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# $CO_2$ capture in integrated gasification combined cycle with SEWGS – Part A: Thermodynamic performances

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## HIGHLIGHTS

- SEWGS separates $H_2S$ together with $CO_2$ with efficiency benefits.
- Sorbent capacity is critical to make SEWGS a competitive technology.
- Efficiency penalty of SEWGS is about 7% points with 95% $CO_2$ avoided.
- Optimal CO2 capture ratio depends on total sorbent volume.
- SEWGS achieves a specific energy consumption for $CO_2$ avoided of 2.1 $MJ/kg_{CO2}$.

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## ABSTRACT

This two part-paper investigates the performance of SEWGS (Sorption Enhanced Water Gas Shift), an innovative system for $CO_2$ capture, applied to a coal fuelled Integrated Gasification Combined Cycle (IGCC). Firstly, two reference cases based on dry feed slagging Shell gasifier, with and without $CO_2$ capture, are defined. Conventional pulverized coal plant, where $CO_2$ capture is carried out with amine scrubbing technology, is also presented. Subsequently, SEWGS optimal integration in IGCC plant is investigated. The optimized parameters are SEWGS carbon capture ratio, $CO_2$ purity and number of vessels. Moreover, two different types of sorbent, *Sorbent Alfa* and *Sorbent Beta*, are considered in order to evaluate the impact of sorbent cyclic capacity on system performances. Both sorbents capture $H_2S$ together with $CO_2$ with efficiency and equipment advantages.

Results show that optimal SEWGS carbon capture ratio is in the range of 95% for both *Sorbent Alfa* and *Sorbent Beta*, with the latter achieving net electric efficiency of 40%. The resulting specific energy consumption for $CO_2$ avoided (SPECCA) is 2.0 $MJ/kg_{CO2}$, which is 40% to 60% lower than reference IGCC and ASC reference cases respectively. Even *Sorbent Alfa*, which features a lower capacity than *Sorbent Beta*, achieves a SPECCA of about 2.5 $MJ/kg_{CO2}$ which is 30% lower than reference case, illustrating SEWGS advantages.

Part B will discuss the economic assessment of the investigated cases in order to determine the $CO_2$ avoided cost.

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## 1. Introduction

The increasing energy demand in recent years has been satisfied by fossil fuels leading to a higher concentration of carbon dioxide in the atmosphere. Simultaneously, the adoption of coal as fuel for electricity production becomes more and more strategic because of its lower price, well-established and spread reservoirs compared to oil and natural gas. On the other hand, coal based power plants have roughly twice as much $CO_2$ specific emissions compared to natural gas fired plants. Therefore, the application of $CO_2$ capture technology becomes essential in order to make coal plants as much sustainable as possible.

Capturing $CO_2$ is the most recognized technology to limit the fossil fuel impact on the environment [1,2]. There are three main routes for $CO_2$ capture in electricity production: (i) post-combustion $CO_2$ capture; (ii) oxy-combustion and (iii) pre-combustion decarbonisation. The first category is based on capturing $CO_2$ in the exhaust gases via chemical or physical absorption. Conventional MEA amine scrubbing can be considered the state-of-the-art technology [3,4], while chilled-ammonia is the enhanced

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**Nomenclature**

| | |
|---|---|
| AGR | acid gas removal |
| CAESAR | CArbon-free Electricity by SEWGS: Advanced Materials, Reactor and process design |
| CCR | carbon capture ratio (%) |
| CCS | Carbon Capture and Storage |
| COT | Combustor Outlet Temperature (°C) |
| E | $CO_2$ emission rate ($kg_{CO2}$/kW $h_{el}$) |
| EXP | Expansion |
| HR | Heat Rate ($kJ_{LHV}$/$kWh_{el}$) |
| HRSC | Heat Recovery Steam Cycle |
| HRSG | Heat Recovery Steam Generator |
| IGCC | Integrated Gasification Combined Cycle |
| LP | Low Pressure |
| SEWGS | Sorption Enhanced Water Gas Shift |
| SH | Super Heating |
| SPECCA | Specific Primary Energy Consumption for $CO_2$ Avoided ($MJ_{LHV}$/$kg_{CO2}$) |
| TIT | Turbine Inlet Temperature (total temperature ahead of the first rotor) (°C) |
| $TIT_{iso}$ | Turbine Inlet Temperature (defined according to ISO standard) (°C) |
| TOT | Turbine Outlet Temperature (°C) |
| WGS | Water Gas Shift |
| WGSR | Water Gas Shift reactor |
| $\eta$ | efficiency (%) |

*Subscripts*

| | |
|---|---|
| El | electrical |
| REF | reference |

solution [5]. The second category consists of an oxygen combustion whose main products are a mixture of $CO_2$ and steam: $CO_2$ can be easily concentrated by water condensation, however further polishing steps are required because of inerts and pollutants. Pre-combustion decarbonisation belongs to the last category and implies transferring the carbon-bounded energy content from fuel (coal or natural gas) to hydrogen; then, hydrogen can feed a combined cycle, without any $CO_2$ emission.

