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Natural Gas Oxy-Fuel Cycles – Part 3: Economic Evaluation

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Abstract

As part of the sixth European framework project on enhanced capture of CO_2 (ENCAP), several novel power generation cycles with CO_2 pre-capture methods are identified and the promising technologies are selected for a techno-economic assessment. For this analysis, the chemical process simulation package ECLIPSE is utilised. Following a detailed mass and energy balance calculation, the economic assessments of the Semi-close Oxygen Combustion (SCOC), Water Cycle and Graz as well as S-Graz Cycles is performed in reference to year 2004. The total capital cost estimation of the studied cycles is implemented in a bottom-up approach. Subsequently, the breakeven electricity selling price (BESP) is determined according to the net present value. Through the modification of parameters such as fuel price or capacity factor, the sensitivity analysis is carried out to assess the effect of endogenous or exogenous changes on the economic viability of the cycles. Among the systems, the S-Graz Cycle is the most cost intensive process. Yet, due to its high plant efficiency, it delivers the lowest electricity price and the lowest CO_2-avoidance costs. The Water Cycle is the least capital intensive technology in this study. Due to its poorer plant efficiency however, the economics of this cycle scored third on the list.

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Keywords: Semi-closed Oxygen Combustion (SCOC), Water Cycle, Graz Cycle, BESP, CO_2 avoidance cost

1. Introduction

This paper gives an overview of the cost estimation and economic evaluation of the semi-closed oxygen-combustion combined system (SCOC), the Water and the Graz Cycles. All these systems are equipped with pre-combustion CO_2 capture facilities. The nominal plant power output is around 390 MWe. The techno-economic assessment is performed using the ECLIPSE process simulation software. Next to the mass and energy balance calculation the bare equipment costs are estimated. The total equipment costs – including factors such as piping, structural and civil costs as well as erection, instrumentation etc. – are extrapolated according to typical factors and constants, which

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were validated over the years. Since the ECLIPSE cost estimation is based on US dollars, an exchange rate of € 0.8 was selected within the ECLIPSE database. The plant cost index is set to 126% and the value of the plant location factor to 0.95. The cost of steel is a very important factor for the economic estimation. The current European rate for carbon steel suggests an index value of 173 (1994: 100) compared to the global value of 160. A short-term low threshold of 130 recorded for August 2005 did not last for a long time followed by a drastic increase in subsequent months.

2. Methodology

The study of a Generic Combined Cycle Gas Turbine (GTCC) as a reference case provides the basis for the evaluation of the novel cycles. This approach allows the measurement of the impacts of CO_2 capture on the power plant performance attributes. The selected systems in this study are: the Semi-Closed Oxygen-Combustion Combined Cycle (SCOC), the Water Cycle (WC) and two types of Graz (GZ) Cycles. The nominal gross power outputs of the systems range from 380 to 400MW. The economic analyses are seamlessly linked to the mass and energy balance computation. Figure 1 shows a schematic flow diagram of the process. In an iterative algorithm, the process design data along with the technical information are employed to generate the mass and energy balance. The generated dataset along with the utility usages enter the economic modelling. The ECLIPSE chemical process simulation package [1,2] is predestined for these types of techno-economic analyses. This software was initially intended for the use of power plant research projects of the European Commission. However, since its development, it has been used for techno economic analysis of many different chemical and engineering processes. Through a large number of real industrial process simulations, ECLIPSE has been validated over the years and gained recognition worldwide among research institutes, governments and industrial companies

The capital costs of all the basic equipment types are estimated using the step count exponential costing method. This approach uses the dominant process variable or a combination of variables to estimate the individual module costs. Based on typical factors and constants, validated over the years, additional expenditures such as civil costs, installation and piping work overheads as well as electrical, instrumentation and insulation costs are approximated. Furthermore, indirect costs including expenditures for the provision of offices, control rooms, services and hidden equipment costs are accounted for. On the other hand, the basic equipment costs of the gas turbines used for the suggested cycles are overridden by the current genset costs given in the "Gas Turbine World Handbook" [3]. Following the plant cost estimation, the breakeven electricity selling price is determined based on the net present value (NPV). The variation of the prices in connection with factors such as fuel cost, discounted cash flow and the capacity factors on the electricity cost is considered in the sensitivity analysis. Finally, the CO_2 avoidance costs of the novel cycles were calculated in relation to the reference case.

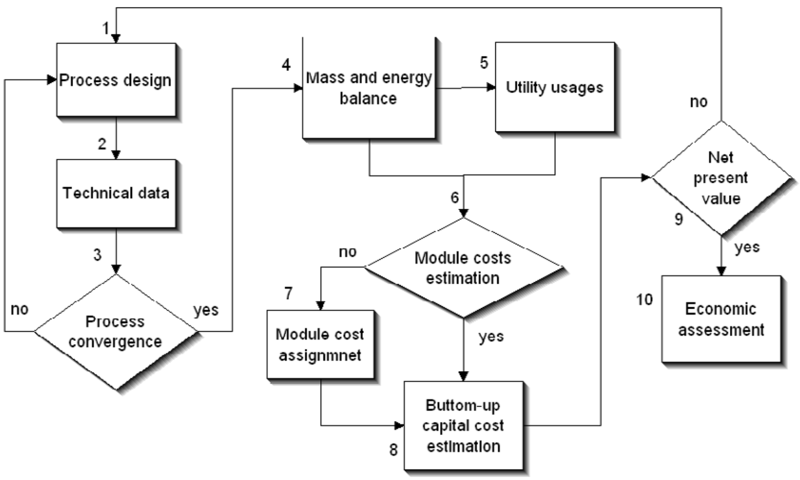

Figure 1: The techno-economic assessment method used in this paper

3. Technical performance attributes of the selected cycles

Prior to the economic analysis, the technical simulation of the base case (GTCC: Gas Turbine Combined Cycle) was carried out using ECLIPSE. This work included the reconstruction of the process flow, the input of the technical data and the convergence of the mass and energy balance. The outcome of the process is very similar to the result generated by NTNU, which used gPROMS and SIMSCI for their simulations [4,5]. With 380.26 MW net power output (gas turbine output: 243 MW, Steam turbine output 137MW), the power generation efficiency is 0.86% points lower than that reported in the paper. This slight divergence is mainly attributed to power plant cycle optimisation and differences in compound database values such as *Cp* accuracy of streams at higher temperatures. All the novel cycles described in the following sections operate on the same total fuel LHV (Lower Heating Value) as GTCC.

3.1 Semi-Closed Oxygen-Combustion Combined Cycle (SCOC)

Figure 2 shows a simplified flow diagram of the SCOC operation with some stream data. The plant generates a net power output of 323.38 MW corresponding to an efficiency of 47.4%. A very similar result was achieved by NTNU Norway using the process modelling gPROMS. The operational condition of the gas turbine within SCOC is different from the one of the reference plant (GTCC). The main parts affected are the compressors and the burners. Furthermore, the system employs a high pressure ratio gas turbine. The power consumption for oxygen generation and CO_2 compression amounts to 74.4 MW. The auxiliary power requirement is 6.1 MW.

