

INTERNATIONAL ENERGY AGENCY, WORKING PARTY ON FOSSIL FUELS

Zero Emission Technologies for Fossil Fuels Technology Status Report

Appendix I: R&D Visions (Request for Project Updates)

A wide array of R&D efforts that address zero emissions technologies for fossil fuels are underway across the globe through sponsorship by country R&D programs, international organizations and industry. The May 2002 publication of the International Energy Agency, *Zero Emissions Technologies for Fossil Fuels: Technology Status Report*, has an appendix that summarizes some of the zero emissions projects by project sponsor. The appendix is by no means a comprehensive listing of the R&D underway in this area and we are in the process of updating and enhancing this information. If you have information that should be included in the next edition of the TSR please contact Pamela Tomski by July 18, 2003.

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INTERNATIONAL

International Energy Agency Greenhouse Gas Programme

The IEA GHG is the leading international collaborative programme on technologies for reducing GHG emissions from use of fossil fuels. IEA GHG conducts technical and engineering evaluations of technology options as well as identifying targets for development and demonstration and then facilitating the progress of such work. It disseminates the knowledge gained so as to enable decision on mitigation technology to be taken with best available information.

IEA GHG was established in 1991 and has since conducted almost 90 separate investigations of technologies. The results form the basis for much of the current understanding and literature on the potential for CO₂ capture and storage as a measure to mitigate climate change.

The IEA GHG is established under the terms of an Implementing Agreement from the IEA. There are currently 16 countries plus the European Commission that support the IEA GHG, along with 8 major industrial companies as sponsors. IEA GHG supports a number of collaborative efforts with industry and governments as found throughout this Appendix.

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Saline Aquifer CO₂ Storage (SACS) and SACS2

The Statoil-operated Sleipner Field in the North Sea is the first case of industrial scale CO₂ storage in the world. CO₂ is being injected into the Utsira formation, a thick saltwater-bearing sandstone at a depth of approximately 1 kilometer below the sea bottom. SACS does careful monitoring of the behavior of the CO₂ storage facility. In addition to demonstrating the long-term feasibility of CO₂ storage in the Sleipner field, the project will also produce a "best practice" manual for CO₂ disposal by monitoring and verifying existing models. To date, approximately one million tonnes of CO₂ are stored in the formation. The SACS project investigates the Utsira Formation and surrounding strata utilizing repeated three-dimensional (3-D) seismic reflection surveys. The CO₂ "bubble" around the Sleipner CO₂ injection well in the Utsira formation was large enough and in such concentrations by September 1999 (3 years after initial injection) to be monitored by a 4D "time lapse" seismic survey. Before the project commenced, it was debated among geophysicists whether CO₂ could be monitored by standard seismic surveys. Expectations changed after the first geological analysis, reservoir simulations and seismic modeling done by the SACS project partners in spring 1999. A major shift in the budget was then made, reducing the volume of geoscience work and moving forward the second seismic survey to the summer 1999. Geochemical work has been hampered by scarcity of sample material. A core from Utsira sand and pore water has been used in initial short and long-term laboratory experiments and the data is still being processed.

SACS was formed by a consortium of energy companies, research institutes and the EU Commission with support from national authorities in Norway, Denmark, The Netherlands, France and the U.K.

Project partners and Funders include: Statoil, IEA GHG EU Energie Programme, BP Amoco, Norsk Hydro, Exxon-Mobil, Vattenfall, TotalFinaElf, the geological surveys of Denmark, France and the U.K., Sintef Petroleum Research, IFP (France), and NITG-TNO (The Netherlands). Statoil and IEA GHG provide international co-ordination and project facilitation.

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GESTCO

(See European Commission for project details.)

CO2NET

IEA GHG is one of the founding members of CO2NET. *(See European Commission for project details.)*

The Weyburn (CO2) Monitoring Project

Facilitated by the IEA GHG, coordinated by the British Geological Survey (BGS) and managed by PanCanadian Resources, the Weyburn Monitoring Project is a joint collaboration among research groups from the U.K., U.S., Canada, Denmark and Italy. *(See project description under Canada.)*

Natural Analogues to the Storage of CO2 in the Geological Environment (NASCENT)

The NASCENT project is a 3-year research study of CO2 accumulations as analogues for geological storage and sequestration of anthropogenic CO2 emissions. *(See European Commission for project details.)*

Recovery and Utilisation of Carbon Dioxide (RUCADI)

RUCADI is a network of 35 partners representing European universities and industry to consider and promote technological, chemical and biological uses of carbon dioxide.

CO2 Capture Project (CCP)

The CO2 Capture Project (CCP), formed in 2000, is an international effort funded by 9 of the world's leading energy companies that places an emphasis on collaboration and partnership with governments, industry, NGO's and other stakeholders. The project seeks to develop new technologies to reduce the cost of capturing and sequestering CO2. The CCP is working to accomplish this objective by: performing benchtop R&D (engineering studies, computer modeling, laboratory experiments) to prove the feasibility of advanced CO2 separation and capture technologies, specifically tagging post-combustion methods, pre-combustion decarbonization, and oxyfuel; developing guidelines for maximizing safe geologic storage, for measuring and verifying stored volumes, and for assessing and mitigating storage risks; developing an economic model to establish lifecycle CO2 separation, capture and sequestration costs for current and best technologies to compare alternatives and direct the research and development towards the most promising technologies; actively transferring and making available the new technologies to industry via publications, presentations, conferences, an internet website, patent licenses and commercial services.

The CCP is leveraging international commitments totaling about \$28 million from the IEA GHG, EU, US DOE, and Norway's Klimatek Programme. Members of the CO2 Capture Project are: British Petroleum, ChevronTexaco, Eni, Norsk Hydro, PanCanadian, EnCana, the Royal Dutch Shell Group of Companies, Statoil and Suncor Energy.

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AUSTRALIA

Commonwealth Scientific & Industrial Research Organization

Capture And Sequestration Projects Within CSIRO

CSIRO is engaged in a number of projects relating to CO2 sequestration. Some of these projects are being run internally within CSIRO, involving collaboration between two divisions, CSIRO Energy Technology and CSIRO Petroleum Resources. There are also projects being carried out through the Cooperative Research Centre for Coal in Sustainable Development (CCSD), in which CSIRO Energy Technology is either a major player or the lead organisation. It should be noted that CSIRO Petroleum Resources is also a major contributor to the GEODSISC program. CSIRO projects include:

Making the Decision on CO2 Sequestration Into Coal Seams

This project is directed at developing fundamental physicochemical descriptions of the coal/ supercritical CO2 interactions as well as the coal/rock/water/CO2 interactions. It will provide quantitative data which will form the basis for deciding what the critical environmental issues are regarding CO2 underground. It involves collaboration between CSIRO Energy Technology and CSIRO Petroleum Resources.

The project, which is in its early stages, is based around laboratory scale experimental studies of absorption and desorption of CO2 on Australian coals. A series of experiments at pressures up to 200 atm and temperatures up to

50°C is planned to investigate the storage characteristics of the coals under supercritical CO₂ conditions. In addition, the kinetics of adsorption/desorption and diffusivity of various coals will be measured to gain fundamental information in relation to movement of gas within coal seams. This will be important when considering injecting CO₂ into deep coal seams.

Development of a Research and Technology Roadmap to Address the Barriers to the Widespread Adoption of Carbon Dioxide Injection Into Deep Coal Seams

The project is directed at producing a Research and Technology Roadmap for the adoption of carbon sequestration into deep unmineable coal seams. The Roadmap will identify areas where research, development or demonstration is required for the technology to be used in Australia as a means of generating low greenhouse gas emission power from Australia's bountiful coal reserves.

The work program is based on a critical evaluation of Australian and overseas publications and expertise in the fields of drainage, capture and sequestration with a focus on the issues critical to sequestration. It will identify the gaps in the knowledge and technology base. The research and technology expertise of the project team, drawn from within CSIRO Energy Technology and CSIRO Petroleum Resources, along with that of selected participants from the Australian Coal Industry will be utilised to identify the most prospective path forward. The project is being carried out with funding from the Australian Coal Association Research Program.

CCSD Projects

The following projects are being carried out within Program 4 of the Cooperative Research Centre for Coal in Sustainable Development (CCSD) to which CSIRO Energy Technology is a major research provider.

Project 4.1 - Portfolio Options and Risk Assessment

In an uncertain environment organisations require investment opportunities that offer flexibility by assisting them to adapt to a range of market or regulatory conditions. The first year of project 4.1 introduced the concept of real options to the CCSD as a methodology for evaluating technological options. The next step is to identify portfolios of existing and emerging electricity generation technologies and their key characteristics. In 2002/2003 a set of portfolio matrices are being developed which list, from a national perspective, portfolios of electricity generation technology options for Australia. These options include capture and sequestration of CO₂ from coal-fired power stations. Once developed, these portfolio matrices will be simulated in CSIRO's Electricity Market Model in order to project the resulting greenhouse gas emissions and electricity prices associated with each scenario. Underpinning the simulations will be a technical and economic evaluation of potential generation systems for Australia.

Project 4.2 - Greenhouse Gas Reduction and Options

This project addresses the transition path for coal in a carbon-constrained world by addressing the technology options for reducing CO₂ emissions from industrial processes using Australian black coal. Large-scale capture and separation of CO₂ at its source and its permanent sequestration represents one of the few pathways by which very significant reductions might be achieved from the point sources represented by coal-fired power stations. This project involves a review of international developments related to carbon dioxide capture/sequestration and zero emission processes, and an evaluation of the technology matches for coal and sequestration options relevant in the Australian context. Work during 2002/2003 is directed at technical evaluation and screening of a number of scenarios for capture and disposal of CO₂ from Australian black-coal fired power stations to determine which are worthy of further investigation, with large scale demonstration as the long term goal.

