PUBLIC ACTIVITY REPORT

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PAGES **46**	RESPONSIBLE **Leif Brandels, Vattenfall/ Kristin Jordal, SINTEF Energy Research**	
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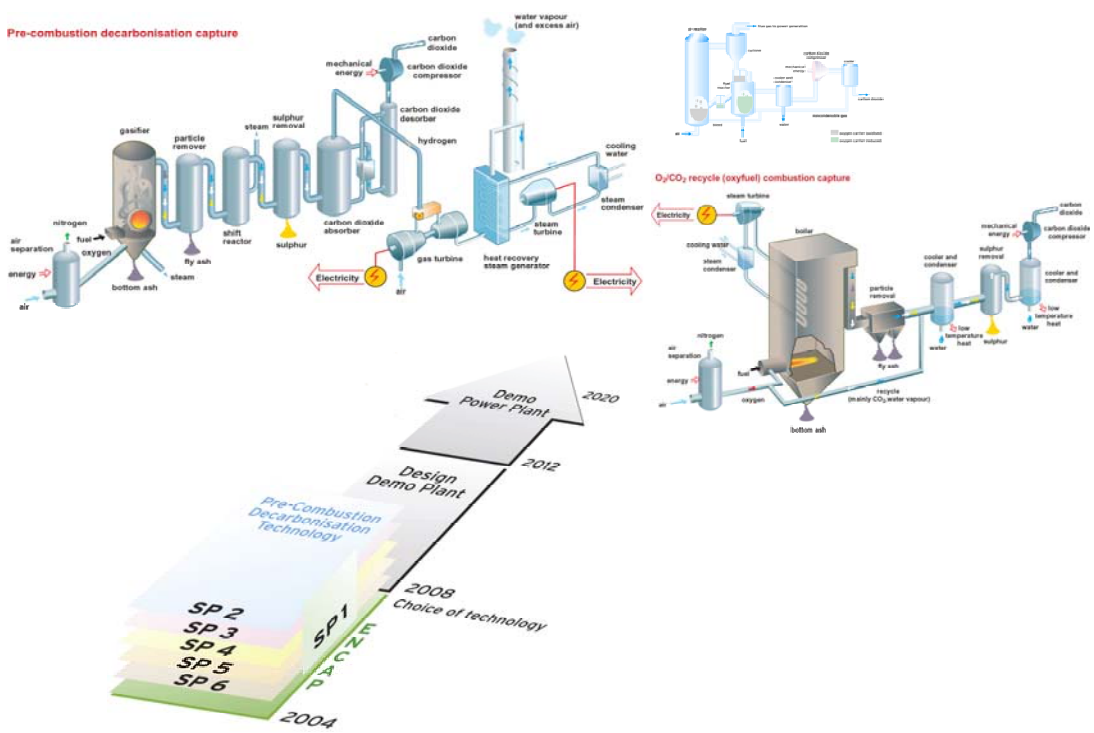

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1 INTRODUCTION

The purpose of the present Public Activity Report is to summarise the work, results and conclusions from the ENCAP project (ENhanced CAPture of CO_2).

The ENCAP project was conducted during five years (March 2004-February 2009) under the EU FP6 research programme.

Targets

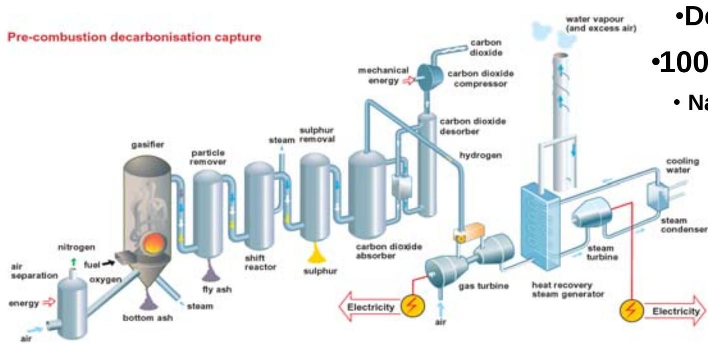
The goal for the ENCAP project has been to develop and validate a number of CO2 pre-combustion technologies that in large Power Plants meet the target:

- 90 % CO2 capture rate and
- 50% capture cost reduction – from a level of 50-60 € per tonne of CO_2 avoided.

Five years of intensive development of many CO2 pre-combustion technologies and components

The ENCAP project has included development and validation of a large number of CO2 pre-combustion capture technologies and concepts.

Significant development of concepts of Pre-Combustion Decarbonisation - IGCC for hard coal and lignite and IRCC for natural gas were initiated in the beginning of the project. Further development and validation of H2-rich fuel combustion concepts gas turbines based on lean-premixed technology have successful performed test rigs.

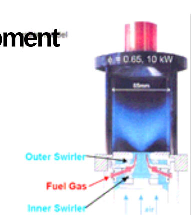


•Developed concepts

•1000 MWel Bituminous coal/lignite

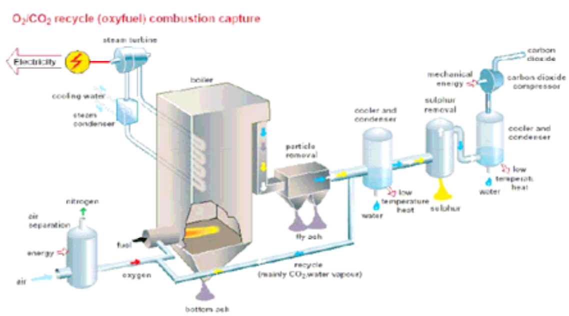
• Natural gas -fired 400 MWel CCGT

•New burner development



•New burner testing

OxyFuel Combustion concepts using hard coal and lignite has been developed and validated for a number of size including both PC concepts and a CFB concept.



•Developed concepts

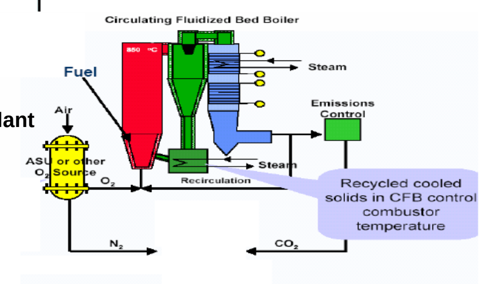
600 MWe Bituminous coal OxyFuel PF plant

•1000 MWe German lignite OxyFuel PF plant

•380 MWe Greek lignite OxyFuel PF plant

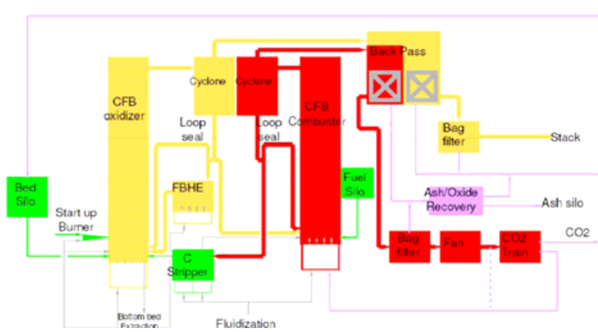
•Developed concept

450 MWe Bituminous coal OxyFuel CFB plant



The development and validation of the IGCC concept and the OxyFuel concept within ENCAP has generated results that put them as candidates for near future actions.

The project has performed development and research on components for a Chemical Looping Combustion using coal and pet coke. The results indicate a promising concept. A number of oxygen carriers have been tested. Tests with different coals has been performed in prototype scale Two innovative prospective concepts based on the chemical looping principle using natural gas has been studied and tested in laboratory scale.



•Developed concept

455 MWe CLC CFB

Coal tests in CLC CFB 10 kW Prototype at Chalmers

Experimental investigation of combustion

-10 kW IVD Stuttgart
-100 kW Chalmers Gothenburg
- 500 kW IVD Stuttgart test rig

The OxyFuel concept and the IGCC concept use oxygen in the process. The ENCAP project has developed three high-temperature oxygen generation concepts including integration of the concepts into power plants in order to investigate their competitiveness to the established cryogenic technique.

The project has investigated a number of prospective emerging technologies and further developed OxyFuel combustion cycles for natural gas and Pre-combustion capture cycles for natural gas and hard coal.

CO_2 Capture influence on the European power situation and the possibility to meet specified CO2 reduction targets has been studied in different scenarios. This study includes descriptions of conditions in all EU member states concerning likely developments of the power generation systems. Development was made of a simulating/optimizing model for scenario analysis on how large-scale introduction of CO2 capture – especially using technologies developed in ENCAP - and storage will influence the European energy system, taking the energy infrastructure into account.

ENCAP consortium – a well composed consortium for the task
The ENCAP consortium has been well composed to take the development and validation towards the project target. The unique consortium includes five large European energy companies, eleven leading European technology providers and twelve high ranked research providers.

Energi E2/DONG	**Air Liquide**	**BOC**
PPC	**ALSTOM Power Boiler (Fr)(GE)**	**Linde**
RWE Power	**ALSTOM Power Centrales**	**Lurgi**
Statoil	**ALSTOM Power Ltd (UK)**	**Mitsui Babcock**
Vattenfall	**ALSTOM Ltd (CH)**	**Siemens**

DLR	**SINTEF**	**Chalmers**	**University of Twente**
IFP	**TNO**	**NTNU**	**University of Stuttgart**
ISFTA		**University of Paderborn**	**University of Ulster**

Project structure
The RTD activities in ENCAP have been structured in 6 sub-projects:

- SP1: Process and Power Systems
- SP2: Pre-Combustion Decarbonisation Technologies
- SP3: OxyFuel Boiler Technologies
- SP4: Chemical Looping Combustion
- SP5: High-Temperature Oxygen Generation for Power Cycles
- SP6: Novel Pre-Combustion Capture Concepts

The R&D issues on ENCAP that affect processes and systems – the developed and validated concepts studied in SP2 through SP6 – have been consistently scrutinised in SP1, thus guaranteeing the coherence of the data performed in the project. The SP1 work has covered the comparison between the power plants with different pre-combustion decarbonisation, oxy-fuel technologies and other pre-combustion technologies developed in the ENCAP.

2 MAIN PROJECT CONCLUSIONS

The ENCAP project had a two-phase approach. The initial phase included the main development of concepts and the construction of test rigs. The development of the concepts and the supporting techniques and new materials during the first phase was successful.

The second phase entered in 2006 focused on further development and validation of the developed concepts in first phase. A specific Large Scale Testing activity was planned for the second phase. The development of concepts in the first phase should be base for the selection of the most relevant test object towards the ENCAP goal for this Large Scale Testing programme.

Developed and studied CO2 Pre-Combustion concepts for large power plants
ENCAP has during the five-year period further developed and optimised the concepts and processes of a selection of large-scale power plant with CO2 pre combustion capture technologies.

Concepts for the near future
The IGCC and IRCC power plant concepts were deemed to be feasible already before the start-up of ENCAP. The further developments of these concepts including CO2 capture process optimising and adaptations of gas turbine combustors to lean-premixed H2-rich low-NOx combustion in ENCAP confirm this feasibility. Significant knowledge of CO2 capture integration and its costs and impact on the overall efficiency has been achieved.

Based on the ENCAP guidelines for consistent concept evaluation and benchmarking, it could be concluded that two of the studied pre-combustion concepts with CO_2 capture have a capture rate of at least 90%. The lignite-based IGCC concept is considered to reach a capture rate of about 85%, mainly due to that the selected fluidized bed gasifier is to produce a syngas with the relatively high methane content (which will generate CO2 when combusted in the gas turbine). The calculated CO2 avoidance cost for the reference case concepts using hard coal is around 25 Euro/tonne and for lignite around 18 Euro/tonne. CO2 avoidance cost for the gas concept is calculated to 36 Euro/tonne.

One of the key issues with the fuel gas that remains after removal of the CO_2 is that it has high hydrogen content. Current syngas/H_2-enriched gas turbine burners run in diffusion mode. For limiting the formation of NO_x, heavy dilution of the fuel is needed (nitrogen, steam) and only moderate turbine inlet temperatures are possible. Such burners and concepts have been further developed by Alstom and Siemens and tested in ENCAP. It is evident from the research carried out in ENCAP that important steps have been taken but lean premix H_2 combustion remains a challenge. It has been concluded that further work is necessary to develop and demonstrate full size low NOx premix burners/ gas turbines with H_2-rich gases for IGCC concepts with CO2 capture.

For the IGCC/IRCC concepts studied all components are commercially available but not with operation experience for similar condition. IGCC with AGR and shift reactor has to be demonstrated reliable. High efficient (F-class) gas turbine with enriched H2 fuel combustors needs further development as earlier mentioned.

Power plant concepts studied in ENCAP on coal-based OxyFuel combustion were known to be feasible before the start of the ENCAP project. ENCAP has included development and specification of various sizes of both PF and CFB OxyFuel concepts. ENCAP high ranked research providers have tested and validated the OxyFuel process and principle in the most relevant OxyFuel test facilities in Europe (10kW, 100kW and 500kW).

The results concerning the use OxyFuel combustion in large power plants generated in ENCAP altogether confirms the feasibility. Significant knowledge of the technical feasibility, costs, efficiency and risks has been achieved.

The consistent concept evaluation and benchmarking carried out in ENCAP concludes that OxyFuel power plant concepts with CO_2 capture have a capture rate of at least 90%. The calculated CO2 avoidance cost for the larger reference case concepts using hard coal is around 18 Euro/tonne and for lignite around 16 Euro/tonne. CO2 avoidance cost for the CFB concept using hard coal is considered to be around 20 Euro/tonne and 12 Euro/tonne for a concept using pet coke.

The project concluded that a relevant further validation step of the OxyFuel technology was 30-50MW. A 30MWth OxyFuel PF Pilot plant was year 2006 selected by the project for the initial planned Large Scale Testing activity in the second phase of the project. However, it was finally concluded that this test programme could not be executed within the time frame of the ENCAP project.

For the OxyFuel concepts studied, it has been concluded that most of the processes are proven technology. The OxyFuel fired PF boiler and the full integration of the process components are however still in pilot-plant stage.

From the research carried out in ENCAP on OxyFuel combustion, it is evident beside validation testing in pilot plant scale, that main areas for further research should be dedicated to finding optimum, corrosive resistant boiler materials for OxyFuel firing conditions and to cleaning of the CO_2-rich flue gas.

A concept for further research
The project has performed development and research on concepts and components for Chemical Looping Combustion technology. A design concept for a 455 MWe supercritical coal CLC-CFB (Circulating Fluidised Bed) boiler operating with coal and pet coke has been developed and sized. The work shows that the CLC CFB is a feasible concept, close to conventional CFB processes.

