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Techno-economical study of the Zero Emission Gas power concept

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Abstract

The objective of this study has been to evaluate the technical and economical feasibility of the novel hybrid Zero Emission Gas power concept (ZEG), featuring production of electrical power from natural gas with integrated CO_2 capture, via a close integration of the Sorption Enhanced Steam Methane Reforming process (SE-SMR) with a high temperature Solid Oxide Fuel Cell (SOFC). Technical design, process simulations and the preparation of detailed equipment lists have been carried out to calculate capital expenditure (CAPEX) and operation expenditure (OPEX) of the process. A cost analysis has been carried out for different price scenarios involving natural gas and electrical power prices, as well as CO_2-quota cost and CO_2 sales value. The ZEG concept has been compared with a more conventional pre-combustion technology alternative as a reference case (REF), involving the coupling of auto-thermal reforming, water gas shift, amine CO_2 capture technology and a combined cycle. The results of this study show that the ZEG-case technology is likely to be profitable with relatively high net present values (NPV) in most of the price scenarios chosen, while the REF-case technology, using more conventional pre-combustion available technologies, shows negative NPV-values for all scenarios. Even with no income for the CO_2 captured and a quite moderate natural gas price of 19 EUR/MWh, the ZEG-case shows profitability for an electric power price of 50 EUR/MWh or higher. The promising and encouraging results of this study show the potential of the two technologies and of their close integration towards future zero emission power plants on a medium to long term perspective.

Keywords: ZEG; SESMR; SOFC; CO_2 capture; techno-economical study

1. Introduction

Because of growing concerns over increased man-made greenhouse gas emissions, technologies for carbon capture and storage (CCS) are being seriously considered to enable reduced emissions. The attractiveness of CCS lies in the possibility to continue using fossil fuels and at the same time reduce the emissions. Natural gas and coal fired power plants have been identified as important point sources of CO_2 emissions, and several technologies for CO_2 capture have been proposed (see Figure 1). Common for these technologies, however, is the large efficiency penalty associated with the separation and compression of the CO_2. Typically, a natural gas fired power plant looses 10%-points of its efficiency. This means that a state-of-the-art combined cycle plant would lower its efficiency from

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60% to 50% which corresponds to 20% higher fuel consumption per kWh produced. A major challenge for the application of CCS is the development of new energy technologies which successfully combine high energy efficiency and CO_2 capture.

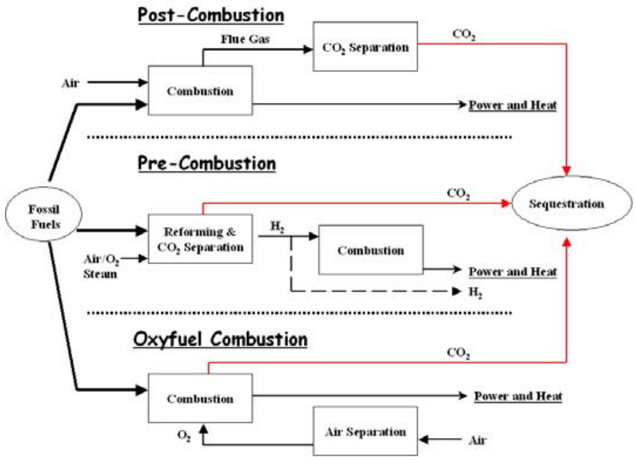

Figure 1: CO_2 capture routes [1]

In order to address the challenge of combining CO_2 capture and high energy efficiency in energy plants, the ZEG concept has been proposed by Institute for Energy Technology (IFE) and Christian Michelsen Research (CMR). In this hybrid high efficiency pre-combustion concept, Sorption-Enhanced Steam Methane Reforming of natural gas (SE-SMR) is closely integrated with a high temperature Solid Oxide Fuel Cell (SOFC). When these two technologies are integrated, the heat from the fuel cell is used for upgrading natural gas to hydrogen and essentially no energy is wasted. This study documents the thermodynamic performance of the ZEG concept, which is also equipped with 100% CO_2 capture, and compares it with a reference case (REF) using more conventional available technologies.

