Int. J. of Thermodynamics **ISSN 1301-9724**
Vol. 9 (No. 1), pp. 21-28, March 2006

AZEP Gas Turbine Combined Cycle Power Plants - Thermo-economic Analysis

Björn Fredriksson Möller*, Tord Torisson, Mohsen Assadi
Lund Institute of Technology, Department of Heat and Power Engineering
P.O. Box 118, SE-221 00 Lund, Sweden
E-mail: bjorn.fredriksson@vok.lth.se

Sven Gunnar Sundkvist, Mats Sjödin, Åke Klang
Siemens Industrial Turbomachinery AB, SE-612 83 Finspong, Sweden

Knut Ingvar Åsen, Kjersti Wilhelmsen
Norsk Hydro Oil & Energy Research Centre, NO-3908 Porsgrunn, Norway

Abstract

Conventional power plants based on fossil fuel without CO_2 capture produced flue gas streams with concentrations of CO_2 between 3% and 15%, contributing to the threat of increasing global warming. Existing capture technologies such as post-combustion flue gas treatments using chemical absorption, pre-combustion carbon removal or combustion in O_2/CO_2 atmospheres suffer from significant efficiency penalties as well as major increases in investment costs. A less energy intensive concept for oxygen production is a mixed conducting membrane (MCM) reactor which produces pure oxygen from compressed air. The MCM reactor is best integrated into a conventional gas turbine combined cycle, called advanced zero emissions plant (AZEP), to provide an efficient and cost-effective power plant altogether. In this paper the economic performance of four different combined cycle alternatives in two different gas turbine sizes are evaluated; two of the combined cycles being based on the AZEP concept. The results show that the AZEP concept presents a more competitive system in terms of efficiency and economy compared to traditional capture systems.

Keywords: CO_2 capture, zero emissions, combined cycles, thermo-economy

1. Introduction

Carbon dioxide has been identified as a major greenhouse gas responsible for a large part of the enhancement of global warming. Combustion of fossil fuels for power generation is one of the main contributors to CO_2 emissions, where flue gas streams contain from 3% (natural gas fired combined cycle) to around 15% (conventional coal fired condensing plant) carbon dioxide by volume.

The capture of CO_2 can be done in several ways, often divided in three main groups as follows:

- The first group includes the post-treatment of flue gases, which separates the carbon dioxide from the flue gas by means of chemical absorption (most common), membranes, distillation or other techniques (Hendriks, 1994; Bolland and Undrum, 2003; Chiesa and Consonni, 2000; Corti et al., 1998; Corti et al., 2001).
- The second group includes pre-treatment of the fuel, most often seen in coal gasification plants where synthesis gas from the gasification is enriched in hydrogen through the shift reaction. The CO_2 is then removed by physical or chemical absorption (Hendriks, 1994; Andersen et al., 2000; Chiesa and Consonni, 1998).
- The third group involves nitrogen-free oxidation, also called oxy-fuel processes, as combustion with pure oxygen in semi-closed systems (Chiesa and Lozza, 1998), chemical looping combustion (Mattisson and Lyngfeldt, 2001), electrochemical reactions in fuel cells

*Author to whom correspondence should be addressed

(Dijkstra and Jansen, 2002; Campanari and Chiesa, 2000; Riensche et al., 2000) or new concepts like AZEP (Sundkvist et al., 2001), all able of producing an exhaust gas consisting of only water and CO_2.

In none of the groups above is the capture done without great effort. The post-combustion treatment, being the most mature technology, needs a significant part of the energy input to regenerate chemicals used in the process, while in pre-combustion treatment some of the fuel heating value is lost in the decarbonisation. Oxy-fuel processes are also very energy demanding if the oxygen comes from conventional air separation units.

2. The AZEP Concept

A less energy intensive proposition is the mixed conducting membrane (MCM) which produces pure oxygen from air. The transport mechanism through the membrane is surface adsorption followed by decomposition into ions. Oxygen ions are then transported by occupying vacancies in the membrane structure. The driving force is partial pressure difference between the air and a sweep stream of recirculated exhaust gas, see *Figure 1*. Previous work by Griffin et al. (2003) has indicated that the most efficient and cost-effective utilisation of the MCM reactor is its integration into a conventional gas turbine system to produce an advanced zero emissions plant, the AZEP concept.

