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Oxy-turbine for Power Plant with CO_2 capture

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Abstract

The IEA Greenhouse Gas R&D (IEAGHG) programme contracted Amec Foster Wheeler to perform a study providing an evaluation of the performance and costs of a number of oxy-turbine plants for utility scale power generation with CO_2 capture. The main outcomes of the detailed technical and economical modelling of the most promising oxy-turbine cycles is presented in this paper, including sensitivity analyses on main technical and financial parameters. Each cycle configuration and optimization is developed jointly with the main cycle developers, i.e. Clean Energy Systems, Graz University of Technology and NET Power. The modelling of the gas turbine, including efficiency and blade cooling requirement, have been performed using a calculation code developed by Politecnico di Milano.

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Keywords: oxy-turbine; CO_2 capture; oxy-combustion; LCOE; power plants

1. Introduction

Post combustion capture is usually considered to be the leading option for capture of CO_2 at natural gas fired power plants but today there is an increasing interest in the alternative of oxy-combustion turbines, which use recycled CO_2 and/or steam as the working fluid instead of air. Increasing interest in this technology is proven by main international

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agency undertaking several studies for investigation the performance and cost of the oxy-turbines cycles. In these preliminary studies, the costs of oxy-turbine cycles were higher than those of natural gas combined cycle with post combustion capture. However, the latest development of these technology recently made available by the main technology licensors indicates that some oxy-turbine plants can be competitive with post combustion capture.

With this premise, the IEA Greenhouse Gas R&D (IEAGHG) programme has contracted Amec Foster Wheeler to perform a study that provides an independent evaluation of the performance and costs of a number of oxy-turbine plants for utility scale power generation with capture of the carbon dioxide.

The identified leading natural gas fired oxy-combustion turbine cycles, including ones that are being developed commercially and ones that have been proposed by academics, are the following (see [1] and references within):

- Semi-closed oxy-combustion combined cycle (SCOC-CC)
- MATIANT cycles
- NET Power cycle
- Graz cycle
- CES cycle
- AZEP cycle
- ZEITMOP cycle.

These cycles mainly differ for two criteria, the main component of the fluid used as moderator of the combustion temperature, being also the working fluid of the power cycle (water or CO_2) and the technology used to produce oxygen: cryogenic distillation rather than membrane separation.

Among the plants using a cryogenic air separation unit, The SCOC-CC, MATIANT and NET Power cycles use recycled CO_2 as temperature moderator, while the Graz (or more precisely the S-Graz cycle, most widely assessed in the recent literature) and CES cycles use water. The AZEP and ZEITMOP cycles differentiate from the other ones because they integrate a high temperature membrane for oxygen production (OTM) in the power cycle. As these membranes require a hot pressurized air stream from which O_2 is separated, an externally heated air cycle is also present as main power cycle (AZEP) or as side cycle of the principal CO_2 cycle (ZEITMOP).

These oxy-fuel cycles have been ranked on the basis of their potential efficiency and of the technological development still required for their key novel, unproven, and hence critical, components which reflects, in the authors' opinion, the expected efforts still required for its commercial development. Based on this analysis, the following four cycles have been selected for a more detailed technical and economic assessment:

- Case 1. SCOC-CC
- Case 2. NET Power cycle
- Case 3. Graz cycle
- Case 4. CES cycle

Except the SCOCC-CC assumed as benchmark for oxy-fuel cycles, each cycle configuration and optimization is developed jointly with the main cycle developers, i.e. NET Power, Graz University of Technology and Clean Energy Systems, respectively. The detailed modelling of the gas turbine for each cycle, including efficiency, stage number and blade cooling requirement, has been implemented by using an independent calculation code developed at Politecnico di Milano (POLIMI).

The study does not aim to provide a definitive comparison of different technologies or technology suppliers because such comparisons are strongly influenced by specific local constraints and by market factors, which can be subject to rapid changes, as well as the development of the novel technology in the next years.

