Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 3
L.I. Eide (Ed.)

INTRODUCTION

Lars Ingolf Eide[1] and Linda Curran[2]
[1]Stian Kristensens vei 33, N-1348 Rykkinn, Norway
[2]BP Alternative Energy 150 W. Warrenville Road, Naperville, IL 60563, USA

BACKGROUND

The CO_2 Capture Project (CCP) is an international cooperative partnership between industry, governments, academics and environmental interest groups. The project is focused on technology development to reduce the cost of CO_2 capture and to demonstrate that geological storage is safe and secure. CCP is a three stage technology development programme with overall objectives to:

- Deliver major cost reductions in the cost of Carbon Capture and Storage (CCS), relative to the 2000 baseline and make CCS cost competitive with other low or no carbon energy alternatives
- Demonstrate to external stakeholders that geological CO_2 storage is secure, measurable and verifiable.

Phase 1 of the programme, CCP1 (2000-2004), progressed capture technologies to proof of feasibility and defined and started closing key technical gaps within geologic storage of CO_2.

Phase 2 of the programme, CCP2 (2005-2009), brought forward the most promising capture technologies from CCP1, and some new ones, to reduce technical and cost uncertainties, scale-up operations by at least one order of magnitude and bring at least one capture technology to a "ready-for-pilot" stage. Other goals for CCP2 were to:

- Contribute to establish best practice for site characterization, process optimization, monitoring and verification and risk assessment for geologic storage of CO_2.
- Increase public acceptance and awareness of CCS.
- Expand economic/ infrastructure scenarios for the whole CCS value chain.
- Advance the science and expand the potential scope of implementation of CCS technologies through international industrial, academic and governmental co-operation.

Within the storage program, the objective of CCP2 was to further develop the most pressing storage issues, with emphasis on:

- Risk assessment and certification guidelines and protocols
- Wellbore integrity
- Geo-mechanical stability of reservoirs and caprocks

The full industry members in CCP2 are BP, Chevron, ConocoPhillips, Eni, StatoilHydro, Petrobras, Shell, and Suncor. Government agencies provided co-funding for select portions of the program. Two sub-programs are co-funded with the European Commission – Chemical Looping Combustion Gas Power (CLC GP) (Chapters 5 – 8 of this book) and CACHET (Chapters 10 – 16),one with the Research Council of Norway - Climit (Chapters 4, 9 and 24) and one with the US Department of Energy (DOE), (Chapters 25-27).

In addition to the co-funding with European and US funding sources, CCP2 participated in Phase 9 of the Canadian CANMET CO_2 R&D Consortium ENERGY Technology Centre program. This program included modeling of advanced supercritical oxy-coal plants, performance testing of a pilot scale unit and investigation of phase change in CO_2 gas mixtures, testing of a novel oxy-fuel steam burner, development of a mercury removal process, and development of pulverized coal combustion processes for oil sands, and petroleum coke in air and oxygen enriched environments. A summary of the Phase 9 program is reported here in Chapter 18.

CCP2 has been a Carbon Sequestration Leadership Forum (CSLF) Recognized Project since September 2004, because it met the evaluation criteria of the CSLF for collaborative research, development, and demonstration projects that reflect the CSLF member countries priorities.

Phase 3 of the CCP programme (CCP3) is planned for the period 2009 – 2013. Phase 3 will continue to develop "ready for demo" selected technologies and target participation in capture and storage demonstrations. Scenarios that will provide the context for which technologies will be demonstrated and further developed are: 1. Natural Gas Combined Cycle (NGCC) power station; 2. Oil refinery (applying oxy-fired Fluidized Catalytic Cracker, FCC); and 3. Once Through Steam Generator (OTSG) for a heavy oil scenario. Within Storage, Monitoring and Verification (SMV) the main themes will be Storage Assurance research and development**,** Field Trials, and understanding stakeholder issues.

ABOUT THIS BOOK

This book is a collection of peer reviewed scientific papers that describe the technological advances made in CCP Phase 2. It is the third volume, following on from the first two, published in 2005, which summarized achievements in CCP1 [1,2]. This introductory chapter provides background on the development of CCP, including its structure, organization and technology selection process and a brief summary of CCP1 results.