Already prior to ENCAP, materials development for stable oxygen carriers was ongoing, without finding an optimum material, which combines good stability with good oxygen carrier properties. This topic has therefore been important part of research in ENCAP. A large number of potential oxygen carrier materials were tested in ENCAP with pet coke and six different coals, and scale-up of manufacturing methods was investigated. Solid fuel Chemical Looping Combustion was demonstrated on a lab-scale (10 kWth) for the first time ever, providing proof of concept. The lab-scale feasibility testing results of the reaction of solid fuels with oxygen-carriers was used for the design study of the large CLC concept.

Results from the design concept study of the 455 MWe CLC-CFB were included in the ENCAP concept evaluation and benchmarking. The results from the benchmarking indicated a promising technology with a low efficiency penalty (~2%) and cost penalty (~10 EUR/tonne CO2 avoided). It must be pointed out that this technology for gas and solid fuels has been tested only at small pilot scale. Much R&D work remains and further steps in up scaling are therefore needed to support the ENCAP conclusions concerning the chemical looping combustion reactors of full-scale power plant size. Further research is also need to find relevant oxygen carriers with stability and low costs.

Two innovative prospective concepts based on the chemical looping principle using natural gas has been studied and tested in laboratory scale.

Development and testing of alternate oxygen production processes

The ENCAP project has developed three high-temperature oxygen generation concepts; Oxygen separator membrane for power plant cycles; High temperature oxygen adsorbent (CAR) and Oxygen-transport membrane systems for power production:

The CAR concept with cyclic oxygen adsorption/desorption was found to be the most mature of three investigated high-temperature oxygen generation options. The two other was found interesting but need significant more time for further development. Due to the ENCAP project time frame the further work then focused on the CAR process and further experimental work was performed in order to find the optimum CAR material and geometry. One material could be selected based on a trade-off between chemical stability and performance (i.e. oxygen storage capacity) under dynamic conditions.

The project includes a study of the CAR oxygen-process integration into IGCC and OxyFuel Power Plants. It was found that oxygen generation with CAR is competitive with the corresponding OxyFuel PF case with a cryogenic ASU in terms of cost of electricity, but that it has a lower thermal efficiency (38.2% with CAR vs. 41.0% with ASU). It should however be pointed out that the relative immaturity of the CAR concept for large-scale operation implies larger uncertainties in the cost estimate of this concept compared to an OxyFuel concept with a cryogenic ASU.

For all high-temperature oxygen generation options, challenges remain with finding the optimum integration in a power process with CO_2 capture and with materials stability.

Novel pre-combustion capture concepts

ENCAP has investigated a number of prospective emerging pre-combustion decarbonisation and OxyFuel capture technologies that are estimated to have a high potential for capture cost reduction while maintaining a high capture rate.

An important result is a structured two-step evaluation of 17 novel process concepts for pre-combustion decarbonisation and OxyFuel combustion revealed the natural gas fired OxyFuel Combustion Cycles as the most promising novel concepts, showing an acceptable thermal efficiency and without requiring any significant scientific breakthrough (in e.g. combustion engineering and aerodynamic design) for their realisation. These options generally can be described as less mature than the other concepts developed in ENCAP, (most are at the conceptual level).

CO_2 avoidance cost for these cycles, however, was estimated to be 40-47 EUR/ton CO2 avoided, meaning that they do not meet the CO2 cost target of ENCAP.

The strength with performing the work within the ENCAP project is the possibility to compare all the selected most promising novel concepts with all other pre-combustion developed in ENCAP based on the ENCAP guidelines for consistent concept evaluation and benchmarking.

ENCAP has created guidelines for relevant comparison of CO2 capture technologies
The ENCAP project has included the development of a number of CO2 capture technologies. One goal for the project has been to compare the developed concept and in the end of the project recommend one of concepts for large-scale demonstration.

The project has created guidelines for such a comparison of the developed large full-scale power plant concepts in ENCAP. The guidelines have been used not only within ENCAP for comparison but also by other project within FP6 and FP7. They can thus be regarded as "unofficial" guidelines used for a number CO2 capture projects sponsored by the European Commission.

From "knowing" of technologies to extended knowledge of two technologies usable as background for decision of pre-design of large demonstration power plants
ENCAP has generated knowledge and results that have been part of information for power companies to launch design projects by 2008-2009 aimed at large-scale demonstration plants. ENCAP has also delivered results that have the potential for commercial exploitation beyond year 2015.

Decision for initiating pre-design on such demonstration project has been announced by the ENCAP partner RWE - 450 MWe (gross) IGCC power plant and the ENCAP partner Vattenfall - 250 MWe (gross) OxyFuel demonstration plant.

ENCAP partners ready for further development and a next step in European efforts of CO2 Capture demonstration
The further development of CO2 pre-combustion by the ENCAP consortium has been carried out during an important period when the interest of the overall CCS concept has gradually increased. The knowledge generated and that is in the hand of the ENCAP consortium and several partners in the consortium have already been activated in further development of CO2 capture technologies in new CO2 capture projects in FP7 and the EC RFCS programme.

A number of ENCAP partners are assumed to take part in the up coming discussed steps of development of CO2 capture demonstration projects. The knowledge archived in the ENCAP will be an important background in these efforts.

CO_2 Capture influence on the European power situation
CO_2 Capture influence on the European power situation and the possibility to meet specified CO2 reduction targets has been studied in different scenarios. The results from the study on CO_2 Capture influence on the European power situation show that it is possible to meet an 85% CO_2 reduction target by 2050, requiring a large contribution from CCS, with a steep ramp-up post 2020, which imposes challenges for timely investments in corresponding CCS infrastructure. The results should not be seen as predictions of energy futures but rather a quantitative analysis investigating the possible roles and limits for different technologies, including CCS.

3 SP1 PROCESS AND POWER SYSTEMS

3.1 Motivation of work

The SP1 work has covered the comparison between the power plants with different pre-combustion decarbonisation, oxy-fuel technologies and other pre-combustion technologies developed in the ENCAP subprojects. A great number of technical descriptions of such concepts and cost data exist in international sources and the development inside and outside Europe was followed. However, these data are based on different presumptions and cannot easily be compared with each other. No directly relevant model was found for the comparison and recommendation that SP1 is making in ENCAP. Altogether, the development of uniform guidelines for the description of relevant power plant performance and cost calculations was necessary to meet the objective of the ENCAP project.

3.2 Objectives

The objectives for the work in SP1 were to:

- Establish a methodology to ensure consistency in evaluations and benchmarking of capture technologies included in ENCAP SP2-SP6.
- Assess the impact of the candidate concepts on the economy of power production and reflection of their technical maturity and development risks
- Consider the impact of CO_2 capture on regional and European level on energy systems.

3.3 Work performed and results

Guidelines for technology concepts and benchmarking of concepts

Within SP1, a common framework was established for the development and benchmarking of power plant concepts in SP2-SP6. This framework included:

- A set of defined baseline power plants without CO_2 capture for lignite, bituminous coal, pet-coke and natural gas, as well as boundaries for technical and economic analysis.
- Three CO_2 quality requirement scenarios for transport and storage, to be used as design basis
- Guidelines describing how the different CO_2 capture technologies should be evaluated both on quantitative evaluation parameters such as break-even electricity cost, specific CO_2 emission avoidance cost etc. and on 18 different qualitative evaluation parameters.

This framework was established and agreed upon by the major European power industries and equipment suppliers, who also are ENCAP partners. The Guidelines and specifications of boundaries for power plants with CO_2 capture developed in ENCAP have been used also in other relevant CO_2 capture EU projects within the 6 FP Programme (CASTOR, DYNAMIS, CACHET).

Assessments were made of the impact of candidate power plant concepts with CO2 capture on the economy of power production and in reflection of their technical maturity and development risks. The project concludes concerning the maturity and development risks that for the IGCC/IRCC concepts studied all components are commercially available but not with operation experience for similar condition. IGCC with AGR and shift reactor has to be demonstrated reliable. High efficient (F-class) gas turbine with enriched H2 fuel combustors needs further development. For the OxyFuel concepts studied, it has been concluded that most of the processes are proven technology. The OxyFuel fired PF boiler and the full integration of the process components are however still in pilot-plant stage. The CLC technology needs Much R&D work remains is needed for the CLC technology and further steps in up scaling are therefore needed to support the ENCAP conclusions concerning the chemical looping combustion reactors of full-scale power plant size. Further research is also need to find relevant oxygen carriers with stability and low costs.

No comparisons were made between different fuels, and no ranking of concepts was made. The results are published in the public reports D1.2.4 and D1.2.6 that can be found on the ENCAP website (www.encapco2.org). The reports can also be sent in pdf-format on request to encap@sintef.no. Examples from this report of quantitative results for coal fired power plant concepts are shown in Figure 1 - Figure 3.

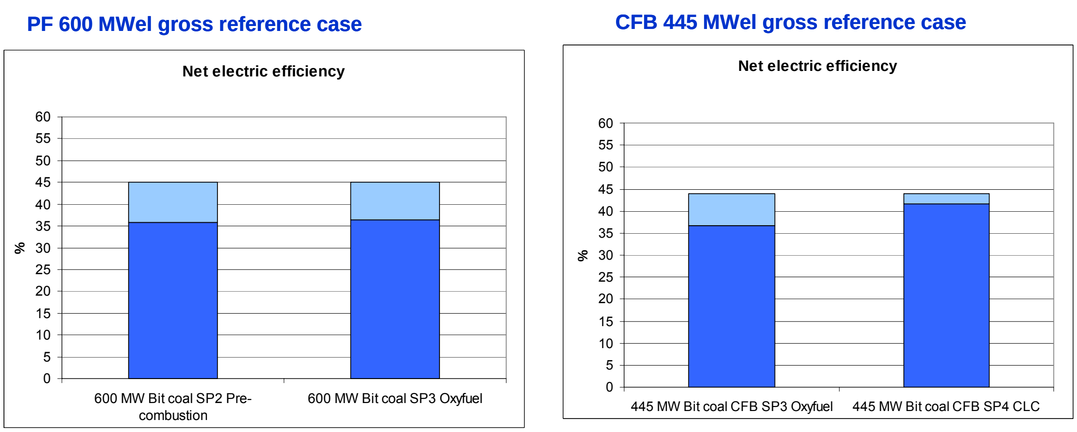


Figure 1: Example of ENCAP benchmarking results: Bituminous coal fired power plant concepts.(Net electric efficiencies).

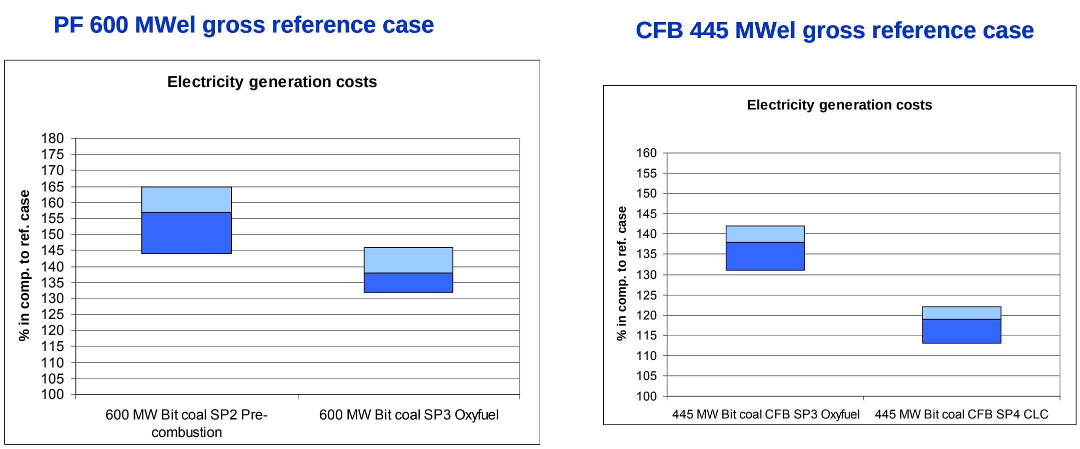


Figure 2: Example of ENCAP benchmarking results: Bituminous coal fired power plant concepts. Cost of electricity in relation to reference power plants. Base case: 1.6 €/GJ fuel, 8% real interest rate, 40 years. Ranges cover sensitivity analysis for fuel prices, interest rates and economic lifetime.

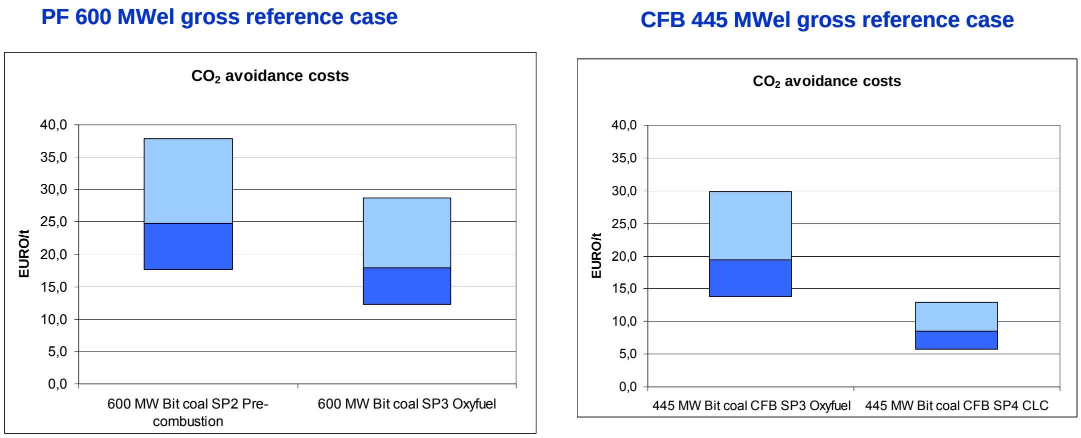


Figure 3: Example of ENCAP benchmarking results: Bituminous coal fired power plant concepts. CO_2 avoidance costs. Base case: 1.6 €/GJ fuel, 8% real interest rate, 40 years. Ranges cover sensitivity analysis for fuel prices, interest rates and economic lifetime.

The same boiler size or type and size of gas turbine are maintained in the power plant concepts with and without CO_2 capture, so that all components that are not directly influenced by the CO_2 capture technologies will remain unaffected. Only minor, not significant changes in the relative assessments were observed by adjusting the reference power plants to the same net capacities as for the power plants with CO_2 capture.

CO_2 Capture influence on the European power situation

Descriptions of conditions in all EU member states concerning likely developments of the power generation systems were made, as well as further development of the Chalmers Energy Infrastructure Database with respect to CO_2 capture technologies and storage and transport options. Development was made of a simulating/optimizing model for scenario analysis on how large-scale introduction of CO2 capture – especially using technologies developed in ENCAP - and storage will influence the European energy system, taking the energy infrastructure into account. Thereafter, scenarios without and with CCS as a base for model analysis were established, taking several useful comments and views from industrial partners into account. The scenarios defined boundary conditions and inputs to the continued modelling and analysis.

