness by 2020.

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring these technologies and concepts to commercial readiness by 2020.

Collaborative RTD projects covering several of the R&D areas below should be considered.

R&D area: Developing and implementing oxy-fuel combustion for boilers

R&D actions (content/scope)

- Intensify laboratory research into combustion, heat transfer, formation of pollutants, excess oxygen, ash compositions and properties, slagging, fouling and corrosivity of flue gases. It is important to investigate the implications of oxy-fuel combustion for a large spectrum of solid fuels covering ranges of fuel properties, such as high contents of sulphur, high contents of chlorine, calcium-oxide rich ashes, etc.
- For circulating fluidised bed (CFB), in addition to above, verify also minimisation of flue gas recycle, bed material behaviour and in-situ sulphur removal
- Develop, based on research results, and adapt engineering and design tools for scale-up, such as CFD and other advanced tools. Validate developed tools against laboratory and pilot plant testing.
- Pilot plant tests (10s of MW_{th}) of full oxy-fuel pulverised fuel (PF) process, to validate results from scale-up based on laboratory tests.
- Development of PF burner designs and piloting in 10s of MW_{th} scale
- Pilot plant tests (10s of MW_{th}) of full oxy-fuel CFB
- Oxy-fuel combustion for CFB boilers: specific design and scale-up issues include strong heat extraction to solid bed material circulation loop. Perform process investigations addressing alternative schemes for fluidisation of i.a. external bed heat exchanger. A wide spectrum of solid fuel qualities of relevance for the European market should be taken into account.
- Investigations of start-up and shut-down procedures, transient conditions and performance during part-load operation, to be performed as combinations of dynamic simulations and verifications in pilot plants for PF and CFB:s

Expected impact

These R&D actions will create a validated, firm basis for design of *oxy-fuel* boilers to be used in large scale demonstrations (100s of MW_{th}) of oxy-fuel power plants.

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Funding scheme

2 large collaborative RTD projects covering PF and CFB technologies

R&D area Material selection and R&D for oxy-fuel

R&D actions (content/scope)

- Investigate long-term operational properties of high temperature materials, for *oxy-fuel* boilers, 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.

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- Investigate low temperature corrosion potential, especially for high ash, high sulphur and high chlorine coals.
- Investigate oxygen heater materials

Expected impact

These R&D actions will create a validated, firm basis for proper selections of construction materials when designing oxy-fuel boilers. This is essential to ensure safe and reliable operation of such boilers, since oxy-fuel flue gas compositions will differ from flue gases from conventional air-firing.

Funding scheme

Small collaborative RTD project

R&D area: CO_2 capture, compression and conditioning process specific for oxy-fuel combustion

High concentrations of other components than CO_2 at entrance of CO_2 compression and conditioning

R&D actions (content/scope)

- Validate, adapt and improve existing technologies for flue gas treatment, to utilization in oxy-fuel conditions.
- Develop flue gas cleaning/ polishing 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, while minimising CO_2-losses.
- Establish thermo-physical properties of high concentration CO_2-mixtures, including model development and validation by experimental data.
- Investigate possible reactions induced under the operating conditions in the CO_2 compression/processing train, and their possible influence on the process conditions and material selection.
- Identification of distribution and options for removal of minor and trace components

Several of these R&D actions require investigations in laboratory and in pilot plants (10s of MW_{th})

Expected impact

These R&D actions aim at developing/adapting technologies for flue gas treatment, to utilisation for CO_2 rich flue gases, and to optimise and create basis for design of large compression and conditioning systems for high concentration CO_2-mixtures.

Funding scheme

Medium collaborative RTD project

R&D area: Adaption of cryogenic air separation unit (ASU) to oxy-fuel power plants

Very large quantities of oxygen delivered at low pressures

R&D actions (content/scope)

- Develop very large air compressor *trains*, potentially of the adiabatic type, to lower the cost of these units and develop new integration possibilities within the heat system of oxy-fuel power plants
- Optimise cycles for cryogenic ASU, for reduced power consumption, when used in large oxy-fuel power plants.
- Investigate the operability of ASU/oxy-fuel boiler combination (load following, minimum load, auxiliaries consumptions) theoretically (modelling) and *validation of these models* in *plants*.