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Geological Disposal of Carbon Dioxide (GEODISC)

GEODISC is a joint Australian Petroleum Cooperative Research Center (APCRC), government, and industry collaboration project researching the applicability of disposing of large volumes of CO₂ into geological formations within Australia. Geoscience Australia manages the geological aspects of this activity. The GEODISC program will document areas where CO₂ injection is geologically feasible and model and monitor the behavior of CO₂ in the subsurface. It will also carry out a risk assessment to ensure that the CO₂ can be safely and essentially permanently disposed of in the deep subsurface and assess the cost of undertaking CO₂ injection on a commercial scale in Australia.

Duration: The \$10 million program started in July 1999 and will run for 4 years.

Funding: The research is directly funded by industry (BHPP, BP, Chevron, Shell, WAPET and Woodside) and indirectly funded by government and university research groups.

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CANADA

There has been interest in the implementation of components of Zero Emissions Technology (CO₂ capture, storage and utilization) for some time in Canada. At the first conference organized by the IEA Greenhouse Gas Programme on CO₂ capture and storage in Oxford, UK in 1993, Canadians gave papers on, among other topics, amine capture, membrane separation and calcium carbonate formation. Canadian activities prior to that time included pilot projects on CO₂ enhanced oil recovery. A western Canadian information network was also in existence, bringing together interested players and exchanging information on CO₂ capture, storage and utilization technologies.

Congruent with the above interests, Canada was 1 of 12 IEA member countries that founded the IEA Greenhouse Gas Programme in 1991. A high national commitment to this initiative resulted in Canada playing a leadership role since 1995 as Chair of the Executive Committee of the IEA Greenhouse Gas Programme.

Since negotiation of the 1997 Kyoto Protocol, Canada has been working towards its ratification. The target is to reduce annual greenhouse gas emissions to a level of -6% by 2008-2012 relative to the 1990 level, which is estimated to have been the equivalent of 601 megatonnes (Mt) of CO₂. In early 1998, the Canadian federal, provincial and territorial ministers of energy and environment initiated work on a national climate change strategy with a mandate to develop a plan to meet the Kyoto target. This in turn prompted the formation of a national initiative on CO₂ capture and storage at a meeting held in Regina (Saskatchewan) in March 1998, with subsequent gatherings in 1999 in Calgary (Alberta), Halifax (Nova Scotia) and once again in Regina.

The Canadian government provided further recognition of the importance of emissions reducing potential of CO₂ capture and storage in October 2000 in its National Implementation Strategy on Climate Change adopted by ministers. This strategy will be implemented through a series of 3 annual national business plans or Climate Change Action Plans, the first one of which started in 2001. Areas of focus of current Canadian initiatives include: technology development and cost reduction of CO₂ capture using oxy-fuel combustion and amine separation amongst others; acid gas re-injection; monitoring of CO₂ storage in enhanced oil recovery; enhancement of methane recovery through monitoring of CO₂ injected into deep coal beds; storage capacity assessments of Canadian coal seams, sedimentary basins, oil and gas reservoirs; and gasification of coal for electricity production and to acquire pure CO₂ suitable for storage. Many of the projects underway involve public and private sector partnerships, international collaboration, with several of the projects being also led by the private sector. A summary of initiatives underway is presented below.

Suitability of Canada's Sedimentary Basins for CO₂ Sequestration

Sedimentary basins have various degrees of suitability for CO₂ sequestration in geological media as a result of different conditions and geological, hydrogeological and geothermal characteristics. The purpose of the project is to identify on a continental-scale the suitability of approximately 70 sedimentary basins in Canada for CO₂ sequestration in geological media. On a regional scale, the suitability for CO₂ sequestration of the Alberta basin and of the Canadian part of the Williston basin (shared with the US) is being assessed both geographically and stratigraphically.

Duration: Study of the Alberta portion completed in 2000; Williston basin will be completed in December 2002

Funding Level and Funders: \$270,000 Canadian from the federal government for operating expenditures, and matching funds for manpower from the Alberta government through the Alberta Energy and Utilities Board.

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Sequestration of Carbon Dioxide in Alberta's Oil and Gas Reservoirs

Alberta currently has approximately 26,000 gas pools and more than 8,500 oil pools in various stages of production and depletion. The ultimate capacity for CO₂ sequestration in these pools has been estimated using the Alberta Energy and Utilities Board reserves database. Results to date indicate that the ultimate CO₂-sequestration capacity in Alberta's gas reservoirs not associated with oil pools is 9.8 Gt CO₂. The sequestration capacity in the gas cap of approximately 5,000 oil reservoirs is 2.2 Gt CO₂. In contrast, the sequestration capacity in depleted oil pools is only 637 Mt CO₂. Of the more than 8,500 oil pools in Alberta, 4,273 reservoirs were identified as suitable for CO₂-flood EOR. Estimates of the incremental CO₂-sequestration capacity in these reservoirs at CO₂ breakthrough and at 25% and 50% hydrocarbon pore volume (HCPV) of injected CO₂ indicate that an additional 117, 360 or 673 Mt CO₂, respectively, would be sequestered through CO₂-flood EOR.

The objective of the last stage (last year) of the project is to develop and apply reservoir ranking methodology that will consider such elements as reservoir characteristics, CO₂ capacity, injectivity, depth, distance from CO₂ sources and timing, in order to identify the hydrocarbon reservoirs that should be considered first in the implementation of large-scale CO₂ sequestration in oil and gas reservoirs in Alberta.

Duration: April 2000 to March 2003

Funding Level and Funders: \$ 240,000 Canadian from the Alberta Energy Research Institute for operating expenditures only. More than \$300,000 Canadian of manpower-equivalent is provided by the Alberta Energy and Utilities Board.

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Assessment of CO₂ Storage Capacity of Deep Coal Seams in the Vicinity of Large CO₂ Point Sources in Central Alberta

Utilization of the many oil and gas well intersections of deep coal seams to determine the distribution, thickness and depth of deep coals; to determine reservoir properties including pressure and temperature and through experimentally-derived CO₂ adsorption isotherms, to determine the in-place storage capacity expressed as megatonnes/square kilometre.

Duration: This work has continued intermittently since 1997 as funding becomes available from groups outside of the Geological Survey of Canada. Ongoing work, to be completed in 2003, is funded by the Climate Change Action Plan.

Funding Level and Funders: Current funding is \$275,000 Canadian for fiscal year 2002-2003. A separate project is under negotiation to assess the CO₂ storage capacity in Nova Scotia with the Canadian Clean Power Coalition.

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International Test Center for CO₂ Capture, University of Regina

Within this project, the intent is to undertake testing of amines for the capture of CO₂ from relatively dilute, but large volume sources of CO₂ such as coal-fired electrical generators, natural gas turbines and commercial boilers. The capabilities of the Center include bench scale work, small-scale pilot testing and pre-commercial testing on a larger pilot facility attached to a slip stream from a coal-fired power generating station at Boundary Dam in Saskatchewan. Current work is evaluating the optimal use of existing amine technologies. Work will soon proceed to the testing of alternative amines or amine mixtures with the ability to reduce process energy consumption, capital and operating costs further.

Duration: Current research will extend over a 3–4 year period.

Funding Level and Funders: Capital is provided from a variety of sources including federal and provincial.

Operating expenses are \$850,000 Canadian annually (cash and in-kind) with more than 50% coming from industry sources.

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CANMET CO2 Consortium

Pre-competitive research consortium led by the CANMET Energy Technology Center to investigate oxy-fuel combustion based CO2 capture methods. Currently in Phase 6 of a work program focused on O2/ CO2 combustion strategies for retrofit to existing pulverized coal fired power plants. CANMET is the primary performer of the work. Core research program is aimed at development of computer simulation of oxy-fuel flames and validation of burner concepts using a purpose built oxy-fuel combustion pilot plant rated at a 0.3 MW input. Multi-pollutant capture mechanisms being studied in a condensing heat recovery and scrubbing environment using technology supplied by McDermott Technologies Inc, USA. Boiler simulation tools being developed for use in a HYSYS working environment. Outputs of the program are confidential to partners, however several papers have been released in the public domain.

Duration: Program started in 1994, currently in Phase 6

Funding Level and Funders: Currently supported by the Canadian federal government, Alberta government, US Department of Energy, TransAlta Utilities, Sask Power, Ontario Power Generation, McDermott Technology Inc and in the past by EPCOR, Nova Scotia Power and Air Liquide.

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Oxy-Fuel Field Demonstration Project

This project will design, build and test the world's first industrial scale oxy-fuel demonstration system for CO2 capture. CANMET Energy Technology Centre, Ottawa will be responsible for optimizing the overall process and scaling up a proprietary oxy-fuel burner concept. The steam generator shall be modular and truck transportable to one or more field sites to support sequestration pilot opportunities that will be developed in Canada by the Alberta Research Council Coal Bed Methane Consortium. The field unit shall burn natural gas or propane and shall demonstrate safe start-up and shut down practices for oxy-fuel operation. The unit will be sized for a 10M Btu/hr firing rate producing a flue gas mixture of variable N2/CO2 composition, suitable for compression and injection into a variety of geological media.

Duration: 5 years

Funding Level and Funders: currently \$1.5 million Canadian over 5 years from Climate Change Action Plan (CCAP); currently looking for industrial partners.

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Closed Gas Turbine Cycle Project

Performance evaluation of various closed gas turbine cycles utilizing oxy-fuel combustion to produce power and capture CO2. Work program includes simulation activities and primary research at two Canadian universities. Carleton University work aimed at fundamental understanding of compressor performance when changing working fluid to CO2. Funding will support project to design and construct a micro-turbine to study the operation of a closed cycle gas turbine. Work underway at the University of Waterloo to develop simulation of solid oxide fuel cell (SOFC) when integrated into a closed cycle gas turbine.

Duration: 5 years

Funding Level and Funders: currently \$250,000 Canadian over 5 years from Climate Change Action Plan (CCAP) Program

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ZECA Corporation – Zero-Emission™ Coal and Carbon

ZECA Corporation is a private company established in New Mexico, USA in 2001 by certain of the participants of The Zero Emission Coal Alliance (a group of 18 American, Canadian and European interests) who had funded an investigation by Nexant Inc. (a Bechtel Company) to assess the potential of a Zero-Emission™ Coal (ZEC) concept that had been developed by scientists at Los Alamos National Laboratory (LANL) and Louisiana State University and for which a patent is pending. The Nexant report concluded that the concept is technically sound and, although it needs substantial further development, it has the potential to: double the amount of energy extracted from a ton of coal (70% efficiency HHV); completely eliminate emissions (including completely capturing CO₂); and that it could do so at prices competitive with both gas (at US \$ 2.70/GJ) and with modern coal fired generators equipped with state of the art pollution controls and CO₂ capture systems. This study was therefore the basis for ZECA Corporation's organization. ZECA Corporation has the exclusive option to license the LANL ZEC Technology.