The final analysis of how large-scale introduction of CO2 capture and storage may influence the European electricity supply system until mid century, i.e. the year 2050, was carried out through analysis of the established scenarios with the aid of a techno-economic model, in which a case including CCS was compared to a case excluding this option. The results can be seen in Figures 4 and 5 below.

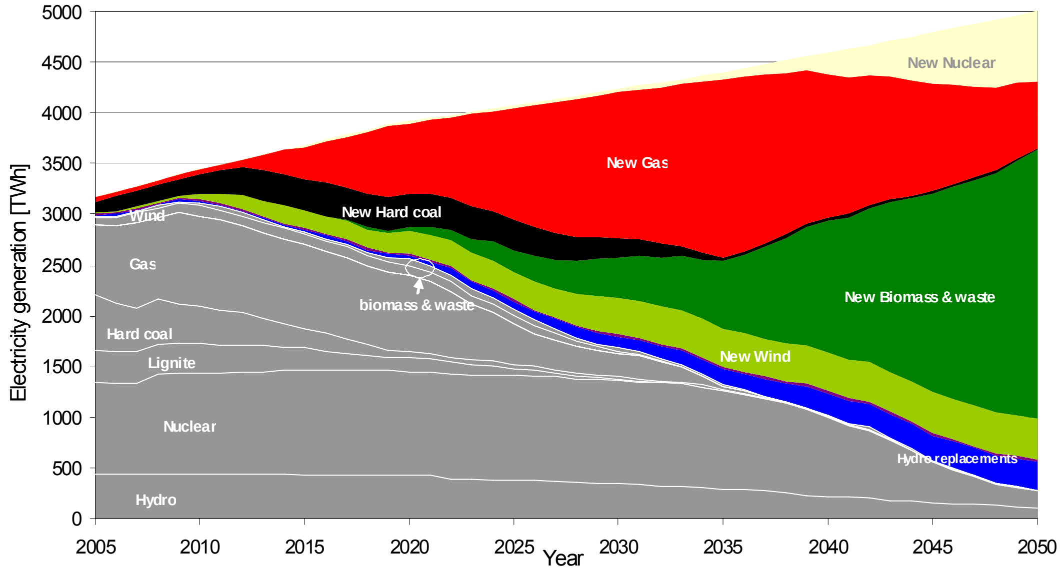


Figure 2 Electricity generation in EU-27 plus Norway aggregated from member state results as derived from the model in the case excluding CCS. Grey field at the bottom represent contribution to electricity generation from present system where fuel mix is indicated by white lines.

Figure 4: Electric generation in EU-27 plus Norway

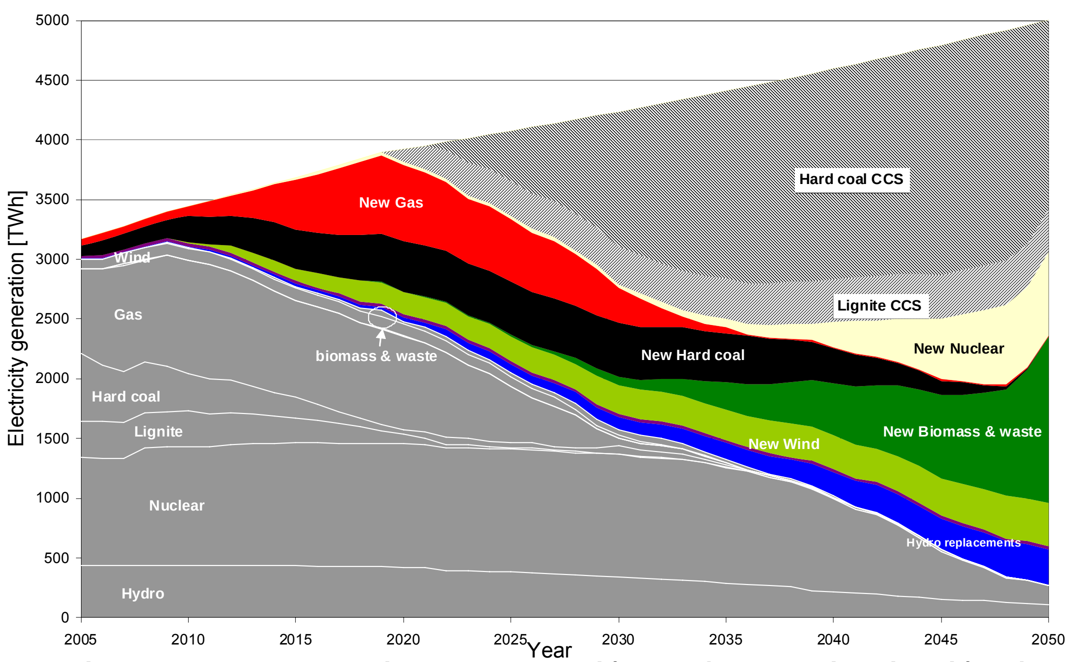


Figure 1 Electricity generation in EU-27 plus Norway aggregated from member state results as derived from the model in the case *including CCS*. Grey field at the bottom represent contribution to electricity generation from present system where fuel mix is indicated by white lines.

Figure 5: Electric generation in EU-27 plus Norway including CCS

3.4 Conclusions

It was found that compared to the corresponding reference power plants without CO_2 capture, net electric efficiencies were reduced with 6 – 9% points for the IGCC pre combustion capture technologies, oxy-fuel PF and CFB technologies for large to medium sized power plants, and around 15% points for the natural gas fired IRCC pre-combustion capture technology. Calculated electricity generation costs for those technologies increase around 30 – 60% compared to the baseline power plants. Of the evaluated more new, and therefore less validated technologies, CLC (Chemical Looping Combustion) for coal, pet-coke and natural gas appear promising, with potentially higher electric efficiencies and lower costs, but need more research and development. The CLC CFB technology is also most relevant in medium sized power plants.

The results from the study on CO_2 Capture influence on the European power situation show that it is possible to meet an 85% CO_2 reduction target by 2050, requiring a large contribution from CCS, with a steep ramp-up post 2020, which imposes challenges for timely investments in corresponding CCS infrastructure. The case excluding CCS results in a doubling of natural gas consumption and would towards the end of the period also require import of biomass to EU-27 corresponding to roughly 15% of the global biomass potential. The results should not be seen as predictions of energy futures but rather a quantitative analysis investigating the possible roles and limits for different technologies, including CCS.

4 SP2 PRE-COMBUSTION DECARBONISATION TECHNOLOGIES

4.1 Motivation of work

The coal-based Integrated Gasification Combined Cycle (IGCC) was deemed as technically feasible already before the beginning of the ENCAP project, and the natural gas-based Integrated Reforming Combined Cycle (IRCC) was conceived as being near commercialization. These concepts have the inherent advantage of producing a pressurized H_2 and CO-rich synthesis gas. After shift of CO to CO_2 it appeared to be possible to capture the CO_2 at conditions that are more favorable than in post-combustion capture. In this sub-project the target has therefore been the process development for IGCC/IRCC based on hard coal, lignite and natural gas to confirm the feasibility of these concepts with integrated CO_2 capture. In addition, capture-free cases for hard coal and lignite were deemed necessary to develop as reference cases, whereas the reference case for the IRCC is a natural gas fired combined cycle. Since both manufacturers and utilities have been involved in the work, this has enabled duly taking into account the user's perspective in the development work.

One of the key issues with the fuel gas that remains after removal of the CO_2 is that it has a high hydrogen content. Current syngas/H_2-enriched gas turbine burners run in diffusion mode. For limiting the formation of NO_x, heavy dilution of the fuel is needed (nitrogen, steam) and only moderate turbine inlet temperatures are possible, which is detrimental to gas turbine efficiency. On the other side, applying modern high temperature gas turbines such as the Siemens F-class (annular combustion chamber) or Alstom GT24/GT26 is needed to promote the breakthrough of IGCC and, based on that, power plant technology with CO_2 capture. Consequently the development in ENCAP has aimed at the adaptation of a gas turbine burner for H_2 to the design requirements of this advanced combustion system. In order to limit NO_x formation, fuel and air should be premixed before being combusted. To enhance the availability and for start-up, IGCC/IRCC plants are planned also for operation with a secondary fuel - natural gas or fuel oil - which also should be burned in premix mode.

CFD combustion models and predictive tools are needed for the development of lean-premixed H_2-rich combustion, and as part of the H_2 combustion activities in ENCAP it was therefore judged necessary to the develop and validate a CFD combustion model including a H_2 reaction mechanism suitable for the fuel lean and high-pressure conditions encountered in gas turbines.

4.2 Objectives

The objectives for SP2 were to investigate candidate pre-combustion decarbonisation processes with reference to:

- the Integrated Gasification Combined Cycle (IGCC) for hard coal and lignite
- the Integrated Reforming Combined Cycle (IRCC) for natural gas - with corresponding adaptations
- The necessary adaptation given particular attention, as motivated above, is the adaptation of gas turbine combustors to lean-premixed H_2-rich low-NO_x combustion.

4.3 Work performed and results

Conceptual power plants

Within ENCAP SP2, heat and mass balances were developed for five power plant concepts:

- Hard Coal/Shell gasification with and without CO_2 capture
- Lignite/HTW gasification with and without CO_2 capture
- Natural gas/autothermal reforming with CO_2 capture.

	Lignite		Hard Coal		IRCC
	w/o capture	with capture	w/o capture	with capture	with capture
Net efficiency (%)	51.7	40.55	46.36	35.9	41.0
CO2-recovery (%)		85		> 92	> 92
spec. CO2-emission (kg/MWh)	799	146	746	81	38
Net Output (MW)	826.2	717.2	874	736.6	754.6

Table 1: Technical key figures of all SP2 power processes

It was concluded early in the project that all required process steps in the fuel preparation and CO_2 capture chain were technically feasible. Technical (and economic) key figures were produced for the five power plant concepts (Table 1) as well as process/block flow diagrams. For hard-coal and lignite, the capture-free cases were developed as a necessary basis for comparison for the cases with CO_2 capture. For the IRCC case, a non-capture case has not been defined, since the realistic reference case without CO_2 capture is a standard NGCC plant without any internal reforming of the fuel. All power plant cases developed within SP2 were defined with the input given from SP1, and the results were reported back to SP1, where the technical and economic comparison between all capture- and reference cases was done. Schematics of the processes with CO_2 capture are shown in Figure 6.

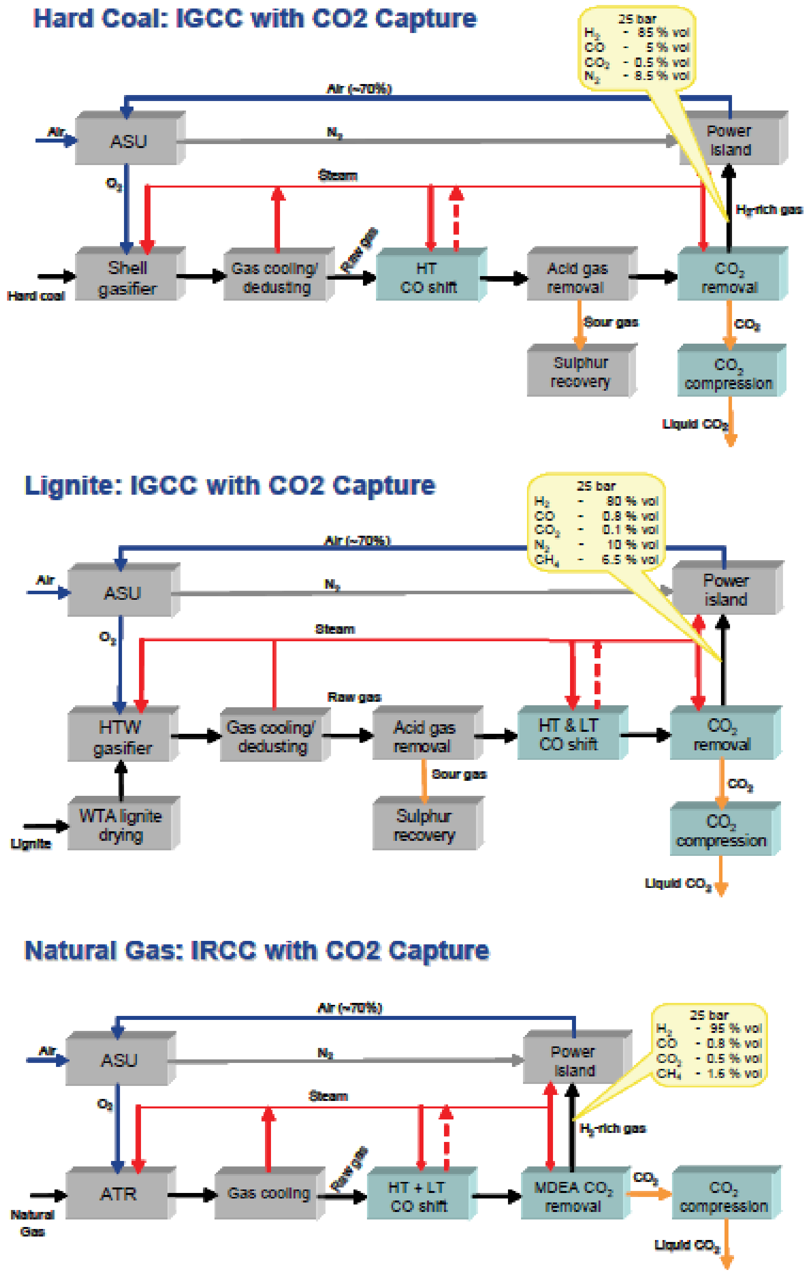


Figure 6: Pre-combustion capture concepts developed within ENCAP

In this study, participants from leading manufacturers (Siemens, Alstom, Lurgi, Air Liquide) and others (IFP, Statoil, RWE Power) have worked together to develop the IGCC/IRCC processes including production of H_2-rich syngas. All power processes developed in SP2 will depend on that gas turbines capable of combusting hydrogen-rich syngas are available. The influence of the new burner design on the overall process was assessed by a parametric approach: i.e. the influence of the probable range of dilution parameters was studied and consequences for the design of the relevant subsystems were evaluated, especially for the saturator and the syngas fuel system. The results show only slight dependency of power and efficiency on the amount of diluent flows.

The work on process development has lead to a considerable increase of the knowledge level of pre-combustion decarbonisation among the participants, and the results have been directly applicable in other work that these companies perform in the area of realising CO_2 capture on a large scale. In particular, the planning by RWE of the 450 MWe (gross) IGCC power plant has relied directly on work and findings from the ENCAP project.