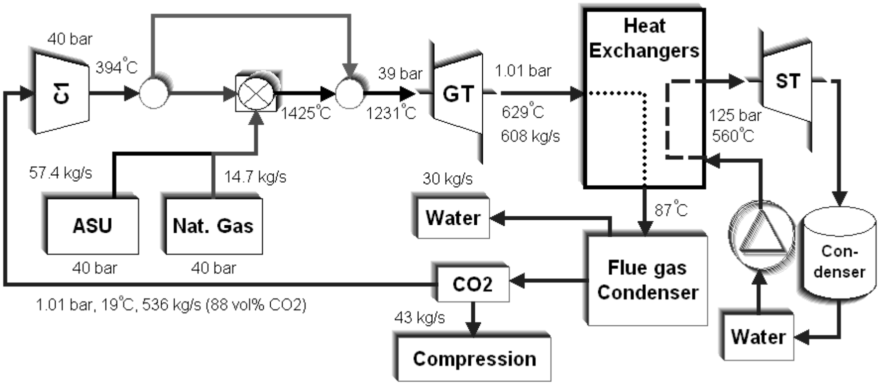

Figure 2: The process flow diagram for SCOC

3.2 Water Cycle (WC)

The net power output of the Water Cycle amounts to 298.38 MW equivalent to an efficiency of 43.74%. The system utilises a burner based on Clean Energy Systems inc. (CES) gas generator [6]. The produced steam-rich gas (88 weight % steam 11% weight CO_2) is fed to a steam turbine at relatively high pressures. A higher percentage of the natural gas is fed to the second burner, which operates at lower pressures. The combusted gas is expanded over a gas turbine. Due to a low pressure exhaust gas, HRSG requires a large heat exchanger surface area. Figure 3 shows the flow diagram. The CO_2 purity of this system configuration is below 80 mass %. This requires a further gas cleaning system.

3.3 Original Graz and S-Graz Cycle

The net power output of the Graz and S-Graz Cycle resulted in 304 MW and 333 MW respectively (efficiency 45% and 49%). Figure 4 shows the process flow diagram for the Graz Cycle. This technology generates CO_2 at a purity of 90.6 mass-% (86.8 mol-%). The cycle requires complicated and well-balanced compressor units. The gas turbine operates at a high pressure ratio and at high temperatures. With regard to the S-Graz Cycle, the main critical component is the low pressure steam turbine with an exit stream below the dew point temperature. The stream also contains other constituents such as carbon dioxide and nitrogen. Figure 4 shows the flow diagram.