2. Plant configuration

In the ZEG concept, natural gas (NG) is reformed to a hydrogen-rich gas mixture using the novel SE-SMR reforming technology. In the SE-SMR process, the reaction of methane with steam is carried out in the presence of a mixture of a reforming catalyst and a selective high temperature solid sorbent for CO_2 (named sorbent in this study). When a solid CO_2-sorbent (in this study calcined dolomite- CaO-MgO) is mixed with a reforming catalyst, the CO_2 in the synthesis gas mixture is removed as it is formed, causing the reforming and water gas shift reactions to proceed simultaneously beyond the thermodynamic limits [2-3]. The water gas shift (WGS) section is then eliminated. Moreover, when CO_2 is captured *in situ*, near to pure CO_2 is obtained by regenerating the sorbent using temperature swing with steam generation, eliminating costly separation steps downstream. Reforming, CO_2 capture and CO_2 removal are integrated within only two vessels: a reformer producing hydrogen and capturing CO_2, and a regenerator releasing CO_2. The hydrogen concentration is typically around 95mole% (dry basis) after the SE-SMR unit and the reformate gas is fed to a SOFC for electricity production. The heat required to regenerate the solid sorbent in the SE-SMR unit is provided by the SOFC waste heat through an internal heat transfer loop. The REF-case chosen in this study combines an auto-thermal reforming (ATR) operated at 40bar, an air separation unit (ASU), a two stages water gas shift, an activated MDEA-based CO_2-separation and a combined cycle power section including gas turbine, steam turbine and heat recovery steam generator [4]. Schematic drawings of the two concepts are shown in Figure 2.

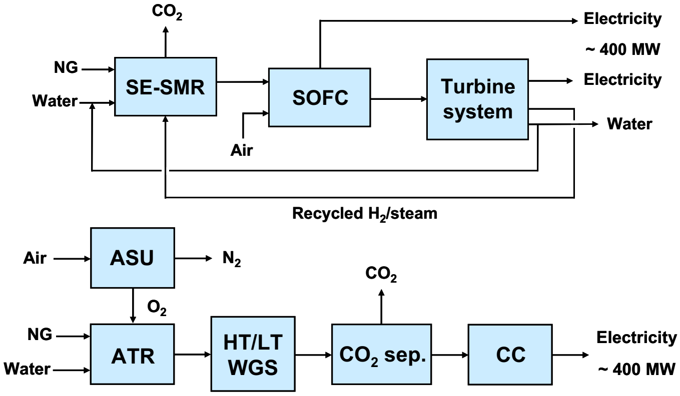

Figure 2: Schematic layout of the ZEG-concept (up) and REF-case (down)

3. Process and reactor technology

The continuous nature of the SE-SMR process makes the use of a fluidized bed technology with circulation of solids a clear alternative to run the process in an efficient manner. The study is based on a reactor concept using a Dual Bubbling Fluidized Bed reactor system (DBFB) with circulating solids, at near atmospheric pressure. The solids are circulated between a reformer and a regenerator. The main advantages of this system are that it can be run continuously, a good temperature uniformity and an efficient heat exchange can be obtained, and solids can be purged and refilled continuously. Figure 3 shows a detailed schematic drawing and a 3D illustration of the SE-SMR DBFB reactor system.

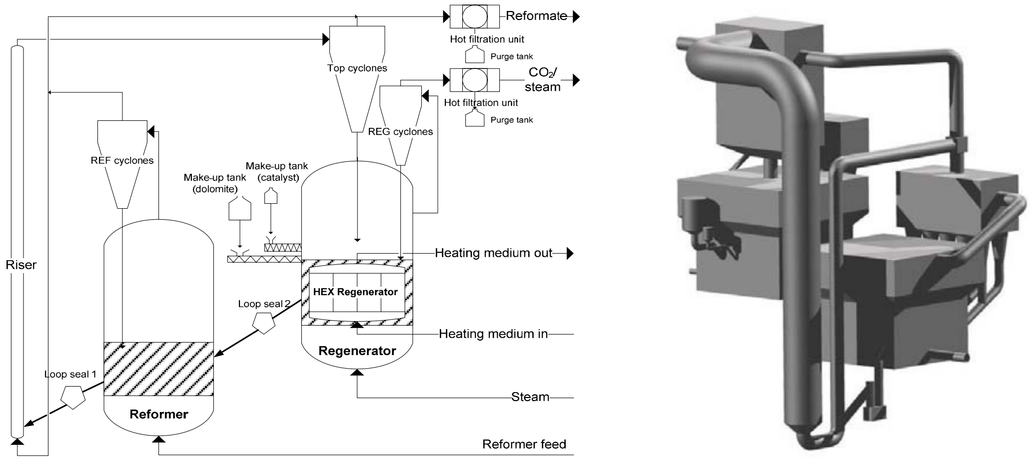

Figure 3: Schematic drawing of the SE-SMR DBFB reactor system and a 3D illustration

The key operational parameters for the reformer and the regenerator are listed in Table 1. The fluidized bed reformer is designed for operation in the turbulent regime, and a maximum superficial gas velocity of 1 m/s is defining the upper production capacity of the reformer. The regenerator is operated in the bubbling bed regime, and a superficial gas velocity of 0.4 m/s is applied here. The circulation of solids is set at a relative high rate to compensate for chemical degradation of the sorbent.