Hydrogen-rich combustion

One of the main activities within the entire ENCAP project has been the work on hydrogen combustion in gas turbine combustors that was performed by Europe's two leading gas turbine manufacturers. The Siemens and Alstom approaches for the next generation of syngas/H_2-enriched gas turbine burners were based on their standard burner designs which are well-proven for natural gas and fuel oil operation at high turbine inlet temperatures. The challenge of applying a premix burner for highly reactive H_2-enriched gases, however, is the risk of flame flash-back.

The design development was supported by theoretical investigations (e.g. CFD), extensive tests, preferably at full-scale machine conditions (Figure 7).

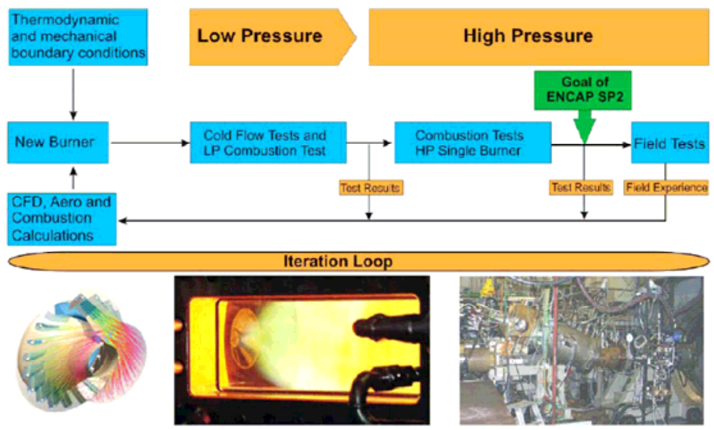


Figure 7: Principle working method

The technical challenges of developing a burner for lean-premixed H_2-rich combustion were as expected significant, due to the excessive reactivity of the fuel. Good experimental results were however obtained, that will constitute the basis for further burner development and optimization after ENCAP.

At project beginning, flame stability and flash-back risks where highlighted as main obstacles for burner operation in premix mode (later confirmed by high-pressure tests). The work on combustion model and reaction mechanisms (done by SINTEF-ER) therefore focused on these conditions in order to generate better predictive tools to support development of low-NO_x H_2 burners. The combustion model was based on the Eddy Dissipation Concept (EDC) and the chemical reaction mechanism by Li et al. The mechanism was reduced from the original 19 elementary reactions down to 11, 4 and 3 reactions. The CFD tool developed ended up in good predictions of the combustion compared to the test results.

A large set of experimental data was provided by DLR, consisting of optical measurements (OH^* chemiluminescence, OH planar laser induced fluorescence and CARS temperature measurements) in the flame as well as NO_x and CO concentrations in the exhaust. These data were used for the validation of the SINTEF hydrogen combustion model. This model was thereafter employed at

Siemens and Alstom for their developmental work on new burner designs. Results are shown in Figure 8.

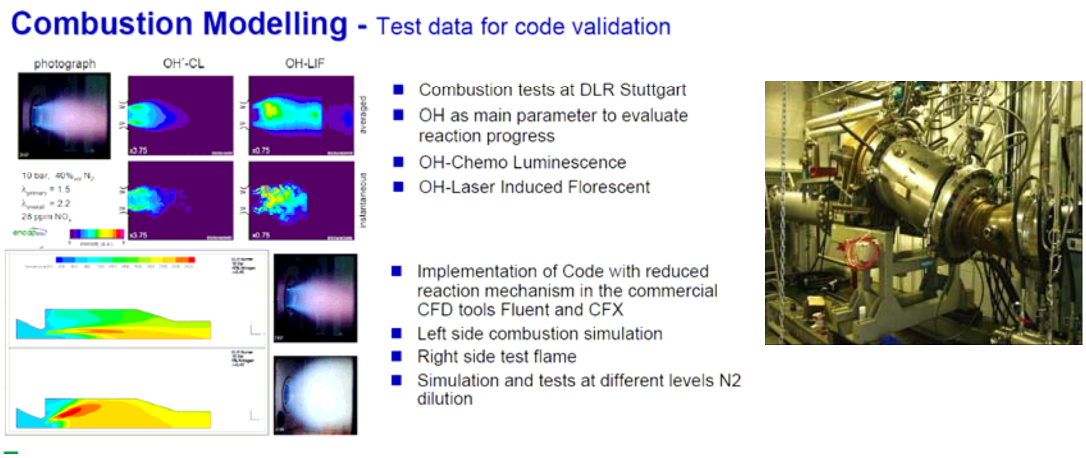


Figure 8: CFD results compared to testing

4.4 Conclusions

Power plant concepts with pre-combustion capture of CO_2 for natural gas, hard coal and lignite were developed and evaluated, and also used in the benchmarking work in SP1. A capture rate higher than the predefined minimum of 90% was obtained for hard coal and natural gas, whereas the capture rate for lignite was 85%, due to the chosen gasification process. CO_2 avoidance cost was around 25 EUR/tonne CO_2 for the bituminous case, around 18 EUR/tonne CO2 for the lignite case and around 35 EUR/tonne CO_2 for the IRCC case, meaning that the coal-fired cases meet the ENCAP cost target, but not the natural-gas fired case.

The reduced 11-step reaction mechanism developed for the CFD modeling decreases the computational time with ~10% compared to the full 19-step mechanism for hydrogen combustion simulations. The 11-step mechanism seems to constitute the best choice concerning accuracy and computational time and will be a good base for the further development of H2-rich burners.

Good burner performance was demonstrated in areas such as safety and NOx emissions, with some cases yielding less than 25ppm (dry, 15% O_2). There is however still room for improvement and optimization of the burner concepts.

5 SP3 OXYFUEL COMBUSTION TECHNOLOGIES

5.1 Motivation of work

The principle of OxyFuel combustion (a.k.a oxycombustion) is that a (carbon-containing) fuel is burnt in the presence of oxygen but without the presence of nitrogen. Part of the resulting flue gas (mainly consisting of CO_2 and H_2O) is recirculated back to the furnace for temperature control. The remaining flue gas is cleaned, including condensation of water, and the remaining CO_2 is compressed for further transport.

Prior to ENCAP, very limited research had been verified in oxy-fuel Pulverised Fuel (PF) boiler technology and Circulating Fluidised Bed (CFB) technology. This was in particular valid for the application of oxy-fuel technology in new, purpose-built power plants, as opposed to retrofit of existing boilers, which had been studied by many others. In ENCAP, the research has been focusing on conceptual work based both on state-of-the-art PF Ultra Super Critical (USC) power plant technology and on a CFB with high recirculation of solids and high oxygen content (70%) in the combustion gas. This conceptual work has been performed in combination with experimental work on several scales to clarify combustion characteristics, emission and ash behaviour. Altogether, the conceptual work has (as planned) been performed on an unprecedented level of detail. Furthermore (as in SP2) since both manufacturers and utilities have been involved in the work, this has enabled duly taking into account the user's perspective in the development work. The experimental work has been performed in different burners, gradually increasing in scale from 20 kW to 500 kW, where the results from the 500 kW test rig have, as foreseen, provided more reliable experimental data than what could be obtained in the smaller test rigs.

5.2 Objectives

With the fuels under consideration in SP3 being bituminous coal, lignite and pet coke[1], all which can be burnt in large combustion plants (boilers), the main objectives were:

- To gain a fundamental understanding of combustion in a mixture of recycled flue gas and oxygen
- To perform conceptual studies of large-scale boiler technologies for pulverised fuel (PF) boilers and circulating fluidised bed (CFB) boilers.
- To suggest conceptual boiler designs and perform synthesis-studies of their integration with a power generation plant
- To provide an economically competitive technology, a work that includes identification and mitigation of technical risks.

5.3 Work performed and results

Conceptual power plants

USC PF concepts were developed for one 600 MW_e (gross) bituminous coal (Figure 9) and one 1000 MW_e (gross) lignite-fired OxyFuel power plant. The work has included design of the furnace and boiler system for large wall-fired vertical-pass boiler for bituminous coal and a tower boiler for pre-dried lignite. Much attention was given to the layout of the system to be employed

[1] Oxyfuel cycles fired with natural gas were investigated in SP6.

for compression and purification of the captured CO_2. The design of the power plant concepts was adapted to meet the ENCAP requirement of 90 % CO_2 capture rate.

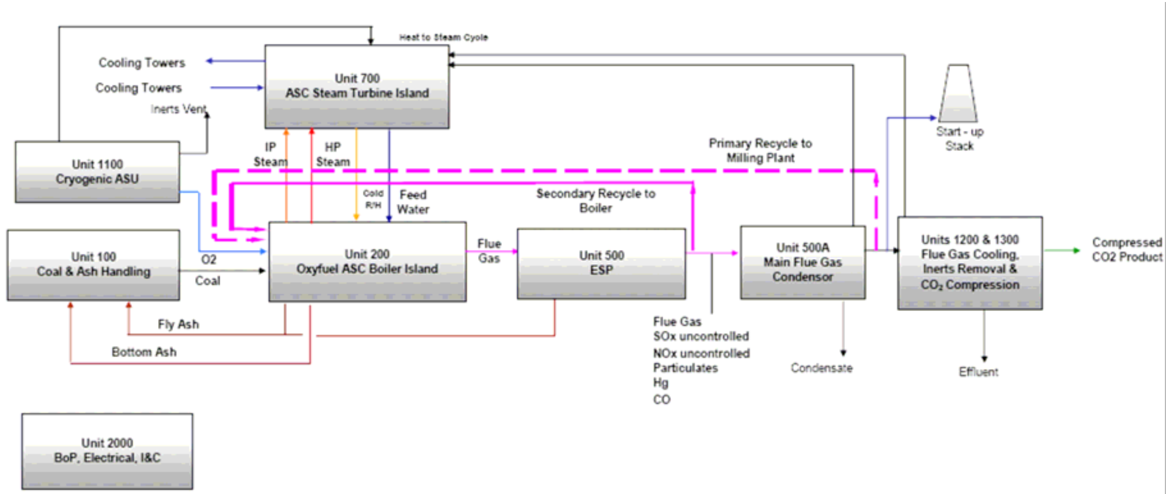


Figure 9: Block Diagram for 600 MW_e ASC PF (Bituminous) OxyFuel Power Plant with CO_2 Capture

Work was done on safety and operability, reliability, availability and maintainability (RAM), concluding that the Availability of OxyFuel USC PF plants is expected to be 86-88%, compared to 90% for conventional air-fired plants. A technical risk assessment was made, and provided important information about the main identified technical risks and future R&D needs to minimize or eliminate these risks.

One of the inherent advantages of the CFB technology is the possibility to use multiple fuels, such as coal, pet coke, biomass and a range of opportunity fuels, including tar sands. The presentation of the conceptual design for a 445 MW_e (gross) OxyFuel CFB in ENCAP was the first of its kind worldwide. The plant concept has a high degree of recirculation of solids for temperature control, which enables a high oxygen concentration (70%) and a significantly more compact boiler than what is possible for an air-fired CFB. Cryogenic ASU and CO_2 compression and purification was integrated in the plant and CO_2 capture was found to reach the ENCAP target of 90%.

The CFB OxyFuel combustion concept was verified experimentally in a small-scale (10 kW_{th}) test rig with up to 90% oxygen fraction in the combustion gas.

For all three concepts above, investment and O&M costs were estimated and supplied to SP1. The accuracy of the costs is estimated to +/- 25%, which is a higher accuracy than in previously published studies on OxyFuel power plants.

In addition to the detailed concept studies described above, a pre-feasibility study was made for a 380 MWe OxyFuel PF plant using low rank Greek lignite, suitable for the Greek power market.

	Bituminous 600MWe		Lignite 1000MWe		Lignite 380MWe		petcoke 445 MWe	
	w/o capture	with capture	w/o capture	with capture	w/o capture	with capture	w/o capture	with capture
Net efficiency (%)	45.0	36.4	49.2	41.0	42.3	34.2	43.5	37.1
CO2 recovery (%)		~90		~90		~90		~90
spec. CO2 emission (kg/MWh)	774	95	812	97	899	100	841.7	92.4
Net output (MW)	574.8	472.5	920.0	767.0	334.5	270.6	403.2	327.7

Table 2: Technical key figures of coal-fired OxyFuel processes (number of MW in heading refers to gross power output)

OxyFuel combustion
Initially in ENCAP, OxyFuel combustion experiments were performed in the 20 kW_{th} (UStuttgart) and 100 kW_{th} (Chalmers) test rigs, under different oxygen concentrations (from 21 to 35% volume), and with air firing as reference case. It was found that combustion with 27% oxygen exhibits similar overall combustion behaviour as the air-fired reference cases. Emphasis was on providing basic combustion characteristics, data for CFD validation, and to enhance the general fundamental insights of OxyFuel combustion. Some key findings were that

- Gas emissivity increases in the case with 27% oxygen compared to air combustion
- OxyFuel staging as primary NOx reduction measure showed similar behaviour as under air-firing conditions and appeared to be as least as effective a measure as for air combustion
- High local CO concentrations during OxyFuel combustion were found, but the concentrations were similar to those at air-firing conditions at reactor outlet
- Ash and slagging behaviour under OxyFuel and air conditions with the bituminous and lignite coals investigated in ENCAP were found to be similar
- The SO2 concentration (ppm) is higher in the OxyFuel cases than for air firing, when the oxygen level is higher than 21%, and it increases with increasing oxygen concentration.

Further OxyFuel combustion experiments were conducted in a 500 kW_{th} test rig at the University of Stuttgart. The configuration of the test rig is schematically illustrated in Figure 10.

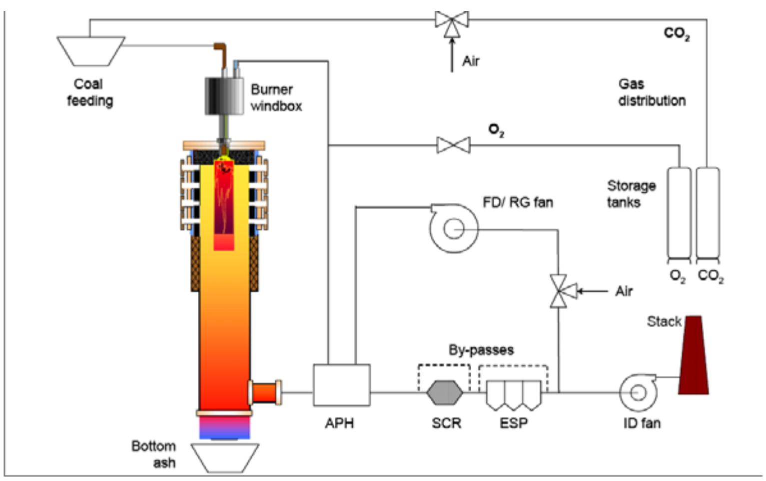


Figure 10: Schematic illustration of the 500 kW_{th} OxyFuel test rig at the University of Stuttgart

During the test campaigns, samples of ash were taken and deposits were collected on probes, Measurements were made of temperatures and flue gas compositions (including SOx and NOx) along the reactor. Superheater and water wall materials were also exposed on probes in the combustion reactor, to study corrosion in OxyFuel atmosphere. Furthermore, SO2/SO3 conversion was also studied, and it was found that the acid dew point is higher at OxyFuel conditions than at air-fired conditions, which will have an influence on the design of the low-temperature section of an OxyFuel boiler.

