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Greek Lignite-Fired Power Plants with CO_2 Capture for the Electricity Generation Sector

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The aim of the paper is to evaluate the performance of a 300 - 400 MWel steam power plant fired with low quality lignite, representative of the Greek electricity generation sector, integrating Carbon Capture and Sequestration technologies (CCS). The CCS technologies under investigation are the oxy-fuel and the chemical absorption with amines, since they are considered to dominate in the demonstration period of the CCS application, which starts at 2015. The basic power plant design is demonstrated by taking into account the special features of the oxy-fuel and amine scrubbing technologies. Due to the resulting efficiency penalty, it is of utmost importance to apply any available measure to improve the power plant's performance. The optimisation options of the thermodynamic design, as well as the economic feasibility study are presented. The electricity production cost is expressed as the minimum electricity selling price which renders the integration of CO_2 capture equipment economically viable. In addition, the cost of avoided CO_2 relative to the reference plant with no CO_2 control is determined, as it is a widely used economic indicator of the cost for the prevention of CO_2 emissions. The economic evaluation of the power plants refers to the demonstration period of the CO_2 capture technologies (year 2015) and the period of commercial maturity (year 2030).

1. Introduction

Nowadays, energy production and consumption are neither sustainable nor efficient from an economic, social and environmental perspective. Without the adoption of immediate and effective measures, greenhouse gas emissions will double by 2050. As a result, there is a world-wide growing awareness that a portfolio of technologies should be involved in order to face the energy problem. Energy efficiency, CCS technologies, renewable energy sources, nuclear power and transport technologies can have a major contribution to the progress towards a low carbon economy, as well as to the security of energy supply. As fossil fuels are necessary to secure sufficient energy supply for the next decades and worldwide deposits are still sufficient (especially of coal), CCS can be an important solution. The cost competitive deployment of CCS after year 2020 lies in the heart of European energy policy. The development of CO_2 capture and sequestration technologies for thermal power plants is a field of intense research activity during the last years. CCS technologies can be categorized in three broad categories: post-combustion CO_2 capture, where CO_2 is separated from the flue gas, pre-combustion CO_2 capture, where a carbon-free fuel is produced and oxyfuel combustion, where pure oxygen is used for combustion instead of air.

2. Power plant simulation and optimisation

The purpose of the current study is the determination of the basic technical characteristics and performance of a steam power plant with CO_2 capture, the optimisation of the performance and the economic evaluation of the steam power plant with CCS for the demonstration period of the CO_2 capture technologies and the period of commercial maturity. The power plant simulations have been performed with the commercial thermodynamic cycle calculation software GateCycle.

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2.1 General assumptions

The reference power plant used in the current study represents a typical size modern lignite unit for the Greek electricity system, with a once-through Benson-type boiler with reheat. The steam cycle comprises 8 regenerative feedwater preheaters with steam extracted from the steam turbine and electrically driven feedwater pumps. A wet natural draught cooling tower is used for cooling of the water coolant flow. Air infiltration rate in the boiler is assumed 10 % of the total combustion air, while air leakage to the flue gas side of the air preheater with flue gas (LUVO) is 4 % of the air flow. Air infiltration rate in the Electrostatic Precipitators (ESPs) is 1.5 % of the inlet flue gas flow. The steam turbine isentropic efficiencies are assumed to be 89 %, 91 % and 85 % for the High Pressure (HP), Intermediate Pressure (IP) and Low Pressure (LP) stages. Ambient air conditions are 15 ºC, 60 % relative humidity, 1,013 mbar, condenser pressure is 48 mbar and cooling water temperature is assumed 18.2 ºC. In order to reach high efficiencies, the latest developments in materials have been taken into account, thus achieving high steam thermodynamic properties (main steam: 280 bar, 600 °C, Reheated steam: 60 bar, 622.1 °C), while a lignite pre-drying unit is incorporated in the process. Pulverised lignite is pre-dried up to a moisture content of 12 % weight, before being fed to the boiler for combustion. The pre-drying unit comprises an atmospheric fluidised bed utilising slightly superheated steam. The water vapour removed from lignite during the process is mixed with the recirculating steam used for bed fluidisation. At the bed exit, a water vapour flow equal to the amount of moisture removed from lignite is fed to compressors. The pressure increase and corresponding condensation temperature increase allows heat to be transferred to the fluidised bed system (Kakaras et al., 2002). The raw and pre-dried lignite ultimate analysis and Lower Heating Value are presented in table below.