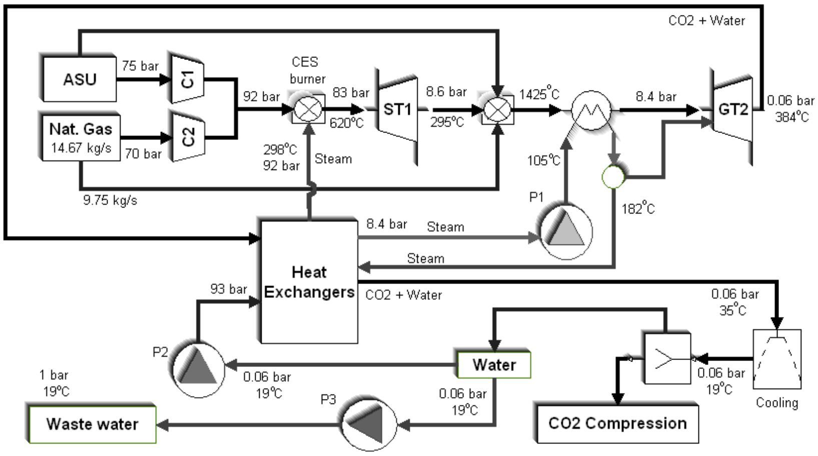

Figure 3: The process flow diagram for WC

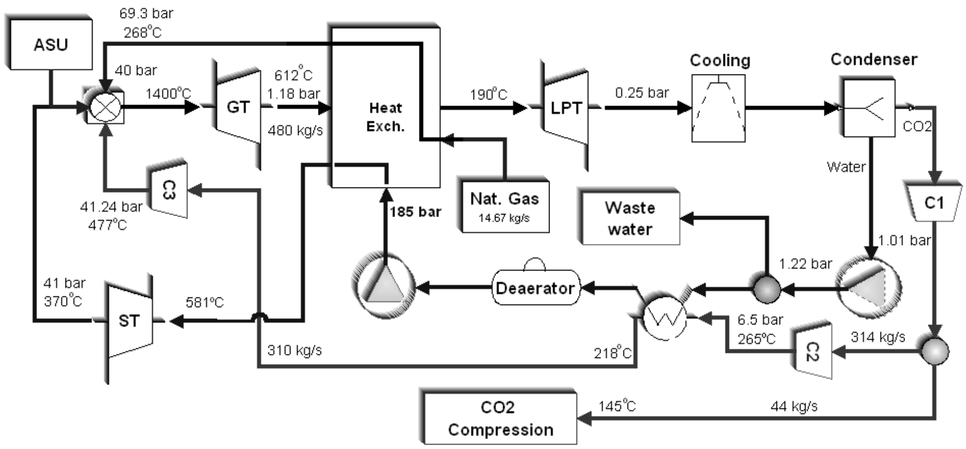

Figure 4: The process flow diagram for the Graz Cycle

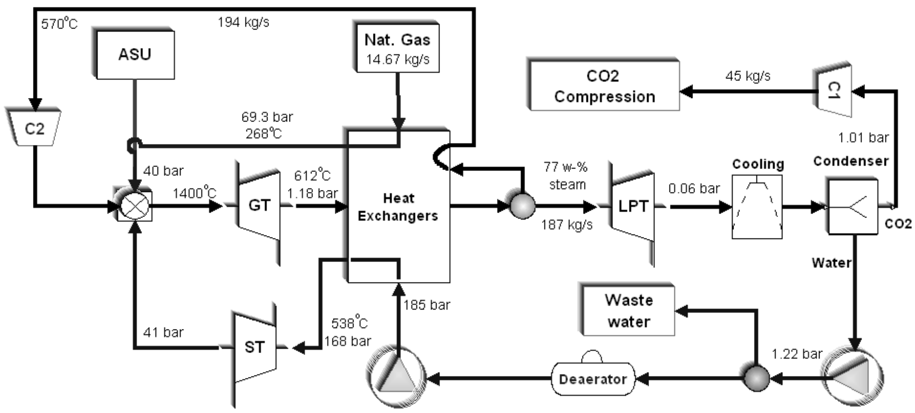

Figure 5: The process flow diagram for the S-Graz Cycle

4. Cost estimation of the investigated cycles

The economics of the studied power plants is strongly correlated to the cycle operating conditions. With regard to SCOC, the volumetric efficiency of the gas turbine compressor is considerably below the reference plant. In theoretical terms, the compressor cost extrapolations suggest an over 60% cost reduction for SCOC. This, however, is unlikely to be achieved since the compressor for SCOC needs to be newly designed. SCOC cannot adopt an air-based compressor module. Further cost implications are likely to accrue for burner and the expander part of the turbine due to the change in gas properties. The gas turbine for SCOC is based on Alstom GT26. The new operating conditions require a gas turbine cost increase of over 22% compared to the reference case. As a result of the higher molecular weight of CO_2 compared to nitrogen, a reduction of the boiler size can be achieved, which in turn improves the economics. The flue gas condensers require additional costs for the cooling pumps and heat exchangers. The plant complexity and the usage of high quality materials within SCOC increase the cost of piping work by over 135%. The air separation unit (ASU) required for SCOC provides 207 tonnes of oxygen per hour at a pressure of 40.5 bar. The required purity of oxygen is set to 95%. The initial ASU cost was estimated at around €81 million using the ECLIPSE model. However, a cost quotation from the company Air Liquide (G. de Souza) suggests a price tag of €75.8 million [7]. It was decided to use the assumptions made by Air Liquide for further assessments. The same type of ASU is also applicable for the Graz and the S-Graz Cycle.

The cost of the gas turbine for the Water Cycle is based on an integrated configuration of the expander, the burner and the compressors. The cost of the latter refers to a natural gas and an oxygen compressor, which increases the pressure from 75 to 98 bar. Two new burner types based on the Clean Energy System Gas Generator need to be devised for the operation with the new streams. The cost of the burner was estimated according to the equation for water injected turbo machinery set by NASA [8] including installation, piping and instrumentation as well as indirect costs (site preparation, building service facilities etc.). The Water Cycle is associated with high boiler costs as a result of very low pressure on the hot side. However, these costs are moderated by a low heat transfer rate and the high heat capacity of the gas due to the high water content in the hot stream. The heat exchanger costs are lower for the Water Cycle, the Graz and the S-Graz, comprising only utilities towards flue gas condensation. Despite high pressure areas and corrosion resistance materials within the Water Cycle, the cost of piping works is comparable to the reference case. This is mainly due to the relatively simple design of the system. Similarly, the Graz and the S-Graz Cycle require high-tech materials to withstand critical conditions such as corrosions and high pressures within some parts of the plant.