5.4 Conclusions

The power process studies carried out in SP3 are based on state-of-the-art technology. Further near-term improvements in efficiency of the PF and CFB OxyFuel plants can be expected through further optimization of gas separation technology (ASU and CPU) as well as increasing the steam parameters (700°C power plants).

Capture rates met the ENCAP target of 90% and investment costs were found to increase with 45-60% based on net power output, compared to the reference air-fired power plants. Cost of electricity was found to have an increase of 38-45%, whereas CO2 avoidance cost was found to be around 20 EUR/ton CO_2 avoided for all cases.

The results from the ENCAP project have supported Vattenfall's initiation (in 2008) of the design of a 250 MWe (gross) large-scale OxyFuel demonstration project at Jänschwalde Power station in Germany. No technical barriers have been found that will prevent the development of large-scale OxyFuel combustion with solid fuels. There is however several research items that have been identified for the support of the construction of a PF or CFB OxyFuel demonstration plant, of which can be mentioned:

- Test of complete OxyFuel process at large pilot scale in order to learn more about the interaction of the individual process components and to test under more realistic operating conditions over an extended period of time

- Model development for OxyFuel combustion to improve accuracy of design tools used for, e.g. CFD and similar engineering design tools, and validation of those design tools against measurements made in pilot scale and small-scale test rigs in order to decrease risks and to cut design margins.

- Further investigations to characterize the slagging and fouling behavior under OxyFuel combustion conditions, in order to ensure a design that minimizes operating problems, boiler performance degradation and material related problems

- Long-term material testing under OxyFuel conditions in order to select materials with low corrosion rate in the OxyFuel environment. This relates to materials in both the high and low temperature region.

- Further development to find the optimal flue gas cleaning technology and to identify differences between air and OxyFuel operation, and to meet specifications on emission levels and CO_2 quality.

6 SP4 CHEMICAL LOOPING COMBUSTION

6.1 Motivation of work

The potential of the CLC combined cycle was to some extent proven to be very important in terms of efficiency already prior to ENCAP, as it has a small energy penalty compared with other CO_2 capture technologies applied to gas turbines. Nevertheless, it could by no means be said that power cycles with CLC for CO_2 capture were fully investigated at that period in time, and further work on cycle simulations was judged necessary, both for gaseous and solid fuels. This work being performed within ENCAP offered the advantage of using the guidelines developed in SP1 for comparison with other CO_2 capture technologies.

Already prior to ENCAP, materials development for stable oxygen carriers was ongoing, without finding an optimum material, which combines good stability with good oxygen carrier properties. This topic was therefore a necessary part to get a complete coverage of the CLC technology within this sub-project. The study of the reaction of solid fuels with oxygen-carriers was completely novel at the start-up of ENCAP and was needed for the development of large CLC Circulating Fluidised Bed (CFB) using coal or pet coke.

Furthermore, development of novel reactor concepts for CLC application in gas turbines are necessary in order to comply with the necessary gas quality needed at the inlet of the turbine, and was thus included in ENCAP. These kinds of reactors are needed since the presence of oxygen carrier material in particle form is prone to damage the turbine blades.

6.2 Objectives

The objectives for SP4 were to develop chemical looping combustion (CLC) technology with focus on:

- Studies of processes with gaseous and solid fuels
- Operation at both atmospheric and pressurized conditions
- Materials development for CLC in order to obtain stable reactive materials at acceptable cost
- Development and characterization of new reactor concepts for CFB boilers (powder oxygen carrier) and for gas turbines (fixed bed oxygen carrier).

6.3 Work performed and results

The CLC development work has covered

- Materials development for CLC in order to obtain stable reactive materials at acceptable cost
- Operation of CLC reactors at atmospheric and pressurized conditions
- Development and characterization of new reactor concepts for CFB boilers (powder oxygen carrier) and for gas turbines (fixed bed oxygen carrier)
- Studies of power processes with gaseous and solid fuels

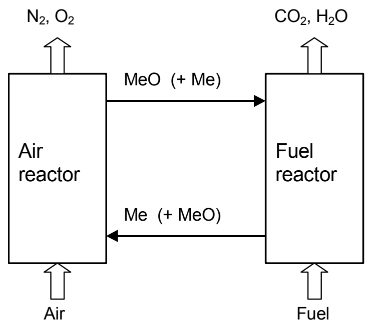


Figure 11: General principle of chemical looping combustion: In the air reactor, a metal reacts with oxygen from the air to form a metal oxide (exothermic reaction). The metal oxide thereafter reacts in a fuel reactor and is reduced back to a metal (exothermic or endothermic reaction). The resulting overall process features inherent oxygen separation and avoidance of nitrogen oxide formation.

Development of reactive materials and lab-scale reactors for Chemical Looping Combustion

A large number of potential oxygen carrier materials were tested in ENCAP with pet coke and six different coals, and scale-up of manufacturing methods was investigated. Several materials were tested among natural ores (such as ilmenite), industrial wastes and specific formulated and prepared materials based on metal oxides such as NiO material. It was demonstrated that low cost materials, e.g. natural ores such as ilmenite, could react with solid fuels in Chemical Looping Combustion. Solid fuel conversion with oxygen carrier was in ENCAP successfully demonstrated for the first time ever in a laboratory-fluidized bed with pet coke and different bituminous coals (Chalmers). The effect of SO_2 and steam in the fluidizing gas was also studied. A lab-scale (10 kWth) CLC-CFB reactor was constructed for solid fuels conversion. The tests performed by Chalmers with coal and pet coke proved the feasibility of the concept. These labscale feasibility studies of the reaction of solid fuels with oxygen-carriers were needed for the development of large CLC Circulating Fluidised Bed (CFB) design concept using coal or pet coke. It must be pointed out that much R&D work remains in order to verify the conclusion of ENCAP and to show stability and costs in the scale-up of chemical looping combustion reactors to full-scale power plant size.

CFB: Chemical Looping Combustion using Circulating Fluidized Bed concept with integration of CO_2 train

A design concept for a 455 MWe supercritical coal CLC-CFB boiler operating with pet coke has been developed and sized by ALSTOM (refer to Figure 12). The work shows that CLC-fired CFB is a feasible concept, close to conventional CFB processes. Part load operation is possible with only a slight reduction in steam temperature. The industrial plant design is based mostly on well-proven technologies: no showstoppers could be identified and in addition possible appropriate improvements were proposed. Based on the work performed in ENCAP, this concept appears very promising. It shows a very low cycle efficiency penalty (2%, mainly for CO_2 compression) and the CO_2 avoidance cost appear very attractive: approximately 10 Euro/tonne CO2 avoided, at a capture rate of 98%, which is lower than the ENCAP target. Still, as indicated above, much R&D work remains before the verification of this estimates and a realisation of a full-scale CLC CFB boiler.

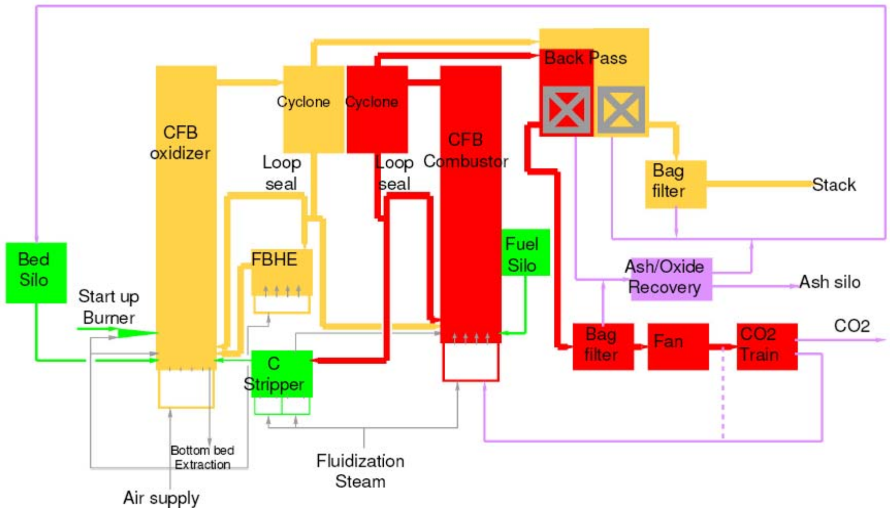


Figure 12: Scheme of CLC CFB for solid fuels

Gas Turbine Power Cycle applications with CO_2 Capture

Feasibility studies of innovative reactor concepts for gas turbine application were performed by IFP (monolith based rotating reactor) and TNO (membrane assisted reactor, where the CLC particles are immobilized in membranes). Experimental setups have been constructed to validate the concepts. For the IFP concept, coated monoliths were produced and tested with natural gas under CLC conditions, providing proof of concept. CLC reactors were designed and sized for gas turbine single and double reheat and Siemens made preliminary cost evaluations. For the TNO concept, a bench-scale unit designed for operation up till 1200° and 35 bar was designed and commissioned, and first tests confirmed the validity of the concepts.

Additional efforts are required to complete the innovative reactor technology feasibility study assess their technical feasibility at industrial scale. In particular, experimental tests showed that the future development of CLC innovative reactor concepts will require a good understanding of side reactions kinetics (steam reforming, shift, carbon deposition) to achieve acceptable conversion. In addition, these technologies depend on specific equipment that is not industrially mature yet.

Early in the project, as a complement to the SP1 guidelines, NTNU provided a common framework for the modeling basis, which was useful in SP4 and SP6 when modeling innovative power plant concepts that could not be based directly on the reference power plants treated by the SP1 guidelines. In SP4 these includes CLC gas turbines with single or double reheat operating in a combined cycle. Process simulations have been performed for several CLC combined cycles with and without reheat, revealing that there is a significant potential for the concept, in terms both of thermal efficiency and of CO_2 capture. The results are illustrated in Figure 13 below, where net plant efficiency is illustrated as a function of reactor or gas turbine combustor inlet temperature. It should be noted that the CO_2 capture rate is 90% for the “conventional” cycle with CO_2 capture (post combustion capture technology), whereas the capture rate is near 100% for the CLC cases. The CO_2 mitigation cost using this technology would be in the range of 15 to 25 EUR/tonne CO_2. The high efficiencies obtained with the investigated gas-turbine based CLC concepts further justified the research on fixed-bed reactors described above.

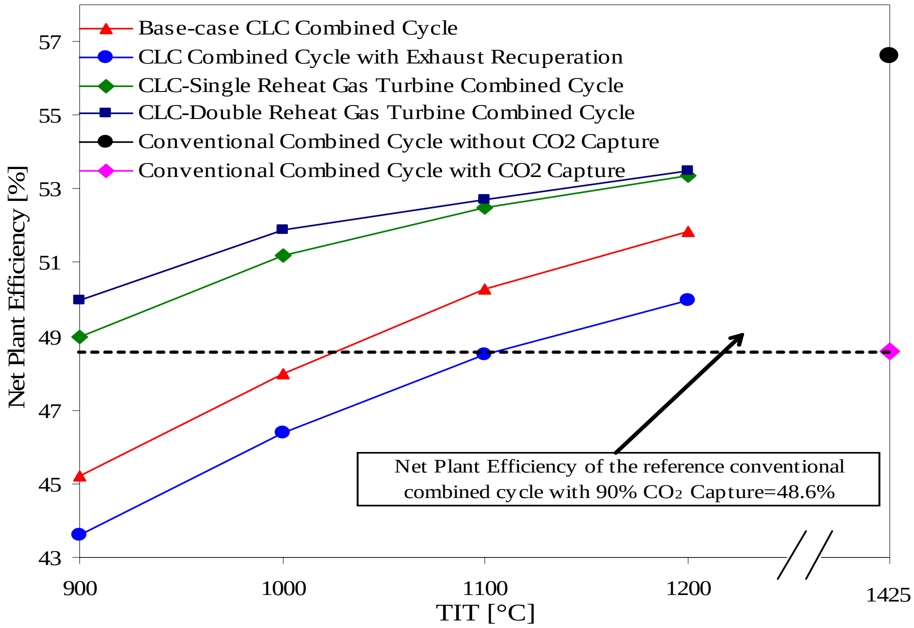


Figure 13: Calculated efficiency of different gas-turbine based CLC cycles at varying reactor temperature.

Power process simulations were also made for CLC application in steam cycles using the CLC-CFB boiler designed in ENCAP. Net plant efficiencies were found to be 43-44% at 850°C oxidation temperature and near 100% CO_2 capture, including the energy penalty for CO_2 compression.

6.4 Conclusions

Altogether in SP4, promising results were obtained but technical maturity is not there yet for chemical looping combustion. Additional development effort of stable and cost effective oxygen carriers is required in the scale-up of CLC reactors and to demonstrate the full operability of the CLC process. The concept studied is in the 450 MW size. Thus this concept is not available in the near future or for larger power plants. Among the process applications considered within ENCAP, the CFB boiler application has a more advanced development status compared to the Gas Turbine Power Cycle application.

7 SP5 HIGH-TEMPERATURE OXYGEN GENERATION FOR POWER CYCLES

7.1 Motivation of work

A major obstacle for OxyFuel combustion and also for pre-combustion decarbonisation is the high-energy penalty and cost associated with cryogenic separation of the oxygen that is vital to these capture processes. The research in SP5 has therefore been devoted to evaluating three high-temperature routes for oxygen separation, and their integration in power plants with CO_2 capture. All three options are based on ceramic materials.

7.2 Objectives

The objectives for SP5 were to identify and develop low-cost advanced high-temperature oxygen separation process options for use in the power plant processes developed in ENCAP SP2 and SP3.

7.3 Work performed and results

General evaluation of three different oxygen generation routes

Initially in SP5, three methods for high-temperature oxygen separation were investigated:

- Ceramic oxygen-separating membrane made from perovskite or similar materials with oxygen generated in a separate unit, after which the oxygen is conducted to the combustion/gasification zone (Figure 14). This option can be employed both for gaseous and solid fuels (option investigated by SINTEF, TNO, University of Twente).

