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Techno-economic comparison between different technologies for CO_2-free power generation from coal

Alberto Pettinau [a,*], Francesca Ferrara [a], Vittorio Tola [b], Giorgio Cau [b]

[a] Sotacarbo S.p.A., Grande Miniera di Serbariu, 09013 Carbonia, Italy
[b] University of Cagliari, Department of Mechanical, Chemical and Materials Engineering, via Marengo 2, 09123 Cagliari, Italy

HIGHLIGHTS

- CO_2-free power plants are compared from technical and economic points of view.
- Capital costs of CCS plants range between 4.5 (for USC and OCC) and 4.9 M€ (IGCC)
- LCOE ranges between 59.6 €/MW h for IGCC and 63.4 €/MW h for USC.
- Fuel price and plant availability play a key role in plant economics.
- OCC promises to became the most profitable technology with a CO_2 avoidance cost of 20 €/t.

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ABSTRACT

Since coal will be widely used in the next decades, mainly in the developing countries such as China and India, carbon capture and storage (CCS) technologies will have a key role in the containment of global warming.

This paper presents a techno-economic comparison between the most promising power generation technologies for a CO_2-free power generation in a short-term future. In particular, three different power generation technologies have been considered in their conventional (without CCS) and CO_2-free configurations: (a) ultra supercritical (USC) pulverized coal combustion, (b) oxy-coal combustion (OCC) and (c) integrated gasification combined cycle (IGCC). Process simulation, based on Aspen Plus and Gate Cycle commercial tools, allows to calculate plant performance, including the energy penalty due to the CCS system (10.9% points for USC and 8.7% points for IGCC). In parallel, a detailed economic assessment shows that, among the commercial-ready technologies, USC could be the most convenient solution for power generation without CCS (presenting a levelized cost of electricity – LCOE – of 38.6 €/MW h, significantly lower than 43.7 €/MW h of IGCC), whereas IGCC becomes competitive for CO_2-free systems (with a LCOE of 59.6 €/MW h, to be compared with 63.4 €/MW h of USC). Moreover, oxy-coal combustion, which is currently not mature enough for commercial-scale applications, promises to become strongly competitive for CCS applications due to its relatively low levelized cost of electricity (62.8 €/MW h).

This kind of analysis typically presents strong uncertainties, due to the variability of several key parameters (e.g. fuel and CCS prices, determined by the fluctuation of the international markets, or an improvement of the technologies). Therefore, a sensitivity analysis has been done to determine the effects of these potential fluctuation or the improvement on the economic performance of the plant.

Acronyms: ASU, air separation unit; BEC, bare erected cost (k€); CCS, carbon capture and storage; CCTS, carbon capture, transportation and storage; CGT, conventional flue gas treatment; CIF-ARA, cost, insurance and freight in Amsterdam, Rotterdam and Antwerp; COE, cost of electricity (€/MW h); ESP, electrostatic precipitator; EUR, euros; FGD, flue gas desulfurization; FW, feed water; HPT, high pressure turbine; HRSG, heat recovery steam generator; IGCC, integrated gasification combined cycle; IPT, intermediate pressure turbine; LCOE, levelized cost of electricity (€/MW h); LHV, lower heating value (MJ/kg); LPT, low pressure turbine; MEA, monoethanolamine; OCC, oxy-coal combustion; O&M, operating and maintenance; SCR, selective catalytic reduction; TASC, total as-spent cost (k€); TPC, total plant cost (k€); USC, ultra-supercritical pulverized coal combustion; USD, U.S. dollars; VAT, value added tax; WGS, watergas shift.

* Corresponding author.
E-mail address: alberto.pettinau@sotacarbo.it (A. Pettinau).

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Nomenclature

Symbols

C	actual capital cost of each component (€)
C_0	cost of the reference component (€)
C_a	CO_2 avoidance cost (€/t)
$C_{cap,i}$	capital cost in year i (M€)
$C_{O\&M,i}$	operating and maintenance cost in year i (M€)
e	specific CO_2 emission (g/kW h)
E_i	overall energy production in year i (GW h)
f	capacity factor (dimensionless)
i	reference year
P	actual size of each component (the unit depends on the specific component)
P_0	size of the reference component (the unit depends on the specific component)