Table 1: Raw and pre-dried lignite ultimate analysis and LHV

	Raw lignite	Pre-dried lignite
LHV (MJ/kg)	7.962	12.044
C (w. %)	22.58	31.44
H (w. %)	2.07	2.88
N (w. %)	0.37	0.51
O (w. %)	9.88	13.76
S (w. %)	0.94	1.31
H_2O (w. %)	36.8	12.00
Ash (w. %)	27.36	38.10

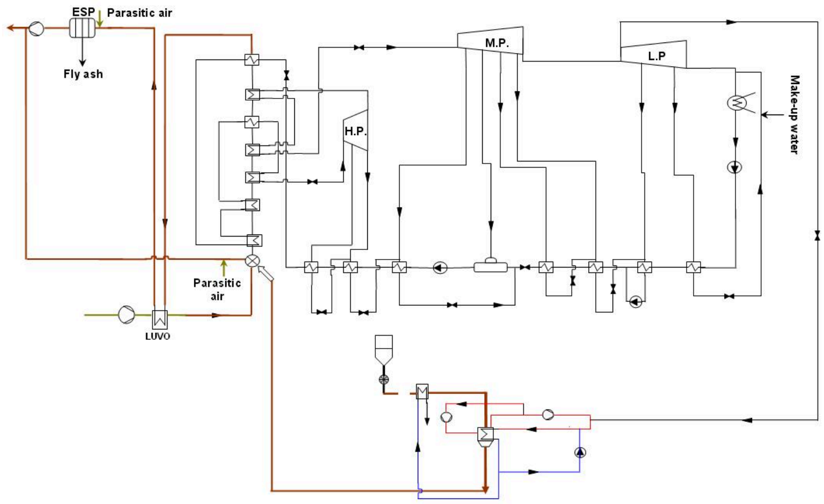

Figure 1: Process flow diagram of reference power plant

2.2 Reference power plant

Figure 1 and Table 2 present the process flow diagram and the performance overview of the reference power plant. The high thermodynamic properties of the HP (280 bar, 600 °C) and RH (60 bar, 622.1 °C) steam in combination with the utilization of an atmospheric fluidised bed dryer with steam, result in the increased performance of the plant. Despite the fact that the power consumption of the dryer is 13.1 MW, it positively affects the efficiency of the power plant, since a considerable increase of the fuel LHV is achieved at the expense of low-grade heat. In addition, due to the removal of lignite moisture, the boiler flue gas heat losses are considerably reduced, as well as the power consumption of the flue gas ID fan. The unit produces a net power output of 326.7 MW with an efficiency of ca. 42.2 %, on raw lignite LHV basis.

Table 2: Performance overview of reference power plant

Gross power output	Fuel consumption	Fuel input - LHV	Gross efficiency	Net power output	Net efficiency
MW_{el}	kg/s	MJ/s	%	MW_{el}	%
375.07	97.32	774.86	48.41	326.72	42.17

2.3 Lignite power plant with post combustion capture with amine scrubbing

In the flue gas scrubbing operation, CO_2 is selectively absorbed from the flue gas by a liquid solvent at 30 % weight (Chavez Guadarrama, 2011). Chemical absorption of CO_2 by an amine solution is currently a commercially available technology (Rochelle, 2009), yet application in large-scale power plants is a new prospect. In the amine scrubbing process, the flue gas flow is cooled down to the absorber column operating temperature of 40 - 60 ºC. A flue gas fan increases the pressure to 1.124 bar in order to compensate for the process pressure drop. CO_2 is absorbed from the flue gas by the liquid solvent inside the counter-current flow absorption column. In a second stripper column (regeneration stage), operating at a pressure slightly above atmospheric and a temperature of 100-140 °C, the charged amine solution is heated with steam, in order to strip off the CO_2. Heat consumption for regeneration of the reach CO_2 solution is assumed 4 GJ/ton CO_2 removed, and is provided in the form of steam extraction from the low pressure steam turbine, with a condensing temperature of 140-145 °C, corresponding to a condensing pressure of 3.6 - 4.2 bar (Abu-Zahra et al., 2007). The gas stream exiting the regeneration column mainly consists of CO_2 and water vapour, and due to its high CO_2 purity, no further cleaning is required. The stream is compressed from 1.5 bar, which is the regeneration column exit pressure, to 110 bar for transportation and storage, in 4 stages with inter-cooling. During the inter-cooling phases, part of the water content is condensed and removed from the stream. The available efficiency optimisation options for the power plant with CO_2 capture are the following: low pressure feedwater preheating from CO_2 compression waste heat, from the flue gas condenser waste heat and from stripper column extraction steam desuperheating and air preheating before LUVO.