Present work is focused on the core 'Los Alamos' ZEC Technology that comprises a gasification/power plant to produce electricity using hydrogasification, a calcium oxide driven reformer and a high-temperature solid oxide fuel cell (SOFC). Using steam from the fuel cell, the reformer converts the coal-derived gas to hydrogen and captures the carbon from the gas, later releasing it as a 'pure' stream of high pressure CO₂ ready for sequestration. The hydrogen is used to fuel both the hydrogasifier and the SOFC while the heat from the SOFC is used to drive the reformer by recycling the calcium oxide. This tightly integrated system has the potential to achieve extraordinarily high efficiencies. The theoretical efficiency is 93% but practical implementations are calculated to be in the order of 68% to 71% using the SOFC and about 55% using a gas turbine. It does this while simultaneously capturing the CO₂ and eliminating all emissions to the air by rejecting other deleterious substances in manageable, solid or liquid streams.

The ZEC Technology not only has the potential to produce electricity from a wide range of carbon fuels (biomass, coke, coal, bitumen, heavy oil, etc...) but it may also have many applications beyond electricity production. As a hydrogen generator and method of CO₂ capture, it may find a place in oil sands, heavy oil and oil refining processes. It could even eliminate the need for carbon (tars, asphaltenes, coke) removal during heavy fuel and oil refining by making complete hydrogenation more practical. In certain configurations it may also be used to produce high quality synthetic natural gas from coal (particularly low-rank coal) or bitumen while presenting the excess carbon as concentrated CO₂ ready for sequestration.

In 2001, ZECA had its significant techno-economic feasibility study done by Nexant. This work did not identify any fatal flaws in the concept and concluded that, when fully developed, the gasification/power plant technology would show good performance, with high overall efficiency (around 70%) and competitive electricity costs when compared to other advanced power generation technologies with carbon capture. Recent work at LANL has shown that the sulfur tolerant, high temperature, solid oxide fuel cells that are essential to the full ZEC Technology concept are likely to be achievable. They have also been able to show that essentially complete removal of mercury is possible from the recirculated aqueous solutions, which would contain all the mercury produced by the power plant. Other advances have been made in the understanding of hydrogasification.

The basic idea of mineral carbonation is that CO₂ can be reacted with magnesium occurring naturally either in brine in deep geological formations or in silicates such as serpentine or dunitite or even in magnesium rich volcanic formations. In the 'surface' case, the CO₂ would be sent to a mineral carbonation plant in which it would be reacted with serpentine or olivine (magnesium silicates) to form magnesium carbonate and silica, which would then be returned to the mine area for permanent disposal. Magnesium carbonate is benign and thermodynamically stable, thus guaranteeing permanent and safe sequestration of the CO₂. The capacity of worldwide magnesium silicate deposits is more than sufficient to handle the captured CO₂ emissions from all the world's coal burning facilities.

The Corporation's policy is to take advantage of early and medium term opportunities that meet its criteria while encouraging development of mineral carbonation. At present, ZECA Corporation is an 'open' organization that invites participation in its share capital and projects. The Corporation's mandate is to become a premier supplier of zero emission coal and carbon technologies. The company is therefore eager to identify and cooperate in the development of a wide range of suitable technologies, applying each to its most appropriate applications.

Investors: current (May 2003) shareholders of ZECA Corporation include: Fording Coal, Caterpillar, Arch Coal, Pinnacle West Capital Corporation, RAG Coal International, Salt River Project (Arizona), EPCOR Utilities and The Coal Association of Canada and, conditionally at their option, SaskPower and OntarioPower Generation.

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Canadian Clean Power Coalition

An association of 7 Canadian utilities and coal producers, the IEA Clean Coal Centre and Greenhouse Gas Programme, and the US Electric Power Research Institute, the Coalition proposes a program focused on "securing a future for coal-fired electricity generation." The proposal provides for the development, construction and operation of a full-scale demonstration project by 2007 that will remove GHG and other emissions of concern from an existing coal fired power facility and a similar demonstration project by 2010 applied to a greenfield coal fired power facility.

The Coalition's proposal is expected to cost approximately \$1.5 billion Canadian. Phase I of the project (conceptual engineering and feasibility studies) has been underway since September 2001, with secure industrial funding and signed agreements with the provinces of Alberta, Nova Scotia, Saskatchewan and the Federal government. Completion of Phase I is planned for mid-2003 with the identification of the technologies to be used in the demonstrations. Phase II (detailed engineering and construction) is expected to commence late 2003. Efforts to find funding for Phase II are just commencing.

Duration: Phase I scheduled completion mid-2003, Phase II scheduled completion 2010

Funding Level and Funders:

Industrial Participants (funding in place)	\$ 1.96 M
Province of Alberta (funding in place)	\$ 0.555 M
Province of Saskatchewan (funding in place)	\$ 0.333 M
Government of Canada (funding in place)	\$ 1.67 M
Nova Scotia Department of Natural Resources (in place)	\$ 15,000 + \$15,000 (in kind)

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IEA Weyburn CO2 Monitoring and Storage Project

The IEA Weyburn Monitoring and Storage Project is an international research project intended to establish the degree of security with which greenhouse gases, particularly carbon dioxide can be sequestered in geological formations during large scale, commercial, enhanced oil recovery operations. This will be accomplished through the scientific mapping of the movement of CO2 in the reservoir, and technical prediction of the future long-term storage and migration characteristics of the CO2. The field laboratory is the Weyburn CO2 Miscible Flood Project, located in south-eastern Saskatchewan, Canada, near the US border with North Dakota. The ultimate deliverable is a credible assessment of the permanent contained of injected CO2 as determined by long-term predictive simulations and formal risk analysis techniques. Results will help answer questions raised by regulatory bodies as to the security of large volume CO2 sequestration/storage not only in the Williston Basin but also at other basins where CO2 storage is contemplated.

Duration: 4-year project

Funding Level and Funders: Total cash funding is \$20.5 million Canadian as well as in-kind contributions valued at approximately the same level. Funding participants include the following organizations: Natural Resources Canada, Saskatchewan Energy and Mines, Government of Alberta, US Department of Energy, European Community, EnCana Corporation, Saskpower, Nexen Canada Limited, BP, Dakota Gasification Co, TransAlta Utilities, ENAA – Japan, TotalFinaElf.

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Enhanced Coalbed Methane Recovery for Zero Greenhouse Gas Emissions

Supported by the IEA Greenhouse Programme and led by the Alberta Research Council, this Canadian project is looking at the commercial viability of coal bed methane (CBM) in Alberta through enhancement of CBM recovery factors and production rates in low permeability CBM reservoirs by injection of carbon dioxide-rich waste streams; and reducing greenhouse gas emissions by subsurface injection (and storage) of carbon dioxide into coal beds with added value from production of CBM. Phase I of the Canadian project was the initial assessment and feasibility of injecting pure CO₂ into deep Mannville coals. Phase II was the design and implementation of a micro-pilot test for injection of pure CO₂ in an existing CBM well located at Fenn-Big Valley in Alberta following Amoco Production Company procedures. Phase III was the assessment of reservoir response to different compositions of injected flue gases and the design and implementation of a multi-well pilot project. Phase IV is the matching of novel combustion and separation technologies to produce a CO₂ waste stream with CBM reservoirs to carry out additional multi-well ECBM pilot tests. To date, all testing undertaken in Phases I-III has been successful and the economics of the process is being accessed.

It is expected that the final results will show gas producers the best way to enhance production from low permeability CBM wells. On the other hand, reducing greenhouse gas emissions is a priority to the utilities and is being addressed. Cost curves will be generated to assess the price per tonne of CO₂ stored in coal reservoirs based on a wellhead price of natural gas and composition of flue gas injected.

Duration: The project started in 1997 and is expected to end in 2005.

Funding Level and Funders: To date more than \$4 million Canadian has been expended. Current partners include IEA Greenhouse Programme, Environment Canada, Canadian Climate Change Action Plan, Geological Survey of Canada, Alberta Innovation and Science, Alberta Geological Survey, Saskatchewan Energy and Mines, US Department of Energy, UK Department of Trade and Industry, Netherlands TNO, Japan Coal, Australian CSIRO, Gas Technology Institute, Suncor Energy, BP, Burlington Resources, Conoco Canada, EnCana Corporation, MGV Energy Inc., ExxonMobil Canada, Husky Energy, PetroCanada, TransCanada Pipelines, EPCOR Utilities, TransAlta Utilities, Air Liquide, Sproule International, Tesseract, University of Alberta, University of British Columbia and BJ Services Canada.

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Acid Gas Re-Injection in Alberta, Canada

At the end of 2001 there were 31 sites in Alberta where acid gas was re-injected into depleted oil and gas reservoirs and deep saline aquifers. The composition of the re-injected gas varies from 20% CO₂ and 80% H₂S to 95% CO₂ and 5% H₂S. These acid gas injection operations in Alberta represent an analogue for geological sequestration of CO₂. Thus, the study of the acid gas injection operations provides the opportunity to learn about the safety of these operations and about the fate of the injected gases, and represents a unique opportunity to investigate the feasibility of CO₂ geological storage.

The Alberta Geological Survey (AGS) of the Alberta Energy and Utilities Board (EUB), and the Alberta Research Council (ARC), are jointly carrying out a project to review the information submitted by operators to EUB in the process of obtaining approval for and running these 31 acid gas injection operations. AGS is reviewing the subsurface characteristics and ARC is reviewing the surface facility characteristics of these operations. One of these sites will be selected and undergo a comprehensive due diligence to establish the viability and importance of this technology for creating greenhouse gas emission credits when a trading market is firmly established.