Since there are not any dedicated gas turbines available for the Graz and the S-Graz Cycle [9], the turbine costs are estimated based on expander, burner and compressor sections. The assumption is based on PG9331FA and W501G with a base load rating of 243 MW and 266 MW for the Graz and the S-Graz Cycle respectively. The modification cost reflects mainly the expander adaptation to the new gas composition and to the high temperature and pressure inlets. The cost of the burner was approximated according to a steam-injected combustor [10], [11]. The configuration of the gas turbine in separate units results in a relatively high capital investment. The development expenditures of an integrated system are not included in this deliberation. Although these development costs are substantial, the equilibrium towards lower overall prices could ultimately be established in connection with the integrated system, if it reaches the commercial maturity. The system proposed by the Graz University of Technology presupposes an integrated gas turbine cycle [12]. The cost estimation is based on a simple gas turbine along with the capital expenditures for the air separation unit, CO_2 compressor and looping. This calculation does not seem to be very realistic. While the high-pressure steam turbines of both the generic Graz and the S-Graz Cycle operate at the conventional condition, a gas mixture of steam with a fraction of flue gas (mainly CO_2) is expanded over the low pressure stage. Furthermore the exit temperature is below the dew point temperature. The effect of this gas composition on the technical and the financial viability of turbine operations need to be investigated in a separate research work. The cost calculations given here are just an estimate based on conventional steam cycles. The low boiler costs of the Graz and especially of the S-Graz Cycle are mainly explicable through the high water and CO_2 content resulting in improved heat capacities at elevated temperatures. A summary of the estimated engineering and procurement costs are presented in Table 1 (excluding contingencies and working capitals).

Table 1: Summary of the equipment costs

	GTCC	SCOC	WC	Graz	S-Graz
WH-Boiler M€	23.04	16.03	22.35	7.01	5.63
HX + Cooling M€	11.45	11.57	8.65	8.47	9.21
Pumps M€	0.80	0.64	0.66	0.79	0.97
Piping M€	0.66	1.54	0.70	0.92	1.13
Compressor M€	0.00	0.00	5.53	55.87	74.91
FG Cond. M€	0.00	0.78	2.65	2.36	2.88
GT M€	86.57	105.73	53.41	62.65	70.70
ST M€	54.94	55.24	21.39	37.18	43.05
Burner M€	0.00	0.00	10.02	1.52	1.52
Misc M€	0.00	0.00	0.60	0.00	0.00
Indirect costs M€	27.94	47.87	34.09	40.60	40.60
ASU M€	0.00	75.75	74.10	75.80	75.80
CO_2 comp. M€	0.00	20.9	23.07	20.90	20.90
Total cost M€	**205.40**	**336.02**	**257.23**	**314.07**	**347.30**
SI €/kW net	**540**	**1039**	**862**	**1032**	**1042**

WHB: Waste heat boiler, HX: heat exchangers, GT: Gas Turbine; in the case of WC, Graz and S-Graz, GT excludes compressors and burners, SI: Specific Investment

5. Economic analysis

For the economics, a natural gas price of €3.5/GJ (sensitivity: €2.6-€5.2/GJ) is presupposed, which reflects the cost for 2004/05. A plant life time of 25 years is set for all the studied systems with a construction time of 24 months. The owner's cost of 15% includes the contingencies and working capitals. The net present value calculation was carried out with a discounted cash flow of 8% (sensitivity: 4% and 12%). All the plants operate at a capacity factor of 85%. The fixed operating costs of the cycles are estimated about €35/kWe (±5%) compared to €26/kWe for the reference case. The costs of consumables and make-up water are reflected in the variable costs, which are calculated at around €0.5/MWh. This is 40% higher than the reference case.

Figure 6 illustrates the typical breakeven electricity-selling prices (BESP) for all the cycles in relation to the specific investment variation of ±15%. Thanks to the high efficiencies, the S-Graz Cycle and SCOC deliver the best economic results, although both cycles are very capital intensive. A 15% lower cost results in 5% BESP reduction and vice versa. Figure 7 shows the influence of different discounted cash flow rates (DCF) on the economics, which is quite significant. This becomes obvious by comparing the slope of both figures. Around 12% lower BESP is achievable if a DCF of 4%, for example through government supports, could be established.

