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Integration of the calcium carbonate looping process into an existing pulverized coal-fired power plant for CO_2 capture: Techno-economic and environmental evaluation

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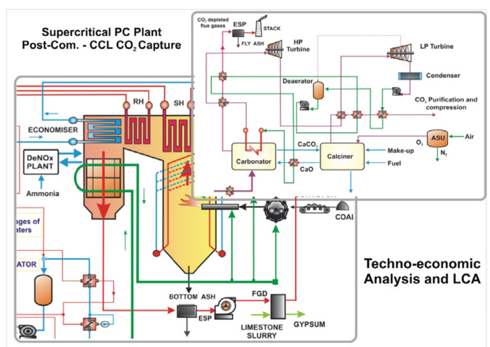
HIGHLIGHTS

- Technical results illustrated a 94% onsite CO_2 capture ratio for the CCL unit.
- The CCL showed a lower efficiency penalty of 7.4% compared to solvent based system.
- The costs of CO_2 captured and avoided were 16.3 and 20.3 €/tCO_2, respectively.
- The integration of the CCL into a PC power plant nearly doubled the plant output.
- The LCA illustrated that the overall climate change impact had been reduced by 75%.

GRAPHICAL ABSTRACT



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ABSTRACT

This work focuses on the techno-economic and environmental evaluation for an existing pulverised coal-fired power plant retrofitted with the calcium carbonate looping (CCL) process. The CCL process is an attractive technology due to relatively low efficiency penalties. To better understand the performance characteristics and benefits of systems integration, the steady-state model for the CCL process, developed in ECLIPSE, was used to perform a techno-economic analysis. The simulation results showed that the net efficiency for the selected 600 MW PC power plant equipped with the CCL process was 33.8% (lower heating value) at 94% CO_2 capture ratio. With respect to the reference plant without CO_2 capture, this resulted in a lower efficiency penalty (7.4% points). The capital cost and maintenance and operating costs were estimated according to a bottom-up approach using the information gained through the mass and energy balance. Specific investment was found to be €1778/kWe, which is approximately 21% higher than for the reference plant. The levelized cost of electricity would be €77.3/MWh with CCL CO_2 capture. The CO_2 capture cost and CO_2 avoidance cost relative to the corresponding reference plant were €16.3/tCO_2 captured and €22.3/tCO_2 avoided, respectively. The SimaPro software was used to perform a life cycle analysis of the capture technology to determine its environmental impact. The results illustrated that the overall climate change impact had been reduced by 75%, while the fossil depletion impact was increased by 22%.

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1. Introduction

1.1. Background context

Globally, fossil fuels remain a major primary energy source. The transition to cleaner and more sustainable energy system is slow. Around 81.1% of the world's total energy supply is based on fossil sources such as coal, oil and natural gas. Electricity generation from fossil fuels also remains high (66.7%) with coal being the dominant fuel at 40.8% [1]. Coal contributes to more than 40% of the world's CO_2 emissions. Over 70% of CO_2 emissions from electricity production are directly related to the combustion of coal [2]. In some regions such as China, coal is expected to remain a dominant power generation fuel at least until 2050 [3–4]. Other regions such as the UK and Europe are aiming to phase out unabated coal power stations by 2025 and 2030 respectively [5]. Even with these policies, coal consumption could increase by 0.2% each year between 2014 and 2040 [6].

Man-made climate change is a major threat both economically and environmentally. According to the Intergovernmental Panel on Climate Change (IPCC) reports [7], the major cause which contributes to climate changes is the emissions of CO_2, an important greenhouse gas (GHG). The Paris Agreement is the latest agreement within the UN Framework Convention on Climate Change. It is an international agreement that aims to tackle climate change and maintain global average temperatures well below 2 °C above pre-industrial levels and ideally below 1.5 °C [8]. To achieve the goals of the Paris Agreement, a vast expansion of low CO_2 emission technologies is required. These include replacing aging and inefficient power plants by pursuing state of the art technologies with more efficient energy conversion rates, increasing renewable energy supply and adopting of carbon capture and storage (CCS) technologies [9–11].