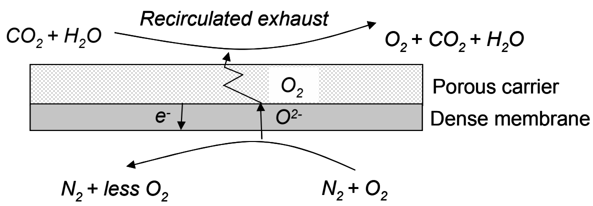

Figure 1. Schematic drawing of the MCM-membrane (Griffin et al., 2003).

The combustion chamber in an ordinary gas turbine is here replaced by the MCM-reactor, which includes a combustor, sections with 'low' temperature heat exchanger (LTHX), the MCM membrane and high temperature heat exchanger (HTHX) as well as a bleed gas heat exchanger, see *Figure 2*.

3. System Boundaries

The scope of this study is to evaluate the optimal AZEP solutions, as shown by Sundkvist et al. (2004), from a thermo-economic point of view and to compare them to alternative low emission solutions. The comparison must be as fair and transparent as possible, meaning that system boundaries should be identical in all cases. The product CO_2 will be delivered at liquid state at 100 bar for all the modelled cases. No district heating is considered from the different exhaust gas condensers present in some cases. The economic viewpoint is the CCGT plant supplier's, meaning that so-called "owner's costs" are not included. Costs like these vary greatly from site to site and are difficult to model without knowledge of the specific site. For CO_2 no transport or end storage cost has been accounted for, nor is any value assigned to the product CO_2, except the "value" of avoided CO_2 taxation.

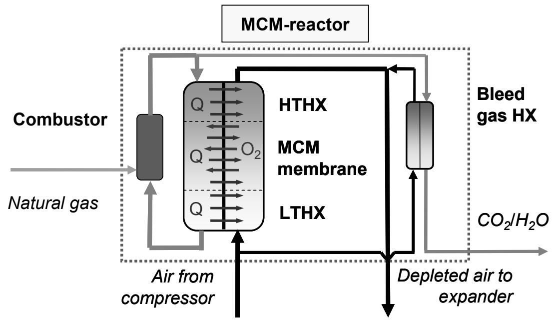

Figure 2. MCM-reactor build-up.

4. Systems Modelled

Two sizes of CCGT power plants are studied: a nominal 50 MW_e size based on a Siemens SGT800 (former GTX100) gas turbine and a nominal 400 MW_e size based on a Siemens SGT5-4000F (former V94.3A) gas turbine. The different systems are modelled in the commercial software IPSEpro (SimTech Simulation Technology, 1991-2000), using model libraries developed within GTPOM, a European Community research project (Knight et al., 2004).

4.1 CCGT based on reference gas turbine

The first system design modelled is a reference system. As such a traditional CCGT power plant is chosen, see *Figure 3*. Data from such plants are in abundance, both in terms of thermodynamical performance used as a base in the modelling, and to some extent also cost data.

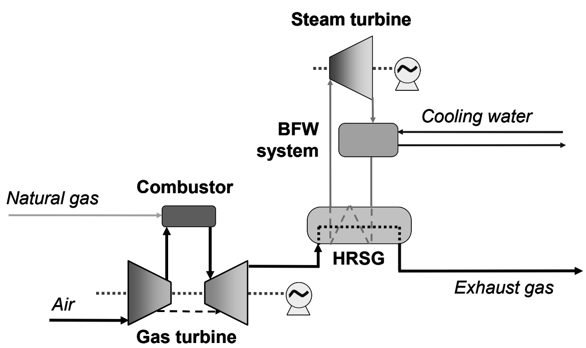

Figure 3. The reference CCGT cycle.