2. Key features of oxy-turbine cycles

2.1. Semi-closed oxy-combustion combined cycle (SCOC-CC)

The SCOC-CC has the simplest arrangement among all the oxy-fuel gas cycles proposed in the literature for gaseous fuels (Fig. 2a). It closely resembles a conventional combined cycle and hence it is conventionally used as benchmark cycle in most of the comparative analyses on natural gas-fired oxy-fuel cycles. The gas turbine compressor recycles part of the cooled CO_2 resulting from the fuel combustion. The amount of CO_2 recycled is set to achieve the desired combustor outlet temperature and to provide the cooling flows for turbine blades. The hot combustion products, at a pressure of around 45 bar, are expanded in the turbine and then heat is recovered in a heat recovery steam generator (HRSG), feeding the steam cycle. Flue gases from the HRSG are finally cooled to nearly ambient temperature in a flue gas cooler, where most of the water in the combustion products is condensed.

2.2. NET Power cycle

The NET Power cycle (Fig. 1) utilizes carbon dioxide as the working fluid in a high-pressure, low-pressure-ratio Brayton cycle, operating with a single turbine that has an inlet pressure around 300 bar and pressure ratio around 9, set so that the turbine outlet pressure matches the requirements of the downstream CO_2 purification unit. The high pressure combustor burns natural gas in an oxidant stream resulting from the mixture of high-purity oxygen stream with the recycle gas stream and provides the feed to a direct-fired CO_2 turbine. A regenerative heat exchanger transfers heat from the high temperature turbine exhaust to the high pressure recycle required to control the combustion temperature and cool the turbine blades. Heat from the hot air from the ASU main air compressor is recovered in the regenerative exchanger to enhance the cycle efficiency.

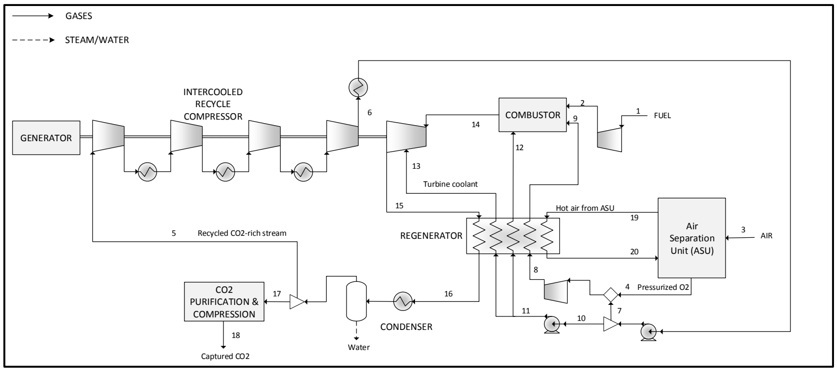

Fig. 1. NET Power cycle.

2.3. Modified S-GRAZ cycle

Different variants of the Graz cycle have been proposed and among the alternatives evaluated in the study, the Modified S-Graz Cycle presents the most attractive results. The cycle (Fig. 2b) consists of a high-temperature cycle, including the gas turbine and associated compressors and combustion chamber, the HRSG, a high pressure steam turbine (back-pressure type) and a low temperature cycle, substantially including a low pressure turbine and condenser. The fuel along with the nearly stoichiometric mass flow of oxygen is fed to the combustion chamber, which is operated at a pressure around 45 bar. The working fluid, mainly composed of steam, is expanded to a pressure slightly above the atmospheric pressure and sent to a single pressure level HRSG, generating high pressure steam to be expanded in the back pressure steam turbine down to the pressure level required for steam injection in the gas turbine expander for blade metal temperature control. Part of the cooled gas from the HRSG are compressed and recycled back to the combustion chamber for combustion temperature control, while the remaining portion is sent to the low temperature cycle.

2.4. CES cycle

This cycle, proposed by Clean Energy Systems (CES) uses water, both in vapor and liquid phases, as combustion temperature moderator. Though different versions have been proposed, the most promising cycle consists of a high pressure oxy-fuel combustor where part of the fuel and oxidant are combusted utilizing steam in supercritical conditions as temperature moderator, while hot gas produced in the gas generator is expanded in a steam cooled HP turbine (Fig. 3). The HP turbine exhaust gas is double-reheated by supplementary oxy-fuel combustion and further expanded in a MP and a LP section of the gas turbine, down to vacuum conditions. The cooling stream for these gas turbine section is part of the flue gas from the upstream turbine sections. This configuration shows the best efficiency among the different schemes proposed by Clean Energy Systems, differing also for the different technology effort and time required to develop some of the key cycle components. CES considers this cycle as their long-term high-efficient solution for oxy-combustion natural gas cycle application.