Expected impact

These R&D actions aim at adapt and optimise the cryogenic air separation process for more energy efficient utilisation, and to investigate its operability, for use in large oxy-fuel power plants.

Funding scheme

Small collaborative RTD project

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5. Emerging and new CO_2 capture technologies

Expected impact:

To promote the development of new and emerging technologies that are yet to be validated for the capture of CO_2, which can be cost competitive with the technologies currently identified as front-runners, and brought to the market in the period post 2020. This area will also contemplate R&D activities that can complement and optimise the current front-running technologies. This long-term exploratory R&D in advanced and innovative concepts for the next-generation of CO_2 capture technologies will enable Europe to maintain the position of leadership in the area of environmentally acceptable fossil fuel power generation.

Develop novel underpinning concepts for demonstration by 2010-2015 and implementation beyond 2020

R&D area: Chemical Looping

****** The priority of this R&D area could be reduced if the first call of FP7 - Topic ENERGY.2007.5.1.2: Fluid-bed based Capture Techniques is directed towards a Chemical Looping project. ******

Chemical looping combustion is a promising concept demonstrated in several laboratory prototypes operating with clean fuel gases at atmospheric pressure. Further development is required to demonstrate the concept at the pilot scale on two fronts: the first for gaseous fuels, and the second for direct application of coal and in chemical looping reformers.

R&D actions

- Demonstration of chemical looping combustion for gaseous fuels employing interconnected high pressure fluidised beds at the next scale to optimise of the operating parameters (for example circulation rates, temperatures, etc) and to develop optimal new carrier materials
- Investigation of the direct application of Chemical Looping Combustion of coal *and heavy oil* in long term pilot tests to verify concepts such as ash and oxygen carrier separation, test possible oxygen carriers in order to characterise them with regard to de-fragmentation and attrition

Expected impact:

Accelerate the development and implementation of Chemical Looping Combustion (CLC) for both gaseous and solid fuels. These projects should result in the demonstration of Chemical Looping Combustion in the first small-scale pilot plants designed specifically for integrated chemical looping combustion.

Funding scheme

RTD Collaborative Project (Medium or large-scale focused project).

R&D area: Post-Combustion Carbonate looping cycles

Carbonate looping cycles in post-combustion applications is an emerging technology that is being promoted by an increasing number of groups in Europe, which currently leads the development in this area. A number of carbonate looping pilot plants of around 1 MW thermal input are currently being considered, and such pilot plants can provide critical information towards the validation of this concept. Larger scale facilities in the range of *several* MWs will be required to validate the technology in real process conditions and to enable further development of the cycle.

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R&D actions (content/scope)

- Development of carbonate looping pilot plants of the scale of *several* MWs to evaluate and optimise the concept in operating conditions equivalent to large-scale industrial units and to address the key issues facing this technology (impurities in the gas and solid phases, chemical and mechanical performance of the sorbent, deposit formation, erosion and corrosion issues, start up and control issues, model simulation and scaling up tools, etc).

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Expected impact

To accelerate the development of CO_2 capture based on carbonate looping cycles to determine if this technology can be cost competitive at the industrial scale in the timeframe of 2020 to 2030.

Funding scheme

RTD Collaborative Project (Medium or large scale focused project)

Support long-term exploratory R&D in advanced, innovative concepts for implementation of next-generation technology

R&D area: Gas Separation Membranes *and* Adsorption Processes

The removal of CO_2 using commercially available polymeric gas separation membranes currently results in large efficiency penalties, compared to a standard solvent process Additionally, the maximum percentage removal is lower than for standard chemical solvent processes. It is believed that improvements can be made if more selective membranes are developed and there is greater integration of the membrane process with the energy conversion process.

Adsorption processes are used commercially in other sectors, however in low CO_2 partial pressures atmospheres the current processes are very costly, both in capital and operating costs. Some improvements can be foreseen to the process, the materials.

R&D actions (content/scope)

- Realisation of small-scale laboratory research experiments to continue the development of membranes and alternative solvents to improve separation efficiency, reliability and resistance to agents and conditions that currently limits the process.
- Realisation of small-scale laboratory research experiments to develop integrated/dual purpose membrane based combustion technologies, which relate to in-situ separation of oxygen from air via high temperature membranes and direct combustion of methane or syngas in an oxygen-rich atmosphere.