Duration: December 2001 to October 2002

Funding Level and Funders: \$ 205,000 Canadian from Canadian federal and provincial governments and government agencies and the IEA Greenhouse Gas Programme.

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Sequestration of Carbon Dioxide in Oil Sands Tailings Streams

The objective of this project is to develop the fundamental understanding of carbon dioxide-oil sands tailings chemistry that will allow for the engineering of a co-disposal process. The amount of CO₂ that could be sequestered in mature fine tailings from oil sands is only roughly estimated at this time (from 0.3 to 3 Megatonnes of CO₂ per year). Because the carbon dioxide that would be used in this process is currently discharged to the atmosphere, there would be a direct reduction in greenhouse gas emissions. The impact of carbon dioxide on process water chemistry needs to be understood in considerably more detail in order to confidently implement the consolidated tailings (CT) process with CO₂ instead of gypsum. Although preliminary results are very encouraging, long-term tailings deposit stability has to be determined, along with the long-term water quality.

Aside from direct chemical sequestration of carbon dioxide, and lowered toxicity, there is also an opportunity for improved bitumen recovery from tailings during the mature fine tailings transfer process. The amount and quality of this bitumen needs to be defined since it could have an impact on the economics of any commercial implementation.

The consolidated tailings process involves the addition of calcium to mature fine tailings and sand; addition of carbon dioxide could both reduce the amount of calcium required for the process and at the same time scavenge excess calcium as a calcite precipitate. The consolidated tailings (CT) process (commercialized at Suncor) involves the transfer of mature fine tailings (MFT), addition of gypsum, and mixing with coarse tailings to create a material that can be eventually reclaimed as a soil. During transfer of MFT, bubbling CO₂ could be used to extract residual bitumen from the MFT, while absorption of CO₂ in the MFT would result in favorable properties relative to CT production. This manipulation of the MFT properties using CO₂ could result in a reduction of the gypsum requirement and ultimately reduce the ionic loading in the recycled water to the extraction process. Preliminary work demonstrated an initial minimum chemical sequestration of 120 tonnes of CO₂ per megatonne of CT. Total CO₂ capture is approximately 100 times greater for the preliminary trials and depending upon the rate at which physically sequestered CO₂ becomes chemically sequestered as carbonate and bicarbonate, these results suggest that chemical sequestration would be at a minimum 1200t/Mt for a conventional CT deposit.

The rate dependence of the carbon dioxide capture and conversion to carbonate and bicarbonate is unknown for the oil sands tailings, but if we assume a simple first order relationship, over saturating the CT with carbon dioxide should ultimately sequester even greater proportions of carbon dioxide. Conservatively, this could be as much as ten times greater. For 100Mt CT per year and with potentially 3 operators using the CT process, this could result in a significant sink for carbon dioxide (anywhere from 0.3Mt/year to 3.0 or more). The fundamental studies will be carried out at the CANMET Energy Technology Centre, Devon, with technical input from industry personnel.

Duration: 5 years

Funding Level and Funders: Climate Change Action Plan (\$1 M Canadian); Industry and provincial interests are being solicited; Suncor has contributed some funds in the past and has agreed to provide up to \$50,000 Canadian (potentially more) in kind for 2002.

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Geologic Sequestration of CO₂ and Simultaneous CO₂ Sequestration/CH₄ Production From Natural Gas Hydrate Reservoirs

This research project addresses the feasibility of geologic sequestration of CO₂ as gas hydrate and the possibility of coincident CO₂ sequestration/CH₄ production from natural gas hydrate reservoirs such as those occurring offshore of Canada's coasts or in the Arctic. A variety of natural gases form natural gas hydrates (crystalline substances composed of water and gas), which are known to occur in significant volumes in offshore sediments and beneath terrestrial permafrost. Carbon dioxide can exist as stable gas in a variety of geologic environments characterized by moderate pressure and relatively cold temperatures. A unique feature of gas hydrate is the capacity to concentrate gases within a crystalline matrix, such that a single unit volume of hydrate may contain over 160 volumes of free gas equivalent at atmospheric pressures. While laboratory and field data are lacking, in theory 2 options are available: 1) geologic sequestration of CO₂ in conventional geologic reservoirs, and 2) co-production of methane during sequestration of CO₂ in existing natural gas hydrate reservoirs.

Realization of these concepts has the potential to substantially reduce net greenhouse gas emissions in Canada. Geologic reservoirs with pressure and temperature conditions favoring the formation of stable CO₂ hydrate occur offshore of Canada's coasts and in numerous Arctic settings. In addition, several of the deeper Great Lakes may have geologic settings conducive to stable CO₂ hydrate formation. Given the intrinsic efficiency of CO₂ storage within the clathrate structure, it can be concluded that a huge sequestration potential exists in close proximity to point source emissions in western and eastern Canada.

Theory, and limited laboratory data suggest that excess CO₂, when introduced into a methane hydrate reservoir, may displace entrained methane in favor of the formation of stable CO₂ hydrate. Areas offshore of Canada's west coast, and a number of onshore Arctic locations are known to contain some of the most concentrated methane hydrate deposits in the world. This raises the attractive possibility of coincident production of methane during sequestration of CO₂. Research in this area is in its infancy.

Duration: 4 years

Funding Level and Funders: Climate Change Action Plan, \$307,000 Canadian for 4 years.

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DENMARK

While Denmark does not have a carbon sequestration project, its geologic survey is active in assessing the geologic storage capacity and sites as noted in the various project descriptions.

EUROPEAN COMMISSION

The European Commission's Research Directorate General (Preserving the Ecosystem Research Actions for Energy) supports zero emissions technologies for fossil fuels through a number of collaborative projects as listed below.

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SACS/SACS2

(See IEA GHG Programme for project details.)

CO2STORE

This project investigates 4 new potential cases for CO₂ reservoirs primarily on land. It will continue reservoir simulations and study geochemical reactions to develop final-fate prediction models. This will be supported by new seismic observations. At the same time gravimetrics is introduced as a new method better suited on land. This proposal is currently being negotiated and builds directly on the Thermie/5FP SACS2 project results, which involved monitoring and modeling the injection of CO₂ into the Utsira Sand aquifer, at Sleipner gas field, offshore Norway.

European Potential for Geological Storage of CO₂ from Fossil Fuel Combustion (GESTCO)

GESTCO's principal objective is to provide a major contribution to atmospheric CO₂ reductions that will ensure a stable, affordable and environmentally acceptable supply of energy for all of Europe. In order to meet that objective, GESTCO is currently evaluating the CO₂ subsurface storage potential in 4 principal geological storage types that are known to exist in several regions throughout Europe, including: onshore/offshore saline aquifers with or without lateral seal; low enthalpy geothermal reservoirs; deep methane-bearing coalbeds and abandoned coal and salt mines; and exhausted or near exhausted hydrocarbon structures. Through various case studies of these geological types in different countries GESTCO will: produce detailed geological data for each area; evaluate the significance of all possibilities for alternative uses of the subsurface; evaluate the impact of any leak that may occur; define the location of potential storage areas relative to large point sources (power plants and major industrial sources) of CO₂; conduct reservoir simulations of each potential storage area; make an economic evaluation of the storage potential in each area, and conduct economic comparison of CO₂ free electricity production cost from conventional and renewable energy sources. This information will be utilized to create realistic scenarios that can help determine the cost of CO₂ avoided and/or the increase in cost of electricity generation. A dedicated decision support system can then be developed so that users can evaluate site-specific source/storage options and cost estimates.

Participants: The main governmental participants include: the geological surveys of Denmark, Great Britain, The Netherlands, France, Belgium, Norway, Germany and Greece, which work jointly within the EuroGeoSurveys Association. Private sector participation includes Ecofys (NL), Vito Engineering (B), Greek National Power Corporation, French Geothermal Company, and the National Oil Company of Denmark.

Funders: Funding is provided from the European Union 5th Framework Programme for Research and Development. GESTCO also leverages its efforts by participating in the SACS project and IEA GHG R&D Programme.

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CO2NET

CO₂NET is the European technology-networking programme for CO₂ sequestration into geological storage. CO₂NET is working to establish and build a European Thematic Network of experienced organisations and individuals to facilitate co-operation between these organisations and, in particular, European-funded CO₂ projects. The Thematic Network will enhance the performance and impact of the projects and increase awareness of European activities and fast-track the developing technologies to meet emissions reduction demands. CO₂NET's initial partners include the EC, IEA-GHG, Technology Initiatives, Ltd., BP, the British Geological Survey. The Geological Survey of Denmark and Greenland, also a founding member, manages the project.

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CO2NET2

This will be the continuation of the CO₂NET accompanying measure. CO₂ Thematic Network will facilitate the development of CO₂ capture and storage as a safe, technically feasible, socially acceptable mitigation option. This is one component of an overall strategy for the provision of a safe, secure, climate-neutral energy supply for the European Union. The foundations of the European CO₂ Thematic Network have been laid over the past 10 months by the CO₂NET initiative supported and funded by the EC. Within 10 months, 29 organisations in 9 European countries and the EU funded CO₂ projects have committed to support the Thematic Network to accelerate the enabling technologies towards CO₂ emissions reduction and develop the European Research Area virtual Centre of Excellence for CO₂. Membership is expected to exceed 40 organisations in 2002.

Weyburn Monitoring Project

The primary objective of the project is to understand geo-sequestration of GHGs, particularly CO₂. In addition to the EC, there are numerous project sponsors. (*See project description under Canada.*)

NASCENT

The NASCENT project is a European Commission supported project that commenced in February 2001 and will run for 3 years. It is a study of CO₂ accumulations as analogues for geological storage and sequestration of anthropogenic CO₂ emissions. An understanding of natural analogues is crucial to ascertaining the long-term chemical impact of CO₂ storage, as water-rock-gas interactions may affect CO₂ storage capacity over time. The project focuses on the porosity and permeability of host formations, the integrity of caprock, ground stability, and quality of ground water in overlying aquifers.

