



SP5 Public Summary Report

Based on the Del. 5.1.3: Economic evaluation of components and sub-systems costs for process selection to proceed to the next step.

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Scope of the work in this report was to perform the necessary engineering, cost, operability and reliability assessment of the leading process options resulting from the previous selection steps in order to enable the recommendation of one most promising technology, i.e. one High-Temperature Oxygen generation system (HTO) integrated in fossil-fuels power plant with CO₂ capture. Final purpose of this integration was the achievement of the ENCAP targets, i.e. a CO₂ capture rate of at least 90% and a CO₂ capture cost reduction of 50%, with reference to the present CO₂ separation technology (scrubbing).

Basis for this process assessment was the information on material and process concepts, the results of experimental activities and cost estimates of material/process components provided by the partners of Subproject 5 (SP5) and the cost estimate of power plant components provided by the partners of other ENCAP SP's.

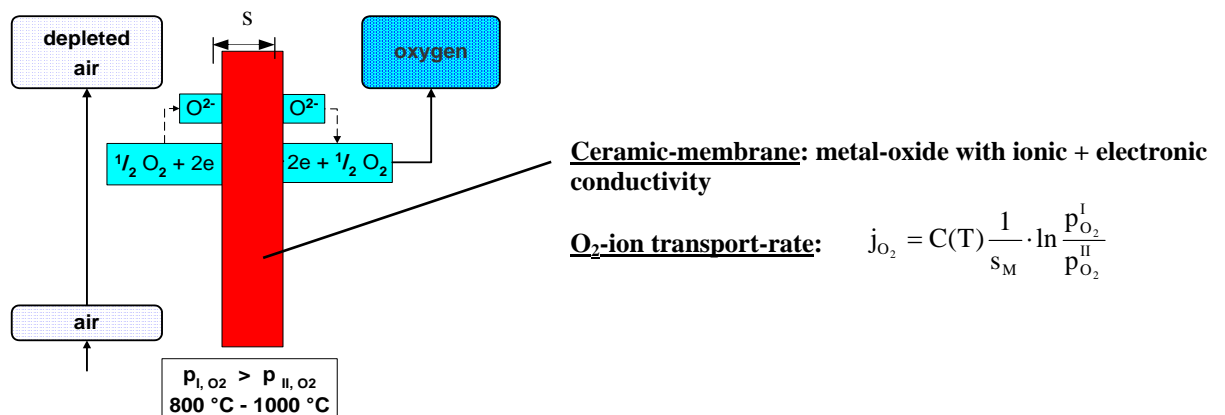
A first part of the report was dedicated to the presentation and evaluation of the technical information provided by the partners of this SP for the selected options. In a second section the overall investment and operating costs of the selected power plant scenarios were presented and on this basis the BET (Break Even Electricity Tariff) was calculated.

The three process options

The three high-temperature working technologies for the oxygen supply considered for the process assessment were all based on special ceramic materials. In particular:

1. "Oxygen separator membrane" based on the transport of oxygen ions through a ceramic membrane made from perovskite or similar structures. The ceramic membrane separates the oxygen from air at high temperatures based on partial pressure ratios (Figure 1). The oxygen flux through the membranes can be maximised by decreasing the thickness of the membrane material and by reducing the partial pressure at the permeate side (pO₂"') by means of a carrier or sweep gas.

Figure 1: O₂ -production by a pressure-driven ceramic membrane.



2. "Oxygen Transport Membrane (OTM) reactor" works on the same principle as the oxygen separator.

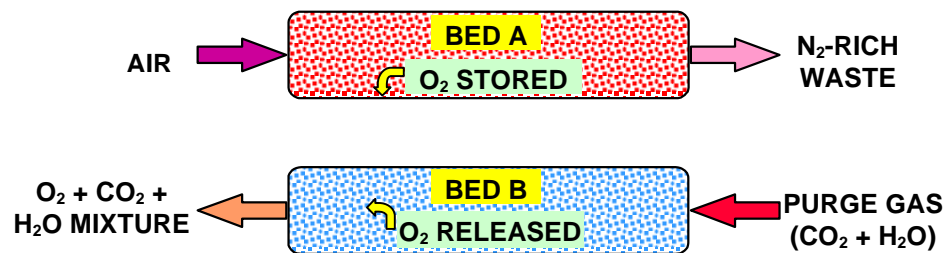
In this case, the "sweep" gas at the permeate side is replaced by a reactive fuel gas, partially or totally oxidised by the permeated oxygen.