Expected impact

To permit the evaluation of whether the difficulties presented by these options can be resolved. The results should identify technical developments that simplify the process, improve efficiency.

Funding scheme

Collaborative RTD Projects (Small scale focused project)

R&D area: Novel Concepts for CCS

Initial validation of novel and breakthrough concepts that could be developed in the period up to 2050. Concepts to be investigated could include development of new materials and sorbents, pre-combustion carbonate looping, sorbent enhancing reformers (SER), Micro-channel reforming and new cycles etc.

R&D actions

Small-scale screening tests of novel and breakthrough concepts is required to assess the validity of each concept, which can be further developed in the period up to 2050 to determine if they are feasible and potentially competitive.

Expected impact

To permit the screening of novel concepts to determine if they justify further development.

Funding scheme

Collaborative RTD Project (Small scale focused project).

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6. CO_2 storage in aquifers

Expected impact:

If in fact CCS is to be widely available for industrial-scale deployment by 2020, considerable urgency exists towards further developing research on CO_2 storage in deep saline aquifers, which is by far the storage option with the largest capacity and the more widespread geographical distribution. This research needs to demonstrate to the public, the regulators, industry and national authorities that there is sufficient aquifer storage capacity available for large-scale CO_2 projects in various parts of Europe and that very large CO_2 quantities (order of 10 Mt/y of injected CO_2 per project) can be stored safely for a very long time. This research must be well underway several years (i.e. by 2015) before full-scale deployment of ZEP becomes viable.

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring to CCS commercial readiness by 2020.

Collaborative RTD projects covering several of the R&D areas below should be considered.

R&D area : Scientific and technical protocol for safe operation of large-scale saline aquifer storage sites

R&D actions (content/scope)

- Develop a common generic protocol to ensure that storage operations will not have adverse local impacts on populated areas, ground waters and ecosystems, neither short-term nor long- term. This protocol must include the scientific and technical basis for site selection and characterisation, design of the injection operations, monitoring, remediation and abandonment phase.
- Build on previous EC and national best practise and research work and further develop and integrate them
- Investigate new methodologies for scenario analysis coupling subsurface evolution with expected HSE impacts in case of leakage or ground deformation. Explore how to evaluate and handle uncertainties.

Expected impact

This project will deliver a common science-based protocol which will ensure that large-scale CO_2 storage in deep saline aquifers can be operated safely. This protocol needs to be generic with some flexibility to fit site-specific contexts. It will form the scientific and technical basis for regulatory, legal and economical frameworks and for building confidence in the CCS technology.

Funding scheme: large collaborative RTD project

R&D area: Impact of the quality of CO_2 on transport and storage behaviour

R&D actions (content/scope)

- Assess the impact of impurities injected with the CO_2 (*i.e.* O_2, N_2, NOx, SOx, CO, H_2S, etc) on fluid properties and geo-chemical reactions in the transport system (truck, ship, pipeline), injection wells and storage system (reservoir and cap rock).
- Develop relevant physical-chemical characteristics of most important mixtures at relevant conditions (i.e. phase diagrams at relevant P and T). Develop algorithms for behaviour predictions.
- Investigate to what extent can impurities modify predictive modelling of the transport and storage system (flow, thermal, chemical, mechanical processes)
- Investigate the impact of impurities on subsurface monitoring
- Analyse and review importance of impurities on legal and economical conditions for geological storage permits
- Link with projects on capture processes and related impurities

Expected impact

CO_2 purity is a key issue within the entire CCS value chain from CO_2 source through the transport system and onto the storage site. The purity has implications of profound technical character as well on economic and legal issues (e.g. the London Convention). Clarity is needed in this area for a valuable contribution to the future planning and deployment of CCS.