Participants: The project coordinators are the British Geological Survey and partners include: Bundesanstalt für Geowissenschaften und Rohstoffe (Germany); Bureau de Recherches Géologiques et Minières (France); Institute of Geology and Mineral Exploration, (Greece); Magyar Állami Földtani Intézet (Hungary); The Netherlands Institute of Applied Science (The Netherlands); Rheinisch-Westfälische Technische Hochschule, Aachen University of Technology (Germany) and Università "La Sapienza" di Roma (Italy). Also collaborating in the project are: BP; IEA Greenhouse Gas R&D Programme and Statoil. The NASCENT project is collaborating with two other projects undertaking research on natural occurrences of CO₂. These projects are: The NACS Project led by Advanced Resources International of the USA and The GEODISC Project in Australia.

AZEP

The 3-year US \$ 9M EC-sponsored Advanced Zero Emission Power Plant (AZEP) project was initiated in 2001 to further develop and test key components such as a membrane reactor and heat exchanger and system integration for a 75 kw unit. A commercial scale demo plant is envisaged in 2007. Norsk-Hydro in co-operation with Alstom is developing the novel concept, which is based on a membrane combustor with integrated oxygen separation. It is envisaged that CO₂ capture can be achieved with significantly lower efficiency penalty than present concepts and that current gas turbine technology can be used hence facilitating retrofit applications.

GRACE

GRACE sets out a 2-year programme that aims to develop technologies that will reduce the cost of capture and separation of carbon dioxide. In addition to further development of existing technologies, the project will research and develop new technologies from their current concept stages to feasible working models.

RECOPOL

In this project the feasibility of greenhouse gas emission reduction by CO₂ storage in subsurface coal seams is studied. Locally produced CO₂ or flue gas from a power plant is injected in the coal at a selected test site in the Silesian Coal Basin (Poland), while CH₄ is produced simultaneously. The CH₄ can be used as fuel for clean energy generation, without net CO₂ emissions. Research is mandatory in this new and complex field of technology to design an optimum development plan for the site. This research involves laboratory work, model simulations, and investigation of time-lapse monitoring. Existing wells at the test site and a newly drilled well will be used for the test, and the injected gas is monitored in time. Together with an evaluation and field upscaling of the results the project will be concluded with a socio-economical and a future technological evaluation, and implemented in a Decision Support System.

JAPAN

Japan has the longest running carbon capture and sequestration technologies research program. The focal point of their program is the Research Institute of Innovative Technology for the Earth (RITE). Established in 1990 as a non-profit organization authorized by the Ministry of Economy, Trade and Industry, RITE focuses on the development of innovative environmental technologies and the broadening of the range of CO₂ sinks. With a budget of JPY9.9 billion, RITE has been conducting R&D and research investigations as well as providing information to the public regarding the advanced technologies and research.

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Project for Biological CO₂ Fixation and Utilization

The focus of this project is to develop technologies to fix CO₂ in the flue gas when generating power at both power plants and factories. In addition to fixation of the CO₂, the project aims to achieve more than 10 times higher efficiency than natural vegetation utilizing photosynthetic microorganisms capable of fixing CO₂ at a higher rate and at extreme temperatures. In addition, the technologies will be studied in order to achieve production of substances from the fixed CO₂ such as hydrocarbons, lipids as well as manure, feed, amino acid and polysaccharide.

Participants: The project is led by a consortium of research organizations and corporations including the Research Center for Advanced Science and Technology, University of Tokyo, Shikoku National Industrial Research Institute, and 15 companies including Hitachi, Ltd, Mitsubishi Heavy Industries, Ltd, and Taisei Corporation.

Project for Chemical CO₂ Fixation and Utilization

This project aims to develop technologies that may continuously recover high-concentration carbon dioxide from stationary sources by large-scale membrane processes, as well as produce useful substances (including methanol) through hydro-generation of the recovered carbon dioxide. Efforts will focus primarily on developing a polymer membrane with excellent separation, permeation and durability performances necessary for CO₂ separation from emission gas. In addition, efforts are being made to develop high performance catalysts with high CO₂ conversion and selectivity toward methanol, as well as to develop a reaction process of high-energy efficiency.

Participants: This project is led jointly by RITE and the Project Center for CO₂ Fixation and Utilization with joint research partners: National Institute of Materials and Chemical Research, National Institute for Resources and Environment, and Osaka National Research Institute.

Project For CO₂ Fixation in Desert Area Using Biological Function

The purpose of this R&D effort is the development of new plants adaptable to the desert environment. Widespread desertification, which has decreased the stock of CO₂ absorbents in the environment, has become one of the main causes of global warming and one of the most critical of global environmental issues. Plant biotechnology and genetic engineering methods will be applied to develop plants capable of withstanding the harsh desert environment of strong sunlight and dry soil.

This research aims at improving plant resistance to drought and light toxicity by ensuring highly efficient photosynthesis through improvement to the critical enzyme RuBisCO. The research also aims at improving the mechanism of toxic-oxygen scavenging. Determining the mechanisms of salt-exclusion and osmotic regulation is yet a further aim of this research.

Study of Environmental Assessment for CO₂ Ocean Sequestration for Mitigation of Climate Change (SEA-COSMIC)

Part of RITE's Ocean Sequestration program, this project aims to determine the behavior of liquid CO₂-seawater injection. This project will conduct research on the technologies of CO₂ transportation to intermediate depths of the ocean as well as to develop models to assess the environmental impacts near the area of injection, including the impact of increased levels of CO₂ on marine organisms. In addition to research, the project will produce a supporting survey on the research trends concerning CO₂ ocean sequestration in Japan and abroad. This is a joint research project sponsored by the National Institute for Mechanical Technology, Hokkaido National Industrial Research Institute, and the Central Electric Research Institute with the cooperation of Massachusetts Institute of Technology (MIT) and the Norwegian Institute for Water Research (NIVA).

THE NETHERLANDS

Many Dutch greenhouse growers burn natural gas in small boilers to produce CO₂ and heat. Although this process is inefficient, conventional CO₂ capture equipment is too expensive and the height of the absorption tower often violates regulations, which require structures not to exceed 15 meters in height. In response to this dilemma, the Dutch TNO Institute of Environmental Studies is developing a membrane gas absorber that can be used for CO₂ capture in cogeneration plants. Only 2 meters high, the absorber utilizes a commercially available polypropylene membrane with a new absorption liquid developed by Dutch engineers. Additionally, the CO₂ available from application of the membrane technology would be 20% cheaper than that produced by burning gas.

Enhanced Coalbed Methane Recovery

The Netherlands Agency for Energy and the Environment (Novem) recently studied the technical and economic feasibility of enhanced coalbed methane recovery (ECBM) in the Netherlands. The work included an investigation of the potential coalbed methane (CBM) reserves underground as well as the related CO₂ storage potential in deep coal layers. The economic evaluation of ECBM recovery analyzed the costs of capturing CO₂ from major stationary sources and CO₂ transport, modeling the production of ECBM using CO₂ injection with reservoir simulations and system analyses to investigate the costs of gas production. The costs of on-site hydrogen and power production (including on site CO₂ removal and injection) were also evaluated.

R&D Inventory of CO2 Removal

Novem commissioned ECOFYS to prepare the R&D Inventory of CO2 Removal.

Norway

Most of Norway's power demand is met by hydropower and any future increase in demand will most likely be met by gas-fired power plants. In order to meet the country's emission targets, the Norwegian Research Council launched the Norwegian National Climate Technology Programme (KLIMATEK) in 1997. The objective was to stimulate a cooperative effort between Norwegian industry, research institutions and government using government funding of US \$18M million (i.e. 25% government cost share). Most of the 50 projects in KLIMATEK's portfolio to date involve offshore petroleum production, process industry, gas fired power production with CO2 capture and CO2 storage. Initially the Norwegian offshore CO2 tax resulted in projects in this sector, however since 2000/2001 the political focus in Norway has shifted towards power generation from natural gas with CO2 capture. To further stimulate this shift, in 2001 the Norwegian government increased its funding to KLIMATEK by NOK 20M to NOK 40M and in 2002 to NOK 65M (US \$ 8M). In 2002 approximately 80% of the KLIMATEK budget supports natural gas fired power generation with CO2 capture and storage. KLIMATEK's financial contribution is cost-shared with industry and typically ranges from 20% to 50% of total project cost. Long-term research in universities and independent research organizations may receive up to 100% financial support.

Funding Level: KLIMATEK is a 5-year US \$ 70M programme to promote the R&D of technology for reducing GHGs.

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Kvaerner Oil & Gas and W.L. Gore & Associates GmbH Project

Kvaerner Oil & Gas and W.L. Gore & Associates GmbH project developed a gas-liquid membrane contactor utilizing a novel membrane absorption process that aims to remove CO2 from flue gas using amine absorption. Unlike conventional capture process technology, the Kvaerner process is both small and compact, enabling the technology to be utilized offshore. The exhaust gas flows through small Teflon membrane fibers, which are surrounded by the absorption liquid. CO2 passes through the membrane and is carried away by the liquid. The huge membrane surface area results in a highly efficient absorption process, thereby reducing the size and weight of process equipment used significantly. The contactor has been demonstrated in a pilot plant at Statoil's gas processing plant in Kårstø on the west coast of Norway.

Electrical Swing Adsorption

In 2001, Kvaerner Oil and Gas, in cooperation with Oak Ridge National Laboratory (U.S.), conducted an initial assessment of electrical swing adsorption. Several fundamental questions still seem to be unresolved.

Funding Level: The Institute for Energy Research in Norway has recently been awarded a NOK 1M research contract by KLIMATEK to pursue critical issues together with ORNL.