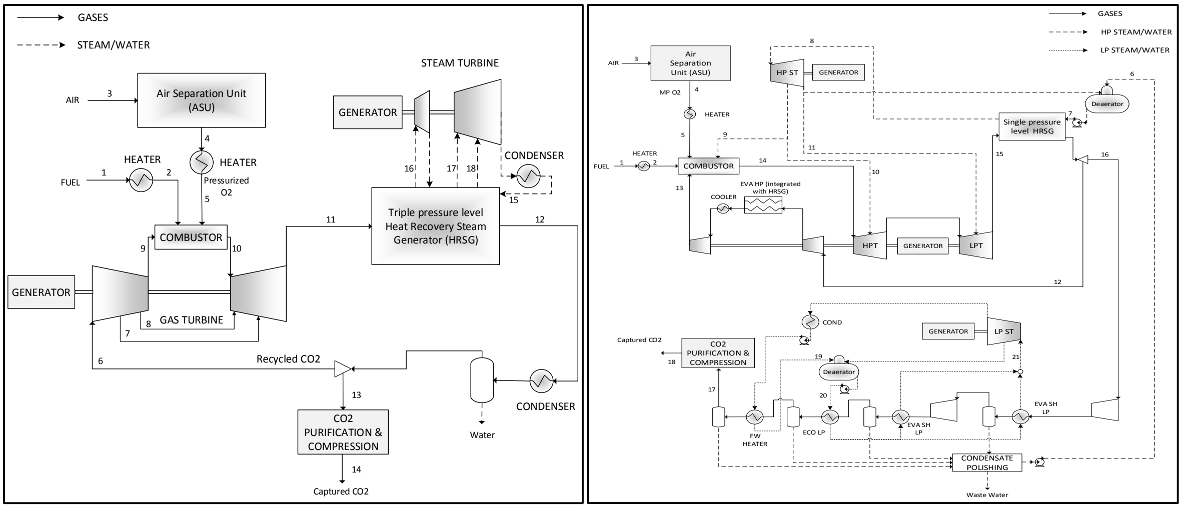

Fig. 2. (a) SCOC-CC; (b) Modified S-Graz.

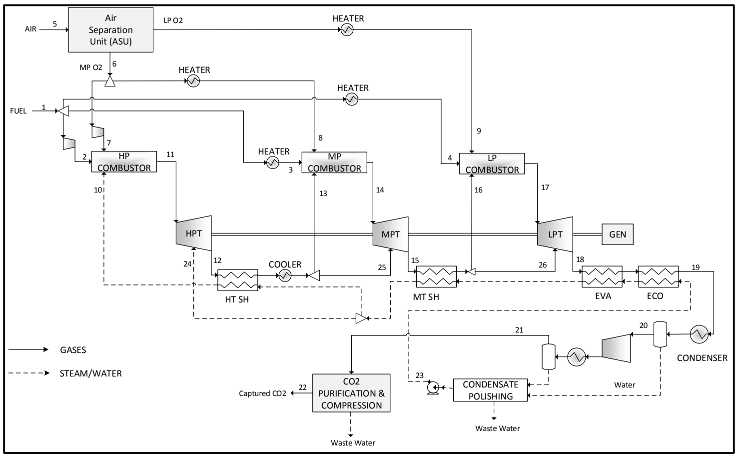

Fig. 3. Supercritical CES cycle.