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Funding scheme: Large collaborative RTD project

R&D area: Wellbore integrity

R&D actions (content/scope)

- Develop novel concepts for well completions and supervision (i.e. new cements, *cement free elements,* logging and sampling).
- Develop new, advanced methods for modelling and prediction of i) corrosion, ii) cement degradation by geo-chemical and geo-mechanical processes, and iii) near-well migration. Use information from all possible levels: labs, field pilots, archeological analogues, etc.
- Assess risk for scenarios of sudden or slow CO_2 escape through wellbores or near-wellbore pathways and develop risk management procedures.
- Develop material and intervention procedures for repairing wells and restoring integrity
- Investigate also the impact of impurities co-injected with CO_2 or any other chemicals co-migrating with the CO_2.
- Optimise the monitoring system with regard to storage performance, local HSE issues and monitoring cost.
- Develop plugging & abandonment procedures for site closure

Expected impact

The vicinity of the wellbore is the most risky area for potential escape of CO_2 to the surface during and after operations.

Funding scheme: medium to large collaborative project

R&D area: Leakage through natural pathways

R&D actions (content/scope)

- Develop a comprehensive understanding of the behaviour and impact of CO_2 and associated substances (co-injected impurities or co-mobilised chemicals, such as trace heavy metals, CH_4, ^{222}Rn, He, H_2, H_2S, etc) when migrating up to the surface through the establishment of natural field laboratories in a number of reservoir depths, geological settings, and terrestrial/marine environments.
- Assess the possible links between leakage and seismicity
- Further develop and integrate geological, geochemical, geophysical, geomechanical, biological and toxicological studies in these natural field laboratories to understand leakage pathways, rates, fluxes and mechanisms as well as possible impacts on populated areas, groundwaters and ecosystems.
- Develop a package of robust methods for visualisation, modelling and monitoring of CO_2 migration and leakage in these settings
- Integrate information from different disciplines and different site contexts to give simple, direct and clear answers to the most frequent concerns about risks of leakage and associated HSE impacts.
- Equip permanently a selection of natural field labs for allowing visits by stakeholders at large for further research, guided field tours and permanent scientific exhibitions.

Expected impact

For CCS to become widely accepted the aspects related to the risk of the CO_2 escaping from the storage must be addressed in a scientifically comprehensive and credible manner. By their very nature, various industry pilot and demo projects are designed NOT to leak and the above project initiative (which could be seen as the European leakage laboratory) is thus best conducted in purpose made RTD project.

This project will deliver the clear scientific messages needed about leakage detection, quantification, variation in space and time, and HSE impacts. This is crucial for helping the set-up of storage regulations and for increasing stakeholders' confidence on CCS.

Funding scheme: large collaborative RTD project

R&D to develop novel underpinning concepts and tools for demonstration by 2010-2015 and implementation beyond 2020

Collaborative RTD projects covering several of the R&D areas below should be considered.

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R&D area : Comprehensive assessment of Europe's capacity for CO_2 storage in deep saline aquifers

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- Compile, collate, and integrate existing aquifer capacity data from EU and national projects
- Further investigate the key reservoir and cap rocks characteristics of aquifers relevant to storage injectivity, capacity and integrity (geometry, structure, mineralogy, fluid chemistry, petrophysics, hydrodynamics, geomechanics,…)
- Develop a tool for predicting spatial reservoir and cap rock characteristics, with assessment of uncertainties
- Develop robust storage capacity classification system and provide input for legal end of storage licensing procedures (national or EU-wide)

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- Map the whole Europe with respect to potential aquifer storage regions
- Construct electronic EU-wide database and maps of potential storage sites using a GIS platform, with possibility of 3D visualisation
- Make scenarios of source-to-sink matching to relate storage sites with CO2 emission sources
- Initiate collaboration with the countries neighbouring the EU (Mediterranean countries, Western Balkan region, Eastern European and Western Asian states) and further collaborate with CSLF countries (China, Russia, India)

Expected impact

It is becoming increasingly clear that for CCS to become widely deployed by industry, sufficient high quality aquifer storage capacity must be made available. The geology of Europe is very variable and the deep saline aquifers are poorly known, except when they have been explored locally for hydrocarbon or geothermal purposes. To help industry and governments to plan CCS projects, it is imperative that considerable aquifer storage capacity is proven across Europe, and that an orderly system for licensing is instigated for the exploration and use of the storage sites.

Funding scheme: large collaborative RTD project

R&D area : Long-term modelling of CO_2 storage in deep saline aquifers

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- Develop methodologies and tools for building 3D detailed, static geological model of the entire aquifer storage sites. Develop up-scaling tools for architectural systems of different depositional systems. Use geostatistics for distribution of key characteristics. Address *sandstone* reservoir types as well as carbonates with complex porosity systems.