3. "Ceramic Autothermal Recovery (CAR)" utilises the oxygen storage properties of perovskite type materials at high temperatures.

The process consists of a cyclic operation in at least two solid-bed adsorber columns containing a ceramic, e.g. perovskite material in spherical pellets, cylindrical extrudates or other shapes similar to well-known sorbent or catalyst materials.

One bed is fed with a high temperature air stream and its oxygen is captured, stored and retained in the material, while the oxygen previously stored in the other bed is released by reduction of oxygen partial pressure and is removed, as illustrated in Figure 2. The two beds exchange their function in cyclic form resulting in the generation of an oxygen-containing gas with low N₂ content. The reduction of the oxygen partial pressure can be achieved by depressurization, by vacuum or by addition of a sweep gas flow.

Figure 2: Working principle of CAR-Process.



Technical comparison of the leading options

After a basic pre-selection work performed during the first period of the project a stepwise selection procedure was established in order to give a systematic approach to the screening and ranking of different candidate scenarios, aimed finally at the identification of one most promising process option. In particular three main steps, characterized by an increasing variety and number of evaluation criteria and by consequence an increasing degree of detail in the analysis of the processes, were defined:

- Step 1: Pre-selection phase,
- Step 2: More detailed modelling of the selected processes from step 1 and
- Step 3: Increased level of detail in the evaluation of the power plant cycle selected from step 2 with the integration of different O₂ generation methods.

The three finalized process options resulting from the first step of the selection procedure were:

1. OTM separator integrated in pf - oxyfuel boiler scenario,
2. CAR unit integrated in pf -oxyfuel boiler scenario
3. OTM reactor in an Integrated Reforming Combined Cycle (IRCC) scenario.

Scenario 1: OTM Separator + Boiler

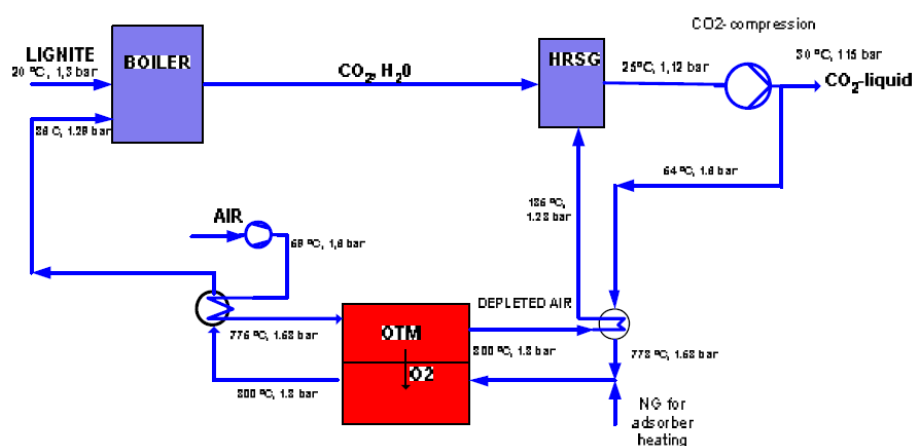


Fig. 3: Oxyfuel boiler power plant with OTM separator- PFD (sweep gas: CO₂)

Air is compressed, preheated by the oxygen-enriched sweep gas and routed to the OTM separator module. Here O₂ was transferred from air to a preheated CO₂-based sweep gas. The depleted air, after preheating the sweep gas stream, was routed to the Heat Recovery Steam Generation block (HRSG) for pre-heating the Boiler Feed Water (BFW). The oxygen-enriched sweep gas was routed to the boiler and burnt

with the lignite feed. The exhaust gases were purified, cooled in the HRSG unit and compressed. A certain fraction of the compressed CO₂ was recycled as sweep gas, while the other fraction was further compressed, dried and liquefied. In order to maintain the high operating temperatures required in the OTM module, an additional heat source was necessary. As indicated in the PFD above, a possible option was represented by the injection of natural gas into the sweep gas, which was then burnt with the oxygen permeated in the OTM module.