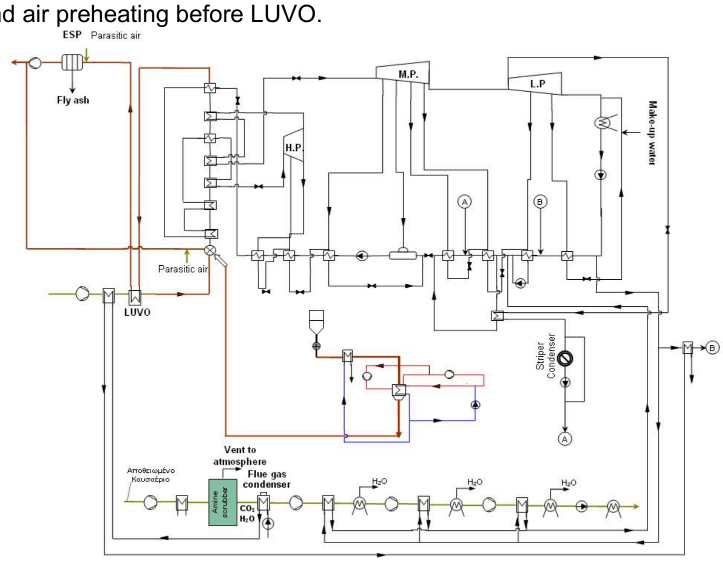

Figure 2: Process flow diagram of optimised power plant with amine scrubbing CO_2 capture

Figure 2 and Table 3 present the process flow diagram and the performance overview of the optimised power plant with amine scrubbing. The gross power output is significantly reduced with respect to the reference power plant. In particular, the non-optimised power plant output is 312.5 MW vs 375.1 MW, a reduction caused by the LP steam extraction for the amine regeneration. The optimised power plant output, on the other hand, is 317.6 MW, 5.1 MW more than the non-optimised case. The auxiliaries consumption of the power plants with CO_2 capture is increased with respect to the reference power plant. The net power output is 230.3 and 235.4 MW, for the non-optimised and optimised case, respectively, while the net efficiency of the non-optimised unit with CO_2 capture is 12.5 percentage points less than the reference power plant. With the integration of low-grade waste heat, the net efficiency of the optimised power plant is slightly increased to 30.4 %, 11.8 percentage points lower than the reference power plant.

Table 3: Performance overview of optimised power plant with amine scrubbing CO_2 capture

Gross power output	Fuel consumption	Fuel input - LHV	Gross efficiency	Net power output	Net efficiency
MW_{el}	kg/s	MJ/s	%	MW_{el}	%
317.58	97.32	774.86	40.99	235.38	30.38

2.4 Oxyfuel lignite power plant with CO_2 capture

The basic characteristics differentiating oxyfuel combustion with air combustion are: (a) Air is separated before entering the furnace with an air separation unit (ASU) and only O_2 (O_2 95 v%, N_2 v%, Ar 3 v%) is used for combustion (Zanganeh and Shafeen, 2007). (b) Part of the flue gas exiting the boiler is recalculated, in order to be used as the lignite transportation medium to the burners and to moderate the furnace temperatures to acceptable limits (Chui et al., 2003). (c) The non-recirculating flue gas is cooled and the water content is condensed and subsequently it enters the CO_2 compression and non-condensable gases removal unit, where it is finally compressed to 110 bar (Jordal et al., 2005). Air infiltration to the boiler has a significant impact on the process efficiency, since it affects the power consumption of the CO_2 processing unit, as well as the CO_2 capture rate. In this respect, improvement of boiler sealing in order to significantly reduce air infiltration rate and regular maintenance throughout its life are important (Deng and Hynes, 2009). For the modelling of the oxyfuel power plant, it has been assumed that air infiltration in the boiler and ESPs is 0.01 and 0.015 kg air/ kg flue gas (Santos and Haines, 2006).