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- Develop dynamic modelling tools to predict CO_2 fate and site behaviour during the injection period up to long-term storage periods. Couple processes such as fluid flow, geochemical and microbiological reactions, thermal processes, geomechanical processes. Address in great detail the behaviour of the reservoir and cap rocks as well as faults.
- Undertake modelling on selected test cases, quantify over time the various physical and chemical trapping mechanisms, the changes of monitorable physical properties, as well as potential migration in the surrounding areas and ground deformation at surface.
- Benchmark modelling codes and approaches. Calibrate parameters from dedicated laboratory and field test data or history matching.
- Develop tools for quantifying uncertainties and visualizing modelling results.
- Make recommendations for the design of injection operations (position of injection wells and injection flowrates) and monitoring strategies.
- Propose a EU Best Practice Manual for the modelling of CO_2 storage sites, including recommendations for the good characterisation of key input data such as site-specific properties

Expected impact

Modelling is used to characterise both short-term and long-term storage performance in terms of injectivity, capacity, containment, and quantitative estimation of potential leakage. A dedicated project is needed to develop and demonstrate the capacity of models to adequately predict the storage behaviour and CO_2 fate. This will increase confidence in the safe implementation of storage sites and will be useful for optimising the injection operations and the short/long term monitoring strategies.

Type of project: small to medium collaborative RTD project

Support long-term exploratory R&D in advanced, innovative concepts for implementation of next-generation technology

Collaborative RTD projects covering several of the R&D areas below should be considered.

R&D area : Mineral carbonation of CO_2 in aquifers

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Comment: Stay as white area

- Build on pioneer studies to further investigate the possibilities of enhancing mineral trapping of CO_2 and impurities in specific types of aquifers (basaltic and ultramafic aquifers, highly saline aquifers, geothermal reservoirs, etc.)
- Study thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, geomechanics.
- Map potential storage sites in Europe, assess potential worldwide
- Carry out a techno-economical feasibility study

Expected impact
In this storage option, the dominant CO_2 trapping mechanism would be mineral trapping under various carbonates form. Then the long-term stability of storage is increased. Also, for those countries (such as India) or regions that do not have significant deep sedimentary basins, this option might provide additional potential for CCS implementation.
Funding scheme: small to medium collaborative RTD project

R&D area : Storing CO_2 in deep marine sediments

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- Explore the possibility of storing CO_2 in deep marine sediments, as liquid CO_2 denser than overlying pore fluid or hydrates trapped in the porosity of the rock at high pressures and low temperature
- Investigate the thermodynamics and kinetics mechanisms
- Map potential storage sites offshore Europe, assess potential worldwide
- Assess CO_2 injectivity and stability in these geological formations
- Carry out a techno-economical feasibility study and explore legal issues

Expected impact
This geological storage option in porous marine sediments under 3000 m water depth and a few hundred meters of sediments might have a huge storage potential and high stability.
Funding scheme: small to medium collaborative RTD project

7. CO_2 use and transport

Expected impact:
Large scale use of CO_2 with the benefit of climate mitigation, is above all use of CO_2 in EOR - Enhanced Oil Recovery, EGR - Enhanced Gas Recovery and ECBM – Enhanced Coal Bed Methane. In addition to the climate effect it can have a significant economic and resource management effect. These are firstly dependent on the improved recovery of oil/gas/methane. Transport in pipelines and ships are ongoing, but needs a better scientific basis for design and safe operations in far larger scales. Impurities following the CO_2 are of vital importance.

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring these technologies and concepts to commercial readiness by 2020.