Table 1: The main results of the process from the HYSYS simulations

LHV net energy efficiency % (dry lignite basis)	35,8
LHV net energy efficiency % (wet lignite basis)	40
Net electricity produced MW	970
CO ₂ captured (kmole/h)	15223
CO ₂ emitted (kgmole/h)	0
(CO ₂ captured)/(CO ₂ captured + CO ₂ emitted) %	100

The main conclusions resulting from a technical analysis of this scenario were:

1. A remarkable effort has been spent on the search and optimisation of an OTM material able to meet the defined oxygen flux targets (10 ml/cm².min). The achievement of the defined flux target wasn't successful. A possible gain in the oxygen flux could be achieved at a pressure of 20 bar at the feed gas side. A further improvement of the O₂ flux would be also achieved by a further decrease in the thickness of the membrane dense layers: the feasibility of this solution firstly need to be demonstrated from a manufacturing and (mechanical) stability point of view.
2. The thermodynamic stability of the membrane material was firstly investigated by high temperature treatments in mixtures of methane and water. No signs of degeneration were observed.
3. Long-time stability tests are needed, in order to attest the thermodynamic stability of the material at representative operating times.

Furthermore, the conclusions on process design basis for the case of OTM separator membrane were that the material development status was not mature enough for a pilot scaling and a conceptual membrane module design is lacking. In the presented simulation of the OTM boiler process, the sweep gas was recycled from the cooled exhaust gas. Dust and sulphur has to be removed before the CO₂ recycle. The gas has to be heated by heat recovery from hot gases and additional combustion of NG. The sufficient gas cleaning for the recycle gas to the membrane will be an issue. The pressure drop in the sweep gas and OTM module was quite sensitive for the power plant efficiency. For the OTM reactor module a pressure drop of 200-300 mbar was calculated. Compared with the combustion with air the O₂ content in the sweep gas has to be raised up to 27 % to achieve the same combustion temperature as with air. In the simulated case there is an O₂ content of 25.5 %.

Scenario 2: IRCC OTM reactor

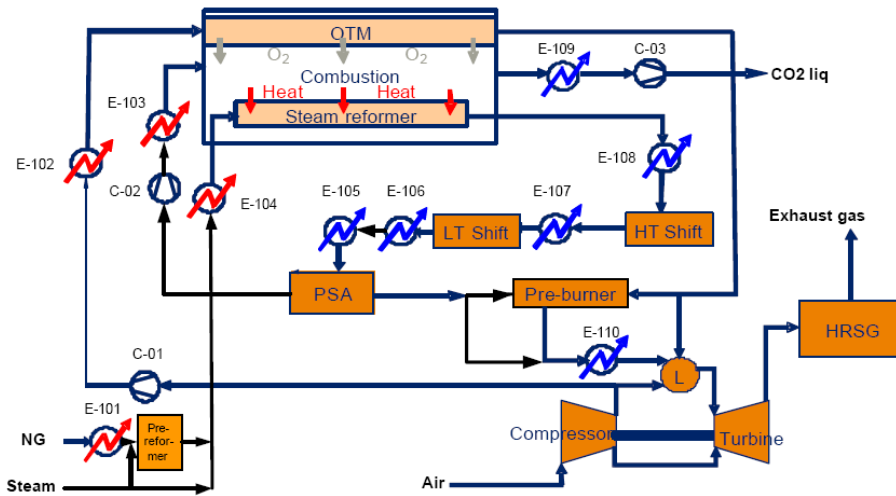


Figure 4: IRCC power plant concept with OTM reactor- PFD.

Natural gas (NG) is preheated, mixed with steam and routed to a pre-reformer, where higher hydrocarbons are converted to CH_4 in order to reduce the coking potential in the steam reforming step. After the pre-reformer, additional steam is mixed with the hydrocarbon feed and routed to the steam reformer section of the OTM reactor. In the reforming channel of the OTM reactor the hydrocarbons are converted to H_2 , CO and CO_2 . The hot effluent is cooled down and the CO is converted to CO_2 and H_2 in a high- and low temperature shift. The resulting gas is further cooled down and then routed to a PSA unit where a H_2 -rich fraction is separated. A fraction of the H_2 -rich gas is burnt with the O_2 - depleted air coming out from the OTM reactor, in order to remove its remaining O_2 content. The resulting O_2 - free gas is mixed with the main H_2 -rich fraction. This mixture is cooled down to a sub critical temperature of $300\text{ }^\circ\text{C}$ and routed to the combustor of the gas turbine. The H_2 -fuel is burnt with additional compressed air and expanded in the turbine of the gas turbine unit. The resulting hot effluent is used for steam production in the “Heat Recovery and Steam Generation” unit (HRSG). The purge gas from the PSA is compressed and routed to the OTM reactor for combustion with the O_2 permeating from the OTM membrane section. This effluent is cooled down and routed to a CO_2 -compression and liquefaction section. A part of the compressed air from the gas turbine is further compressed, heated and routed to the OTM reactor membrane section where O_2 is extracted at the membrane surface. The resulting O_2 - depleted air goes to the pre-burner and finally to the combustion chamber of the gas turbine.