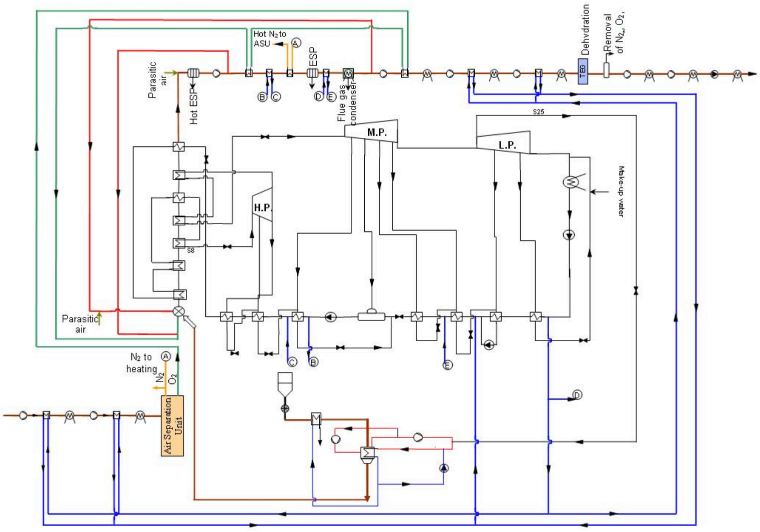

Figure 3: Process Flow Diagram of optimised oxyfuel power plant with CO_2 capture

The selected air separation technology is cryogenic separation, with an oxygen purity of 95 v%, which is regarded as an optimum, since the high energy demand for achieving a higher purity is not counter-balanced by the reduction in CO_2 processing energy requirements (Andersson and Maksinen, 2002). The produced O_2 is mixed with the flue gas recirculation flow. The ASU produces O_2 and N_2 at a pressure of 1.2 and 1.3 bar and comprises of air compressors with inter-cooling, an evaporative cooler, molecular sieves, the main heat exchanger and a distillation column. For an oxygen purity of 95 % volume, the required pressure is 5.52 bar. The air before entering the ASU is compressed in two stages with inter-cooling. The molecular sieves are used for water vapour and other air components removal and they are regenerated using dry N_2, produced by the ASU at 150 ºC (Allam, 2009). The available efficiency optimisation options for the power plant with CO_2 capture are the following: ASU oxygen preheating up to 320 °C / high pressure and low pressure feedwater preheating from flue gas cooling waste heat, low pressure feedwater preheating from air compression waste heat and ASU oxygen preheating up to ca. 110 °C / low pressure feedwater preheating from CO_2 compression waste heat. Figure 3 and Table 4 present the process flow diagram and the performance overview of the optimised oxyfuel power plant. In spite of the fact that both gross power output and gross efficiency are increased, the net power output and efficiency are significantly reduced, due to the increase of the auxiliary consumption. The net power output of the optimised plant is 269.7 MW, while the power output of the non-optimised plant is 248.7 MW vs 326.7 MW of the reference power plant. The net efficiency of the optimised and non-optimised oxyfuel power plant is calculated at 7.4 and 10.1 percentage points less than the reference power plant, respectively.

Table 4: Performance overview of optimised oxyfuel power plant with CO_2 capture

Gross power output	Fuel consumption	Fuel input - LHV	Gross efficiency	Net power output	Net efficiency
MW_{el}	kg/s	MJ/s	%	MW_{el}	%
401.31	97.32	774.86	51.79	269.74	34.81

3. Economic evaluation of CO_2 capture technologies

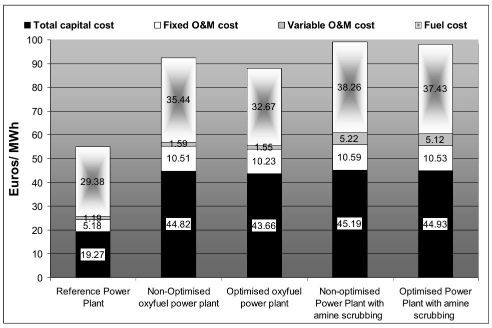

Figure 4: Electricity production costs for the CCS demonstration phase - Payback period 25 y

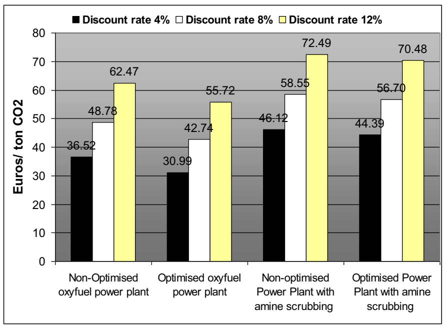

Figure 5: CO_2 avoidance costs for the CCS demonstration phase - Payback period 25 y