Following this introduction, a paper by the Chair of the CCP Advisory Board (CAB), Vello Kuuskraa, summarizes the views and recommendations of the CAB. Thereafter follows a section devoted to CO_2 capture. There are 13 scientific papers, of which one, Chapter 18 by CanmetEnergy, is a collection of several shorter contributions rather than one long paper. In addition there are three non-scientific chapters and one concluding chapter. The non-scientific chapters include an overview of the entire capture program of CCP2 and introductions to the two projects co-funded with the European Union: Chemical Looping Combustion Gas Power (CLC GP) and Carbon Dioxide Capture and Hydrogen Production from Gaseous Fuels (CACHET). Following the technical capture papers is a paper with the performance and cost evaluations of 22 combinations of the CCP2 technologies and different applications (scenarios).

Thereafter follows a section on underground storage of CO_2. The section follows the same pattern as that on capture – an overview chapter of the program in the beginning followed by seven scientific papers and a concluding chapter.

The book ends with two chapters summarizing activities within Policy and Incentives (P&I) and Communications.

The scientific papers report on the results from work carried out under CCP2. Several of the capture technology projects were continuations of work carried out under CCP1. This must be kept in mind when reading the papers.

The CCP Executive Board and management as well as the editor have strived for a selection of papers of high scientific standard. All technical/scientific papers, except the contribution from CANMET, have been reviewed by at least two referees. All but three of the twenty reviewed papers, were reviewed by persons without connections to CCP. Only one paper was reviewed solely by persons employed by a CCP company. Overview and summary papers have not been reviewed.

All chapters of this book will be available for downloading as individual papers from the website http://www.co2captureproject.org

THE STRUCTURE OF THE CO_2 CAPTURE PROJECT

CCP2 has two levels of membership:

- Full membership for companies that take part in all CCP2 activities and have representation on the Executive Board and all working groups.
- Associate membership for companies that are focused on advances in CO_2 geological storage, policy development and stakeholder discussion and engagement. In addition to regular SMV and Policy meetings, Associate Participants participate in annual meetings of the CCP Executive and Technical Advisory Boards, NGO outreach meetings and public/government meetings. Associate Participants have opportunities to participate in future technology demonstrations. Associate members in CCP2 have been EPRI (Electricity Power Research Institute) and Repsol YPF.

Structure and Management Process

The structure of the CCP2 project is illustrated in Figure 1. The Project has technical teams staffed with experts from the participating companies and technology providers that work together to deliver the program results. These teams are focused on technology development to reduce the cost of CO_2 capture, demonstrate that geological storage is safe and secure, and communicate policy matters that will impact the effectiveness of CCS technology.

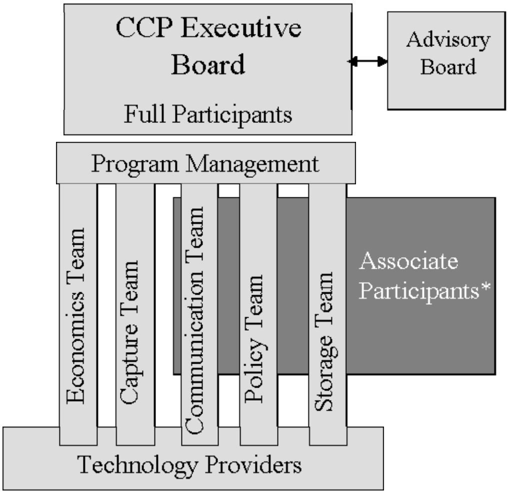

Figure 1. The CCP2 Project Structure.
* See text for definition of Associate Participants

Executive Board

The Executive Board consists of one member from each of the eight CCP2 full member companies and exercises overall control and governance of the program of work and prioritization of specific projects to be undertaken and funded by CCP2.

CCP2 Advisory Board

The CCP2 Advisory Board (CAB) consists of international technology experts selected by the Executive Board to provide independent advice and review of the CCP2 technology program. The CAB provides assurance for the quality and integrity of the technology program and challenges the Technical Teams and Executive Board to reach beyond short term needs to define an approach to technology development encompassing a broad range of industrial users of energy and fuel sources.

Program Management

The Project Manager provides direction to the teams for the delivery of the program goals within the overall budget and timeframe set by the Executive Board.

Technical Teams

Each of the technical teams was led by a designated Technical Team Leader. Technical Teams were formed by the Executive Board for the purpose of progressing development of technology in approved areas. Each Technical Team included at least one representative from each participating company. The teams regularly reviewed and compared the development of technologies, allowing the teams to prioritize and focus on the technologies with the best results for specific applications.

The technical teams were assigned the following tasks within their areas:

- Capture and Economics: advance technology development of the selected technologies; assess their performance, evaluate cost and compare the costs and benefits of various approaches to capture.
- Storage, Monitoring, and Verification: verify the feasibility of underground storage, and develop improved assessment, monitoring and verification methods.
- Communications: build awareness of technical developments among policy makers and interested stakeholders.
- Policy: assess the impact of proposed government policies and regulations on CO_2 capture and storage processes and costs.