Table 2: The main results from the HYSYS simulations

LHV net energy efficiency %	47.7
Net electricity produced MW	428
CO_2 captured (kmole/h)	3990
CO_2 emitted (kgmole/h)	201
$(\text{CO}_2 \text{ captured})/(\text{CO}_2 \text{ captured} + \text{CO}_2 \text{ emitted})$	0.952

The main conclusions from the technical analysis of this scenario were:

- For the OTM reactor concept the material development activities performed in the past reported satisfying values for flux and chemical material stability. A reactor concept was presented, based on theoretical reaction calculations and heat transfer considerations. A preliminary stress analysis was included in the provided modelling work.
In general, the technical feasibility of the presented reactor concept within the ENCAP time frame seems not yet mature enough for further recommendation. In particular, the mechanical stability of the ceramic plates under the assumed operating conditions and the verification of the proposed sealing concept OTM plates-air shell are critical issues that were preliminary assessed in this work and needed more work.
Furthermore, the availability (shut-down in case of crack of a ceramic plate), flexibility (no possibility to switch to a power plant operation without CO₂ capture) and reliability (technical risk in case of crack of a ceramic plate) of the proposed reactor concept were left to the pilot unit to be demonstrated.
- The electrical efficiency of the OTM reactor integrated in IRCC (Integrated Reforming Combined Cycle) is 48 %.
In consideration of the efficiency calculated for the most closely corresponding scenario investigated in ENCAP using cryogenic air separation (SP2, "Case 4: Natural Gas/Autothermal reforming (ATR), net efficiency: 41%), the OTM reactor integrated in IRCC appears competitive with the equivalent scenario using the traditional air separation system for the oxygen supply.

Scenario 3: PF oxyfuel boiler+CAR

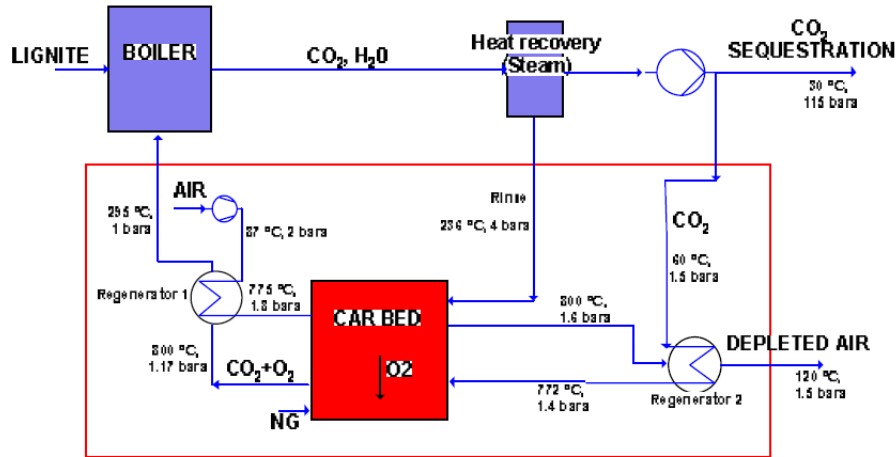


Fig. 5: Oxyfuel boiler power plant with integrated CAR unit - PFD

Air is compressed before entering the multi- vessel CAR unit. The adsorber vessels are interconnected with valves which operating temperature is limited to about 300 °C. Each CAR-adsorber bed consists of three layers. The first and the third are "heat storage" layers, based on an inert ceramic material, while the middle layer consists of the O₂- storage perovskite material. The air is further heated up by the first regenerator- layer to about 780 °C before entering the adsorbent layer. The O₂ depleted air is cooled down firstly by the third layer of the CAR bed to an exit temperature of ~ 120 °C. The stored O₂ is swept out by a compressed CO₂ flow, recycled from the boiler- flue gas. The resulting CO₂+O₂ mixture is routed to the boiler, where it is burnt with lignite to a CO₂, H₂O and ash-containing flue gas. The combustion heat and the out coming hot flue gases are used for steam production in a heat recovery system steam generation (HRSG) unit. Part of the produced steam is employed for two rinse steps in the CAR-bed, before and after the adsorption step, in order to remove N₂ and CO₂ from the bed-void volume. The heat losses arising during the cyclic sorption process and the steam-rinse steps are compensated by addition of natural gas to the CO₂ flow, burnt in the perovskite layer with the desorbed oxygen.