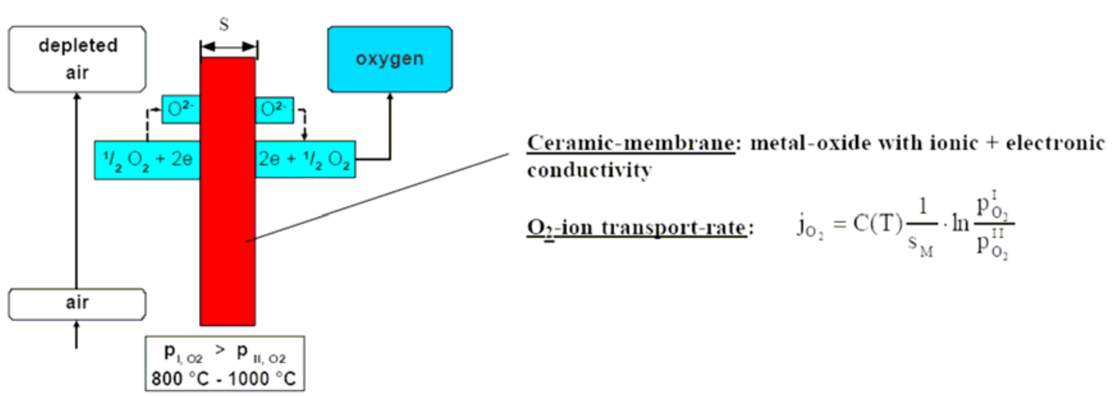


Figure 14: Oxygen production by a pressure-driven membrane

- Ceramic oxygen-separating membrane made from perovskite or similar materials where the membrane is included in a membrane reactor, meaning that the fuel oxidation takes place in the immediate vicinity of the membrane. This option is limited to gaseous fuels (option investigated by Statoil).

- Ceramic Autothermal Recovery (CAR) (Figure 15), which uses the *oxygen storage* capacity of perovskite type materials at high temperature (~600-1000°C) rather than *oxygen transport* properties. (Option investigated by BOC, Alstom).

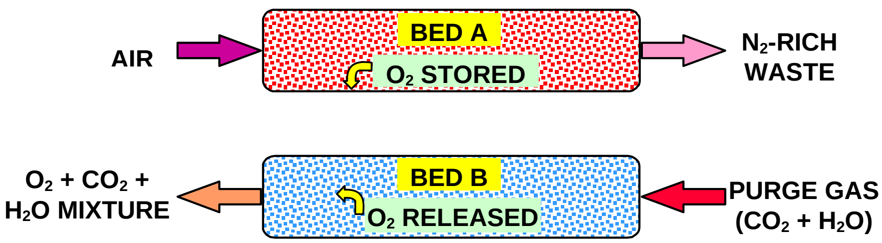


Figure 15: Working principle of the CAR process. Cyclic operation of the process, meaning that when air passes through one bed, purge gas passes through the other and vice versa

In addition to the investigation of these concepts, an entire work package was dedicated to the investigation of the relation between performance and stability for the different materials at conditions relevant for ENCAP.

Investigation was not only made of the high temperature oxygen separation concepts, but also of their integration into different power cycles with CO_2 capture and their ability to be integrated in power plants with CO2 capture in an efficient manner. More than 20 power plant process concepts were analysed and an economic study with sensitivity analysis was performed. These studies were made based on the guidelines from SP1 and SP4/SP6. After technical evaluation, one power plant concept for each oxygen separation option was selected:

1. OTM separator integrated in PF - OxyFuel boiler
2. CAR unit integrated in PF -OxyFuel boiler
3. OTM reactor in an Integrated Reforming Combined Cycle (IRCC).

After this first 18-month evaluation of all three oxygen generation concepts, the CAR process was selected for further validation work within ENCAP in order to be able to suggest a candidate for large scale testing later on in the project. The basis for the selection of the CAR process was the relative technical maturity of this concept and the possibility for scale-up at a reasonable risk level, since no clear long-term winner was possible to define based on the performed techno-economic study.

Further evaluation of the CAR process

Further experimental work was performed in order to find the optimum CAR material and geometry. Eventually, one material could be selected based on a trade-off between chemical stability and performance (i.e. oxygen storage capacity) under dynamic conditions. For this selected material, further optimization work was made with respect to material porosity and geometry. Further work on this material thereafter focused on the investigation of the effects of CO_2 and SO_2 on the material performance.

After the selection of the CAR process for further analysis, a detailed investigation of the CAR process integrated in a lignite-fired PF oxyfuel boiler power plant was made, with the work in SP3 as a basis. It was found that oxygen generation with CAR is competitive with the corresponding oxyfuel PF case with a cryogenic ASU in terms of cost of electricity, but that it has a lower thermal efficiency (38.2% for CAR vs. 41.0% for ASU). This result was obtained with the use of flue gas as purge medium in the CAR process. It should however be recalled here that the relative immaturity of the CAR concept for large scale operation implies larger uncertainties in the cost estimate of this concept compared to an oxyfuel concept with a cryogenic ASU. One result from the testing of selected CAR material samples with flue gases as purge medium was a decrease of the O_2 adsorption capacity because of the sulphur in the flue gas. The process calculation was therefore also performed using steam as purge medium instead of flue gas. The calculated net efficiency for the CAR boiler process then resulted to be about 5 % points lower than for the oxyfuel process with cryogenic ASU. The main reason for this efficiency decrease is the reduction of power generation in the LP steam turbine, since a major part of this steam is employed as purge gas for the CAR reactor.

The selected CAR materials were exposed to CO_2, SO_2 and flue gases in order to investigate materials performance and stability. The results indicate that the current CAR materials are vulnerable to both SO_2 and CO_2-containing gas streams. The damage caused by exposition to CO_2 (reduction of surface exchange activity) can largely be restored by heating in air to around 850°C, whereas long-term exposure to SO_2 ultimately would lead to a loss of performance (due to decomposition of the material). Removal of sulphur from the flue gas down to a few ppm therefore appears to be necessary in case of use of flue gas as purge medium.

These results confirmed again that additional, relevant efforts in the material stability and performance and in the process integration are needed in order to improve the competitiveness and attractiveness of CAR technology.

A new natural gas fired power plant concept with an integrated CAR unit was also investigated. This concept included a CAR unit for O_2 production, a steam reformer fired with pure O_2, a CO_2 recycle to the steam reformer, a PSA unit for H_2-separation and a H_2 fired combined cycle.

7.4 Conclusions

Thanks to the composition of the SP5 working group, with European top experts in the field of ceramic oxygen conducting and oxygen storing materials the activities in SP5 have allowed for an objective and realistic picture of the state-of-the-art in this field during the first 18 months where thee different oxygen generation routes were investigated. The main technical challenges remain material stability and performance, and also concept development for a modular oxygen separation system to be integrated in a power plant, as well as the optimum plant configuration for high-temperature oxygen separation integration.

In-depth investigations were made on the CAR material and on the integration of the CAR process in a lignite-fired PF oxyfuel boiler power plant. Thermal efficiency for this option is better when using flue gas than when using steam as purge medium. If using flue gas, however, current CAR materials have insufficient resistance to CO_2 and SO_2 exposure. These results confirmed again that additional, relevant efforts in the material stability and performance and in the process integration are needed in order to improve the competitiveness and attractiveness of CAR technology.

No corresponding in-depth materials and process performance studies were made in ENCAP for the membrane-based high-temperature oxygen generation concepts, and no corresponding conclusions can therefore be drawn.

8 SP6 NOVEL PRE-COMBUSTION CAPTURE CONCEPTS

8.1 Motivation of work

Besides the options identified and studied in ENCAP SP2-SP5, there are several other options for prospective emerging power generation systems with CO_2 capture. These options generally can be described as less mature than the SP2 and SP3 options, (most are at the conceptual level) and not covered within SP4 and SP5, but needed to be studied in order to identify possible attractive candidates for CO_2 capture through pre-combustion decarbonisation or oxyfuel combustion. The strength with performing this work within the ENCAP project was that this enabled the work to be based on the SP1 framework, and thus the results could be included in the benchmarking of different concepts.

8.2 Objectives

The objectives for SP6 were to investigate prospective emerging pre-combustion decarbonisation and OxyFuel capture technologies that are estimated to have a high potential for capture cost reduction while maintaining a high capture rate.

8.3 Work performed and results

Sometimes in the literature, favorable and perhaps even unrealistic computational assumptions have been employed to promote some technologies at the expense of others. Therefore, as a complement to the SP1 guidelines, a framework for simulation of innovative power processes was developed as a joint task between SP4 and SP6. This SP4+SP6 framework made it possible to deal with the general problem of comparison of power plant performance statements from various sources. The SP4+SP6 framework provided a detailed and transparent set of computational assumptions, models and fluid properties, as well as a definition of the boundary conditions for calculating plant efficiency. Furthermore a number of parameters were defined in order to describe performance beyond that of power plant efficiency. Since the framework was based on the SP1 guidelines, this means that the more innovative cycles (studied primarily in SP6 but also in SP4 and SP5) could be included in the SP1 benchmarking.

A large number of pre-combustion and oxy-combustion cycles (using either coal or natural gas as fuel) were analyzed with heat and mass balances, and characterized according to the evaluation criteria. Altogether the results from the innovative cycle analysis in ENCAP represents as of today the most comprehensive comparison of performance of power cycles, where the results are comparable because of the underlying common framework that was employed. Furthermore, when performing a comparison of process performance in SP6, some selected CLC cases from SP4 were included, as can be seen in Figure 16.

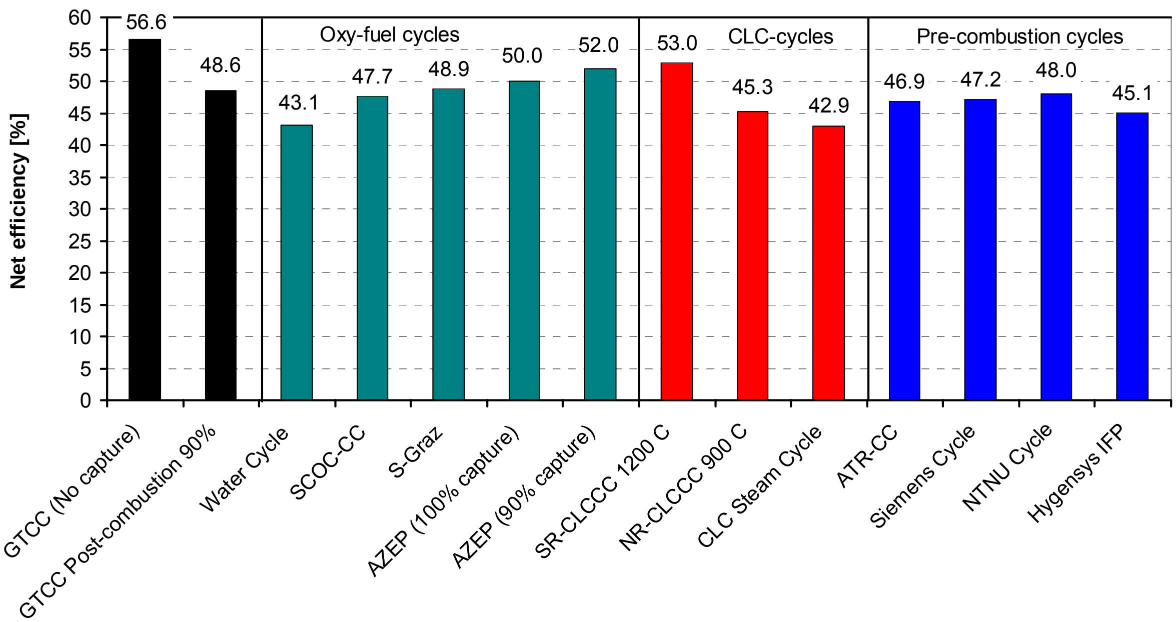


Figure 16: Net plant efficiency for natural gas fired cycles. For explanations of acronyms, refer to list at the end of this document.

The research in SP6 has followed a vertical three-step approach with screening of candidate cycles, modelling and verification of different technologies. For 17 studied cycles, a component book was elaborated giving (for each major component in each cycle) expert opinions considering available technology, best design practices, state of the art in materials existing experience and other relevant issues. Also complexity was considered as an important aspect of these cycles, as simpler cycles usually suggest higher reliability. Based on the conclusions drawn from the thermodynamic analysis of the seventeen cycles and from the assembly of the component book, the SP6 partners primarily selected the Semi-Closed OxyFuel Combustion Combined Cycle (SCOC-CC)[2] and the Steam Graz Cycle for further more detailed studies on a component level (Figure 17). The AZEP cycles with 90% and 100% capture rate were included in the analysis as a reference, since these are well-known cycles that have previously been well described in the literature. Due to the previous through work on these concepts, these cycles were never candidates for further detailed evaluations within ENCAP.

[2] Also known from the literature as the Matiant Cycle

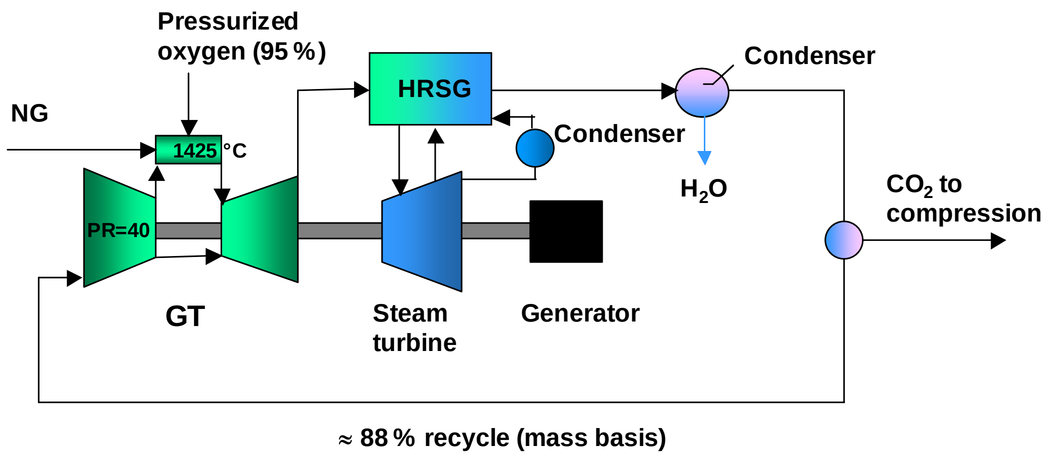


Figure 17: The Semi-Closed OxyFuel Combustion Combined Cycle – SCOC-CC

Alstom made one-dimensional and chemical kinetics studies of combustors for all oxy-fuel cycles previously studied in WP6.1: SCOC-CC, Graz cycle and S-Graz cycle. It was found that combustors for these natural gas oxy-fuel cycles and the recirculation process in these cycles can be designed to produce the conditions considered in the cycle studies, with acceptable levels of emissions, either in start-up conditions or in steady-state conditions.

Conceptual aerodynamic design of compressors and turbines for the Semi-Closed Oxy-Fuel Combustion (SCOC) combined cycle and the Steam Graz cycle were made, resulting in the assessment of the feasibility of these components, without any new scientific development and within current engineering practices. It was found that compressors and turbines for natural gas oxy-fuel cycles, can be designed, from aerodynamic and performance point of view, within the current state of engineering science and also, to a great extent, within the current engineering practice. Conceptual design of these components was possible within conventional levels of parameters such as Mach number, flow coefficient, load coefficient and hub/tip ratio. It must be pointed out, however, that neither structural analysis of such components nor any investigation on materials to be used in their construction was made. So, other obstacles may be found in the future, in areas not investigated in this project.