The cost models can therefore be calibrated to Siemens CCGT power plant prices and from there extrapolated to all cases, making comparisons fair and objective. For the 50 MW_e case, a dual-pressure HRSG is chosen with live steam at 80 bar and 510°C for the HP steam turbine and for the 400 MW_e case a triple-pressure cycle with reheat is chosen. In this case the live steam data is ~130/30/5 bar (absolute) and ~560/545/240°C.

4.2 The AZEP 100% case

This is a "traditional" type of combined cycle arrangement, but with an MCM-reactor system replacing the traditional combustion chamber. Air is compressed in the gas turbine and is then heated in the MCM-reactor. Due to MCM material and reactor design limitations the MCM-reactor outlet temperature has been restricted to 1200°C, which is considerably lower than the reference CCGT. A percentage of the oxygen contained in the air, typically 50%, is transferred through the membrane and is carried along by the CO_2/H_2O sweep gas. The oxygen containing sweep gas is then reacted with natural gas to generate heat in a combustion chamber. A share of the sweep gas is bled off to keep the sweep gas mass flow constant in the MCM-reactor. The heat contained in the bleed gas is recovered in a separate CO_2/H_2O HRSG, providing extra steam for the steam cycle and preheating of the natural gas fuel. The heat recovery has to be terminated at a higher temperature than in the ordinary HRSG due to the high water content in the bleed gas. After the HRSG the water is condensed and the remaining CO_2 is compressed from the MCM-reactor pressure at around 20 bar to delivery pressure at 100 bar and liquefied. A layout of the AZEP 100% cycle is shown in *Figure 4*.

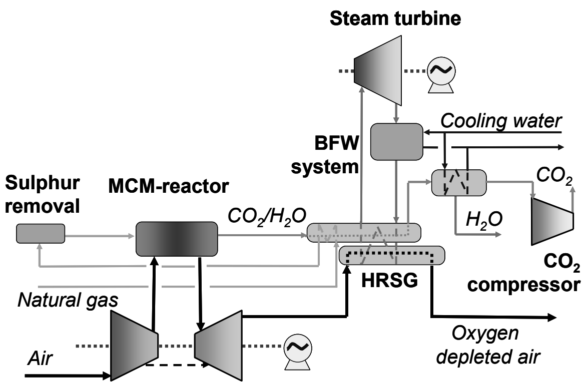

Figure 4. The AZEP 100% case.

Compared to the reference system the power output is significantly reduced due to the lower turbine inlet temperature reducing gas turbine output, but also due to the lower exhaust gas temperature reducing steam production in the steam cycle. In the 400 MW_e case it is not feasible to sustain the triple-pressure reheat steam cycle from the reference case due to the low exhaust gas temperature. A dual-pressure steam cycle is therefore considered both for the 50 MW_e and the 400 MW_e case in the AZEP 100% case.

4.3 The AZEP 85% case

The third alternative, the AZEP 85% case, includes a sequential combustion chamber to increase the turbine inlet temperature. This is to improve the thermal performance of the MCM based power plant. *Figure 5* shows a power plant including a sequential burner increasing the turbine inlet temperature to 1327ºC on the air-side using natural gas as fuel.

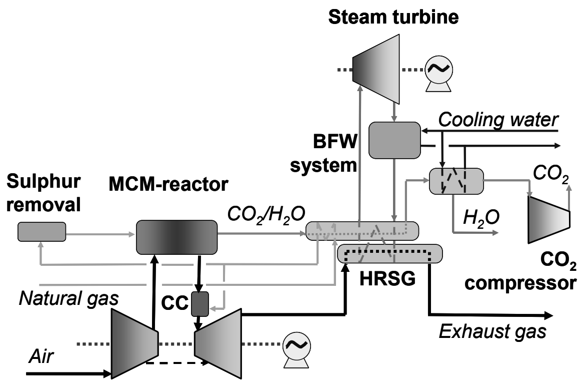

Figure 5. The AZEP 85% case.

This concept is not a "pure" AZEP concept since the sequential burner will add CO_2 to the exhaust gas stream and thereby reduce the degree of CO_2 capture to 85%; a figure comparable to what is achievable in traditional amine-based CO_2 capture systems. Power plant efficiency and power output will however increase due to the higher temperature level. In this instance the 50 MW_e case is modelled with a dual-pressure steam cycle with a HP steam temperature of ~500°C. The 400 MW_e alternative is modelled with a triple-pressure steam cycle with live steam data at ~130/30/5 bar and ~510/485/240°C.