R&D area: EOR/EGR/ECBM with improved recovery of resources
R&D actions (content/scope)

- URGENT! Demonstrations of EOR/EGR/ECBM in a variety of geological settings.
  (Prior to final decision points on large scale investment in power plants with capture)
- Evaluation of EOR/EGR/ECBM potential over Europe;.
- Systematic mapping of properties of CO_2 with a variety of impurities.
- Improved reservoir simulation models with field case verifications.
- *Fundamental research into the interaction between CO2 (as well as N2 and impurities) and coal and its effects on reservoir injectivity.* ECBM *recovery and CO" storage characterisation in situ.*

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Expected impact
The most critical factor for an economic viable EOR/EGR/ECBM is the recovery factor of oil/gas/methane. Little scientific basis and field experience for the CO_2 behaviour in the reservoirs, necessitate low estimates and poor economy. Better basis and models reduces risk. There are untapped resources in hundreds of potential small and large fields in most European countries from on land in the Balkans, through Central Europe to offshore the Norwegian Sea.
Funding scheme: Large demo and medium size collaborative RTD projects

R&D area: Equipment modifications on existing installations to accept CO_2
R&D actions (content/scope)

- Precise corrosion prediction tools for high CO_2 contaminated fluids
- Evaluation of remaining safe operation life for process equipment
- Specific monitoring techniques for extended operation life
- Develop low cost steels more tolerant to high CO_2 levels
- Verify cracking behaviour of pipeline materials for CO_2 (safety and cost)
- Adapted equipment for CO_2 leak detection in a variety of environments.

Expected impact
The existing field installations – on land or offshore – are often not prepared for CO_2 rich fluids. Low cost rebuild will depend on precise prediction and monitoring of its safe performance. This is often the second largest cost factor the resource reclaim is depending on. Future oil & gas prices are less controllable. Pipelines and terminal equipment for handling of CO_2 before/after shipping is mostly dependent on the same materials, design and monitoring techniques as for process installations.
Funding scheme: small size collaborative RTD project

8. Cross cutting issues

Expected impact:

Highly efficient power plants to offset the energy cost of CO_2 capture. Gas turbine combined cycle power plants capable of supporting high efficiency, as a prerequisite for development of affordable Zero Emissions IGCC concepts. Develop recipies for being capture ready depending on technology, and so that power stations built before 2020 easily can retrofit capture technology. Demonstrate the operability and achievable efficiency gain using ultra super critical boilers. Demonstrate how low temperature steam turbines can improve overall efficiency and how CHP plants best can be designed and operated for optimal energy efficiency and CO_2 capture. Show how the CO_2 compression process should be designed and integrated with the power plant in order to minimise the energy penalty from the process.

R&D to enable integrated, large-scale CCS demonstration projects Europe-wide and bring these technologies and concepts to commercial readiness by 2020.

Collaborative RTD projects covering the R&D area below should be considered.

R&D area: Power plant efficiency improvements

R&D actions (content/scope)

Develop materials and determine how ultra or supercritical steam cycles can reach above 50% efficiency in steam power plants, be operated and how processes can be made capture ready depending on the chosen CO_2 capture technology. Achieve over 63% efficiency in gas turbine combined cycle power plants as a prerequisite for development of affordable Zero Emission IGCC plants

- Test plants with 650 °C super heater temperature
- Testing of materials and components for AD 700 boilers, pipe work and turbines (i.e. beyond the COMTES 700 project); design of ultra high-strength materials (e. g. for gas turbine rotors or blades) and associated production technology for (large) components as well as the compilation of assessment methods for material properties and new materials.
- High temperature coating and cooling systems needs to be taken into account.
- Improved combustion systems with low-emission technology to ensure increased efficiencies while meeting environmental needs.
- Development of thermo-mechanical models and simulation tools for evaluating material properties as well as enhanced lifetime modelling.
- Demonstrate advanced and ultra super-critical steam cycle
- Developments to steam systems to take advantages of gas turbine improvements
- Research low pressure steam turbine for improved flexibility when integrating with post-combustion capture plant
- Efficiency improvement in and with combined heat and power production (CHP)
- Recipe for how to make power plants “capture ready” depending on the technology chosen
- Demonstration of various efficiency improvement concepts
- For fuels with high moisture contents, such as lignite, develop, optimise and demonstrate fuel drying technologies, that could be efficiently integrated into power plants.

- Define characteristics of catalytic combustion to minimize O_2 concentration in the incoming flue gas

Funding Scheme

One to two collaborative large scale RTD projects.

Expected impact

Highly efficient power plants to offset the energy cost of CO_2 capture. Gas turbine combined cycle power plants capable of supporting high efficiency as a prerequisite for development of affordable Zero Emissions IGCC concepts. Develop recipies for being capture ready depending on technology, and so that power stations built before 2020 easily can retrofit capture technology. Demonstrate the operability and achievable efficiency gain using ultra super critical boilers. Demonstrate how low temperature steam turbines can improve overall efficiency and how CHP plants best can be designed and operated for optimal energy efficiency and CO_2 capture. Demonstrate the operation of catalytic combustion for flue gas oxygen content reduction

R&D area "Cryogenic Air separation unit" (ASU)

R&D actions (content/scope)

- Ensure developments in air separation are reflected in both pre-combustion and oxy-fuel processes even though the optimum design conditions, e.g. pressures, are different. *Link to specific R&D activities to adapt cryogenic ASU to large oxy-fuel power plants*
- Efficiency and load following advances through development of unit internals.
- Air separation unit compressor development, in size and responsiveness.
- Contaminant control.
- Oxygen production at the optimum conditions for the integrated power plant.

Expected impact

Air separation units for large CCS demo projects which have minimum impact on efficiency, start-up times and load following characteristics.

Funding Scheme

Medium collaborative RTD project

R&D area "Other aspects including i*ssues* generic to all CO_2 capture options (pre-combustion, post combustion and oxyfuel)*"*

R&D actions (content/scope)

- Pre-combustion CO_2 capture may provide opportunities to produce useful by-products other than electricity, for example hydrogen or high grade transport fuels but these are not our current priority.
- Standardisation of economic and efficiency comparisons
- Markets, legal issues, competition, collaboration and funding of large projects
- Efficient funding routes
- Education to meet the long term skills requirements to construct and operate the technologies as well as to allow the general public to understand the generic issues..
- Narrowing down the number of options to maximise the potential gain from all investment routes.

Expected impact

Optimising the economics and long term market position of CCS.

Funding Scheme

Small scale collaborative RDT Project

Develop novel underpinning concepts for demonstration by 2010-2015 and implementation beyond 2020

Collaborative RTD projects covering the R&D areas below should be considered.

R&D area: Ultra High Efficient Steam power plants >50% efficiency

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Comment: Should be adressed in either the oxyfuel or the precombustion chapter

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Comment: these are topics dealt with in other ZEP groups, delete it

golds00d 16-4-07 16:40
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Comment: Move this bullet to the precombustion chapter

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Comment: Merge it with the first one and elaborate it

Further long term research to qualify new designs and materials for the next generation of thermal power plants permitting 700°C+ operation and the testing of these materials in oxy-combustion atmospheres.

R&D actions

- Development of novel steam turbine designs with steam cooling, ceramic coatings, improved clearance control, new sealings and improved aerodynamics, plus further testing of materials and coatings for steam generator, piping, valves and turbine components for 700°C+ operation in pulverised coal air firing and oxy-combustion environments. Cost effective production techniques for these materials need to be investigated.
- Concept studies for alternative approaches for plants with 700°C+ operation and CO_2 capture
- Development of enhanced design tools and codes in order to calculate heat transfer, aerodynamics, component design, and permit fuel and operational flexibility.

Expected impact

Ultra efficient thermal fired power plants will provide benefits to many of the concepts currently being considered for CO_2 capture and will offset the energy penalties associated with this capture.

Funding scheme

At least two large-scale collaborative/demonstration projects.

R&D area: Next Generation Gas Turbines (High efficiency 63% and New Cycle Concepts)

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Comment: Change title to "Gas turbine development for CCS processes" and elaborate

Promote the development of tools and the materials required for the next generation of Combined Cycle Gas turbines with electrical efficiencies of 63%.

R&D actions

- Development of ultra high-strength materials and coating systems for gas turbine rotors, and the production technology to employ them in large components in conjunction with new thermo-mechanical models and simulation tools for evaluating material properties.
- Development of new Sealing and Combustion Systems
- Development of plants with fuel flexibility (different natural gas compositions, syngases, H_2-rich gases and low heating value fuels, such as bio-fuels and industrial gases)
- Basic Research and Development into the Oxy-fuel gas turbines and combined cycles to establish a sound engineering basis for these designs
- Investigation of New cycles for gas turbine based processes integrated with pre- or post-combustion CO_2 capture technologies, including recirculation and closed cycles.

Expected impact

- To provide the bases for the design and development of the reliable next generation gas turbine plants. With regard to oxy-fuel gas turbines, the research and development should be the forerunner to future pilot designs that could be tested within the next 5 to 10 years

Action

Collaborative RTD Projects (Small, Medium and Large Scale focused projects)

R&D area: Improved CO_2 compression process and integration with power plant

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Comment: Elaborate and check wether it makes sense to include also oxyfuel compression?

R&D actions (content/scope)

Demonstrate the optimized compressor integration with power plant:

- Optimization *and* integration of compressor drive with power plant
- Recovery of compressor waste heat
- Minimizing number of compressor trains

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Funding Scheme

One collaborative small scale RTD project.

Expected impact

Show how the CO_2 compression process should be designed and integrated with the power plant in order to minimise the energy penalty from the process.

Support long-term exploratory R&D in advanced, innovative concepts for implementation of next-generation technology

Collaborative RTD projects covering the R&D areas below should be considered.

R&D area: New "Air separation unit" for pre-combustion capture and oxy-fuel

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Comment: move it to emerging technology chapter

Development of new oxygen production or oxygen transfer techniques for incorporation into CCS power plants

R&D actions

- Support development of new technologies for large-scale oxygen production for both pre-combustion and oxy-fuel processes.

Expected impact

Economic and performance improvements to Air Separation units designed for the expected operational conditions for pre-combustion and oxy-fuel processes.

Funding Scheme

Medium collaborative RTD project

R&D area: Reduction in turbo-machinery energy consumption of CCS technology

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Optimising Carbon Capture and Storage (CCS) processes is key to promoting zero emission power plants. Turbo-machinery used for air separation and CO_2 compression units in IGCC and in Oxy-fuel plants are energy intensive and further development of air- and CO_2-compression trains is required.

R&D actions

- Projects focussed on improving efficiency of compressor turbine trains in air separation and CO_2 compression and their related components as well as their integration into the power plant design with possible recovery of compressor waste heat.

Expected impact

Optimisation of the design of Turbo-machinery and it's integration into the plant design to minimise the energy penalty from the process.

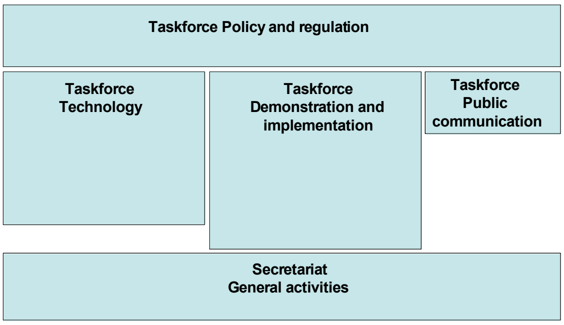
Funding scheme

Collaborative RTD Projects (Small and Medium scale focused projects)

Terms of reference ZEP taskforces

This document describes the proposed terms of reference for the taskforces of ETP-ZEP, as discussed at the workshop of 5 December 2006. These ToR will be the basis for an action plan to be developed by the individual taskforces and to be approved by CG / AC.

The following taskforces have been formed:



The **Taskforce Technology** is asked to carry out the following tasks

1	Organise R&D	
	1.1	Map R&D needs&R&D landscape. Identify and specify the gaps and priorities
	1.2	Induce a higher level of activities&expertise from R&D-side
	1.3	Improve coordination between national programmes and FP7
	1.4	Maintain SRA&working group papers, possibly through a technol. Assessment group
2	Ensure public funding	
	2.1	By mapping the need for additional finance for R&D
	2.2	Through public bodies (EC, member states), jointly with taskforce policy&regulation
	2.3	By initiating public-private-partnership(s)
3	Network and disseminate	
	3.1	Organise technical days aimed at networking researchers and industry

The taskforce Technology will closely work together with the Taskforce Policy&Regulations regarding task 2 (ensure public funding)

TIMING

- ***TF Technology***

<u>Co-leads of TF Technology :</u>

Lars Strømberg, Vattenfall
Dirk Goldsmidth, Siemens
Niels Peter Christensen, GEUS

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 CO2 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 CO2 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 CO2 capture systems.

b) Demonstrate the safety of CO2 geological storage

Experts already agree that CO2 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 CO2 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.