Technology Providers

CCP2 engaged with Technology Providers to develop the CCP technical program. Technology providers include academic institutions, research companies, CCP2 participants, national laboratories and expert consulting firms.

Within the Capture and SMV teams, dedicated persons were given the responsibility to act as technical focal points for the Technology Providers.

CCS TECHNOLOGIES IN CCP

Technology Selection Process

The foundation for CO_2 Capture and Storage (CCS) technologies selected for CCP2 was laid in CCP1, where approximately 200 technologies were evaluated for potential application to full-scale development. The selection process is described in [1]. Here follows a brief summary:

The Phase 1 selection of technologies took place in two stages. First, numerous concepts being promoted by technology developers, researchers, and entrepreneurs were screened for their potential in a Review and Evaluation (R&E) process. The criteria selected by the teams for the R&E stage were:

- Likelihood to achieve target cost reductions relative to existing (baseline) technology.
- Health, Safety, and Environmental performance requirements must be met. The technologies must be safe for workers and the environment. The technology must be robust to ensure that the plant will operate efficiently and have high availability for use.
- Relevance to Participants' emission sources: The technologies must have the potential to be applied to Participants' commercial operations without significant negative impact.
- Able to meet CCP's schedule: The technologies must be sufficiently well advanced to prove that the concept will work by the end of 2009. The preferred technology must be sufficiently developed to be ready for larger scale implementation by 2010-11.
- Acceptable to government and public stakeholders. Potential emissions must be understood and control methods available to limits currently defined. Ideally, one would like to identify a small number of full system-based capture technologies that could serve in many different industrial applications. Phase 1 revealed that none of the considered technologies would be likely to achieve this; also it indicated that no technology had been developed to a stage where one could be certain about the performance and cost. Therefore, the selection of technologies to be brought into the next step took place in the Analysis Phase, in which the goals were to:
  - Screen and rank technologies relative to CCP Key Success Criteria.
  - Select technologies for further development.
  - Decide budget allocations by:
    - Technology theme (pre-, post-, oxy-fuel combustion)
    - Technology theme for each Scenario
  - Agree slate of potential technology developers.
  - Agree process to access novel technologies.

The research, engineering and analysis phases (the main work of CCP1) provided strategic direction for the third and last activity of CCP1, the Technology Development Phase. The technologies that passed the Analysis Phase were funded for further development. The results are presented in 34 technical papers in [1].

CCP1 ACHIEVEMENTS - BACKGROUND FOR CCP2

Capture

In the Technology Development Phase, CCP1 commissioned around 35 engineering and/or research studies for further development and performance assessment of the selected technologies. The technologies were evaluated within four different application scenarios, Table 1. The capture technologies listed in Table 1 were compared to a state-of-the-art, post-combustion solution using amines (MEA) or, in the Canadian case, a state-of-the-art Integrated Gasification Combined Cycle (IGCC).

Table 1. CO_2 capture scenarios used in CCP1.

Application	Location	Fuel source	CO_2 source	Capture technology
Refinery	Europe	Hydrocarbon gas and liquids	Heaters and boilers	Oxy-fuel, Pre-combustion
Natural Gas Combine Cycle power plant	Western Norway	Natural gas	Large gas turbines	Post- and pre-combustion
Distributed turbines	Alaska North Slope	Natural gas	Small gas turbines	Pre-combustion
Gasification	Western Canada	Sold fuels, petroleum coke, coal	Steam, electricity and hydrogen coproduction	Advance capture solutions

Post-combustion approaches included integrated solutions, exhaust gas recycle and membrane contactors. The pre-combustion cases included membrane water gas shift (MWGS), sorption enhanced water gas shift (SEWGS) and a complete membrane based hydrogen reformer. The oxy-fuel approach included revamping heaters and boilers for burning the fuel in pure oxygen as well as the Chemical Looping Combustion (CLC) technology.

The studies revealed that significant cost reductions may be achievable. Pre-combustion technologies had the largest potential, with cost reductions between 44% and 60%, depending on technology, whereas post-combustion and oxy-fuel showed cost reduction potential in the ranges 43% - 54% and 38% - 48%, respectively.

Despite the extensive research and development behind the studies it became clear that the cost reductions are connected with large uncertainties, as none of the technologies were tested beyond laboratory scale, and some did not progress further than economic analysis studies. Additionally the uncertainty in the cost estimates was $\pm$ 30%.