1.2. Carbon capture and storage

A basic CCS system has two stages; the absorption stage uses a sorbent to separate CO_2 from the flue gas and the regeneration stage, where the CO_2 is released from the sorbent as an almost pure stream [12]. The aim of CCS is not to reduce the formation of CO_2 during the combustion of fossil fuels but to capture it before the point of emission. Therefore, the CO_2 captured is transported to suitable geographical locations such as disused natural gas fields for long term storage. There are three technology categories for CO_2 capture from coal fired power plants; pre-combustion, oxy-fuel combustion and post combustion systems. Pre-combustion systems use an integrated gasification combined cycle with a shift reactor and physical solvent scrubbing to split fuel into hydrogen and CO_2. Post-combustion systems adopt a suitable solvent scrubbing process to remove CO_2 from exhaust gases. In oxy-fuel combustion, fuel is burnt with almost pure oxygen diluted by recycled flue gases. This results in flue gases that mainly consists of CO_2 and water vapour which produces exhaust gas with high CO_2 concentrations and enables easier purification [13]. Post combustion technologies are considered significant for decarbonising the power generation industry as they are relativity easy to retrofit to existing coal power plants and can be integrated into the design of new plants [14]. However, there are barriers to large-scale deployment of CCS technologies. These range from high energy penalties and additional costs for the capture and compression of CO_2, to a lack of suitable storage sites. A full discussion of barriers to CCS can be found in [15].

1.3. Literature review

This work has been done in conjunction with the FP7 SCARLET (Scale-up of Calcium Carbonate Looping (CCL) Technology for Efficient CO2 Capture from Power and Industrial Plants) funded by the European Union [16]. The aim of the SCARLET project is to bring the CCL technology closer to full scale commercialisation, by experimental investigation in a 1 MWth scale and upscaling and engineering to a 20 MWth pilot plant. Other strands have included the long-term pilot testing of the CCL plant at 1 MWth scale, the results proved the performance of the process in steady state operation under varying operating parameters. The CO_2 absorption rates in the carbonator were higher than 90% and the overall capture rates higher than 95% [17]. Process models have been developed and validated against the 1 MWth pilot plant [18]. The accumulation of impurities such as ash and $CaSO_4$ cause performance losses by requiring heating and cooling along with the circulation of the solids stream in the system. The influence of fuel type and particle size on the sorbent is observed in [19]. Other works include the simulation of a 1 MWth pilot plant CFB carbonator unit with the coarse grain DEM model [20] and the 3-D CFD simulation of the reacting flow inside the 1 MWth calciner [21].

The CCL process is a second generation, post combustion CO_2 capture technology that employs solid CaO based sorbents to remove CO_2 from flue gases, generating a concentrated CO_2 stream which is suitable for transportation and long term storage. The CCL process is being developed as it has potentially lower energy penalties and less toxicity than first generation capture technologies such as amine scrubbing [22]. The suitability of CCL for PC power plants operated in sub- and super-critical conditions and integrated gasification combined cycle (IGCC) power plants was examined in [23]. It was concluded that CCL for PC power plants could lower the energy penalty compared to amine CO_2 capture methods. A review of the evolution of CCS technology over the last 10 years can be found in [24]. CCL for PC fired boilers has been classified as at the demonstration stage. The majority of patent activity over the last 10 years has been related to absorption and adsorption processes.

In [14], economic aspects of CCS, including the impact of uncertainty in economic models were considered. The key parameters impacted by uncertainty were identified. It was found that the levelized cost of electricity (LCOE) and specific capital costs were greatly impacted by uncertainties. The environmental impacts of CO_2 capture technologies, has been considered in [12], where a LCA for a sub-critical power plant was performed and compared to three CCS technologies. It was concluded that CCS reduces the emissions of the plant in those categories that are directly associated with flue gas emissions. The climate change impact for CCL was reduced by 73%, 66% for conventional amine processes and 72% for advanced amine processes. The LCA for amine-based post combustion, aqueous ammonia post combustion and CCL CCS technologies have been compared giving a 49%, 48% and 59% reduction in global warming potential, respectively [25]. It should be noted that the differences seen in the latter two works are a result of different assessment methods, with [12] using the ReCiPe (a method for the life cycle impact assessment) midpoint characterisation method for Europe, v1.04 and [25] using the CML 2001 method.

This work builds on and uses previously validated data developed with the aim to provide an update on the techno-economic and environmental performance for the integration of CCL into a supercritical pulverized coal (PC) power plant. It will be of interest to those working in the coal fired power generation industry, those responsible for carbon reduction policies and other academics with similar interests. The results will allow decision makers to examine and weigh the potential technical, economic and environmental benefits and penalties of CCL integrated with a supercritical PC power plant and compare them to the base power plant.

2. Technical description

2.1. Reference PC plant without CO_2 capture

To assess the impact of CO_2 capture facilities on the overall power plant performance, an advanced super-critical PC boiler system was initially simulated in the conventional mode. In this way, the direct comparison provides useful information such as efficiency penalty, CO_2