1. Introduction

Nowadays, coal still remains a key fuel for electrical energy production: in 2014 it contributed to about 41% of the overall electricity production, with a generated electrical energy of 9707 TW h and an expected increase up to 15,305 TW h in 2040 with the current energy policies, according to the projection of the International Energy Agency [1]. On the other hand, coal feeding involves in substantial environmental concerns related to pollutant (NO_x, SO_x, dust, mercury, etc.) and greenhouse gases emissions [2]. Worldwide, the combustion of fossil fuels represents the main contribution to anthropogenic CO_2 emission [3,4] and, as a matter of fact, the combustion of coal leads to a CO_2 emission nearly double in comparison to natural gas combustion. In particular, coal alone accounts for about 76% of Europe's CO_2 emissions from power generation [1]. Nevertheless, alternative technologies with a lower environmental impact, as for example renewable sources and nuclear, cannot fully satisfy the worldwide energy demand and a further diffusion of coal-fired power plants can be still expected in several developing countries, such as China [5–7], India [8], Brasil [9], and Vietnam [10]. In this framework, the integration of coal-fired power generation plants with carbon capture and storage (CCS) systems could represent a key solution for reducing carbon dioxide emissions [11].

Currently, ultra supercritical (USC) pulverized coal combustion power plants are the most suitable technology for power generation from coal. The introduction of a post-combustion CCS system in an USC plant involves in a very strong reduction of plant efficiency (about 8–12 percentage points) [12–14]. In this context, integrated gasification combined cycle (IGCC) and oxy-coal combustion (OCC) are promising alternatives for CO_2-free power generation. Despite higher costs and lower reliability and efficiency than USC, IGCC plants integrated with CCS are more affordable, due to integration with the more effective CO_2 pre-combustion capture technology, with an energy penalty of about 7–10 percentage points [15–17]. Also oxy-fuel combustion can be an interesting solution for CO_2-free power generation from coal, involving a flue gas mainly composed by CO_2 and water vapor, which can be easily separated. In OCC, power plant performance is hampered by energy penalties related to the air separation unit, but CO_2 capture is less energy expensive [18].

Most of the studies on CO_2-free power generation from coal [15,19,20] are focused on commercial applications of the technologies. As a consequence, these works compare plants with different sizes (determined by the availability of commercial components) and they typically do not include oxy-fuel option (still not mature enough for commercial application). Moreover, several studies evaluate the levelized cost of electricity (LCOE) considering power generation with CO_2 capture and compression, but without considering project financing and the costs for CO_2 transport and geological sequestration. This study aims to compare plant configurations from both the technical and economic points of view; so, it reports a comparative assessment of USC, OCC and IGCC plants. This approach allows to estimate the current potential applications of CCS technologies. In particular, each technology has been analyzed with reference to both the conventional configuration (without CCS) and the corresponding CO_2-free configuration, considering a reference thermal input of 1000 MW. In particular, the performance assessment has been carried out by using simulation models implemented through Aspen Plus 7.3 [21] and Gate-Cycle 5.40 [22] commercial tools. More specifically, Aspen-Plus models simulate gasification processes and both conditioning and purification processes of syngas and flue gas, whereas Gate-Cycle models simulate power generation sections [23]. On the other hand, the economic assessment has been performed through a detailed simulation model, properly developed by Sotacarbo for feasibility studies on CCS power generation plants.

This kind of analysis typically presents strong uncertainties, due to the variability of several key parameters (e.g. fuel and CCS prices, determined by the fluctuation of the international markets, or an improvement of the technologies). Therefore, a sensitivity analysis has been done to determine the effects of these potential fluctuations or an improvement on the economic performance of the plant.

Whereas previous works by the authors [23–25] have been mainly focused on the performance comparison of the technologies, this paper updates the technical comparison and gives more relevance to the economic assessment. So, the integration between technical and economic simulation models allows a detailed feasibility assessment.

2. Plant configurations and performance assessment

As mentioned, three different power generation technologies are compared in this study: an USC plant, an IGCC plant based on a slurry-feed entrained-flow gasifier and an OCC plant based on the same USC cycle. Simplified schemes of USC, IGCC and OCC power plants are reported in Figs. 1–3, respectively. For comparative purposes the same coal chemical power input of 1000 MW has been assumed to feed all the plants. A commercial coal characterized by a lower heating value (LHV) of 25.03 MJ/kg has been chosen as reference fuel. Main coal characteristics are reported in Table 1. A brief overview of plant configurations is reported above. More details can be found in Tola et al. [24].

2.1. USC plant

Ultra supercritical (USC) power plants are characterized by hard operative conditions: steam temperature up to 600–620 °C and cycle maximum pressure higher than 30 MPa. As a matter of fact, overall efficiencies up to 45–46%, LHV basis, can be obtained with