Heat transfer in the turbines for natural gas oxy-fuel cycles was shown by Siemens to have some quite different characteristics, as compared to conventional equipment, but the differences would probably lead to the design of new cooling systems, not necessarily to the need of new scientific developments on materials, for example.

Two studies on membranes were also made. One of them was the simulation of a one-dimensional membrane reactor with a hydrogen transporting Pd/Ag-membrane, for integration with a gas turbine. The proposed design of the reactor involved two concentric tubes (NTNU analysis). The other membrane study was about the integration of an oxygen membrane reactor, in a novel way, in a lignite-fired oxyfuel power plant (UPaderborn analysis). A one-dimensional model was studied. The main variations have been done in the pressures and mass flow rates of the sweep stream. The overall conclusions from the analyses made were that membranes either for air separation or for H_2 / CO_2 separation show two problems: 1) required areas may be too large for economic feasibility and 2) good performance may be at odds with the operating conditions required for long life and good reliability of the membrane reactor.

Economic evaluation of several cycles was made at the University of Ulster, using the Eclipse program, which includes heat and mass balance and a top-down approach for the economic analysis of a cycle. Based on the scales and operating conditions of utilities and components used in the suggested power cycles, the capital requirement for individual modules such as compressor, pipes and turbines were estimated. These expenditures along with those for site preparation, service facilities and engineering were used to calculate an estimate of the overall plant costs. The results were delivered to ENCAP SP1 for the benchmarking analysis. It must be emphasized in this context that the plant economic data for power plant concepts based on 2004 level of technology, and to a more significant extent on existing technology, that were applied in e.g. SP2 and SP3 are of higher reliability than the cost data calculated in SP6.

Typical results calculated in SP6 to characterize the different cycles are the CO_2 avoidance cost and the break-even electricity sale price versus EPC, fuel cost, O&M cost and capacity factor, and economic input was thereafter delivered to the benchmarking in SP1. Sensitivity analyses were also made.

An assessment was also made of emerging technologies through a structured screening of different sources in the literature (NTNU).

8.4 Conclusions

A large number of cycles were analysed, the most critical components of the most interesting cycles were studied to considerable level of detail and a full economic assessment of these cycles was made on a consistent basis.

Out of seventeen cycles studied in SP6, eight cycles for natural gas and three cycles for coal exceed the target of 90% CO_2 capture. The work of SP6 has thus well achieved the ENCAP objective of at least 90% capture.

Out of eight IGCC systems studied in SP6, six cycles have shown CO2 avoidance costs of less than 30 Euros per ton of CO2. As to the four natural gas oxy-fuel cycles studied in SP6, the CO2 avoidance cost varied from 40 to 47 Euros per ton of CO2. So the work of SP6 achieved the cost reduction target of ENCAP on coal IGCC systems with pre-combustion but showed that difficulties exist to achieve the cost reduction target for natural gas oxy-fuel systems. The work in SP6 showed, however, as mentioned above, that IGCC systems based on membranes are still not at short distance from practical realization. On the other hand, development costs of components have not been considered in the economic assessments of the cycles and so the avoidance costs of the natural gas oxy-fuel cycles may be still higher than the calculated figures because of the costs to develop new turbomachinery. The same applies to IGCC systems with membranes and to CLC. Nevertheless, apart from membranes and within the scope limitations of the sub-project (materials, for example, have not been investigated), the work of SP6 shows that most components can be developed with the available scientific knowledge and within the current engineering practices. Some of the most attractive cycles in terms of efficiency and CO2 capture penalty are based on feasible components. In particular it was demonstrated that oxy-fuel cycles for natural gas do indeed demand the development of new turbo-machinery, but require no scientific breakthrough in order to enable realization.

9 PREPARATIONS FOR LARGE SCALE TESTING

ENCAP was already from the beginning planned in two phases: Phase I with main focus on research and Phase II which included research as well as large scale testing (LST) of a selected technology. This two-phase approach was based on the fact that it was not possible to decide already from the start of the project, which of several possible technologies studied in ENCAP SP3-SP6 would be the most relevant for the Phase II testing, in order to meet the overall objectives of the project.

In SP2, substantial funds for testing were included already from the beginning of the project, since it was possible to pinpoint the testing necessary already at the project start up (gas turbine combustors for hydrogen combustion).

Based on the research work performed during the first two years of ENCAP, the following technologies were identified as possible candidates for LST:

- 30 MWth OxyFuel PF boiler tests (SP3)
- 1 MWth OxyFuel CFB boiler tests (SP3)
- 1 MWth Chemical Looping Combustion (SP4)
- High-temperature Oxygen separation with Ceramic Autothermal Recovery (CAR) (SP5)
- Corrosion effects from CO_2 and steam mixtures (SP6)
- H_2O/CO_2 condenser (SP6)

Based on an overall judgement of the suggested test programs, the maturity of the technology, the relevance of the suggested tests for the fulfilment of the ENCAP objectives, the selection fell on the 30 MWth OxyFuel PF Boiler owned by Vattenfall in Germany to conduct the ENCAP large scale tests.

ENCAP entered Phase II in August 2006, and major activities were thereafter carried out to perform more detailed planning of the tests, contractual agreements between the different ENCAP partners participating in the LST, and defining in agreement with the owner of the Pilot plant and equipment providers to the 30 MWth plant what measurement data would be made available for the ENCAP LST partners. The negotiations with ENCAP partners and the plant owner and the equipment providers turned out to be time consuming. The Large Scale Testing programme was planned to be carried out late in the ENCAP project time frame. The testing had also to correspond to the erection and the commissioning of the pilot plant. However, it was finally concluded that the planned and prepared Large Scale Test programme could not be executed within the time frame of the ENCAP project.

The results thus reported in ENCAP are detailed plans and a detailed test programme for an Oxy Fuel Pilot Plant that includes the whole chain of components of the 30 MWth size.

APPENDIX 1: ABOUT ENCAP

The technological objective of ENCAP was to cut lead-time and improve cost for emerging pre-combustion decarbonisation and oxyfuel combustion technologies attributed to power generation for continued use of fossil fuels in Europe - and the world - in a resource-efficient and environmentally benign manner.

The stated target of ENCAP was to provide pre-combustion capture technologies in power cycles operated by natural gas, hard coal and lignite with the objective of achieving:

1) at least 90% capture rate for CO_2
2) 50% capture cost reduction – from a level of 50-60 € per tonne of CO_2 avoided.

The target of at least 90% capture rate for CO2 was achieved for almost all studied power plant concepts. The lignite-based IGCC concept is considered to reach a capture rate of about 85%, mainly due to that the selected fluidized bed gasifier is to produce a syngas with the relatively high methane content (which will generate CO2 when combusted in the gas turbine).

Out of seventeen cycles studied in SP6, eight cycles for natural gas and three cycles for coal exceed the target of 90% CO_2 capture.

The target of 50% cost reduction down to at least 25-30 €/tonne of CO2 avoidances cost was achieved for almost all coal/pet coke fired cycles (except two IGCC cases studied in SP6). For the natural gas fired concepts, the cost reduction was difficult to achieve.

The scientific objective was to generate new knowledge and comprehension of systems, processes, materials and matter by characteristics of potentiality, constraints and governing mechanisms pertaining to pre-combustion capture from fossil fuels, with a bearing on solutions that (might) facilitate sequestering of CO_2. The fulfilment of this objective has required targeted fundamental and applied research and topical involvement by some of the leading European R&D institutions.

The total budget for the five years of development, testing and validation was 19 179 500 Euro with an EC contribution of 9 650 349 Euro. The total costs reported to the EC for the project period are 21 558 000 Euro.

The ENCAP project gathered 31 European entities. The consortium consisted of highly ranked RTD providers, leading European manufacturers and large energy providers, and created an important European Research Area of CO_2 capture technologies.

The ENCAP partners were:

Vattenfall*	ALSTOM**	DLR	Chalmers
DONG Energy	Siemens	CERTH/ISFTA	NTNU
RWE Power	Doosan Babcock	TNO	Universität Paderborn
PPC	Linde	IFP	University of Stuttgart
StatoilHydro	Lurgi	SINTEF***	University of Twente
	BOC		University of Ulster
	Air Liquide		

*Participates with three legal entities within the Vattenfall Group
**Participates with five legal entities within the ALSTOM Group
***Participates with two legal entities within the SINTEF Group

The French company Total France has joined the consortium under a specific agreement.

The work in ENCAP has ended up in 157 deliverables (technical reports) and 56 scientific publications (of which 21 journal publications) have been reported to the European commission.

More information about ENCAP and project results can be found on the ENCAP website (www.encapco2.org). The website will remain active also after the completion of the project. The website contains general information about the ENCAP project and its outcome, in particular

- Public summary reports of selected deliverables
- Links to the Proceedings from two major public dissemination events (ENCAP-CASTOR Training Seminar / Workshop, held in Billund, Denmark in March 2006 and CASTOR - ENCAP - CACHET - DYNAMIS Common Technical Training Workshop, held in Lyon, France in January 2008)
  Five Newsletters, issued during the project's lifetime, and circulated to a wide range of readers (in hard-copies and in electronic form), covering the Project's progress.
- Executive Summaries from Annual Activity Reports to the European Commission
- Links to the Networks, other relevant European Commission's funded Projects websites
- An updated list of public events (conferences, workshops, etc.) related to CO_2 issues.

The list of scientific publications is included below:

Nr	Title	Author(s)		Conference/Journal
		Name	Affiliation	
01	Analysis of Detailed Kinetic Mechanisms for Hydrogen Combustion	T. Myhrvold, J. Ströhle, Ø. Langørgen	Sintef ER	IEA Combustion Meeting
02	Gas Turbine Cooling Model for Evaluation of Novel Cycles	M. Jonsson[1], O. Bolland[1], D. Bücker[2], M. Rost[3]	[1]NTNU, [2]AP-CH, [3]Siemens	ECOS 2005
03	Off-Design Evaluation of a Natural Gas Fired Chemical Looping Combustion Combined Cycle with CO_2 capture	R. Naqvi[1], O. Bolland[1], J. Wolf[2]	[1]NTNU, [2]Vattenfall	ECOS 2005
04	Ceramic Sr-Ce-Co Oxides with high Oxygen Exchange	E. Girdauskaite[1], H. Ullmann[1], V. Vashook[1], M. Bülow[2], U. Guth[1,3]	[1]TU Dresden, [2]BOC, [3]Kurt-Schwabe-Institut für Mess- und Sensor Technik	Solid State Ionics Conference
05	Flame and Radiation Characteristics of gas-fired O2/CO2 recycle combustion	K. Andersson, F. Johnsson	Chalmers	Fuel **86** (2007) 656-668
06	Experimentelle Untersuchung und Bewertung zur Oxyfuel-Verbrennung fossiler Brennstoffe in einem Flugstromreaktor	P. Mönckert, B. Dhungel, H. Wörner, J. Maier, G. Scheffknecht	U Stuttgart	VDI Flammentag
07	An Integrated Gasification Zero Emission Plant Using Oxygen Produced in a Mixed Conducting Membrane Reactor	E. Lindfeldt[1,2], M. Westermark[2]	[1]AP-CH, [2]Royal Institute of Technology, Sweden	ASME Turboexpo 2006
08	CO2 Capture by Means of Chemical Looping Combustion	D. Pavone	IFP	FEMLAB Conference
09	Reduction of a Detailed Reaction Mechanism for Hydrogen Combustion under Gas Turbine Conditions	J. Ströhle, T. Myhrvold	SINTEF ER	Combustion and Flame **144** (2006) 545-557
10	CO2 capture using chemical looping combustion for gas turbine application	D. Pavone, M. Rolland, E. Lebas	IFP	GHGT-8, Trondheim
11	Natural Gas Fired Power Plant Concept with Oxygen Transfer Membrane Reactor and H2 Fired Combined Cycle	G. de Koeijer, M. Gjerset, S. Aasland, H. Kobro, B. Sivertsen, E. Rytter	Statoil	GHGT-8, Trondheim
12	Oxyfuel Technology for CO2 Capture from Advanced Supercritical Pulverised Fuel Power Plants	Gnanapandithan Sekkappan[1], Peter J Melling[1], Marie Anheden[2], Göran Lindgren[2], Frank Kluger[3], Ivan Sanchez Molinero[4], Claus Maggauer[5], Aggelos Doukelis[6]	[1]Mitsui Babcock Energy Limited, [2]Vattenfall Utveckling AB,[3]ALSTOM Power Boiler, [4]Air Liquide R&D, [5]Siemens AG Power Generation, [6]National Technical University of Athens	GHGT-8, Trondheim
13	Combustion and flame characteristics of oxy-fuel combustion - Experimental activities within the ENCAP project	K. Andersson[1], P.Mönckert2, J. Maier[2], G. Scheffknecht[2], F.Johnsson[1],	[1]Chalmers University of Technology, [2]University of Stuttgart	GHGT-8, Trondheim
14	The use of petroleum coke as fuel in chemical-looping combustion	Henrik Leion, Tobias Mattisson, Anders Lyngfelt	Chalmers University of Technology	*Fuel* **86** (2007) 1947-1958

15	Development of pre-combustion decarbonisation technologies for zero-CO_2 power generation	[1]W. Renzenbrink, [2]K.-J. Wolf, [3]F. Hannemann, [4]G. Zimmermann, [5]E. Wolf	[1,2]RWE Power AG, [3,4]Siemens Power Generation AG	GHGT-8, Trondheim
16	Development of a Gas Turbine Burner for the Lean-Premixed Combustion of H2-Rich Fuels	R. Carroni	ALSTOM-CH	GHGT-8, Trondheim
17	Characteristics of Cycle Components for CO_2 Capture	Flavio Franco[1], Theo Mina[1], Gordon Woollatt[1], Mike Rost[2], Olav Bolland[3]	[1]Alstom UK, [2]Siemens, [3]NTNU	GHGT-8, Trondheim
18	Radiative properties of a 100 kW Oxy-fuel flame experiments and modelling of the Chalmers test facility	K. Andersson1, F. Johnsson	Chalmers University of Technology	Clearwater conference
19	Coal Combustion and Emission Behaviour under Oxyfuel Condition	J. Maier*, B. Dhungel, P. Mönckert, G. Scheffknech	University of Stuttgart,	Clearwater conference
20	On the performance of mixed conducting CaTi0.9Fe0.1O3-δ membranes	J. B. Smith*, M,-L. Fontaine, Y.Larring, R.Bredesen	SINTEF	Solid State Ionics (to be submitted, approved for publication by ENCAP EB)
21	Modelling of an oxygen transport membrane for an IGCC process with CO_2 capture	F. Sander, R. Span	University of Paderborn	GHGT-8, Trondheim
22	Model of an Oxygen Transport Membrane for coal fired power cycles	F. Sander, S. Foeste, R. Span	University of Paderborn	ICIM-9, Lillehammer
23	Model of Oxygen Transport Membrane for coal fired power cycles with CO_2 capture	F. Sander, S. Foeste, R. Span	University of Paderborn	ASME Turbo Expo 2007, Montreal