Table 1: Operation figures of the SE-SMR reactors

Reformer	
Temperature	600°C
Pressure	~1 barg
Steam/Carbon mole ratio	2.5
Superficial gas velocity	1 m/s
Regenerator	
Temperature	880°C
Pressure	~1 barg
Superficial gas velocity	0.4 m/s
CaO conversion	32 mole%
Solid circulation rate	204 kg/s

The ZEG-concept uses the SOFC waste heat via an indirect heat exchange system to transfer the heat required for the regeneration of the sorbent. The heat exchange is achieved by the integration of a high temperature heat exchanger in the regenerator. The SOFC has an operation temperature around 1000°C. The SOFC consists of 87 stack modules of 3.97 MW each, which consist of 90 stacks of 600 cells each. The main SOFC process data are shown in Table 2.

Table 2: Main SOFC process data

Cell area specific resistance	400 mΩ.cm^2
Open circuit voltage	0.833 V
Operating voltage	0.732 V
Current density	0.251 A/cm^2
Power density, electricity	0.184 W/cm^2
Heat produced per area	0.133 W/cm^2
Total active cell area	1.871 .10^9 cm^2
Number of cells	4 679 000
Power per cell	73.6 W
Stack	
Number of cells	600
Power per stack	44.16 kW
Pressure loss	2 mbar
Stack module	
Number of stacks	90
Power per module	3.97 MW
Plant	
Number of stack modules	87
Total power output	344.3 MW

The steam turbine power generation section utilizes excess high quality heat and produces mechanical energy to drive compressors or electric power generators. A maximum working temperature of 550°C was chosen in this study.

The CO_2 captured by the solid sorbent is released in the regenerator using steam as fluidization gas, and the condensate water is separated out prior to compression. The gas is first compressed to 80 bar in a sequence of compressors with inter-coolers and flash drums for water separation, then condensed (cooled to 20°C) and finally pumped up to 110 bar.

A process flow diagram of the ZEG concept is shown in Figure 4.

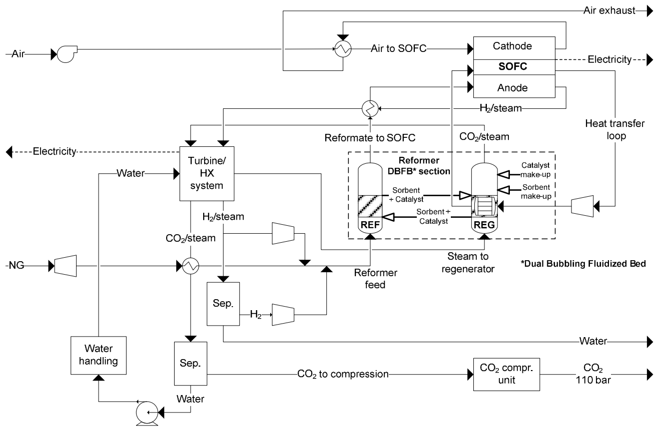

Figure 4: Process flow diagram of the ZEG-concept

4. Plant performances

The process simulation software Aspen HYSYS has been used to simulate the total process. The HYSYS model simulates heat exchange, power production, chemical reactions, pressure losses and compression work. In addition to the heat exchangers, the HYSYS simulations consists of a SOFC unit, a turbine unit, a reformer/regenerator unit, two separator units and a compression unit for CO_2. The operating point of the fuel cell is found from the heat balance. Heat required to the heat transfer loop and internal preheating is subtracted from the total energy production in the SOFC. The electric energy production from the SOFC is the remaining energy. The SOFC operating point is checked based on operation voltage at current efficiency and physical size. The turbine system used in the ZEG concept has been modeled and contains 2 steam turbines in series, with a superheating stage in between. In addition, an expander is installed in the natural gas feed stream to take advantage of the delivery pressure of the natural gas (70 bar). A reactor model is built up in the reformer/regenerator sub-flowsheet. The model is based on one conversion reactor, one Gibbs reactor and calculations on solid component reactions and heat capacity utilizing spreadsheet operations in HYSYS. The energy balance of the reformer includes heat capacity data of the solids transferred between the reactors and reaction enthalpy of the carbonation and calcination reactions. The results are the required preheating temperature for the fuel gas and the required heat supply from the heat transfer loop from the SOFC. Results from the HYSYS simulations are in very good agreement with a Matlab reactor model for SE-SMR in a DBFB reactor system developed earlier [5]. CO_2 compression is simulated using compressors and flash drums in series. Cooling water is used to reduce the temperature between each compression stage. CO_2 is compressed to a pressure of 74 bar to dense phase and then pumped to the final pressure of 110 bar. A component splitter is included to remove all water in the CO_2 stream. The small amounts of CO_2 which are not captured in the reformer are recycled in the system so that basically no CO_2 is emitted.