Hydrokraft Project: Integrated Reformer Combined Cycle (IRCC)

In April 1998, Norsk Hydro initiated the Hydrokraft Project to evaluate an Integrated Reformer Combined Cycle (IRCC) for a proposed 1200 MW installation on the west coast of Norway. (The plant size was determined by the goal to supply 60M tones of CO2 to the Grane oil field for EOR over a 15-year period.) The proposed plant comprised an auto-thermal reformer (ATR) with CO-shift and absorption using Selexol. The proposed power plant will include a triple-train combined cycle unit with both gas turbine and heat recovery steam generator (HRSG) integrated with the reforming section. Combustion tests carried out in 1999 by Norsk Hydro concluded that commercially available gas turbines can be successfully fired with the hydrogen-rich (40% to 80% in volume) fuel gas, but that its efficiency was around 50%, slightly lower than that achieved with natural gas. The cost of CO2 capture was estimated at US \$36 per tonne. Through this process, CO2 emissions can be reduced by 90%, compared with conventional modern gas-fired power plants. The ATR constituted about 35% of the total equipment costs, while the power plant was estimated to cost 42%. CO2 compression was 7% of the cost and reduced plant efficiency by 2%. The plant was considered too risky because its development was linked with the development of Grane, scheduled to come on-line in 2003.

Zero Emission Gas Power (ZEG) Project

The Zero Emission Gas Power (ZEG) Project (2001-2005) addresses the problem of energy efficient co-production of electricity and hydrogen from natural gas with integrated CO₂-capture. The basic concept of the ZEG-process is to combine solid oxide fuel cells (SOFCs) and a hydrogen production process utilizing the waste heat from the SOFC. Taking advantage of the fact that the fuel and air-streams can be kept separated in a SOFC-system and a novel reforming process featuring integrated CO₂-removal, it is possible to achieve high overall efficiencies and still capture the CO₂. Applications of the ZEG-process range from medium sized, 10 MW, "gas-stations" producing electricity for the local community and supplying FCVs with hydrogen, to large scale power plants in the 100 MW range. The ZEG-process bears resemblance to a process initiated by Los Alamos and now being developed through the Zero Emission Coal Alliance (ZECA) in the US. Contact has been established between the ZEG-consortium and Los Alamos in order to pursue a potential bi-lateral collaboration within technology areas of common interest to the 2 research groups. The process is scheduled to be demonstrated in the laboratory in 2003/2004.

Participants: The ZEG-consortium consists of the Institute for Energy Technology, Christian Michelsen Research and Prototech.

Funding Level: The project is funded by KLIMATEK on a NOK 29M contract; KLIMATEK has also funded NOK 10M (2003-2005) to support SOFC materials technology at Prototech together with the University of Bergen.

Aker Maritime: HiOx Power Plant Project

In 1997, Aker Maritime launched a long-term development programme for emissions-free gas power production. A special-high oxygen based power plant (HiOx), a concept based on boiler or combine-cycle-gas turbine with flue gas recycle, has been examined by Aker Maritime with Alstom Power and other industrial sponsors for a North Sea installation. The closed process produces pure CO₂ and pure water. Together with nitrogen from air separation these components have a potential value, e.g. N₂ and CO₂ are suitable for injection for EOR or CO₂ may be stored. On-going development focuses on the design of a 25 MW CC pilot plant.

SINTEF Energy Research

A long term research programme to improve the energy conversion of natural gas in power cycles with capture of CO₂ started in 2001 at SINTEF Energy Research. The programme covers topics such as high temperature decarbonization, novel CO₂ absorption/adsorption processes, improved combustion systems (pressurized combustion, enriched fuels) and novel power cycles (e.g. chemical looping systems).

Funding Level: Overall budget is NOK 50M (US \$ 7M) over the period 2002 – 2005 funded by KLIMATEK.

Advanced Zero Emission Power Plant (AZEP)

Norsk-Hydro in co-operation with Alstom is developing the novel concept called Advanced Zero Emission Power Plant (AZEP). The concept is based on a membrane combustor with integrated oxygen separation. It is envisaged that CO₂ capture can be achieved with significantly lower efficiency penalty than present concepts and that current gas turbine technology can be used hence facilitating retrofit applications. A 3-year EC sponsored project was initiated in 2001 to further develop and test key components like membrane reactor, heat exchanger, system integration for a 75 kw unit. A commercial scale demo plant is envisaged in 2007.

Funding: US \$9M.

CO₂ Storage Research Projects

Storing CO₂ in geological structures is an attractive option outside Norway, both because of possibilities to improve oil production and existing large saline structures (aquifers) ideally suited for CO₂ storage. SINTEF Petroleum Research and University of Bergen have both been awarded long term research contracts to improve understanding of fundamental mechanisms and critical issues of CO₂ storage in geological reservoirs. Sintef Petroleum Research is focusing on the development of an experimentally verified mathematical model of all processes involved in CO₂ injection and transformation of hydrate and removal/release of natural gas in reservoirs. University of Bergen is concentrating on aquifers and specifically fundamental geochemistry and hydrate mechanisms in relation to long-term safe storage.

Participants and Funding Levels: Sintef Petroleum Research has a NOK 24M contract (2002-2006); University of Bergen budget is NOK 20M (2002-2005). Both projects are partly co-sponsored by industry. Government sponsorship amounts to NOK 33M for both projects.

Ship Transportation of CO₂ Project

The aim of this project is to assess technical solutions and costs for different transport cases between capture sites (power plants and high CO₂-concentration process plants) and point of storage or use of CO₂ (aquifers and CO₂-EOR) in the Northern Europe/Norwegian Sea Basin.

Funders: The project is funded by KLIMATEK, Statoil and other industry partners.

Framo Purification AS: Countercurrent Gas-Liquid Contactor

Framo Purification AS is developing a countercurrent gas-liquid contactor for CO₂-washing using seawater. The project investigated the possibility of permanent ocean storage of CO₂-enriched seawater and solidification of CO₂ from ionic reactions using naturally occurring minerals. Finally the contractor considered the commercial risks to be too large and the development was redirected towards other application areas.

Funding Level and Funders: NOK 13M from KLIMATEK and industrial sponsors in 1999-2000.

The Nansen Environmental and Remote Sensing Center

The Nansen Environmental and Remote Sensing Center is modeling CO₂ injection and uptake in the ocean through its participation in the international project, Global Ocean Storage of Anthropogenic Carbon (GOSAC). Together with leading European research groups and groups in US and Japan the Nansen Center does detailed modeling and validation of numerical models of ocean sequestration of CO₂ from 2-phase droplet plume models to global carbon cycle models.

Funders: Financing is largely from government sources and industrial sponsors.

Umoe Technology: Reducing CO₂ Emissions from Gullfaks Field

Umoe Technology has been investigating measures for reducing CO₂ emissions from the Gullfaks field. Increasing offshore power production efficiency by utilizing gas turbine waste heat in combined cycle power production was identified as the most cost-effective measure. In a detailed follow-up project, the CO₂-reduction potential was confirmed and found cost-effective even for retrofit application at current Norwegian offshore CO₂-tax level (NOK 300/tonne CO₂). Uncertainty related to future offshore CO₂ tax policy and alternative economic CO₂ measures like emission trading was identified as a major obstacle to implementation.

Norske Shell & Siemens Westinghouse: Zero Emission Fuel Cell

Norske Shell and Siemens Westinghouse are conducting a development project directed toward the first demonstration of a unique "zero emission" fuel cell power generation technology fuelled by natural gas. A 250 kW fuel cell system is planned for installation in Norway. The system is intended to demonstrate that the CO₂ normally emitted in exhaust gases can be successfully recovered at low additional cost from a high electrical efficiency power plant. Shell Hydrogen and Norske Shell share a vision to develop efficient fuel cell power plants to eventually be deployed in the offshore Exploration and Production domain.

Saline Aquifer CO₂ Storage Project (SACS)

Statoil is coordinating the Saline Aquifer CO₂ Storage Project (SACS), an international project to develop methodologies for the assessment, planning and monitoring of underground CO₂ storage at the Sleipner field in the North Sea. (*See International Projects for more detail.*)

CO₂ Capture Project (CCP)

Both Norsk Hydro, Statoil and Norwegian technology providers are involved in the international CO₂ Capture Project (CCP), which is conducting comprehensive research on separation methods, developing procedures and guidelines for monitoring and verifying storage of CO₂, and encouraging policies to further the technical and economic viability of CO₂ capture and storage.

Funders: The Norwegian government through the KLIMATEK programme supports these initiative together with DOE in the U.S. and the EC. (*See International Projects for more detail.*)

CO₂ Ocean Sequestration Field Experiment

The Norwegian Institute for Water Research plans to participate in the CO₂ Ocean Sequestration Field Experiment that will inject small amounts of liquid CO₂ into the deep ocean. The test will take place in water nearly 3,000 feet deep, over a period of about 2 weeks. The Norwegian focus will be on the consequences for the marine environment. (*See International Projects for more detail.*)

Coordination Polymers as CO₂ Absorbents

A long-term (2002-2006) basic research project on "Coordination polymers as CO₂ adsorbents" is started at University of Oslo. In this project new and novel adsorbent materials (coordination polymers) will be studied that can selectively and reversibly adsorb/desorb carbon dioxide from ambient to 300°C.

Funding Level and Funders: Overall budget is NOK 10M and KLIMATEK funding is 68%. Major international industry partners are supporting the work.

Projects Without Government Funding:

Statoil: MDEA and Hybrid Solvents

In 1997 Statoil initiated a development programme using improved MDEA and hybrid solvents to separate CO₂ from flue gas. This development reduced costs by 40% and removed 87% of the CO₂ from the flue gas of a 400 MW conventional NGCC power plant.

Statoil: Snøhvit LNG Project

Statoil has proposed to develop the gas discoveries in the Snøhvit area of the Barents Sea and supply LNG primarily to North American markets. The Snøhvit LNG project will require construction of a single-train LNG terminal on the small island of Melkøya near Hammerfest. The gas would be transported through a 160 km pipeline to land where CO₂ will be removed to meet commercial gas specifications and transported via pipeline to a saline aquifer beneath the gas field where it will be re-injected and stored. The project is currently on hold.

Sintef Petroleum: Feasibility and Economic Model Study of CO₂-Infrastructure in North Sea Basin

The aim of this study is to explore the full CO₂-chain (various capture points, temporary storage, ship and/or pipeline transport, CO₂ recovery from offshore storage and final storage or use for EOR or other industrial purposes) and to provide a management and decision tool by the end of 2003 whereby alternatives and possibilities for linking sources and sinks of CO₂ in an area with no CO₂ infrastructure can be assessed.