4.4 CCGT with CO_2 capture using MEA

The last system design modelled is the reference system with a traditional amine-based CO_2 capture system. In this case steam data is the same as for the reference system, although steam is extracted from the LP steam turbine to provide the energy needed to regenerate the amines. This steam is condensed in the reboiler section of the CO_2 capture plant and then pumped back to the steam cycle. A schematic process layout of the CCGT with an amine-based CO_2 capture system is shown in *Figure 6*, hereafter called the MEA 85% case. Assumptions for the CO_2 capture plant can be seen in TABLE I.

TABLE I. ASSUMPTIONS FOR THE CO_2 CAPTURE.

Parameter	Unit	Value
Regeneration temperature	°C	120
Regeneration heat consumption	MJ/kg CO_2	4.5
Fan pressure increase	bar	0.06
Reboiler pinchpoint	°C	15

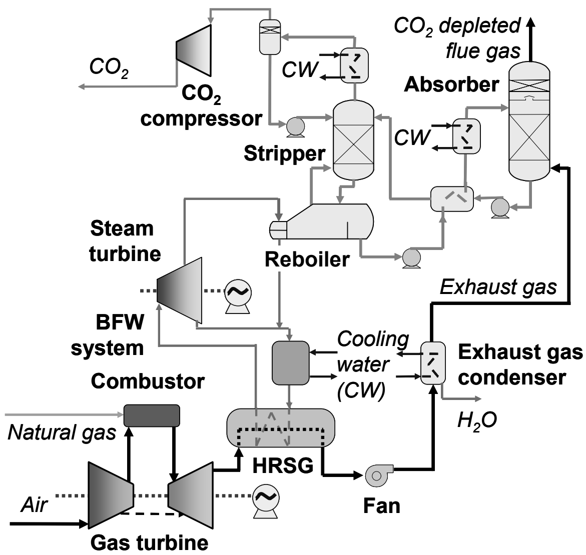

Figure 6. CCGT with post-combustion CO_2 capture.

5. Economic Analysis

A detailed economic model for an AZEP power plant delivery covering main equipment, auxiliary equipment and engineering has been developed for one economic reference case: the AZEP 100% case in the 50 MW_e size. The scope is based on the vendor's scope of supply and does therefore not include the client's costs for preparing the site with connections to the main grid, to the fuel supply line, etc. (Thorèn, 2003). The scope is divided into different cost groups as follows:

- Gas turbine/genset
- Steam turbine including condenser and feed water system
- HRSG including drums, stack and ancillaries
- MEA/AZEP specific components and installation
- Buildings and civil works
- Auxiliary systems including electricals and instrumentation not included in the main component groups
- Project management, erection costs, commissioning, engineering, etc.

The reference case, based on the experience of several delivery projects for CCGT plants using the SGT800 gas turbine, determines specific cost factors based on total capital cost for each of the three last groups. Auxiliary systems and project cost factors are, for example, considered to have approximately the same ***cost*** for an AZEP plant as for a CCGT plant of similar size (the specific AZEP equipment cost group includes both engineering and system costs), while the MEA case is considered to have a similar ***cost share*** for auxiliary systems and project costs as an AZEP plant. Buildings and civil works are treated in a special way, assuming they are based on HRSG cost, total plant power output and AZEP/MEA specific costs. The specific cost factors for project and auxiliary systems are tuned to match the reference case, while in-house rules-of-thumb and literature data are used to determine AZEP/MEA specific costs, see TABLE II. In a similar way the operation and maintenance (O&M) cost is divided into gas turbine, steam turbine, HRSG and AZEP/MEA O&M costs. Cost of electricity for each of the cases can then be calculated as the sum of capital cost, fuel cost, O&M costs and, if applicable, cost for CO_2 taxes.

TABLE II. SPECIFIC COST DATA USED IN THE ECONOMIC ANALYSIS (SIMBECK, 2001).

	MEA/AZEP cases	CCGT case
Proj. cost 50MW_e	18%	23%
Aux. cost 50MW_e	11%	14%
Proj. cost 400MW_e	8%	10%
Aux. cost 400MW_e	9%	12%
MEA plant	6.25 k€/kg/s flue gas + 32.5 k€/kg/s CO_2	
CO_2 compressors	800 €/kW_e	
MCM reactor 50MW_e	54 k€/MWth @1200°C†	
MCM reactor 400MW_e	45 k€/MWth @1200°C†	

In order to determine the economic parameters having the greatest impact on the thermo-economic performance of the compared power plant concepts, a sensitivity study is performed. Apart from the ordinary parameters like discount rate and fuel price, the cost and life of the MCM-reactor and CO_2-tax are also included, see TABLE III.

TABLE III. SENSITIVITY ANALYSIS PARAMETERS USED IN THE STUDY AND THEIR VARIATION RANGE.

Parameter	Unit	Lower cost	Base case	Higher cost
Discount rate	%	7.5	**10**	15
Fuel price	€/GJ	3	**4.5**	6
CO_2-tax	€/ton CO_2	-	**0**	40
MCM reactor cost	%	-25	**±0**	+25
MCM exchange period	years	2.5	**5**	7.5

† Includes reactor with pressure vessel and support structures

TABLE IV. PROCESS SIMULATION RESULTS OF THE 50 MW_e CASES.

Plant data 50 MW_e power plants	**CCGT**	**AZEP 100%**	**AZEP 85%**	**MEA 85%**
Net power output (MW)	63.8	46.2	53.8	55.0
Plant fired heat (MJ/s)	120.5	95.4	107.1	120.5
Net plant efficiency (LHV) (%)	**53.0**	**48.4**	**50.3**	**45.6**
CO_2 compression power (MW)	-	0.49	0.47	1.63
Plant total auxiliary power (MW)	0.7	1.1	1.1	4.0

TABLE V. PROCESS SIMULATION RESULTS OF THE 400 MW_e CASES.

Plant data 400 MW_e power plants	**CCGT**	**AZEP 100%**	**AZEP 85%**	**MEA 85%**
Net power output (MW)	400.9	248.1	300.4	346.9
Plant fired heat (MJ/s)	692.4	500.5	562.5	692.4
Net plant efficiency (LHV) (%)	**57.9**	**49.6**	**53.4**	**50.1**
CO_2 compression power (MW)	-	2.95	2.85	9.2
Plant total auxiliary power (MW)	4.9	5.5	7.5	22.5

6. Results and Discussion

6.1 Thermodynamic evaluation

The thermodynamic performance of the different concepts varies very little from the results presented in the preceding study (Sundkvist et al., 2004), and is summarised in TABLE IV and TABLE V. Efficiencies decrease from less than 3 percentage points (AZEP 85%, 50MW_e) to over 8 percentage points (AZEP 100%, 400MW_e) in the low CO_2 emission alternatives, compared to the reference CCGT plants. Power output also decreases in all cases, most for the AZEP 100% case and least for the CCGT-MEA case, with the AZEP 85% case in between. For the AZEP cases the decrease in power output is less significant using the smaller gas turbine, due to a smaller difference in COT between the unmodified gas turbine and the AZEP concept. The efficiency decrease for the MEA 85% case, around 7.5 percentage points, is at the lower end of the range previously found in literature (Bolland and Undrum, 2003; Rubin et al., 2004; Kvamsdal et al., 2004). Assumptions for the MEA case have on purpose been rather optimistic, due to the comparison between an MEA power plant, available more or less today, and AZEP power plants available some years into the future.

6.2 Thermo-economic evaluation

The results of the thermo-economic evaluation of the 50 MW_e system models are compared in TABLE VI. It can be seen that all of the CO_2 reduced cases suffer from large increases in cost of electricity. The lowest cost of electricity of the low CO_2 emission alternatives is shown by the AZEP 85% case with a 20% increase in cost of electricity. Then comes the AZEP 100% case with 28% increase and worst is the MEA 85% case with an increase of 36% in cost of electricity. It can also be seen that the fuel price, apart from CO_2 taxation for the CCGT case, is the single variation factor that has the largest impact on cost of electricity. Furthermore, the influence from MCM reactor cost and exchange period is rather small. For all variations in MCM reactor cost and exchange period the AZEP 85% is clearly superior to the AZEP 100% which in turn is superior to the MEA 85% case.

TABLE VI. Cost of electricity for the 50 MW_e cases.

Cost of Electricity (€/MWh)	**CCGT**	**AZEP 100%**	**AZEP 85%**	**MEA 85%**
Base Case	**50.0**	**64.1**	**60.0**	**67.9**
Discount rate – low	47.8	60.4	56.8	64.1
Discount rate – high	54.6	71.9	67.0	76.2
Fuel price – high	60.2	75.2	70.7	79.7
Fuel price – low	39.8	52.9	49.2	56.0
CO_2-tax – high	65.4	64.1	62.4	70.4
MCM reactor cost – high	-	65.1	60.8	-
MCM reactor cost – low	-	63.0	59.1	-
MCM exchange period – long	-	63.6	59.6	-
MCM exchange period – short	-	65.4	61.1	-

TABLE VII. COST OF ELECTRICITY FOR THE 400 MW_e CASES.

Cost of Electricity (€/MWh)	CCGT	AZEP 100%	AZEP 85%	MEA 85%
Base Case	**39.5**	**53.9**	**49.7**	**52.9**
Discount rate – low	38.4	51.6	47.7	50.6
Discount rate – high	41.9	59.1	54.1	57.8
Fuel price – high	48.8	64.8	59.8	63.7
Fuel price – low	30.2	43.0	39.6	42.1
CO_2-tax – high	51.7	53.9	52.1	55.2
MCM reactor cost – high	-	54.6	50.3	-
MCM reactor cost – low	-	53.2	49.1	-
MCM exchange period – long	-	53.5	49.3	-
MCM exchange period – short	-	55.3	51.0	-

If a CO_2-tax set to 40 €/ton is applied, the results will be very different, with the AZEP 85% case showing the best economy followed by the AZEP 100% case and the reference case. The MEA 85% case is still the worst from an economic point of view. From *Figure 7* a breakeven CO_2-tax can be expected at 31 €/ton for the AZEP 85% case and at 37 €/ton for the AZEP 100% case compared to the reference CCGT.

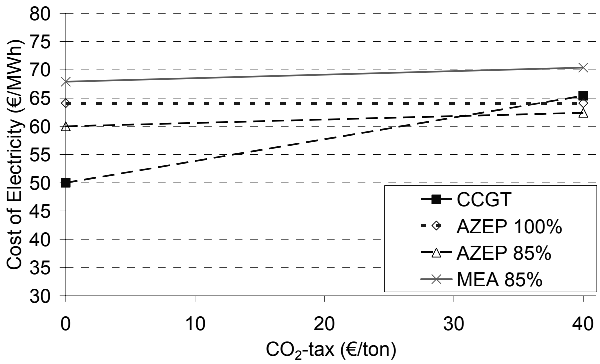

Figure 7. Influence of CO_2-tax on cost of electricity, 50 MW_e cases.

The results of the thermo-economic evaluation of the 400 MW_e system models are compared in TABLE VII. As for the 50 MW_e cases, all of the CO_2 reduced cases suffer from large increases in cost of electricity. For the 400 MW_e systems it is again the AZEP 85% case showing the best results of the low CO_2 emission alternatives with 26% increase in cost of electricity.

The MEA 85% case and the AZEP 100% case show similar economic performance with the MEA case having a somewhat lower cost of electricity for all cases, except when a CO_2-tax is applied. The increase in COE for the base case is 34% for the MEA 85% case and 36% for the AZEP 100% case. Similar to the 50MW_e cases, it is the fuel price that is the single variation factor having the largest impact on cost of electricity. The impact from uncertainties in the MCM reactor cost and exchange period is rather small also in the 400 MW_e cases. From *Figure 8* a breakeven CO_2-tax can be expected at 40 €/ton for the AZEP 85% case. It can also be seen that the AZEP 100% case becomes more economical than the MEA 85% case at about 20 €/ton.