3. Technical and economic basis

The technical and economic basis for the assessment is described in more detail in reference [1]. The main base case assumptions are:

- Greenfield site, Netherlands coastal location, with 9°C ambient temperature, natural draught cooling towers
- Oxy-fuel plants based on two fully loaded gas turbines, equivalent to the commercially available, air-fired, heavy duty F-class turbine, as the reference NGCC without CO_2.
- Net power output of the reference NGCC without CO_2: ~ 900 MWe. Oxy-fuel plants: based on the same gas turbine thermal input (768 MWth each, LHV basis)
- European pipeline natural gas: 46.5 MJ/kg (LHV), 3% total inerts; Price: €8/GJ LHV basis
- CO_2 to storage: 11MPa, 100ppm O_2, 50ppm H_2O
- 2Q2014 costs, ±35% (AACE Class 4), discount rate: 8% (constant money values)
- Operating life: 25 years, construction time: 3 years
- Capacity factor: 90%
- Carbon tax: 0 €/t; CO_2 transport and storage cost: €10/t stored

4. Cost definitions

The cost estimates in this paper were derived in general accordance with the White Paper "Toward a common method of cost estimation for CO_2 capture and storage at fossil fuel power plants", produced collaboratively by authors from IEAGHG, EPRI, USDOE/NETL, Carnegie Mellon University, IEA, the Global CCS Institute and Vattenfall [2].

The capital cost is presented as the Total Plant Cost (TPC) and the Total Capital Requirement (TCR). TPC is defined as the installed cost of the plant, including direct materials, construction, EPC services, other costs and project contingency. TCR is defined as the sum of Total Plant Cost (TPC), interest during construction, spare parts cost, working capital, start-up costs and owner's costs.

The oxy-turbine power plants include novel equipment that are either under development or at conceptual stage only, and overall integrated plants have not yet been operated. The study, however, has investigated the potential of the oxy-turbine power plants with respect to benchmark technologies for capture of the CO_2, these latter generally assumed as ready for commercial application. Therefore, the study has treated the oxy-turbine cycles at Nth-of-a-kind (NOAK) plants for estimating purposes and has evaluated the cost of novel equipment as already developed and suitable for large-scale commercial application with no additional contingencies applied with respect to the reference case without CCS.

Levelised Cost of Electricity (LCOE) and the Costs of CO_2 avoidance are widely recognized as the convenient tool for comparing different technologies with CO_2 capture over their economic lifetime. LCOE is defined as the price of electricity which enables the present value from all sales of electricity over the economic lifetime of the plant to equal the present value of all costs of building, maintaining and operating the plant over its lifetime. Costs of CO_2 avoidance were calculated by comparing the CO_2 emissions per kWh and the levelised costs of electricity of plants with capture and a reference plant without capture.

$$CO_2 \text{ avoidance cost (CAC)} = \frac{LCOE_{CCS} - LCOE_{Reference}}{CO_2\ Emission_{Reference} - CO_2\ Emission_{CCS}} \quad (1)$$

Where:
CAC is expressed in Euro per tonne of CO_2
LCOE is expressed in Euro per MWh
CO_2 emission is expressed in tonnes of CO_2 per MWh

For calculation of the cost of CO_2 avoidance, the reference plant for the natural gas fired oxy-combustion turbine plants is the conventional NGCC without capture, having the same capacity in terms of natural gas thermal input.

5. Main cases results

5.1. Plant performance

A summary of the performance of the main study cases is given in Table 1. The plants all have the same natural gas feed rate of 1,536 MWth (LHV basis).

Table 1. Plant performance summary

	Net power output, MWe	CO_2 captured, kg/MWh	CO_2 emissions, kg/MWh	Efficiency (LHV basis), %	Efficiency penalty for capture (LHV), %points
Reference NGCC	904	-	348	58.8	-
SCOC-CC	757	377	39	49.3	9.5
NET Power cycle	846	336	37	55.1	3.7
Modified S-Graz cycle	756	375	41	49.2	9.6
Supercritical CES	751	379	41	18.9	9.9

The highest efficiency of 55% is for the NET Power cycle, the other three oxy-combustion processes have lower efficiencies of around 49%. The developers of the NET Power cycle have estimated an efficiency of 59% for their cycle using proprietary improvements and CES has estimated an efficiency of 53% for its cycle. The supercritical version of the CES cycle is a relatively recent innovation. Adopting a lower coolant temperature would be likely more advantageous and is currently being pursued by CES as part of their on-going cycle optimization work.