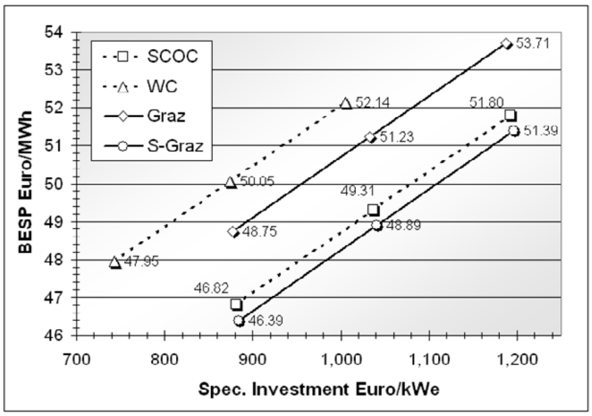

Figure 6: BESP versus SI (DCF=8%)

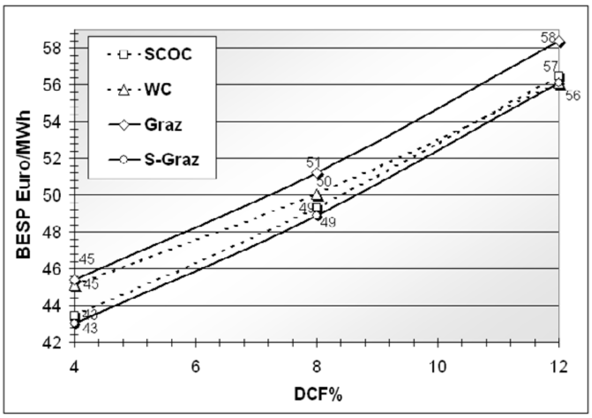

Figure 7: BESP versus DCF

The influence of fuel price on the electricity cost is demonstrated in Figure 8. The electricity price is very sensitive to fuel price fluctuations. A 20% increase in fuel price inflates the BESP at around 11% and vice versa. In the volatile market environment, to moderate the effect of the fuel price escalations, it is vital to target a low DCF and to establish measures to balance extreme economic fluctuations. Figure 9 shows the correlation between the capacity factor and BESP. While lower capacity factors affect the electricity cost significantly, the cost is more stable in higher load intervals. A similar behaviour can be observed with regard to the plant efficiency losses. Roughly speaking, a 5% drop in efficiency corresponds to an above 5% higher BESP.

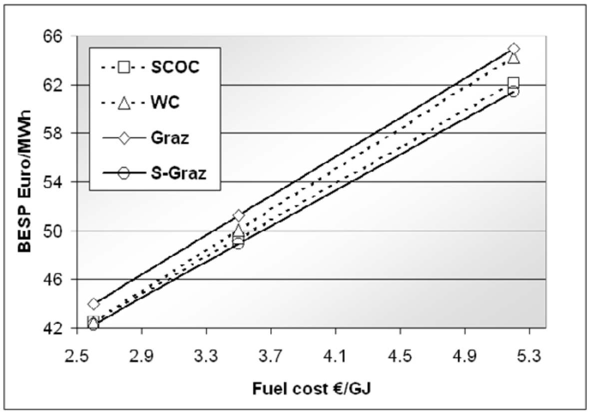

Figure 8: BESP versus fuel price (DCF=8%)

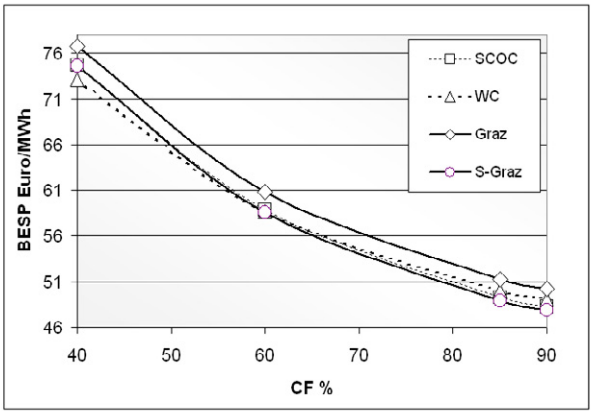

Figure 9: BESP versus capacity factor (DCF=8%)