Power consumptions, efficiencies and CO_2 capture figures are given in Table 3.

Table 3: Process efficiency and CO_2 capture

	ZEG-case	REF-case		ZEG-case	REF-case
Thermal input NG (MW)	484.7	872.3	NG feed (kmole/h)	2 090	3 750
Power output (MW)	402.1	432.4	Carbon in NG feed (kmole/h)	2 285	4 067
Process auxiliaries (MW)	29.3	79.4	CO_2 captured (kmole/h)	2 285	3 508
Net power output (MW)	372.8	353.0	CO_2 capture (%)	100	86.3
Overall gross efficiency	82.9	49.6	CO_2 emissions (%)	0	13.7
Overall net efficiency	76.9	40.5	CO_2 emitted (kmole/h)	0	557

5. Cost estimates and net present value analysis

Based on detailed equipment lists, capital expenditure (CAPEX) calculations have been performed. Most of the equipment costs are generated by employing the Aspen Icarus Project Management cost database (Aspen IPM version 2006 and version 14.0). From the equipment costs, the plant costs have been generated using a method based on the "factor estimation method" [6]. Based on operating conditions and material costs, calculations have been performed to obtain the cost of the SOFC modules. The total SOFC cost has been calculated from different cost predictions and evaluated to 277.6 kEUR/MW, including a cost for the heat transfer loop of about 54.8 kEUR/MW. The plant location is uncertain so the location factor has been kept equal to one, indicating a centralized location where the necessary manpower for erection of the plant can be found in the nearby area. Contingency is generally set to 20% of identified costs. The results are summarized in Table 4.

Table 4: Summary of plant cost data (CAPEX) in MEUR (million Euro)

Costs in MEUR	**ASU**	**Reforming**	**CCGT**	**SOFC**	**Auxiliaries**	**Total**
ZEG-case	-	108.6	-	95.2	196.3	400.0
REF-case	59.6	143.0	270.9	-	-	473.5

The reforming catalyst and the dolomite sorbent are replaced continuously through make-up streams. Total renewal of solids inventory is accomplished after approximately one year. For the SOFC, a replacement interval of 10 years (80 000 hours) is estimated. This cost is spread out as annual cost. The destruction cost of the solids residues (catalyst and sorbent) is also taken into account and has been evaluated to 250 kEUR/tonne. Annual cooling water costs are included as well. The plant will have some fixed costs related to maintenance, administration and staff. Maintenance is calculated as 4% of the investment cost. Administration and staff costs are based on experience from earlier projects in relation to the size and complexity of the plant.

The operation expenditure (OPEX) value is calculated as the balance between the annual income and expenditures related to the input streams and cost elements. The total annual income is calculated as the value sum of the produced electric power and the captured CO_2, when it has a sales value. The annual energy costs are the value sum of the natural gas feed and the electric power consumption of the plant. Based on the specified values of the parameters above, the OPEX is calculated and together with the CAPEX data it forms the basis for the net present value (NPV) calculation. The NPV-values are based on 8000 operating hours/year, 25 years operation and 7.5% interest rate. The unit prices for natural gas, electric power and CO_2 are difficult to foresee. In the present analysis, two different price scenarios are assumed and shown in Table 5. Price scenario 1 assumes a fixed relation between the cost of natural gas and electric power. I.e. a doubling of the natural gas price doubles the electrical power price. The CO_2 sales value and quota cost are both kept equal to zero. In price scenario 2, the NG cost and electric power cost are similar to those in scenario 1, but the CO_2 quota cost and sales value are now varied. The quota cost is set to a starting point which is equal to the present trade value of about 17 EUR/tonne. It is assumed that this value will increase, and the end point used here is the long-term projections from the CCP project of about 21 EUR/tonne. The CO_2 sales value starts from zero, as today, and increases linearly up to a value which is equal to the long-term projections. The results of the NPV calculations are given in Figure 5.