24	Operation of a Retrofitted 0.5 MWth PF Combustion Facility under Oxyfuel Conditions – An Experience Report	P. Mönckert, D. Reber, J. Maier, G. Scheffknecht,	Institute of Power Plant Technology IVD, Universität Stuttgart	Clearwater Clean Coal Conference, 2007
25	Design and operation of a 10 kWth Chemical-Looping Combustor for solid fuels- Testing with South African Coal	Nicolas Berguerand*, Anders Lyngfelt	Chalmers University of Technology	Fuel **87** (2008) 2713-2726
26	160 hours of Chemical Looping Combustion in 10 kW reactor system with a NiO-based oxygen carrier	Carl Linderholm*, Alberto Abad, Tobias Mattisson , Anders Lyngfelt	Chalmers University of Technology	International Journal of Greenhouse Gas Control **2** (2008) 520-530
27	The use of petroleum coke as fuel in a 10 kWth Chemical-Looping Combustor	Nicolas Berguerand*, Anders Lyngfelt	Chalmers University of Technology	International Journal of Greenhouse Gas Control **2** (2008) 169-179
28	Verhalten von Stickoxiden bei der Oxyfuel-Verbrennung mit Rauchgasrezirkulation	P. Mönckert, D. Reber, J. Maier, G. Scheffknecht,	Institute of Power Plant Technology IVD, Universität Stuttgart	VDI Flammentag 2007
29	Combustion and Emission Behavior under Oxyfuel Conditions	J. Maier, B. Dhungel, P. Mönckert, G. Scheffknecht,	Institute of Power Plant Technology IVD, Universität Stuttgart	Kraftwerkskolloquium Dresden 2007
30	Radiation intensity of lignite-fired oxy-fuel flames	Klas Andersson*, Robert Johansson, Stefan Hjärtstam, Filip Johnsson, Bo Leckner	Chalmers University of Technology	Experimental Thermal and Fluid Science **33** (2008) 67-76
31	Radiation intensity of propane-fired oxy-fuel flames: Implications for soot formation	Klas Andersson*, Robert Johansson, Filip Johnsson, Bo Leckner	Chalmers University of Technology	Energy and Fuels (submitted)
32	An evaluation of detailed reaction mechanisms for hydrogen combustion under gas turbine conditions	Jochen Ströhle, Tore Myhrvold	SINTEF-ER	International Journal of Hydrogen Energy **32** (2007) 125-135
33	Ramp-up of CO2 capture and storage within Europe	M. Odenberger, J. Kjærstad, F. Johnsson	Chalmers University of Technology (WP1.3)	International Journal of Greenhouse Gas Control **2** (2008) 417-438
34	Lean-Premix H2 Combustion Technology for Gas Turbines	Richard Carroni	ALSTOM-CH	Schweizer Verbrennungs-forschung Tagung, Nov. 2007
35	Solid Fuels in Chemical-Looping Combustion	Leion, H., Mattisson, T. and Lyngfelt, A.	Chalmers University of Technology	International Journal of Greenhouse Gas Control, **2** (2008) 180-193
36	The use of ilmenite as an oxygen carrier in chemical-looping combustion	Leion, H., Lyngfelt, A., Johansson, M., Jerndal, E., and Mattisson, T.	Chalmers University of Technology	Chemical Engineering Research and Design **86** (2008) 1017-1026
37	Chemical-Looping with Oxygen Uncoupling for Combustion of Solid Fuels	Mattisson, T. Lyngfelt, A., and Leion, H.	Chalmers University of Technology	International Journal of Greenhouse Gas Control **3** (2009) 11-19
38	Chemical-looping with oxygen uncoupling using CuO/ZrO2 with petroleum coke	Mattisson, T, Leion. H., Lyngfelt, A.	Chalmers University of Technology	Fuel **88** (2009) 683-690
39	Techno-Economic Evaluations and Benchmarking of Pre-combustion	Clas Ekström, Frank Schwendig, Ole Biede,	VRD, RWE, VAS, AP-UK, Siemens,	GHGT-9

	CO2 Capture and Oxy-fuel Processes Developed in the European ENCAP Project	Flavio Franco, Günther Haupt, Gelein de Koeijer, Charalambos Papapavlou, Petter E. Røkke	StatoilHydro, PPC, SINTEF-ER	
40	Natural Gas Oxy-Fuel Cycles – Part 1: Conceptual Aerodynamic Design of Turbo-Machinery Components	Woollatt, G.[1], Franco, F.[1], Bolland, O.[2], Keyser, J.[4], Rezvani, S.[5], Sander, F.[3], Span, R.[3]	[1]ALSTOM UK, [2]NTNU, [3]Previously Univ. of Paderborn, [4]Siemens, [5]Univ. of Ulster	GHGT-9
41	Natural Gas Oxy-Fuel Cycles – Part 2: Heat Transfer Analysis of a Gas Turbine	Hammer, T.[4], Keyser, J.[4], Bolland, O.[2], Chen, J.X.[1], Franco, F.[1], Rezvani, S.[5], Sander, F.[3], Span, R.[3]	[1]ALSTOM UK, [2]NTNU, [3]Previously Univ. of Paderborn, [4]Siemens, [5]Univ. of Ulster	GHGT-9
42	Natural Gas Oxy-Fuel Cycles – Part 3: Economic Evaluation	Rezvani, S.[5], Huang, Y.[5], Bolland, O.[2], Feraud, A.[1], Franco, F.[1], Keyser, J.[4], Sander, F.[3], Span, R[3]	[1]ALSTOM, [2]NTNU, [3]Previously Univ. of Paderborn, [4]Siemens, [5]Univ. of Ulster	GHGT-9

43	Verbrennungstechnische Fragen im Zusammenhang mit dem Oxyfuel-Prozess	G. Scheffknecht, J Maier	Institute of Power Plant Technology IVD, Universität Stuttgart	VGB Conference, Kassel
44	Firing Issues Related to the Oxyfuel Process	G. Scheffknecht, J Maier	Institute of Power Plant Technology IVD, Universität Stuttgart	VGB Power Tech 11/2008
45	Impact of recycled gas species (SO2, NO) om emission behaviour and fly ash quality during oxy-coal combustion	J. Maier, B. Dhungel, P. Mönckert, R. Krull, G. Scheffknecht	Institute of Power plant Technology IVD, Universität Stuttgart	Clearwater Clean Coal Conference, June 2008
46	CO_2 capture from direct combustion of solid fuels with Chemical-Looping Combustion	Leion, H., Mattission, T., Lyngfelt. A.	Chalmers University of Technology	Clearwater Clean Coal Conference, June 2008
47	On the preparation of asymmetric $CaTi_{0.9}Fe_{0.1}O$[illegible] membranes by tape-casting and co-sintering process.	M.-L. Fontaine, J.B. Smith, Y. Larring, R. Bredesen	SINTEF Materials and Chemistry Department	Journal of Membrane Science 326 (2009) 310-315
48	The use of ores and industrial products as oxygen carriers in chemical-looping combustion	H. Leion, T. Mattisson, A. Lyngfelt	Chalmers University of Technology	Fuel
49	Solid fuels in chemical-looping combustion using a NiO-based oxygen carrier	H. Leion, T. Mattisson, A. Lyngfelt	Chalmers University of Technology	Industrial Engineering Chemistry Research
50	The use of CaMn_0.875Ti_0.125O3 as oxygen carrier in Chemical Looping with Oxygen Uncoupling (CLOU)	Leion, H., Larring, Y., Bakken, E., Mattisson, T., Bredesen, R., Lyngfelt. A	Chalmers University of Technology, SINTEF Materials and Chemistry Department	Manuscript ready and approved by ENCAP EB, to be submitted.
51	Comparative Assessment of physical absorption, water gas shift membrane reactor and chemcial looping integrations in a coal fired IGCC system with CO2 capture	Rezvani, S., Ye, H., McIlveen-Wright, D., Hewitt, N., Deb Mondol, Y	University of Ulster	Submitted to Fuel
52	Short term corrosion testing in a burner rig with oxyfuel and conventional firing	Montgomery, M, Hjörnhede, A., Bjurman, M., Gerhard, A.	Vattenfall, IVD	EuroCorr2009, Nice

53	The role of CCS in the European electricity supply system	M, Odenberger, F, Johnsson	Chalmers University of Technology	GHGT-9 conference, Washington D.C., 16th - 20th November, 2008 (oral presentation)
54	Ramp-up of large-scale CCS infrastructure in Europe	Jan Kjärstad, Filip Johnsson	Chalmers University of Technology	GHGT-9 conference, Washington D.C., 16th - 20th November, 2008 (poster)
55	Capturing CO_2 to power the future	Leif Brandels, Nikolaos Koukouzas	Vattenfall AB, CERTH/ISFTA	e-Strategies Projects Magazine, British Publishers, January issue 2009
56	The ENCAP Integrated Project – Development and Validation of enhanced Pree-combustion CO2 Capture Technologies in the EU 6th Framework Programme	Leif Brandels	Vattenfall AB	GHGT8

APPENDIX 2: LIST OF ACRONYMS AND ABBREVIATIONS/ DEFINITION OF CAPTURE COST AND CO2 AVOIDED

Acronyms and Abbreviations

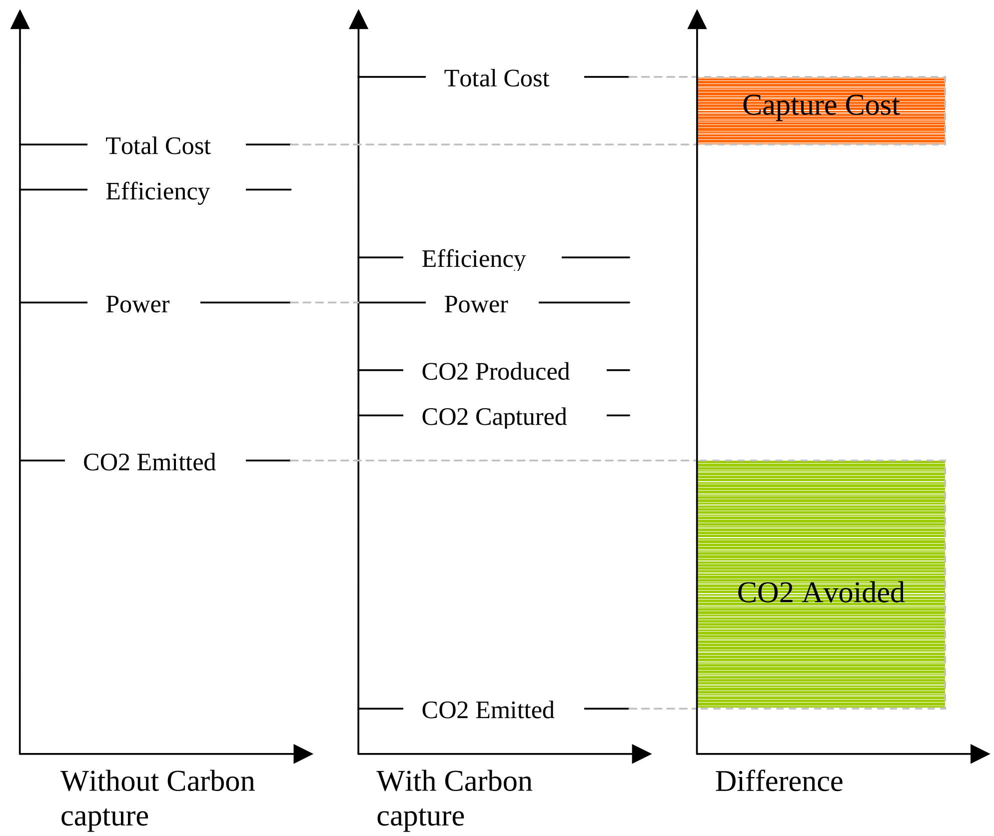
ASC PF	Advanced Supercritical Pulverised Fuel (boiler plant)
ASU	Air Separation Unit
ATR-CC	Auto-Thermal Reformer Combined Cycle
AZEP	Advanced Zero Emission Power
CAR	Ceramic Autothermal Recovery
CARS	Coherent Anti-Stokes Raman
CC	Combined Cycle / Carbon Capture (depending on context)
CCS	Carbon Capture and Storage
CFB	Circulating Fluidised Bed
CFD	Computational Fluid Dynamics
CLC	Chemical Looping Combustion
ENCAP	Enhanced capture of CO2
ETAC	ENCAP Technical Advisory Committee
FP	Frame programme
GT	Gas Turbine
GTCC	Gas Turbine Combined Cycle
IGCC	Integrated Gasification Combined Cycle
IP	Integrated Project
IRCC	Integrated Reforming Combined Cycle
LHV	Lower Heating Value
MEUR	Million Euros
MWth	Megawatt thermal power
MWe	Megawatt electric power
NR-CLCCC	No Reheat Chemical Looping Combustion Combined Cycle
O&M	Operation & Maintenance
R&D	Research & Development
RTD	Research and Technology Development
SCOC-CC	Semi-Closed Oxyfuel Combustion Combined Cycle
SP	Sub Project
SR-CLCCC	Single Reheat Chemical Looping Combustion Combined Cycle
th	thermal
w	with
w o	without
WP	Work Package

Definition of Capture cost and CO2 Avoided

Capture of carbon in a power process requires some energy. Looking at two power processes, one with CC (Carbon Capture) and one without CC producing the same amount of power, the capture-process needs more fuel and produces more CO2 than the other due to reduced efficiency. It is important to distinguish between the following expressions:

- CO2 captured: Total amount of CO2 captured in the capture process.
- CO2 avoided: Amount of CO2 emitted in case of a no-capture process (producing the same amount of energy) minus the amount CO2 not captured in the capture processes.

These expressions are shown graphically below.



Power processes with carbon capture produce more CO2 than processes without capture. CO2 avoided is the reduction of emissions by replacing a plant without and with CC.

Terms related to costs can be distinguished in the following way:

- Euro/ton CO2 captured: The additional costs related to the carbon capture (Capture Cost in figure above) divided by the amount CO2 captured
- Euro/ton of CO2 avoided: The Capture Cost divided by the amount CO2 avoided
- Euro/kWh: Total cost of power generation divided by power generated in the process.

Total cost includes CapEx, fuel costs and O&M.