5.2. Financial results

The capital costs, the levelised cost of electricity and the cost of CO_2 avoidance of the plants are summarized in Table 2. The NET power process shows the best economics, while the three other cycles are quite similar. Breakdowns of the total plant costs and of the levelised cost of electricity are given respectively in Figures 4a and in Figure 4b. The main contribution to the LCOE in all cases is the fuel cost, which depends on the thermal efficiency, but the main contribution to the additional cost of capture is the additional capital cost. The absolute cost and LCOE figures are strictly conditioned by the reference year and the plant location. However, it is worth to be highlighted that, being the basis of design the same for all the cases including the reference NGCC, the main considerations and outcomes of the study, in particular on the impact of CO_2 capture in NGCC are less affected by the specific cost basis. In any case, sensitivity cases are included to address some of the main design and assumptions changes with respect to those listed above.

Table 1. Cost of natural gas fired power plants

	Total plant cost (TPC)		Total capital requirement (TCR)	Levelised cost of electricity		CO_2 avoidance cost
	€/kW	%increase for capture	€/kW	€/MWh	%increase for capture	€/ton
Reference NGCC	655	-	855	62.5	-	-
SCOC-CC	1470	124	1905	92.8	48	98
NET Power cycle	1320	102	1715	83.6	34	68
Modified S-Graz cycle	1500	129	1955	93.7	50	101
Supercritical CES	1540	135	2000	95.1	52	106

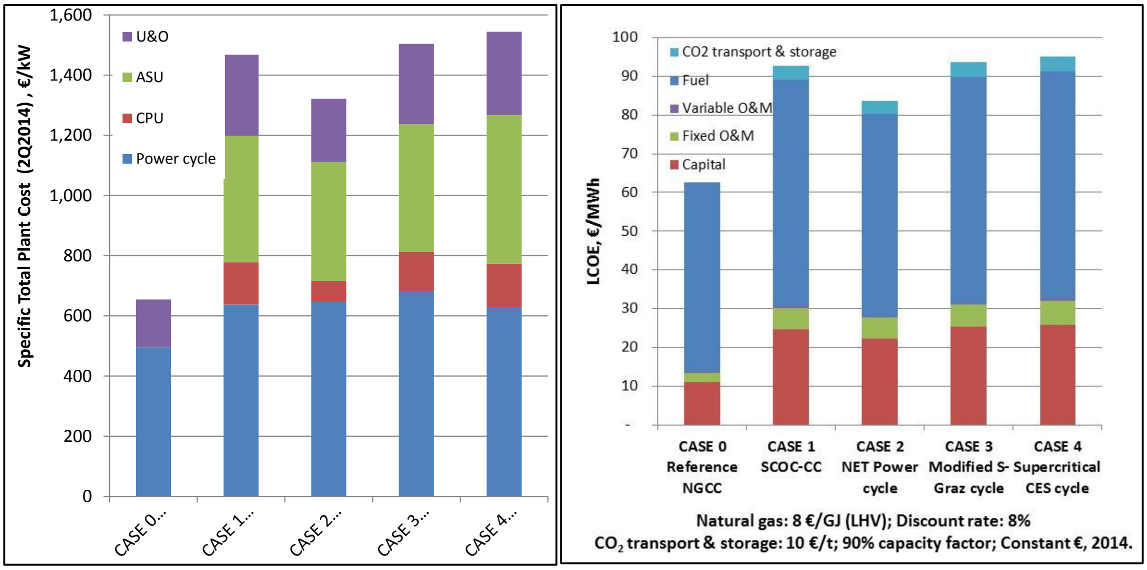

Fig. 4. a) Specific Total Plant Cost of natural gas fired power plants; b) Levelised Costs of Electricity

5.3. Comparison of oxy-combustion and post combustion capture plants

The two most promising oxy-combustion turbine cycles have been compared with the best performing NGCC with post combustion capture, using the new generation of proprietary MEA-based solvent in the capture unit. Main technical and economic results are summarized in Table 3.