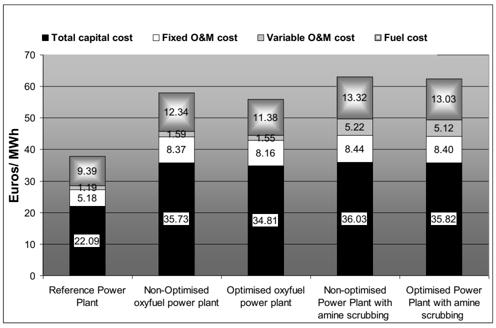

Figure 6: Electricity production costs for the CCS commercial phase - Payback period 25 y

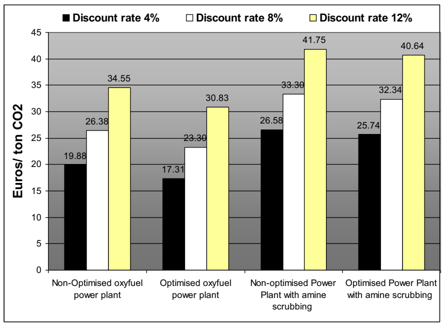

Figure 7: CO_2 avoidance costs for the CCS commercial phase - Payback period 25 y

The application of CCS technologies significantly affects the economics of thermal power plants. The direct economic consequences are related to the increased capital investment and operating and maintenance costs of the plant. On the other hand, the CO_2 capture equipment results in an electricity generation reduction with respect to a conventional power plant and, as a consequence, in the reduction of revenues. Given the volatility of electricity prices and the difficulty for long-term predictions, the Net Present Value (NPV) indicator has been chosen for the assessment of yearly revenues and cash flows. The electricity selling price that renders NPV zero is defined as the minimum selling price which renders the integration of CO_2 capture equipment economically viable. The electricity selling price calculated from the cash flows is based on particular assumptions for the investment costs, operating and maintenance costs and fuel costs (Davison, 2006). CCS technologies are not yet commercially mature, but are today in the implementation study phase for the erection of small or large-scale demonstration units. Therefore, in order to assess the economic viability of thermal power plants integrating CCS, it is necessary to make a number of technical and economic assumptions. The development and application of CO_2 capture and storage technologies can be divided in three basic phases: demonstration, primary commercial phase and commercial maturity phase. The operation of demonstration units in the EU is estimated in 2015, while the primary commercial phase is expected to start at the earliest by 2020 and the commercial maturity phase is estimated after 2030. The electricity production cost for the demonstration phase of CCS technologies, taking into account that the engineering and installation costs will be higher due to the innovation risk taken on by the manufacturer and the power company, is presented in Figure 4, while Figure 5 presents the corresponding CO_2 avoidance cost. Figures 6 and 7 present the electricity production cost and CO_2 avoidance cost for the commercial maturity phase of the CCS technologies. The electricity generation cost is increased by 60 % for the optimised oxyfuel power plant and by 78 % for the optimised power plant with amine scrubbing, while the CO_2 avoidance cost is between 43 - 59 Eur/t, for a discount rate of 8 %. For the reference power plant, the total capital cost represents 35 % (19.27 €/MWh) of the electricity generation costs, while fuel is ca. 53 % (29.38 €/MWh). The power plants with CO_2 capture have a significantly higher total capital cost and its contribution to the electricity generation cost is higher (about 50 %). For the optimised oxyfuel power plant, the total capital cost portion of the electricity generation cost is 43.66 €/MWh, increased by 130 % with respect to the reference power plant while the fuel cost portion is 32.67 €/MWh, increased by 11.2 %. For the optimised power plant with amine scrubbing, the total capital cost portion of the electricity generation cost is 44.93 €/MWh, while the fuel cost portion is 37.43 €/MWh.

4. Conclusions

The performance of a small-scale (demo-scale) CCS steam power plant fired with low quality lignite, representative of the Greek electricity generation sector has been evaluated for oxy-fuel and chemical absorption with amines and performance optimisation through extensive heat integration was performed. Both technologies result in a significant net power output and efficiency decrease with respect to the reference power plant, which for the optimised power plant with amine scrubbing is 235.4 MW and 30.4 %, while for the optimised oxyfuel power plant, which performs better, it is 269.7 MW and 34.81 %, vs 326.7 MW and 42.2 % of the reference power plant. The electricity production cost, expressed as the minimum electricity selling price which renders the integration of CO_2 capture equipment economically viable, is considerably increased by 60 – 80 %, due to the high performance penalty in combination with the associated increased capital and O&M costs.

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