Figure 10 shows the relation between the total operating and maintenance (O&M) cost and the BESP. This includes fixed and variable costs excluding the fuel expenses. The O&M cost variations seem to have a modest influence on the economics of the plant. The amount of CO_2 avoided around 350 to 360 g/kWh. The amount captured, however, is more variable according to the technologies used. The lowest amount is given for the S-Graz Cycle at 420 g/kWh and the highest for the Water Cycle at around 475 g/kWh. The CO_2 avoidance costs (€/tonne CO_2) in connection with the specific investments are illustrated in Figure 11. As shown, the highest value corresponds to the original Graz Cycle and the lowest to the S-Graz Cycle.

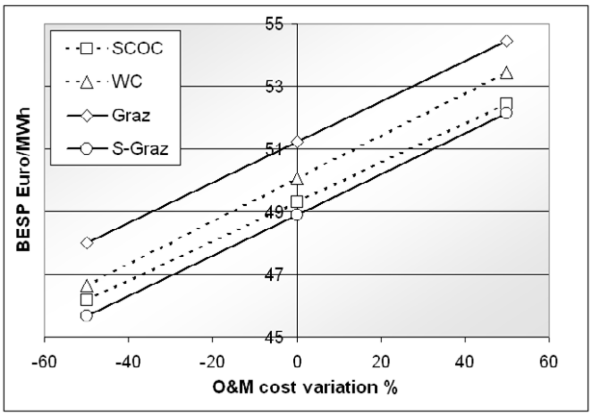

Figure 10: BESP versus O&M (DCF=8%)

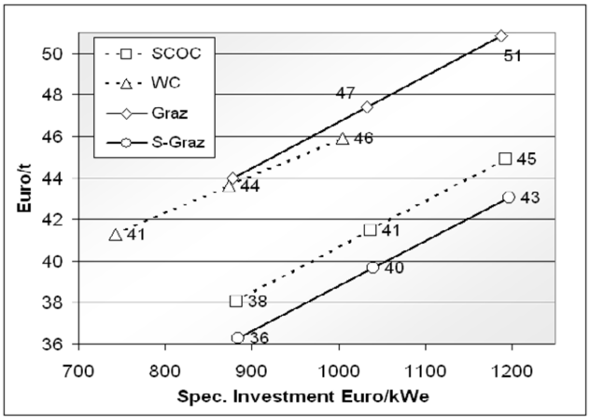

Figure 11: CO_2 avoidance cost versus SI (DCF=8%)

6. Conclusion

Although the S-Graz Cycle demonstrated the lowest electricity selling price and best avoidance cost, a general assertion could be made that all the cycles with CO_2 capture resulted in an approximately similar breakeven electricity selling price. With regard to the water, the Graz and the S-Graz Cycle, a cost reduction of around 3, 10 and 15% can be achieved respectively, if the new turbo-machinery cost could be balanced to the conventional systems. With regard to the Water Cycle, a cost reduction is going to be less significant, since the oxygen is provided at very high-pressure levels negating the requirements for high compression ratio compressors. Despite significant differences in the capital investments, comparable economics are achieved through different efficiency levels and therewith the fuel cost becomes the main driver of the economic viability of the cycles. For example, the overall fuel cost for the Water Cycle (29.24 €/MWh) is the highest among the systems followed by Graz (28.27 €/MWh), SCOC (26.42 €/MWh), and S-Graz (25.75 €/MWh). Further cost reductions can be achieved by curbing cost drivers such as indirect costs, system erection and the selection of utilities. The comparison of the novel natural gas fired cycles with the low cost GTCC resulted in a relatively high CO_2 avoidance costs. According to the economic analysis, the lowest avoidance cost is associated with the S-Graz cycle. The value can be pushed below €30/tonne CO_2, if, apart from a 15% lower capital investment, a government supported discounted cash flow rate of 4% could be established.

Acknowledgement

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