Table 3. Comparison of oxy-combustion and post combustion capture plants

	Efficiency, % (LHV)	Total plant cost, €/kW	LCOE, €/MWh	CO_2 avoidance cost
Reference NGCC	58.8	655	62.5	-
SCOC-CC	49.3	1470	92.8	98
NET Power cycle	55.1	1320	83.6	68
NGCC with post-combustion capture	52.0	1200	84.7	71

The Total Plant Cost of the oxy-combustion plants are higher than that of the NGCC with post-combustion capture, however, the higher efficiency of the NET Power cycle allows lowering the relevant LCOE and consequently the CO_2 avoidance cost below those of the post combustion capture based plant.

6. Sensitivity to key design parameters

The study base cases were assessed considering a set of standard technical bases used by IEAGHG in its studies to facilitate comparability, however it is recognized that performance and financial results will depends on local conditions and design assumptions. Several sensitivities to the following technical parameters are analyzed in the study in order to address this issue. Some of the main results are reported hereafter.

- Application of new high-temperature materials, affecting the turbine combustor outlet temperature and the maximum metal temperature
- CO_2 purity and capture rate requirements
- Oxygen purity
- Natural gas with high nitrogen or CO_2 content

- Higher ambient temperature conditions
- Alternative cooling system: mechanical draft cooling towers

6.1. Application of new high-temperature materials

The potential increase in efficiency related to the application of a new generation high-temperature materials, currently under development to improve the conventional NGCC efficiency, is investigated. Higher allowable temperature material leads to a potential increase of the combustor temperature and reduction of the turbine cooling flow requirement. Increasing the combustor outlet temperature and increasing the allowable turbine material temperature by 90°C increased the efficiencies of the NET Power and SCOC-CC cycles by 1.6 and 0.5 percentage points respectively. Table 4 shows the impact on the main cost parameters. Impact on the equipment cost of the application of the new materials is evaluated as a percentage increase with respect to the equipment cost based on conventional materials.

Table 4. Application of new generation high-temperature materials

		COT, °C	Efficiency, % (LHV)	Total plant cost, €/kW	LCOE, €/MWh	CAC, €/ton
SCOC-CC	Metal temperature: 860°C	1533	49.3	1470	92.8	98
	Metal temperature: 950°C	1613	49.8	1475	92.2	96
NET Power cycle	Metal temperature: 860°C	1150	55.1	1320	83.6	68
	Metal temperature: 950°C	1200	56.7	1325	82.0	63

6.2. CO_2 purity and capture rate requirements

CO_2 purity specifications for CCS are not yet clearly defined and they may vary between different applications, e.g. EOR and saline reservoir storage, and plant location. The conservative oxygen specification of 100 ppmv considered in the study implies the application of cryogenic CO_2 purification unit which removes O_2 and other impurities (N_2 and Ar) resulting in a CO_2 purity of about 99.8%. The impurities vent stream includes some CO_2, resulting in incomplete CO_2 capture. The base case plants in this study were designed for 90% CO_2 capture, but higher capture rates could be achieved if required. If lower purity CO_2 were acceptable the CO_2 purification unit could be removed, capturing 100% of the CO_2. Alternatively if high capture rate and CO_2 purity were required the vent gas from the purification unit could be processed, for example in a membrane unit, resulting in around 98% overall CO_2 capture. These schemes were assessed for the NET Power cycle and the results are summarized in Table 5.

Table 5. Sensitivity to CO_2 purity and capture rate for NET Power cycle

CO_2 capture	CO_2 purity	Efficiency, % (LHV)	Total Plant cost, €/kW	LCOE, €/MWh	CAC, €/tot
90	99.8	55.1	1320	83.6	68
98	99.8	54.7	1340	84.7	65
100	97.9	55.3	1270	82.7	58

6.3. Oxygen purity

The selection of the oxygen purity affects the efficiency in the oxy-combustion processes as higher oxygen purity affects negatively the internal consumptions of the air separation unit while reduces the consumption of the compression section of the CO_2 purification unit for the cycles where the turbine exhaust are at almost atmospheric pressure or below (SCOC-CC, S-Graz, CES), or of the CO_2 rich-stream re-pressurization in very high pressure cycles such as the NET Power cycle. Sensitivity cases indicated that the oxygen purities selected for the study, i.e. 99.5% for the NET Power cycle and 97% for the other cycles are close to the optimum.

