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Oxy-combustion of coal, lignite and biomass: A techno-economic analysis for a large scale Carbon Capture and Storage (CCS) project in Romania

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HIGHLIGHTS

- In-depth techno-economic assessments of oxy-fuel combustion power plants.
- Oxy-combustion delivers reduced carbon capture energy and costs penalties.
- Evaluation of fuel quality influence on oxy-combustion power plant performances.

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ABSTRACT

Power generation sector is facing important challenges to develop energy efficient solutions at the same time with reducing the greenhouse gas emissions (mainly CO_2). Oxy-fuel combustion is a promising power generation technology for reducing both energy and cost penalties for CO_2 capture. This paper presents a detailed techno-economic analysis for oxy-combustion power plant to generate about 350 MW net power with a carbon capture rate higher than 90%. Both fossil fuels (coal and lignite) and renewable energy sources (sawdust) were used to fuel a super-critical power plant (live steam parameters: 582 °C/29 MPa). The assessment is based on numerical analysis, the models of various power plant sub-systems being built in ChemCAD and Thermflow software. As benchmark option used to quantify the CO_2 capture energy and cost penalties, the same super-critical power plant without CCS was considered. The investigated coal, lignite and sawdust oxy-combustion cases show an energy penalty of 9–12 net efficiency percentage points, 37–50% increase of total capital investment, the O&M costs are increasing with 7–15% and the electricity cost with 54–95% (all compared to coal-fuelled non-CCS case). Sensitivity studies were also performed to evaluate the influence of various economic parameters on electricity and CO_2 avoidance costs.

1. Introduction

In transition to the future low carbon energy systems (mostly based on renewable energy sources), the fossil fuels are predicted to remain the backbone of heat and power sector in the next decades [1]. The main environmental drawback of continuing the fossil fuel usage in power generation sector as well as other energy-intensive industrial applications (cement, metallurgy, chemistry, etc.) is relating to the high greenhouse gas (CO_2) emissions. Renewable energy sources (e.g. biomass) are representing a viable option to reduce fossil CO_2 emissions. The carbon footprint of power generation is especially reduced when biomass is used in conjunction with carbon capture technologies. Carbon Capture and Storage (CCS) technologies have the potential to significantly reduce the greenhouse gas emissions and to permit the usage of fossil fuels as a bridge to future low carbon economy [2].

The most technological and commercial mature carbon capture option to be implemented into power generation sector is based on post-combustion CO_2 capture configuration using chemical gas–liquid absorption [3,4]. This carbon capture technology has the significant advantage of little interference with the existing power plants, the flue gases are treated in a separate gas–liquid absorption cycle for CO_2 capture. The main drawback of chemical gas–liquid absorption technology applied for CO_2 capture is represented by the high thermal duty for solvent regeneration (at least 3 GJ/t CO_2) which implies an overall energy penalty for CO_2 capture of at least 10 net electricity percentage points [5,6]. As

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consequence, innovative energy efficient carbon capture options need to be developed.

Among other carbon capture options (either pre- or post-combustion configurations); the oxy-fuel combustion has also the advantage of minimum process modifications compared to existing energy conversion technologies [7]. Oxygen, instead of air, is used for fuel combustion to avoid the nitrogen contamination of the flue gases. Subsequently, the flue gas consists mainly of carbon dioxide and water vapour; this gas is subjected to a relatively low-energy consuming for purification (CO_2 separation). To control the temperature in the combustion chamber, a large part of the flue gases (about 70%) are recycled to the boiler. The most important energy penalty of the oxy-combustion process is the Air Separation Unit (ASU) which provides the oxygen. The power consumption of an industrial-size cryogenic air separation process is about 200–225 kW h/t oxygen. Various other oxygen separation methods (e.g. membrane, chemical looping, etc.) are currently under investigation but up to now most of them are just in research and development phase [8].

Numerous oxy-fuel combustion systems are being tested worldwide from laboratory to pilot plant sizes up to 50 MW_{th}. For instance, to demonstrate the technology, a 30 MW_{th} oxy-fuel pilot plant was built and operated since 2008 at Schwarze Pumpe, Germany [9]. To become fully commercial for power generation sector, the oxy-fuel combustion technology needs further implementations and scale-up to demonstrate its viability and performance at industrial size (hundreds of MW). Moreover, further evaluations are needed concerning optimisation and integration of plant sub-systems as well as the whole plant, evaluation of various fuel performances, techno-economic and environmental assessment, etc.