Pre-combustion technology for $CO_2$ capture in coal fuelled power plant can be applied in Integrated Gasifier Combined Cycle (IGCC) without significant modifications to the base cycle. Firstly, coal is converted into syngas in the gasifier at a pressure in the range of 40 and 70 bar depending on gasification technology; the former reflects Shell technology, while the latter GE's. Syngas consists mainly of CO, $CO_2$ and $H_2$, where the proportion also depends on gasification technology [6]. The adoption of high and low temperature Water Gas Shift (WGS) allows converting CO and steam into $H_2$ and $CO_2$, which can be separated by a physical absorption at low temperature (physical separation is preferred in IGCC because of the higher $CO_2$ partial pressure in the syngas than stack gas).

The innovative $CO_2$ capture system investigated in this work, named SEWGS from Sorption-Enhanced Water Gas Shift, is a concept for pre-combustion $CO_2$ capture which integrates water–gas-shift and $CO_2$ separation steps: removal of the $CO_2$ produced in the water gas shift reaction (WGS) enhances CO conversion and enables a reduction in $CO_2$ emissions [7]. Main advantages of this technology are: (i) high CO conversion and $CO_2$ capture (about 98% vs. 90% of conventional technologies) and (ii) high temperature $CO_2$ separation (about 400 °C) avoiding the temperature swing required by conventional pre-combustion separation processes (Selexol or MDEA). A further advantage of SEWGS investigated in this work is the simultaneous separation of $CO_2$ and $H_2S$. Scope of part A paper is to assess the application of SEWGS in a coal fired power plant with $CO_2$ capture from a thermodynamic point of view and compare it towards reference cases. In particular, the adoption of two different sorbent, both developed within CAESAR project [8], will be investigated to determine their impact on system efficiency. Finally, it must be stressed that results presented in this work are different from previous calculations on the same subject [9] because of recent measurements on sorbent capacity and, consequently, SEWGS performances.

In part B, the economic assessment of SEWGS will be discussed in order to find the minimum cost of $CO_2$ avoided and compare it to the reference cases.

## 2. Reference cases with and without $CO_2$ capture

### 2.1. ASC

The plant is based on an Advanced Super Critical (ASC) Boiler and Turbine producing about 820 MWe (gross) without any carbon capture. The auxiliary power consumptions require 65 MW leading to a final net power plant output of 754.3 MWe, yielding a net cycle efficiency of 45.5% [10]. The general arrangement layout for the reference power plant is based on an inland site with natural draft cooling towers and delivery of the coal by rail. For the control of combustion product emissions, the power plant is equipped with selective catalytic reduction (SCR) DeNOx plant located between the boiler desulphurization exit and air heater inlet, electrostatic precipitators and wet limestone based desulphurization plant before exhausting to atmosphere via a flue stack. $NO_x$ ad $SO_x$ emission limits are assumed to 120 mg/$m^3$ and 85 mg/$m^3$, respectively. For ash handling, a dry ash conveying system is employed for fly ash and a continuous ash removal system with submerged chain conveyer for furnace bottom ash.

### 2.2. IGCC

The reference IGCC technology is based on an entrained flow, oxygen blown, dry feed slagging Shell gasifier. The adoption of a Shell gasifier among other technologies (i.e. GE) is justified by the highest efficiency as well as availability of gasification heat and mass balances provided by Shell within EBTF [11]. The assumed lay-out, shown in Fig. 1, reflects Shell experience.

The gasification pressure is 44 bar, high enough to feed the gas turbine without syngas compression. The choice of a dry feed gasifier with high carbon conversion (99%) gives a higher cold gas efficiency and consequently higher plant efficiency, compared to slurry fed gasifier. Due to the high gasification temperature, the gasifier wall must be water cooled; water pressure has to be higher than syngas. During the operation the main thermal barrier is provided by the ash layer, composed by a solidified part attached to the wall and a melted part which flows towards the bottom of the reactor; the slag layer also prevents corrosion of the wall. Before feeding, coal is pulverised and dried with an auxiliary fuel.

One gasification train is assumed, generating syngas for one gas turbine. Oxygen is produced in an air separation unit (ASU) in which 50% of the air comes from the gas turbine compressor, generating a 95 mol% pure oxygen flow. The distillation column of the

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