6.4. Alternative cooling water system

The cooling water system selected for the study reference case is the natural draught cooling tower system. A sensitivity case of the NET Power cycle was assessed in which natural draught towers with an approach of 7°C were replaced by mechanical draught cooling towers allowing a more aggressive approach of 4°C. Using mechanical draught cooling towers increased the net electrical efficiency, because the power requirement for cooling tower fans is more than offset by reductions in the compression power requirements, mainly the recycle gas compression, as well as small reductions in the ASU and the final CO_2 purification unit. Efficiency and cost figures are shown in Table 6.

Table 5. Alternative cooling system for NET Power cycle

Cooling system	Approach, °C	Efficiency, % (LHV)	Total Plant cost, €/kW	LCOE, €/MWh	CAC, €/tot
Natural draft	7	55.1	1320	83.6	68
Mechanical draft	4	55.4	1245	81.7	61.5

7. Economic sensitivities

There is significant uncertainty in the estimated costs of innovative equipment used in the oxy-combustion cycles. The proportion of innovative equipment, mainly gas turbines and high temperature/high pressure heat exchangers, is different in the different cycles. The sensitivity of LCOE to variations in the costs of innovative equipment is shown in Figure 5. A wider sensitivity range is considered for the cycles with components that require more development, such as the supercritical CES and the high-pressure parts of the NET Power cycle.

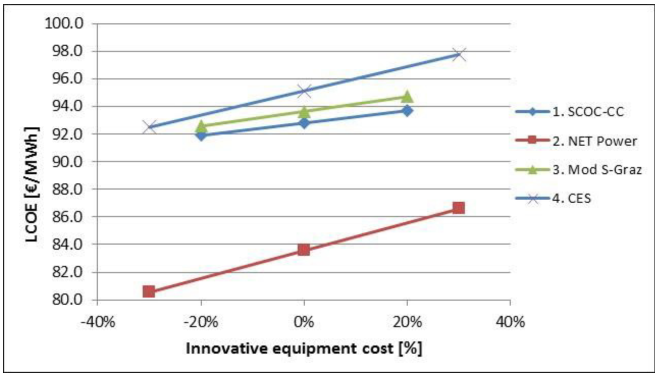

Fig. 5. LCOE sensitivity to novel equipment cost

The costs of CCS also depend on economic parameters that will vary over time and between different plant locations. The sensitivities of LCOE and CAC to the natural gas price, economic discount rate, plant life, cost of CO_2 transport and storage, operating capacity factor and the cost penalty for non-captured CO_2 emissions were evaluated for all of the cycles and the results are presented in the main report [1]. As an example the results for the NET Power cycle are shown in Figures 6 a) and b), in which the green bars represent increases from the base case and the red bars are reductions.

The greatest sensitivity of LCOE is to the natural gas price, as gas prices vary substantially depending on location and gas source. Reducing the annual capacity factor to 50% results in a substantial increase in the LCOE but, if this is because the plant is only operated at times of relatively high power prices and is shut down when the power price is lower, the overall economic viability of the plant may not necessarily be adversely affected. Increasing the CO_2 transport and storage cost has a relatively small impact on the LCOE but if CO_2 could be sold for EOR the economics of the plant would be significantly improved. The impacts of the economic parameters on the CO2 avoidance cost are substantially different to their impacts on LCOE. Fuel price has only a small impact because it depends only on the relatively small difference between the efficiencies of the reference plant and the oxy-combustion turbine plant. Reducing the capacity factor has a much larger impact because the capital costs of oxy-combustion turbine plants are much higher than the cost of the reference plant. CO_2 transport and storage cost has a much larger impact on the CO2 avoidance cost than LCOE because it has no impact on the cost of the reference plant.