Funders: Sintef Petroleum together with industry and university partners.

UNITED KINGDOM

The UK Department of Trade and Industry (DTI) maintains several programmes that develop technologies and processes for power generation focused on improving environmental performance and sustainable development. One of most important of these is DTI's Cleaner Coal Technology Programme, a six-year collaborative programme of activities linking R&D with technology transfer and export promotion. The primary objective of the Cleaner Coal Technology Programme is to reduce the environmental impact of fossil fuel power generation, while at the same time maintaining its economic viability as a source of electricity. The DTI hopes that the Cleaner Coal Technology Programme will encourage collaboration between UK industrial, academic and government interests in the development of new methods of electricity generation, including those that incorporate zero emissions technologies.

Closely linked to the Cleaner Coal Technology Programme is an industry-led group, the Advanced Power Generation Technology Forum. The APGTF (www.apgtf-uk.com) meets regularly to consider technology options and R&D needs for the UK. It has issued a number of publications on the approach to zero emissions, including recently a compilation of recommendations from 3 key technology groups (fossil fuel systems, nuclear power, and renewable energy sources) to create an integrated and workable zero emissions strategy.

The DTI has commissioned several studies to help the UK Government define its role in taking forward zero emissions and, more specifically, carbon capture and storage. To this end, a summary report is to be drafted and will review conclusions and recommendations from the studies. The studies include:

Study	Description
Technology status	A review of the status of technologies for capture, transport and storage of CO ₂ . To establish the technology options available, their maturity and where further effort is needed.
Legal issues	To establish very clearly all legal issues surrounding the onshore and offshore handling and disposal of CO ₂ .
Economics	Estimate costs of implementing carbon capture and storage in the UK. To examine various cases studies. To compare costs with other low carbon means for generating power.
Risk	Though non-toxic, it is important for a comprehensive risk assessment to be undertaken. Apart from issues of health and safety, the integrity of the storage process to permanently remove the CO ₂ needs to be examined.
Public perception	To determine the current state of awareness/knowledge and understanding of the general public with regard to carbon capture and sequestration.
International cooperation	Interest in deployment of carbon capture and storage is widespread amongst developed countries. The potential for information, task and cost-sharing offers some attraction. There are also common interests for countries located around the North Sea basin.
Communications	The deployment of carbon capture and storage will have impacts on the general public. In implementing these technologies, it is important that a proactive approach to positively communicate the issues is adopted. A scoping study will consider the options.

The UK Government's recently published Energy White Paper pledged to "*set up an implementation plan with developers, generators and the oil companies to establish what needs to be done to get a demonstration project off the ground.*"

In addition to its national activities, the UK is host country to both the IEA GHG R&D Programme and the IEA Clean Coal Centre. The UK is also active in many projects that have already been described such as Weyburn, GESTCO, SACS, NASCENT, and CO2STORE.

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Gas-Zero Emissions Plant (ZEP)

Alstom Power's Gas-ZEP project captures CO₂ as it is produced in a natural gas-fired power plant. The project explores methods to capture the CO₂ without substantial reductions in plant efficiencies.

Duration: The project will last for 3 years, and the results will be utilized by other groups conducting related research throughout Europe.

Funding Level and Funders: Alstom Power's GAS-ZEP project is partially funded through the DTI's Foresight Link Award scheme. DTI and the research councils will provide Alstom Power and its partners approximately half of the £3.4 million funding requirement.

Development of Advanced Reservoir Characterisation and Simulation Tools for Improved Coalbed Methane Recovery

Led by Imperial College of Science Technology and Medicine, the main objective of this project is to develop technology and tools to more accurately assess the potential for improved methane recovery and CO₂ sequestration by investigating the basic scientific phenomena of CO₂ coal injection and retention. Improvement of coalbed methane (ICBM) is one potential way to improve energy supply diversification options currently under development for coalbed methane (CBM) extraction. Coal reservoir ICBM recovery is broadly analogous to enhancement of oil recovery using injected CO₂ (*i.e.*, injection of CO₂ into the reservoir makes fuel more viscous, thus it flows more readily from the reservoir).

The researchers' primary objective is to achieve a more comprehensive understanding of the fundamental mechanisms of water and CO₂-CH₄ adsorption/desorption, diffusion/counter diffusion, and 2-phase flow under simulated reservoir conditions (stress, pore pressure, and temperature). The results of these studies will then be applied to design of a CO₂-ICBM recovery and CO₂ sequestration simulator for the European industry.

This project investigates the effects of matrix swelling on coal permeability for enhanced coalbed methane (ECBM) recovery and CO₂ sequestration assessment. This investigation will also probe the effects of adsorption induced coal matrix swelling on the permeability of different coals as they undergo methane desorption under laboratory-simulated reservoir conditions.

Enhanced coalbed methane recovery and CO₂ sequestration theory is based on the principle that CO₂ adsorbs onto the coal matrix more readily than methane. Laboratory isotherm measurements for single gases demonstrate that by volume, coal adsorbs approximately twice as much CO₂ as it does methane. Therefore, researchers assume that the enhanced coalbed methane (ECBM)/CO₂ sequestration process stores 2 moles of CO₂ for every mole of methane desorbed.

Generally accepted principles dictate that adsorption/desorption of gas swells/shrinks the coal matrix; because permeability is directly proportional to the cube of cleat width, a small increase/decrease in cleat width may significantly increase/reduce permeability. The project will undertake extensive laboratory testing and numerical relationships in order to determine the matrix swelling effects on permeability of coal. The project will conduct extensive laboratory testing, including an examination of numerical relationships, to assess coal and reservoir properties.

Funders: This project is supported by the EPSRC and led by ICSTM.

The High Pressure Interaction of Coal with CO₂: Implications For CO₂ Disposal and For Methane Displacement From Coal Seams

The project, led by the University of Strathclyde, aims to provide fundamental information about CO₂/coal interactions at high pressure in order to optimize methane displacement and CO₂ disposal. The project will investigate how much CO₂ can be stored in coal at different pressures and how difficult it is to diffuse through coals of different rank, while determining the amount of coal irreversibly absorbed. A range of experimental techniques will be used including high-pressure differential scanning calorimetry, volumetric adsorption, high-pressure gravimetric analysis, high-pressure small angle neutron scattering and temperature programmed desorption/mass spectrometry.

Funders: Funded jointly by DTI and the British Coal Utilisation Research Association (BCURA)

UNITED STATES

The U.S. is undertaking a broad range of carbon sequestration R&D throughout various government agencies, universities and the private sector. The U.S. Department of Energy's Office of Fossil Energy and the National Energy Technology Laboratory administer DOE's Carbon Sequestration Program. There are currently 60 projects in DOE's portfolio with total funding of about \$100M-- industry cost share represents 40% of the total. In FY03 program funding was \$40M.

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CO ₂ Capture Projects	Primary Contractor
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO ₂ Capture and Sequestration Description: Develop a novel oxy-fuel boiler to reduce the complexity of CO₂ capture.	Praxair, Inc.
Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation Description:	Tennessee Valley Authority
CO ₂ Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream Description: Develop a process that captures CO₂ by combining it with water at low temperature and high pressure, thus forming CO₂/water hydrates, ice-like macromolecular structures of CO₂ and water. Laboratory experiments seek to determine the level of CO₂ removal achievable, measure energy requirements, and assess any negative effects attributable to hydrogen sulfide and methane gases.	Nexant
A Collaborative Project to Develop Technology for Capture and Storage of CO ₂ from Large Combustion Sources Description: Conduct an integrated collaborative technology development project aimed at proving the feasibility of advanced CO₂ separation and capture	BP Corporation

technologies. The team will develop an economic model to compare different approaches and will also develop guidelines for safe CO ₂ storage in underground formations.	
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents Description: Develop a CO ₂ separation technology that uses a regenerable, sodium-based sorbent to capture CO ₂ from flue gas. Thermodynamic analysis and preliminary laboratory tests indicate that the technology is viable. Process data will be collected to assess the technical and economic feasibility of various process configurations. This retrofit process is amenable to all conventional steam-generating power plants.	Research Triangle Institute
CO ₂ Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO ₂ Description: Develop a high temperature CO ₂ -selective membrane to enhance the water-gas-shift reaction efficiency, while recovering CO ₂ for sequestration. The improved membrane is ideally suited to integrated gasification combined-cycle power generation systems.	Media and Process Technology Inc.
CO ₂ Separation Using a Thermally Optimized Membrane Description: Manufacture a high-temperature polymer membrane with better separation capabilities than current polymer membranes. The project focuses on the separation of CO ₂ , methane, and nitrogen gases in the range of 100 to 400°C.	INEEL
CO ₂ Separation Using a Thermally Optimized Membrane Description: Manufacture a high-temperature polymer membrane with better separation capabilities than current polymer membranes. The project focuses on the separation of CO ₂ , methane, and nitrogen gases in the range of 100 to 400°C.	LANL
CO ₂ Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO ₂ Capture/Utilization/Disposal Options	ANL
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers Description: Build upon international work in the area of fossil fuel combustion in mixtures of oxygen and recycled flue gas. Consider advanced combustion systems in the context of producing salable by-products, for example, CO ₂ used in enhanced oil recovery.	ALSTOM Power, Inc.
Carbon Dioxide Capture by Absorption with Potassium Carbonate*	University of Texas at Austin
An Integrated Modeling Framework for Carbon Management Technologies Description: Develop a computer model that will allow different technology options for carbon capture and storage to be systematically evaluated at the level of an individual plant or facility, considering both carbon emissions control and the impact on criteria air pollutants, air toxics, and solid wastes.	Carnegie Mellon University
Zero Emissions Power Plants Using SOFCs and Oxygen Transport Membranes	Siemens Westinghouse Power Corp.
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO ₂	Princeton University
Methodology for Conducting Probabilistic Risk Assessments of CO ₂ Storage (BP Project)	INEEL (BP)