Table 3: The main results from the HYSYS simulations

LHV net energy efficiency % (dry lignite basis)	34%
LHV net energy efficiency % (wet lignite basis)	38%
Net electricity produced MW	983
CO ₂ captured (kmole/h)	15181
CO ₂ emitted (kmole/h)	601
(CO ₂ captured)/(CO ₂ captured + CO ₂ emitted)	0.96

The main conclusions from the technical analysis of this scenario were:

- The CAR material development activities showed some progress in the achievable O₂ loading capacity. The material stability for the new material compositions was not tested for long operation times.
In general, the technical concept at the basis of the CAR process seems practicable. The availability should be high as the adsorber concept in principal is technical proofed in H₂ purification plants over a long period. The flexibility to change to an operation without CO₂ capture is possible in principal, because the boiler can although be operated with air. The technical risk is low. In case of a failure of a valve only a single adsorber will be blocked and the plant operation with lower load will be possible. The adsorbent itself can be damaged only by impurities of the purge gas. This will be a long term effect which has to be tested in a pilot plant.
- The electrical efficiency of the CAR unit integrated in the boiler process is 38 %.
In consideration of the efficiency calculated for the equivalent scenario investigated in ENCAP using cryogenic air separation (SP3, pf-oxyfuel boiler , net efficiency: 40%), the CAR unit integrated in the boiler process appears at the time being not competitive with the equivalent scenario using the traditional air separation system for the oxygen supply.
There is some potential for a further improvement of the efficiency of CAR + boiler scenario, based et. al. on an optimisation of the material performance, reduction of void volume and pressure drop and related process operating conditions like purge-gas flow rate and steam- rinse flow rate reduction.

Economic comparison of the leading options

The overall investment costs for the power plants with CO₂ capture was estimated as:

$$\begin{aligned}
 & \text{Investment costs reference power plants without CO}_2 \text{ capture} \\
 & + \\
 & \text{Additional costs for the power plant with CO}_2 \text{ capture equipment}
 \end{aligned}$$

On this basis, NPV (Net Present Value) and BET (Break even electricity tariff) for the selected scenarios were calculated.

The results provided by the cost estimate, the BET calculation and from the technical evaluation were inserted in the decisional matrix used in step no.2 and finally 3 of the selection procedure

Table 4: Step 3 - Selection criteria for final assessment.

Oxygen generation system		OTM reactor	Cryogenic ASU	OTM-Separator	CAR-Process
Power plant type		IRCC-Reform*	IGCC-ASU*	Boiler-OTM-s *	Boiler-CAR*
Fuel type		NG	Lignite	Lignite	Lignite
Spec.Investment cost for O2 generation	Mio.€/MW el. net	0.160	0.065	0.266	0.247
Spec. Invest. cost CO2 capt. at 100 % capture rate	€/t CO2	2.192	7.0	11.4	12.6
Electrical net efficiency PPC ref. plant without CO2 capture	%	41.0	45.0	49.3	49.3
Electrical net efficiency PPC with CO2 capture	%	47.9	41.0	40.0	38.2
Spec.CO2 capture ref. plant	g/kWh net	501.9	897.8	819.0	819.5
Break even electricity tariff (BET)	€/kWh	0.0445	0.0449	0.0447	0.0451
BET + 20 % Invest	€/kWh	0.0463	0.0484	0.0482	0.0486
BET + 20 % Fuel cost	€/kWh	0.0480	0.0519	0.0517	0.0521
Ranking BET		1	3	2	4
Expected technical concept until Aug 05		yes	yes	no	yes
Maturity of process		no	yes	no	yes
Technical risk		high	low		low
Part load op.		yes	yes		yes
Availability		low	high		medium
Flexibility		high	medium		medium

Fuel quality		high	medium		medium
CO2 capture %		95	100		96
Construction time		2	4		4
Technical life		10 OTMR	25		?
Additional emissions		no	no		no
Waste water quality		?			
CO2 purity		?			

As indicated in the Table above, the BET of the OTM reactor concept resulted approx. 2 % lower than for the CAR boiler concept. On the other hand, in consideration of the uncertainties in the cost estimate (10 to 20%), this difference didn't offer a significant statement on the ranking of the different scenarios.

In the final selection step the CAR process was selected by Subproject 5 for a further validation work within ENCAP, in preparation to the eventual construction of a pilot plant, because of the following criteria:

- higher maturity of the adsorption process
- higher availability
- higher flexibility
- Bypass CO2 capture possible

The selection was approved by the ENCAP executive board and the ENCAP Technical Advisory committee.