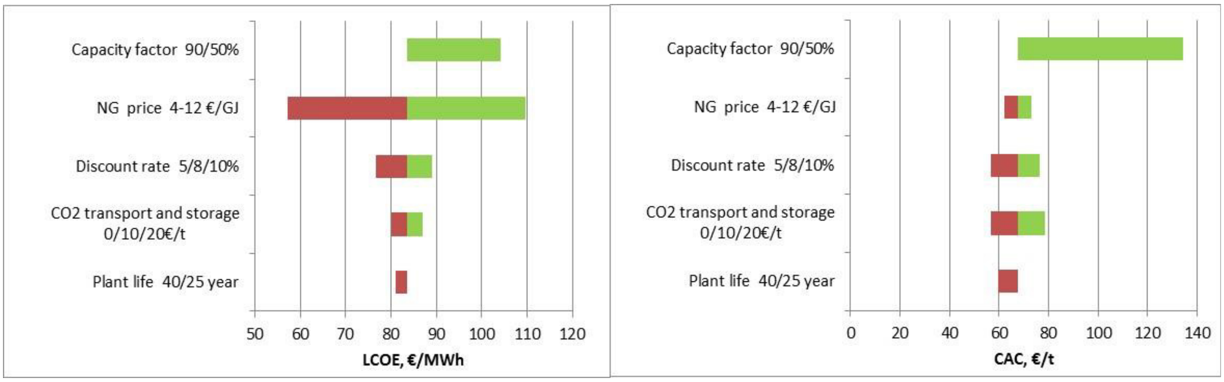

Fig. 6. a) LCOE sensitivity; b) CAC sensitivity

8. **Conclusions**

The results of the technical and economic assessments made in this study shows that the oxy-turbine power plants have the technical and economic potential to be a valid solution for CO_2 capture from natural gas fired power plants.

The regenerative NET Power cycle shows a potential outstanding efficiency (~55%) compared to post combustion capture based combined cycle using a new generation proprietary amine-based solvent (52%), while the other cycles show a net electrical efficiency around 49%. Depending on the cycle type, the specific total plant cost of oxy-turbine power plants varies from 1,300 to 1,550 €/kWe, approximately 2-2.4 times greater than the specific cost of a standard combined cycle without CO_2 capture (655 €/kWe). NET Power cycle shows the best economics, mainly due to its outstanding efficiency and lower specific total plant cost (1,300 €/kWe) which lead to a LCOE of around 84 €/MWh. Mainly due to a similar net electrical efficiency in the range of 49%, the other cycles show also a similar LCOE, in the range of 93-95 €/MWh. Costs of CO_2 emissions avoidance range from 67 to 106 €/t.

The specific total plant cost of a combined cycle plant with post combustion capture using a new generation proprietary amine-based solvent is around 1,200 €/kWe, i.e. approximately 10% less than the NET Power plant and 25% less than the cost of the other oxy-turbine cycles. However, the higher efficiency of the NET Power cycle (~55% vs. 52% of the post-combustion) decreases the cost component of the natural gas so the overall LCOE of the plant with post-combustion capture is similar to that of the NET Power plant (85 €/MWh vs. 84 €/MWh) and the cost of CO_2 avoidance is also similar.

In the near future, proprietary improvements by process developers may result in increasing efficiencies. In particular, NET Power and CES are commercially deploying their technologies in partnership with commercial gas turbine suppliers, like Toshiba, General Electric or Siemens, so further improvements are expected in the next years. NET Power is confident that the efficiency of their cycle can be as high as 59%, leading to an evident economic improvement, while CES claims for its supercritical cycle an efficiency target of 53%.

References

[1] IEAGHG, 2015. Oxy-combustion turbine power plants, Report 2015/5, August 2015, IEAGHG, Cheltenham, UK, available at link http://ieaghg.org/docs/General_Docs/Reports/2015-05.pdf.
[2] IEAGHG, 2013. Toward a common method of cost estimation for CO2 capture and storage at fossil fuel power plants. IEAGHG report 2013/TR2, March 2013, IEAGHG, Cheltenham, UK, available at link http://ieaghg.org/docs/General_Docs/Reports/2013-TR2.pdf.
[3] IEAGHG, 2012. CO2 capture at gas fired power plants, Report 2012/08, July 2012, IEAGHG, Cheltenham, UK, available at link http://ieaghg.org/docs/General_Docs/Reports/2012-08.pdf