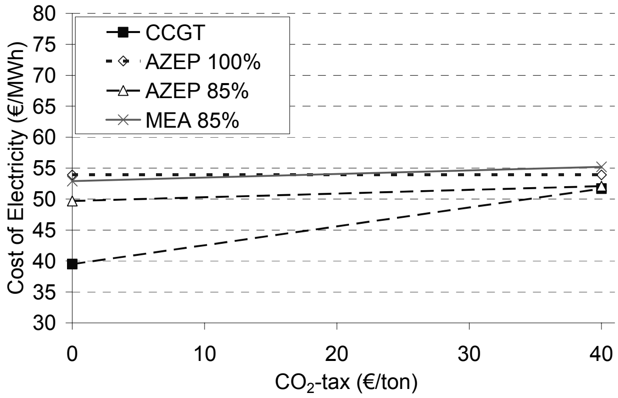

Figure 8. Influence of CO_2-tax on cost of electricity, 400 MW_e cases.

7. Conclusions

With the economic assumptions made in this study it has been shown that the two optimal AZEP cycles (AZEP 85% and AZEP 100%) are more economical than one comparable alternative (MEA 85%) using a medium sized gas turbine, SGT800. Using a larger industrial gas turbine, SGT5-4000F, the AZEP 85% alternative is still more economical than the alternative (MEA 85%), while the AZEP 100% case needs support from CO_2 taxation to compensate for the lower emission level. With an assumed CO_2-tax of 40 €/ton the two AZEP alternatives show better economic performance than a conventional CCGT at the smaller size.

It has also been shown that uncertainties in MCM reactor cost and the life expectancy of MCM reactor ceramics do not have a big influence on the cost of electricity. It should be emphasized that the current study does not include so-called “owner’s costs”, due to the inherent difficulties in modelling these. However, they could be expected to be bigger for a post-combustion capture plant due to the much larger footprint of that plant.

Acknowledgments

The authors want to thank all partners in the AZEP project for their contributions to the results of the project. The AZEP project is partly funded by the European Commission in FP5, contract number ENK5-CT-2001-00514, and the Swiss Government (BBW 01.0054-1), the support of which is gratefully acknowledged.

Nomenclature

AZEP	Advanced Zero Emissions Plant
BFW	Boiler Feed Water System
CCGT	Combined Cycle Gas Turbine
COT	Combustor Outlet Temperature
HP	High Pressure
HRSG	Heat Recovery Steam Generator
LP	Low Pressure
MCM	Mixed Conducting Membrane
MEA	Monoethanolamine
O&M	Operation and Maintenance

References

Andersen, T., Kvamsdal, H. M. and Bolland, O., 2004, "Gas turbine combined cycle with CO_2 capture using auto-thermal reforming of natural gas", *Proceedings of ASME TurboExpo 2000*, München, Germany.

Bolland, O. and Undrum, H., 2003, "A novel methodology for comparing CO_2 capture options for natural gas-fired combined cycle plants", *Advances in Environmental Research,* Vol. 7, pp. 901-911, Elsevier Science.

Campanari, S. and Chiesa, P., 2000, "Potential of solid oxides fuel cells (SOFC) based cycles in low-CO_2 emission power generation", *Proceedings of Fifth Int. Conf. on Greenhouse Gas Control Technologies*, GHGT-5, Williams, D. J. et al, ed., Cairns, Australia.

Chiesa, P. and Consonni, S., 1998, "Shift reactors and physical absorption for low CO_2 emission IGCCs", *Proceedings of Int. Gas Turbine & Aeroengine Congress & Exhibition*, Stockholm, Sweden.

Chiesa, P. and Consonni, S., 2000, "Natural gas fired combined cycles with low CO_2 emissions", *J. of Eng. for Gas Turbines and Power,* Trans. of the ASME, Vol. 122, pp. 429-436.