Storage, Monitoring and Verification (SMV)

The Research & Engineering Phase of CCP1 produced state-of-the-art descriptions of the technologies, technical gaps needing additional work and recommendations that were carried into the Analysis Phase. The technologies were organized into the following areas:

- "Integrity" - assessing the competence of natural and engineered systems to retain CO_2 over extended periods.
- "Optimization" - strategies for improving the efficiency and economics of CO_2 transportation and storage.
- "Monitoring" - identification of techniques suitable for tracking CO_2 movement within (performance) and outside (leakage or seepage) the injection target.
- "Risk Assessment" - development of concepts, protocols and methodologies to quantify probability and impact of CO_2 leakage from storage sites.

The SMV program for the Technology Development stage was comprised of some 30 projects. The constellation of industry, academic and government programs addressing geological CO_2 storage considered risk-based approaches that entailed identifying technical questions and addressing them by leveraging the existing natural and industrial analog knowledge base and developing new R&D avenues. Whereas some projects were based on a specific asset or storage venue type, the applications developed are universally applicable.

CCP2 – FURTHER PROGRESS

The CCP2 Capture Technology portfolio

The CCP2 portfolio of capture technologies consists of seven pre-combustion technologies, two oxyfiring concepts and one post-combustion technology. The scenarios were reduced to two – a natural gas fired power plant in Northwest Europe and a refinery. The refinery scenario included studies of a fluidized catalytic cracker (FCC) in South America in addition to heaters and boilers in Northwest Europe. A summary of the CCP2 capture Programme is given in Chapter 2 of this book and the results of the different technology projects are reported in Chapters 3 – 18. The technologies may be grouped as follows:

- Technologies with completion date in 2008. These technologies received a major part or all of the funding from CCP2.
- Technologies with completion date in 2009. These technologies received funding from CCP2, the EU and the technology providers.

One major outcome of the CCP2 capture work is that the uncertainties in cost and performance that were still lingering from CCP1 have been reduced. Several of the technologies have now been produced at significantly larger scales and have been subjected to much longer and more realistic tests. In addition, improved manufacturing methods have made cost estimates more accurate and realistic. Although the improvement in uncertainty has not been quantified, it is fair to say that there is now a better understanding of the cost of CO_2 capture than existed at the completion of Phase 1 in 2004.

Although the uncertainties in cost and performance have been reduced in CCP2, the evaluations in Chapter 17 basically confirm the CCP1 estimates of CO_2-avoided costs and the ranking of the technologies. This raises the issue of what can be done to reduce the costs further. The Economics Team points out in Chapter 17 that there appears to be a relationship between high capture rate and low efficiency and that although this relationship may not hold for all technologies it would be worthwhile pursuing the cost implication for relevant technologies.

The CCP2 Storage Technology Portfolio

The CCP2 portfolio for storage, monitoring and verification (SMV) consists of seven technologies. Chapter 20 summarizes the technologies together with the participating R&D institutions and co-funding sources. The portfolio consists of 1) Certification Framework (CF), an integrated platform for site certification for CO_2 permitting, operation and decommissioning; 2) well integrity logging, sampling, modelling, history matching, and simulation of post-closure sealing capability over extended time periods; 3) testing the capability of standard logging tools to detect a sharp interface between free-phase CO_2 and brine; 4) coupling of geo-chemical and geo-mechanical models; 5) simulation of safe and effective operational constraints and monitoring for CO_2 injection in coal beds; and 6) a field test of airborne remote sensing technologies. Details of the study results are given in Chapters 21 - 27.

At the start of CCP2, site assessment and other regulatory developments were high on the international agenda. The integrity of wells that have been exposed to CO_2 over long periods was thought to be a potential CO_2 storage "showstopper" and there was a focus on coal beds as a major potential venue for CO_2 storage. The CCP Storage program has addressed these issues and significant progress has been achieved:

1. The CF contributed to the CO_2 and brine leakage-risk part of the process for licensing and permitting and has provided a useful set of guidelines and procedures for assessing the viability of a CO_2 storage site.

2. The examination of wells exposed over long time periods has indicated this likely is not a major issue. Phase 3 will provide additional focus on this question.

Furthermore, the SMV Program of CCP2 has made advances in the development of reservoir simulators that combine reactive transport with geo-mechanical analysis and in modelling and monitoring CO_2 injection in coal beds. The industry standard RST tool was evaluated for use in detecting the presence of CO_2 in saline waters, and an airborne multispectral imaging system was evaluated for detecting CO_2 and methane leakage from perforated pipelines.

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