Table 5: Unit price scenarios

	Price scenario 1			**Price scenario 2**		
	Array 1	Array 2	Array 3	Array 1	Array 2	Array 3
NG cost (EUR/MWh)	13	19	26	13	19	26
El. power cost (EUR/MWh)	38	56	76	38	56	76
CO_2 quota cost (EUR/tonne)	0	0	0	17	19	21
CO_2 sales value (EUR/tonne)	0	0	0	0	10	21

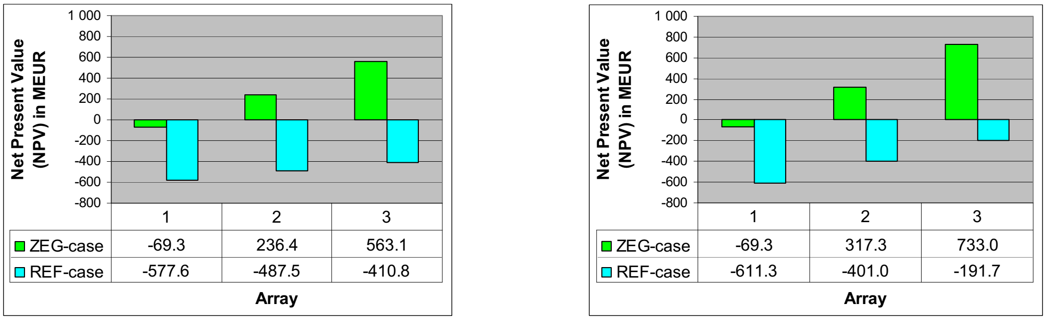

Figure 5: NPV values for the 2 price scenarios studied. Scenario 1 (left), scenario 2 (right).

The first results of these study show that the reference case technology is not likely to be profitable in any of these scenarios while the ZEG technology shows positive NPV-values for all scenarios, except for array 1 values of both scenarios representing low energy prices. The ZEG-case shows also a steeper increase in NPV-values than the REF-case for both scenarios.

The exact values for electric power cost and CO_2 sales values that give a NPV equal to zero, i.e. the limit value for that variable, are calculated from the model. This establishes some limiting values which will represent a minimum for a given case to become profitable. The array 1 input values of the price scenario 2 are used but with a moderate NG cost equal to 19 EUR/MWh. The results are shown in Table 6.

Table 6: Electric power cost and CO_2 sales value for NPV to be equal to zero

	Electric power cost (EUR/MWh)		**CO_2 sales value (EUR/tonne)**	
	48	**74**	**38**	**83**
NPV (MEUR)				
ZEG-case	0	776.0	0	368.1
REF-case	-748.3	0	-560.5	0

Here again, the results show that considerably higher electric power cost and CO_2 sales value are necessary for the REF-case to become profitable compared to the ZEG-case. An electric power cost close to 50 EUR/MWh makes the ZEG-case profitable with a moderate NG cost of 19 EUR/MWh, a CO_2 quota cost of 17 EUR/tonne and no income for the CO_2 captured.

6. Conclusions

This techno-economical study of the Zero Emission Gas power concept (ZEG) shows that the combination of high system efficiency and high CO_2 capture is possible by closely integrating a sorption-enhanced steam methane reforming process (SE-SMR) and a high temperature solid oxide fuel cell (SOFC). Efficiencies close to 77% with 100% CO_2 capture and no NOx emissions could be obtained.

The profitability of the ZEG-case is strongly dependent on energy and CO_2 prices. The results of this study show that the ZEG-case technology is likely to be profitable with relatively high net present values (NPV) in most of the price scenarios chosen, while the reference case technology (REF), using more conventional pre-combustion available technologies, shows negative NPV-values for all scenarios. Even with no income for the CO_2 captured and a quite moderate natural gas price of 19 EUR/MWh, the ZEG-case shows profitability for an electric power price of 50 EUR/MWh or higher.

Therefore, this novel hybrid high efficiency concept seems to be promising and has a great potential on a medium to long term perspective if the critical technical challenges are solved. The designed system does not include any new technologies, but the SOFC technology and the reformer dual bubbling fluidized bed reactor system still need to be verified at pilot scale before considering any further up-scaling at large industrial scale. As far as the SOFC technology is concerned, the proposed heat transfer loop for high temperature heat exchange still has to be demonstrated. Regarding the reformer system, the main issues are related to the mechanical and chemical stabilities of the CO_2 sorbent and reforming catalyst.

Finally, as these two technologies are relatively new, the cost estimates for capital expenditure (CAPEX) are rather difficult to define for large scale applications and have an uncertainty of about ± 35% (80% confidence interval).

The promising and encouraging results of this study show the potential of the two technologies and of their close integration towards future zero emission power plants.

Acknowledgments

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