Sequestration Projects**Primary Contractor**

Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University
Geologic Screening Criteria for Sequestration of CO ₂ in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama Description: Develop a broad-based geologic screening model to quantify the CO ₂ storage potential of the Black Warrior coalbed methane region in Alabama, and apply the model to identify additional sites with high CO ₂ -storage potential.	Alabama Geologic Survey
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers Description: Compile a regional data inventory of saline water-bearing formations in the domestic United States. Develop criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO ₂ .	University of Texas at Austin (BEG)

<p>Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide</p> <p>Description: Create a novel well-logging technique using nuclear magnetic resonance to characterize geologic formations. Explore the use of hydraulic fracturing to improve the permeability of saline formations and thus lower the cost of CO₂ injection.</p>	Texas Tech University
<p>Geologic Sequestration of CO₂ in Deep, Unmineable Coalbeds</p> <p>Description: An Integrated Research and Commercial-Scale Field Demonstration: Use existing recovery technology to evaluate the viability of storing CO₂ in deep unminable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. Apply the knowledge gained to verify and validate gas storage mechanisms in coal seams, and to develop a screening model to assess CO₂ sequestration potential.</p>	Advanced Resources International/ BP Amoco
<p>Enhanced Coalbed Methane Production and Sequestration of CO₂ in Unmineable Coal Seams</p> <p>Description: Demonstrate the use of "slant-hole" drilling to degasify unmineable coal seams. Upon drainage of 50-60 percent of the CBM, CO₂ will be injected into some of the slant-hole wells to enhance CBM production.</p>	Consol
<p>Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production</p>	University of Kentucky Research Foundation
<p>CO₂ Sequestration Potential of Texas Low-Rank Coals</p>	Texas Engineering Experiment Station
<p>Reactive, Multi-phase Behavior of CO₂ in Saline Aquifers Beneath the Colorado Plateau</p> <p>Description: Conduct an in-depth study of deep saline formations in the Colorado Plateau and Rocky Mountain region with the goal of determining how much CO₂ can be stored, what happens to the stored gas, and the long-term environmental acceptability of the storage.</p>	University of Utah
<p>Experimental Evaluation of Chemical Sequestration of CO₂ in Deep Saline Formations</p> <p>Description: Evaluate and examine factors that affect chemical reactions in underground saline formations, specifically reactions that convert CO₂ to a stable solid. Focus on conditions typical of deep saline formations in the Midwestern United States. Current results indicate the most promising long-term option for sequestration is to store CO₂ in a dense, supercritical phase in deep saline sandstone formations.</p>	Battelle Columbus Laboratories
<p>GEO-SEQ</p> <p>Description: Investigate safe and cost-effective methods for geologic sequestration of CO₂. Targeted tasks address the following: (1) siting, selection, and longevity of optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO₂.</p>	LBNL
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<p>Effects of Temperature and Gas Mixing in Underground Coalbeds</p>	Oak Ridge National Laboratory
<p>Feasibility of Large-Scale CO₂ Ocean Sequestration</p> <p>Description: Monterey Bay Aquarium Research Institute will use a Remotely Operated Vehicle (ROV) to deploy small quantities of liquid CO₂ in the deep ocean. Below about 10,000 feet the density of liquid CO₂ exceeds that of seawater, and the liquid CO₂ is quickly converted into a solid hydrate by reacting with the surrounding water. Using a Raman spectrometer, scientists will assess the impact that the CO₂ hydrate material has on the ocean floor and ecosystem.</p>	Monterey Bay Aquarium Research Institute

Environmental Permitting	PICHTR
Ocean Carbon Sequestration (Offshore hydrate evaluation) Description: Synthesize CO ₂ /water hydrates in the laboratory and study their physical properties. Explore a concept where the methane hydrate is replaced with CO ₂ hydrate, enabling hydrocarbon recovery and carbon sequestration in a single step.	Naval Research Laboratory
International Collaboration on CO ₂ Sequestration (CO ₂ Ocean injection) Description: A demonstration injecting 40-60 metric tons of CO ₂ 3,000 feet below the ocean's surface is currently scheduled to take place in the summer of 2001 at Keahole Point off the Kona Coast of the big island of Hawaii. It is an international effort, involving the governments of the United States, Japan, Norway, Australia, and Canada and two private corporations, ABB of Switzerland, and the Central Research Institute of the Electric Power Industry (CRIEP).	MIT
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians Description: Assess methods for reforesting mine lands to achieve long-term carbon sequestration. Apply growth and yield models to commercial tree species and quantify the maximum amount of carbon that can be stored. Use this information to predict the per ton cost of carbon sequestration. Investigate a "carbon credit" market between landowners and utility and coal companies, and analyze the impact of carbon trading and sequestration on the local economy.	Stephen F. Austin State University
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University
Carbon Sequestration on Surface Mine Lands	University of Kentucky
Exploratory Measurements of Hydrate and Gas Compositions	LLNL
Enhanced Practical Photosynthesis Carbon Sequestration	ORNL
Soil Enhances from Solid Wastes*	PNNL ORNL
Advanced Plant Growth (The plant-centric component)	LANL

(NETL projects not included)

Measurement Monitoring & Verification Projects	Primary Contractor
Weyburn Carbon Dioxide Sequestration Project Description: There is an ongoing CO ₂ enhanced oil recovery project at the Weyburn field in Canada. The objective of this effort will be to measure and study the movement of the injected CO ₂ at the Weyburn field with the goal of expanding the knowledge base of the capacity, transport, fate, and storage integrity of CO ₂ injected into geological formations.	Natural Resources Canada - CANMET
Natural Analogs for Geologic Sequestration Description: Perform a multi-disciplinary geologic and engineering study of U.S. CO ₂ deposits to 1) evaluate the safety and security of geologic sequestration, 2) adapt specialized CO ₂ operations technology to an emerging sequestration industry, and 3) document analogs for public review. Efforts will be focused on the McElmo Dome and the St. Johns Dome in Colorado.	Advanced Resources International
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO ₂ Migration	University of California, San Diego
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)
Development of a Carbon Management Geographic Information	MIT

System for the US	
Economic Evaluation of CO ₂ Sequestration Technologies Description: Develop methodology for evaluating the storage potential and efficiency of different CO ₂ storage options.	Tennessee Valley Authority
MIDCARB (Interactive Digital Carbon Atlas) Description: Develop a database of CO ₂ point sources and potential sequestration sites in five Midwestern states (Illinois, Indiana, Kansas, Kentucky, and Ohio). Make the database available to potential users to facilitate awareness of sequestration opportunities.	University of Kansas Center for Research
CO ₂ Reservoir Improvements	ANL
Sequestration of CO ₂ in a Depleted Oil Reservoir Description: Investigate down-hole injection of CO ₂ into depleted oil reservoirs in New Mexico. Conduct a comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts to understand the geomechanical, geochemical, and hydrogeologic processes involved. Use the observations to calibrate, modify, and validate the modeling and simulation tools.	Sandia National Laboratories
Sequestration of CO ₂ in a Depleted Oil Reservoir Description: Investigate down-hole injection of CO ₂ into depleted oil reservoirs in New Mexico. Conduct a comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts to understand the geomechanical, geochemical, and hydrogeologic processes involved. Use the observations to calibrate, modify, and validate the modeling and simulation tools.	LANL
Ecosystem Dynamics and Econ. Anal	LANL
GEO SEQ Project (Project in Sequestration Area)	LBNL
GEO SEQ Project	LLNL
GEO SEQ Project	ORNL
Long Term CO ₂ Monitoring, Containment, and Storage Technology Development (BP Project) Description: Conduct an integrated collaborative technology development project aimed at proving the feasibility of advanced CO ₂ separation and capture technologies. The team will develop an economic model to compare different approaches and will also develop guidelines for safe CO ₂ storage in underground formations.	LLNL (BP)
Geologic Carbon Sequestration Monitoring and Modeling (BP Project)	LBNL (BP)

(NETL projects not included)

Breakthrough Concepts Projects	Primary Contractor
Recovery & Sequestration of CO ₂ from Stationary Comb. Systems by Photosynthesis of Microalgae Description: Characterize types of flue gas and determine what separation and clean-up technologies are necessary to maximize conversion of CO ₂ to microalgae. Select species of microalgae that can withstand the harsh conditions associated with flue gas, have optimal rates of carbon fixation, and have the ability to convert CO ₂ into inorganic carbonates. Design an industrial-scale sequestration system for combustion units. Model the sequestration process to perform an economic analysis and provide cost-effective solutions.	Physical Sciences, Inc.
Chemical Fixation of CO ₂ in Coal Combustion Products and Recycling Through Algal Biosystems	Tennessee Valley Authority
Enhanced Practical Photosynthetic CO ₂ Mitigation Description: Demonstrate the technical and economic feasibility of an enhanced photosynthetic system that uptakes CO ₂ from flue gases at power plants. The systems will separate sunlight into spectral regions to maximize cyanobacterial growth. The goal is to have a self-powering system that can decrease CO ₂ concentrations on-site in a	Ohio University

relatively small space.	
Fuel-Flexible Gasification-Combustion Technology for Production of H ₂ and Sequestration-Ready	GE Energy and Environmental Research Corporation
CO ₂ Mineralization Description: Design and build pilot-scale mineralization test facilities. Conduct experiments aimed at (1) speeding up mineralization reactions, (2) reducing heat input requirements, and (3) lowering reactor operating pressure.	Albany Research Center
Photoreductive Sequestration of CO ₂ to Form C1 Products and Fuel	SRI International Corporation
Advanced CO ₂ Cycle Power Generation	Foster Wheeler
Enhancement of CO ₂ Emissions Conversion Efficiency by Structured Microorganisms (cyano-bacteria conversion of CO ₂)	INEEL
Mineral Sequestration of CO ₂ - Chemical Dissolution Approaches	LANL

Non-CO ₂ GHG Mitigation Projects	Primary Contractor
Full-Scale Bioreactor Landfill Description: Demonstrate controlled landfilling techniques that can affect waste decomposition rates, optimize landfill gas recovery, and reduce long-term environmental risks.	Yolo County
Capture and Use of Coal Mine Ventilation Air Methane	CONSOL Energy Inc.