Chiesa, P. and Lozza, G., 1998, "CO_2 emission abatement in IGCC power plants by semiclosed cycles. Part A: with oxygen-blown combustion", *Proceedings of Int. Gas Turbine & Aeroengine Congress & Exhibition*, Stockholm, Sweden.

Corti, A., Lombardi, L. and Manfrida, G., 1998, "Absorption of CO_2 with amines in a semiclosed GT cycle: Plant performance and operating costs", *Proceedings of Int. Gas Turbine & Aeroengine Congress & Exhibition*, Stockholm, Sweden.

Corti, A., Beconi, B. M. and Lombardi, L., 2001, "Alkali absorbing for CO_2 removal: Thermo-economic comparison between carbonate and sodium hydroxide based processes", *Proceedings of Italian Conf. on Chemical and Process Engineering*, Florence, Italy.

Dijkstra, J. W. and Jansen, D., 2002, "Novel concepts for CO_2 capture with SOFC", *Proceedings of Sixth Int. Conf. on Greenhouse Gas Control Technologies*, GHGT-6, Kyoto, Japan.

Griffin, T., Sundkvist, S. G., Åsen, K. I., Bruun, T., 2003, "Advanced zero emissions gas turbine power plant", *Proceedings of ASME TurboExpo 2003*, Atlanta, GA, USA.

Hendriks, C., 1994, "Carbon Dioxide Removal from Coal-fired Power Plants", Ph. D. dissertation, University of Utrecht, Kluwer Academic Publishers, Netherlands.

Knight, R., Obana, M., von Wovern, C., Mitakakis, A., Perz, E., Assadi, M., Fredriksson Möller, B., Sen, P., Potts, I., Traverso, A. and Torbidoni, L., 2004, "GTPOM: Thermo-Economic Optimization of Whole Gas Turbine Plant", *Proceedings of ASME TurboExpo 2004*, Vienna, Austria.

Kvamsdal, H. M., Maurstad, O., Jordal, K. and Bolland, O., 2004, "Benchmarking of gas-turbine cycles with CO_2 capture", *Proceedings of Seventh Int. Conf. on Greenhouse Gas Control Technologies*, GHGT-7, Vancouver, Canada.

Mattisson, T. and Lyngfeldt, A., 2001, "Applications of chemical-looping combustion with capture of CO_2", *Proceedings of Second Nordic Minisymposium on Carbon Dioxide Capture and Storage*, Gothenburg, Sweden.

Riensche, E., Achenbach, E., Froning, D., Haines, M. R., Heidug, W. K., Lokurlu, A. and von Andrian, S., 2000, "Clean combined-cycle SOFC power plant – cell modelling and process analysis", *Journal of Power Sources,* Vol. 86, pp. 404-410, Elsevier Science.

Rubin, E. S., Rao, A.B. and Chen, C., 2004, "Comparative assessments of fossil fuel power plants with CO_2 capture and storage", *Proceedings of Seventh Int. Conf. on Greenhouse Gas Control Technologies*, GHGT-7, Vancouver, Canada.

Simbeck, D. R., 2001, "CO_2 Mitigation Economics for Existing Coal-Fired Power Plants", *Proceedings of First National Conf. on Carbon Sequestration*, Washington, DC.

SimTech Simulation Technology, 1991-2000, *IPSEpro User Documentation version 3.1.001*, Graz, Austria.

Sundqvist, S. G., Griffin, T. and Thorshaug, N.P., 2001, “AZEP - Development of an integrated air separation membrane – gas turbine”, *Proceedings of Second Nordic Minisymposium on Carbon Dioxide Capture and Storage*, Gothenburg, Sweden.

Sundkvist, S. G., Klang, Å., Sjödin, M., Wilhelmsen, K., Åsen, K., Tintinelli, A., McCahey, S. and Ye, H., 2004, “AZEP gas turbine combined cycle power plants – thermal optimisation and LCA analysis”, *Proceedings of Seventh Int. Conf. on Greenhouse Gas Control Technologies*, GHGT-7, Vancouver, Canada.

Thorèn, M., 2003, “AZEP project island preliminary scope of supply”, Internal Siemens document, Finspong, Sweden.