The main aim of this work is to perform a detailed techno-economic assessment for an oxy-fuel combustion CCS project to be developed in Romania. As power plant type, the ultra-supercritical (USC) pulverized fuel combustion based on an advanced USC boiler (29 MPa/582 °C with two steam reheats at 7.5 MPa/580 °C and 2 MPa/580 °C) was considered. The power plant is equipped with electrostatic precipitator (ESP) and Flue Gas Desulphurization (FGD) units. The evaluated oxy-combustion cases do not consider a de-NOx system because the nitrogen concentration in the burning environment is lower than for air combustion and it is expected that formed NO_x to be removed in the cryogenic CO_2 separation system. Various fossil (coal and lignite) and renewable (biomass) fuels are evaluated to study their influence on the power plant performances. The lignite and biomass (sawdust) were dried prior to oxy-combustion using the innovative fluidised bed with internal waste heat utilisation (WTA) process. The various power plant concepts generate 343–376 MW net power with a carbon capture rate higher than 90%. As a benchmark case used to assess the energy and cost penalty for CO_2 capture, a similar USC double reheat air combustion power plant without carbon capture was considered. Different from the oxy-combustion concepts, the benchmark plant has a Selective Catalytic Reduction (SCR) unit for NO_x removal. The performances of oxy-combustion power plants were also compared to the techno-economic performances of similar super-critical power plants with post-combustion CO_2 capture using alkanolamines (e.g. Methyl-Di-Ethanol-Amine – MDEA) reported in details in a previous study [10].

2. Description of evaluated USC oxy-fuel combustion power plants

Oxy-fuel combustion power plants have the following sub-systems [11]: a cryogenic air separation unit to provide the oxygen for oxy-combustion, the fuel drying facility (for lignite and sawdust cases) using a fluidised bed with internal waste heat recirculation (WTA process), the boiler and super-critical steam cycle together with the steam turbine to generate power, the flue gas purification & drying and the CO_2 separation & conditioning unit. The conceptual layout of the oxy-fuel combustion power plant is presented in Fig. 1.

For comparison reason as a benchmark case, a conventional coal-fuelled air combustion USC power plant generating 475 MW net power without carbon capture was considered. The benchmark power plant without carbon capture was selected as a European reference case based on Danish Nordjylland double reheat power unit [2]. The oxy-fuel plant performances were also compared to the post-combustion CO_2 capture using alkanolamines, the detailed description of post-combustion CO_2 capture using MDEA was presented in [10]. As fuels used in oxy-combustion power plants, Table 1 presents the fuel composition and thermal characteristics considering the local supply (Romania). For lignite and sawdust processing, the fuel must be dried prior to combustion due to high moisture content (higher than 40% reported on as received basis). The energy-efficient fluidised bed with internal waste heat utilisation drying process was considered [12]. In this process, the water vapour resulted from the fuel drying process is used to provide the heat as well as for fluidisation purposes. The layout of WTA process is presented in Fig. 2.

The moisture content of the dried fuel prior to combustion is set to 10% and the average specific power consumption of the WTA drying stage is about 120–140 kW h/t removed water. The RWE pilot plant unit at Niederaussem, Germany with capacity of 210 t/h demonstrates the energy-saving advantages of WTA technology (up to 10% efficiency increase) [12]. Other key advantages (e.g. safe plant operation, high drying capacity, compact design, etc.) show the benefits of this innovative drying technology.

The oxygen stream used for oxy-fuel combustion is produced by a cryogenic air separation unit. The power consumption of air separation unit considered in this analysis was 200 kW h/t of oxygen (95 vol.% oxygen purity). For all evaluated power plants, an ultra super-critical double reheat steam cycle was considered: 290 bar/582 °C with two steam reheats at 75 bar/580 °C and 20 bar/580 °C. The flue gases are cooled down for steam production followed by an electrostatic precipitator (ESP), a Flue Gas Desulphurization (FGD) unit and then at about 80 °C they are washed with water in a direct contact scrubber. This step is condensing most of the moisture and also it removes any carried over particles. A major part (about 75%) of dry gas is recycled back to the boiler to maintain the required mass flow rate and oxygen concentration. The remaining part of the flue gases is further cooled before it is send to the CO_2 separation unit.

The CO_2 purification unit is based on compression and cryogenic separation. The flue gases are compressed to about 30 bar, dried in a desiccant dryer and then enter in a cold box. This unit has two flash tanks operated at −25 °C and −55 °C to separate the liquid CO_2 from insoluble inert gases. The liquid CO_2 is then evaporated to produce the refrigeration duty for the cold box. The inert gases are vented to atmosphere after expanded in a turbine to recover some electricity. The captured CO_2 stream is compressed again at 120 bar and sent to the storage site. The purity of captured CO_2 should be higher than 95% as requested considering the transport and the storage requirements. The most restrictive storage option, namely Enhanced Oil Recovery (EOR) was chosen in this analysis [13].

3. Assessment of technical performances for oxy-fuel combustion power plants

The following power plant designs were evaluated in this paper: