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Selective Exhaust Gas Recirculation in Combined Cycle Gas Turbine Power Plants with Post-combustion CO_2 capture

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Abstract

In the context of the process intensification of Post-combustion Carbon Capture (PCC), Selective Exhaust Gas Recirculation (SEGR) in Natural Gas-fired Combined Cycle (NGCC) plants, a concept where CO_2 is selectively recycled to increase concentration and reduce flow rates of the flue gas, is analysed. SEGR operated either in parallel or in series with a downstream PCC system increases CO_2 concentration beyond 14 vol% and maintains oxygen levels in the combustor to approximately 19 vol%, well above the 16 vol% limit reported for non-selective Exhaust Gas Recirculation (EGR). Process modelling shows that the current class of gas turbine engines can operate without a significant deviation in the compressor and in the turbine performance. Compressor inlet temperature and CO_2 concentration in the working fluid are the two critical parameters affecting the gas turbine net power output and efficiency. A higher turbine exhaust temperature allows the generation of additional steam in the HRSG. This results in an increase in net power output of approximately 42 MW (5.2%) and 18 MW (2.3%), and in net thermal efficiency of 0.55 %point and 0.83 %point, for the investigated configurations with SEGR in parallel and SEGR in series, respectively. With 30 wt% aqueous monoethanolamine scrubbing technology, SEGR leads to operation and cost benefits. SEGR in parallel with 70% recirculation, 97% selective CO_2 transfer efficiency and 96% PCC efficiency results in a reduction of 46% in packing volume and 5% in specific reboiler duty, compared to air-based combustion CCGT with PCC, and of 10% in packing volume and 2% in specific reboiler duty, compared to 35% EGR. SEGR in series operating at 95% selective CO_2 transfer efficiency and 32% PCC efficiency results in a reduction of 64% in packing volume and 7% in specific reboiler duty, compared to air-based CCGT with PCC, and of 40% in packing volume and 4% in specific reboiler duty, compared to 35% EGR. On selecting a technology for SEGR applications, CO_2 selectivity, pressure drop and heat transfer flow rate are the operating parameters with a larger effect on the power plant performance with SEGR. It is important to minimise oxygen leakages from the air into the flue gas, minimise heat transfer that would otherwise increase CO_2-enriched air temperature at compressor inlet, and minimise pressure drop, e.g. a 1kPa pressure drop results in gas turbine derating of 2 MW (0.7%).

1. Introduction and background

Power generation from natural gas-fired Combined Cycle and Open Cycle Gas Turbines (CCGT and OCGT) appears as a cost-effective option to meet the need for new electricity generation and contribute to reduce CO_2 emissions from the power sector. In the UK, approximately 20 GW of new generation capacity with CCGT plants is expected to contribute to the UK fossil fleet that will be used to fill the gap between the demanded electricity and renewable and nuclear output to ensure security of supply while maintaining operational flexibility required in the electricity system (CCC, 2015; DECC, 2015). A shift from coal to unabated gas would help to reduce emissions in the short term, yet CCGT plants still produce on average 350-400 gCO_2/ kWh, well above the levels required for deep decarbonisation of electricity generation of 50 gCO_2/kWh (CCC, 2015).

Post-combustion CO_2 capture (PCC) from exhaust flue gases in natural gas-fired power plants raises new challenges due to lower CO_2 concentrations and the larger size of the capture plant absorber train and auxiliary equipment. In this context, the selective recycling of CO_2, referred hereby as Selective Exhaust Gas Recirculation (SEGR), is an effective concept to increase CO_2 concentration and reduce flow rates of exhaust flue gases. In particular, it allows higher CO_2 concentrations than those with "non-selective" Exhaust Gas Recirculation (EGR), while maintaining oxygen levels in the gas turbine combustor. It effectively intensifies the capture process to achieve cost reduction in the PCC absorber train. The UK Energy Technology Institute reports that every 10% reduction in in the capture plant capital costs (CAPEX) reduces the electricity cost of CCGT with CCS by 1.5 – 2% for load factor of base load plants (ETI 2016). These benefits become increasingly significant for low load factor operation, a likely outcome in electricity grids with increasing amount of variable renewable generation.

SEGR consists on selectively transferring CO_2 from a flue gas stream into an air stream which enters the gas turbine compressor. Since other components in the flue gas are ideally not recirculated, e.g. nitrogen and water vapour, less amount of excess air is replaced and higher CO_2 concentrations are possible in the flue gas, while the oxygen concentration in the combustor remains above the 17 vol% limit reported for non-selective EGR in a GE Class F gas turbine engine (ElKady *et al.*, 2009; Evulet *et al.*, 2009). The technical challenges for the integrated power generation system associated with SEGR have received little attention to date, unlike for EGR.

1.1 Exhaust Gas Recirculation

The highest CO_2 concentration achievable in the flue gas with EGR is limited by the lowest oxygen levels in the combustor that ensure flame stability and complete combustion, with levels of CO and unburned hydrocarbons (UHCs) at exhaust that achieve environmental compliance with local environmental regulations (Li, Ditaranto, et al. 2011).

Combustion tests performed on a bench-scale lean pre-mixed burner used in Dry Low-NO_x (DLN) combustor systems, currently employed in General Electric (GE) Class F gas turbine technology concluded that minimum oxygen concentration of 16-17 vol% is necessary for good combustion efficiency. Yet lowering the oxygen level below 16 vol% might be possible with minor modifications of the combustion system or at larger operating pressures while complying with CO emissions (Røkke and Hustad 2005; ElKady et al. 2009; Evulet et al. 2009). A 17 vol% oxygen concentration in the combustor is achieved at 35% recirculation ratio in a GE Class F gas turbine typically operated at 150% excess of air. This results in 6 vol% CO_2 and 7.5 vol% O_2 in the flue gas at the turbine exhaust and allows to a NOx emissions reduction of approximately 50% (ElKady *et al.*, 2009). The recirculation ratio that corresponds to a O_2 concentration in the combustor depends on the design turbine inlet temperature (TIT), since this parameter defines the amount of excess of air, and on the cooling air requirements. A lower TIT allows for higher recirculation ratios but acts on detriment of the gas turbine thermal efficiency.

The feasibility of operating GT26/24 sequential combustion gas turbine engines with EGR has been investigated conducting process simulations (Guethe, Cruz Garcia and Burdet, 2009) and experimental combustion tests in a full-sized industrial lean premix burner (Burdet *et al.*, 2010), and in a single burner reheat combustion test rig (Guethe *et al.*, 2011). The engine operates at higher pressure ratio and the sequential combustion system, which consists of a generic lean premix dry low-NOx burner followed by reheat burner with a high-pressure expansion stage in between, allows to decouple the two main limiting factors for operation with EGR, i.e. flame stability and CO emissions. The premix burner flame is sustained and stable for O_2 concentrations in combustion gases within a range from 2 to 5 vol%, which leads to CO_2 concentrations in flue gases within a range from 6 to 9 vol% (Burdet *et al.*, 2010; Sander *et al.*, 2011) and CO emissions are lowered in the reheated burner, which runs stable in auto ignition mode due to the high inlet temperature (Guethe *et al.*, 2011).

With most of the work focused on the combustion process, the performance of the gas turbine with EGR have received less attention. Jonshagen *et al.* (2011) conduct process simulations of a CCGT plant equipped with a GE Class F gas turbine engine. A small deviation of the compressor and the turbine operating conditions from the design point is expected at recirculation ratios up to 40%, as result of the small variation of the dimensionless parameter groups typically used to describe off-design performance (Jonshagen, Sipöcz and Genrup, 2011). Sander *et al.* (2011) have investigated the effect of EGR in sequential combustion gas turbine engines through process simulations. The temperature of the recycled gas stream has a large effect on the combined cycle performance, since a higher gas turbine compressor inlet temperature leads to gas turbines derating, yet the higher exhaust temperature may balance the previous effect, with an overall increase in the combined cycle net power output (Sander et al. 2011).

Operating and cost benefits on the capture plant have been evaluated for two PCC technologies: flue gas scrubbing with amine-based solvents and membrane systems. Process simulations with rigorous models of a capture system using 30 wt% monoethanolamine (MEA) aqueous solutions are conducted to quantify the reduction in the specific reboiler duty and the size of the absorber column (Aboudheir and ElMoudir, 2009; Li et al., 2011; Sipöcz and Tobiesen, 2012; Biliyok and Yeung, 2013; Vaccarelli, Carapellucci and Giordano, 2014). A 30 wt% piperazine (PZ) aqueous solution has been used in recent work (Zhang et al., 2016) focused on intercooling options in the absorber.

A considerably decrease in the specific reboiler duty is expected for high CO_2 concentrations in the flue gas up to approximately 6 vol%. For higher CO_2 concentrations, the specific reboiler duty continues to decrease at a lower rate (Li et al., 2011). Li *et al.* (2011) report that EGR at 50% recirculation ratio allows to increase CO_2 concentration from 3.8 vol% to 7.9 vol% and reduce the mass gas flow rate entering the absorber by 51%. It results in an 8% reduction of the reboiler energy consumption, from 4 to 3.7 MJ/kg CO_2. Simulations performed at SINTEF/NTU (Sipöcz and Tobiesen 2012) show the possibility to achieve a CO_2 concentration of 7.8 vol% at the absorber inlet for 40% recirculation ratio. It results in a 9% decrease in the specific reboiler duty, from 3.97 to 3.64 MJ/kg CO_2. Biliyok and Yeung (2013) report an increase in the CO_2 concentration from 4 vol% to 6.6 vol% at 40% EGR ratio and a decrease in the reboiler duty of 7.5%, from 4 to 3.72 MJ/kg CO_2. The reduction in the absorber packing volume is approximately equal to the fraction of recycled flue gas.

An experimental test campaign has been conducted at the Pilot-scale Advance Capture Technology (PACT) facilities at the UK Carbon Capture and Storage Research Centre (UKCCSRC) for 30 wt% MEA scrubbing technology. Akram et al. (2016) show a reduction in the specific reboiler duty of around 7.1% relative per unit percent increase in CO_2 concentration (Akram et al., 2016), from 7.1 to 5.3 MJ/kgCO_2 when the CO_2 concentration is increased from 5.5 to 9.9 vol%. Yet, there is a need to compare results on a consistent basis in a PCC system optimised for the reference configuration.

1.2 Selective exhaust gas recirculation

Merkel et al. (2013) report that CO_2 concentrations of approximately 19 vol% and 14 vol% are possible at inlet of the PCC system with SEGR in parallel and SEGR in series respectively, significantly higher than with EGR, for a 16 vol% oxygen level in the gas turbine combustor. Large selective recirculation ratios and/or considerably high efficiencies for the selective CO_2 transfer system are however required (Merkel et al. 2013).

The technical challenges of SEGR in a CCGT plant are, similarly to "non-selective" EGR, changes in operability, flame stability, combustion efficiency, emissions of carbon monoxide (CO) and unburned hydrocarbons (UHCs), heat transfer with a modified working fluid. CO_2 acts as a combustion inhibitor leading to a flame instability, blow-off and eventual extinction of the flame. The first combustion study at operating conditions which are consistent with the configurations presented in this article was recently reported by Marsh et al (2016). They used a representative swirl burner with premixed flame to identify the range of equivalence ratios for stable operation, between the blow-off and the flashback limits, for a range of CO_2 concentrations in the comburent up to 20 vol%, although at combustion pressures of 1.1 bar and 2.2 bar, which is well below the operating pressure of a large scale gas turbine. They show that high CO_2 concentrations require near stoichiometric air-fuel ratios for stable operation, with subsequent increase in CO emissions at these low pressures (Marsh *et al.*, 2016).

Energetic savings and capital cost reduction in the capture plant has been investigated for selective CO_2 membrane systems (Merkel *et al.*, 2013; Swisher and Bhown, 2014; Voleno *et al.*, 2014; Turi *et al.*, 2017) and chemical absorption with amine-based solvents (Merkel *et al.*, 2013; Zhang *et al.*, 2016). Merkel et al. (2013) use the concept of the ideal minimum energy for CO_2 separation, compression and liquefaction, however a rigorous investigation is still required.

1.3 Objectives

This article first evaluates a range of possible CO_2 concentrations that can be achieved in the exhaust flue gas and the corresponding oxygen levels in the combustor. An operating framework where SEGR presents advantages compared to non-selective EGR at 35% recirculation ratio is then identified. Information regarding operating conditions to conduct combustion tests within the scope of the EPSRC SELECT project (SELECT, 2014) have also been provided.

Two configurations of an integrated CCGT plant with SEGR and PCC are compared in this work. They are based on previous work by Membrane Technology & Research (Baker et al. 2011; Wijmans et al. 2011; Wijmans, Merkel and Baker 2012; Merkel et al. 2013), which focuses on membrane based systems for air enrichment with CO_2 and downstream CO_2 capture.

- A configuration consisting of diverting a fraction of the exhaust of the HRSG into a system transferring CO_2 into the inlet air stream of the gas turbine compressor. The selective CO_2 transfer system operates "in parallel" to the PCC process.
- A configuration consisting of a selective CO_2 transfer system operated downstream of, and "in series" to, the PCC process.

The process flow diagrams for a CCGT plant with SEGR in parallel and SEGR in series are illustrated in Figure 1 and Figure 2, respectively.

Strategies to enhance CO_2 capture rates should aim to introduce minimal modifications in the gas turbine engine, since current gas turbine technology presents a high efficiency and play an important role in achieving a high combined cycle net power output. Any mayor modifications to gas turbine engines requires long lead development time to be implemented tested and optimised and development cost may only be justified if they can be amortised via deployment on a representative fraction of the market, that with CCS. It is therefore important to investigate whether the existing class of gas turbines can be operated with a fraction of combustion gases being recycled to the inlet of the system, and assess the overall impact on the CCGT power plant with CCS. A technical investigation of the overall effect on the integrated power system with CO_2 capture, including the compressor and the turbine of a Class F gas turbine engine and the HRSG/combined cycle, is conducted for the first time here, adapting the methodology of Jonshagen *et al.* (2011) for EGR.

Operating and costs benefits on the PCC system should balance costs associated to the additional system for CO_2 transfer. Rigorous process model simulations are then performed to quantitatively evaluate the effect of the high flue gases CO_2 concentrations on the CO_2 capture process, using chemical absorption technology with MEA aqueous solvent as a benchmark system. Results are compared to an air-based combustion CCGT plant with PCC and to a CCGT plant with EGR at 35% recirculation ratio and PCC on a consistent basis.

Finally, this paper identifies the design parameters and operating variables of a generic selective CO_2 transfer system that have a larger effect on the combined cycle performance. A sensitivity analysis of the gas turbine and combined cycle performance to a variation of these parameters is conducted with the purpose of covering a wide range of operating conditions and, thus, extend the results and discussion to a range of possible technologies.

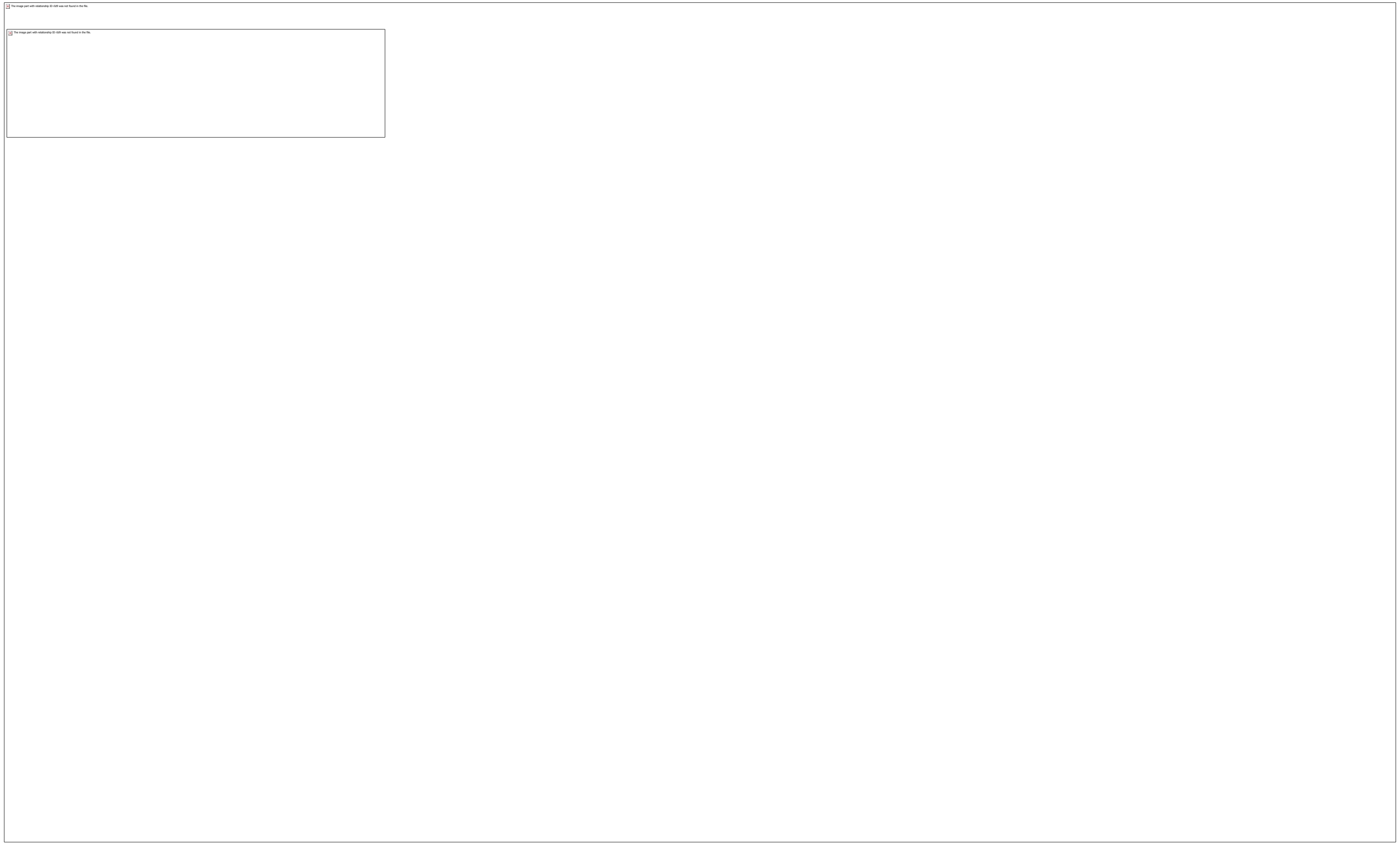


Figure 1.- Process flow diagram for a Combined Cycle Gas Turbine power plant with Selective Exhaust Gas Recirculation in parallel to the Post-combustion CO_2 Capture process.

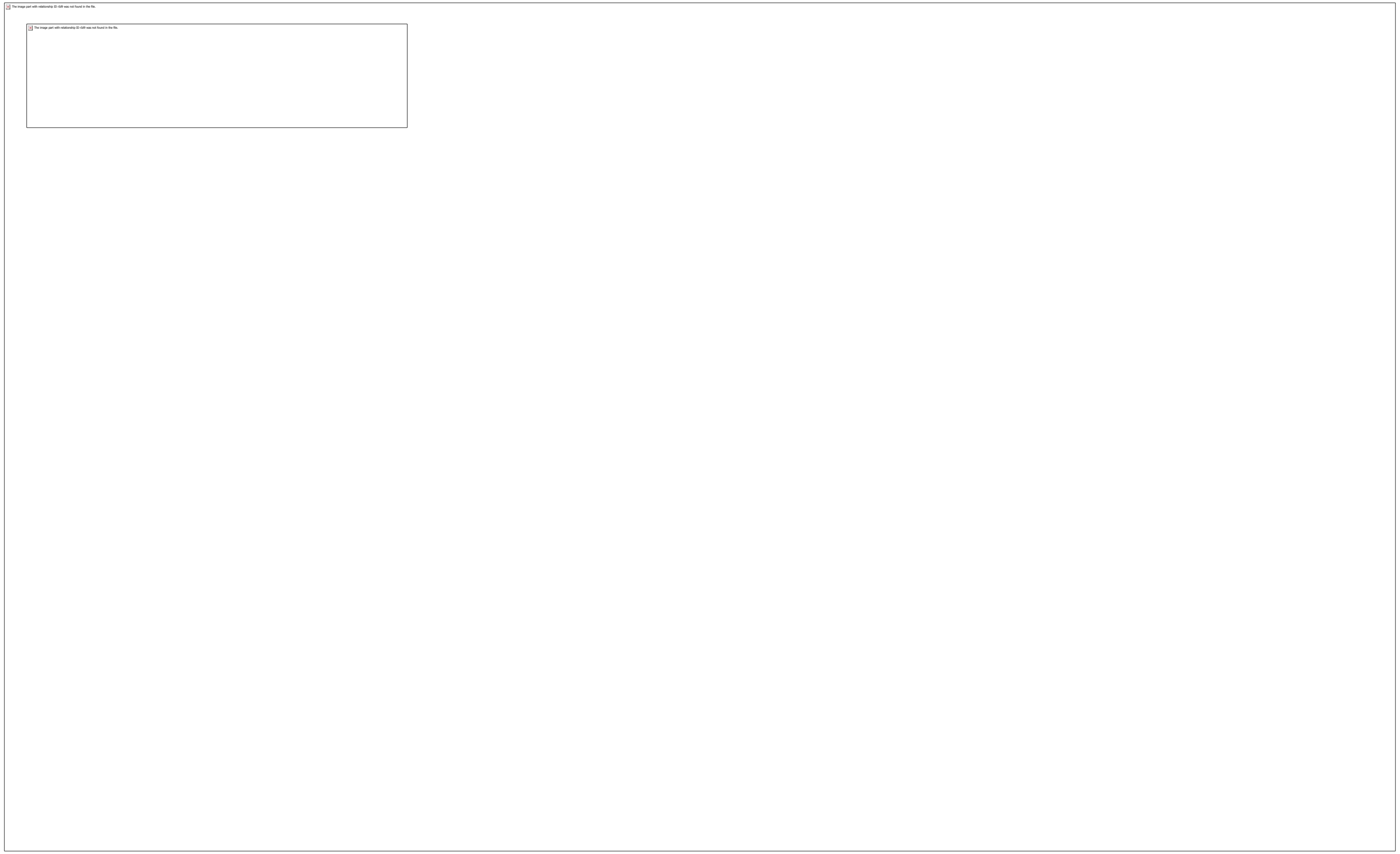


Figure 2.- Process flow diagram for a Combined Cycle Gas Turbine power plant with Selective Exhaust Gas Recirculation in series to the Post-combustion CO_2 Capture process.

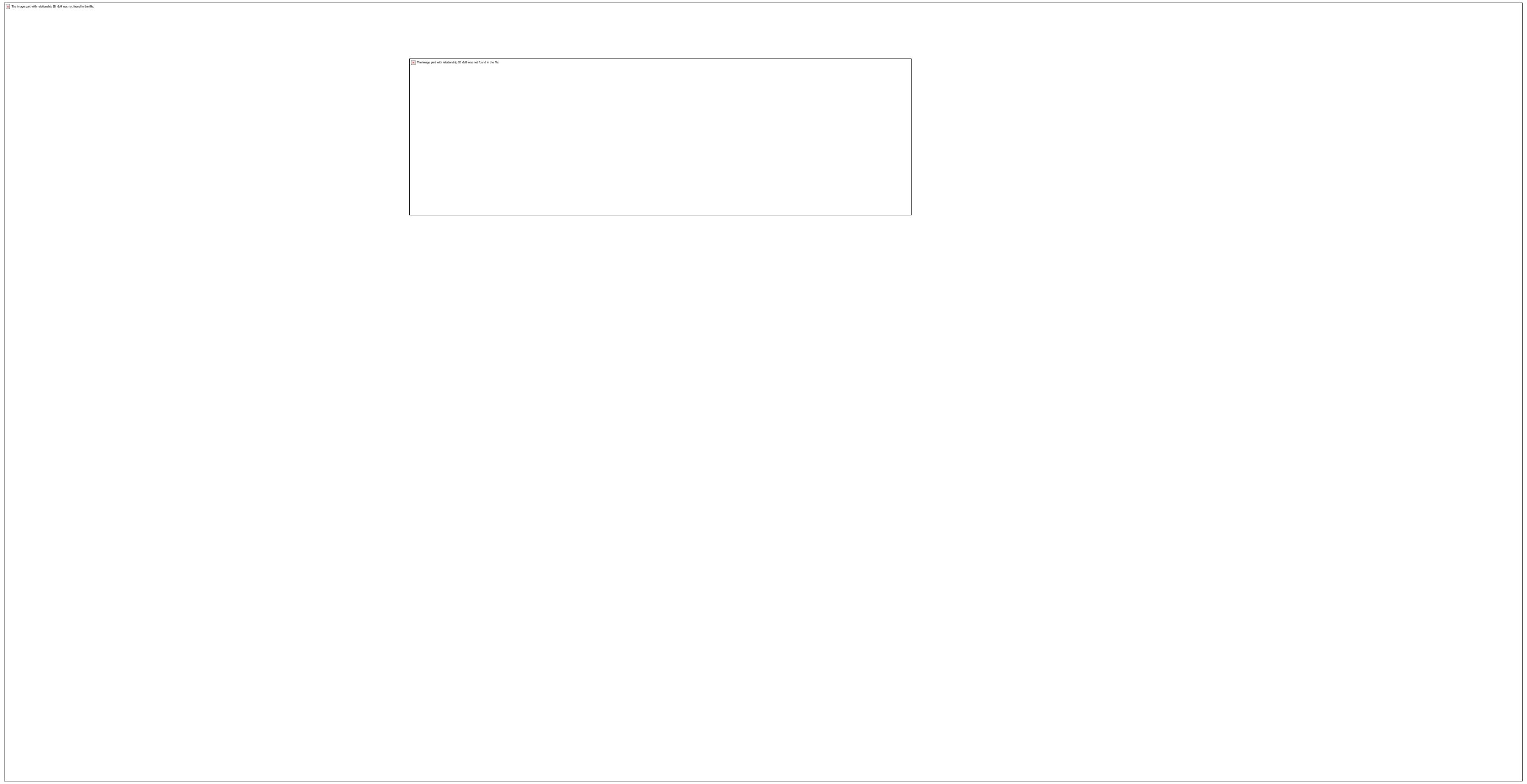


Figure 3.- Process flow diagrams of the Post-combustion CO_2 Capture plant with amine-based chemical absorption technology and the CO_2 compression train.

2. Methodology

The assessment of the effect of SEGR on the performance of a CCGT plant and of the benefits on the PCC system are investigated for two configurations:

- A CCGT plant with SEGR in parallel to the PCC system
- A CCGT plant with SEGR in series to the PCC system

Results from process model simulations are compared to those for an air-based combustion CCGT plant with PCC and a CCGT plant with non-selective EGR and PCC, which are also modelled in this work to be able to establish a comparison on a consistent basis. For comparison, a 35% recirculation ratio is considered for non-selective EGR, since it leads to the highest CO_2 concentration in exhaust flue gases maintaining an oxygen level of 16 vol% (wet basis), limiting level for GE Class F gas turbine engines, as explained in Section 1.1. The methodology is extensively described in Herraiz's work (2016) and summarised here.

2.1 Reference configuration: Air-based combustion CCGT plant with PCC

The reference plant is a natural gas combined cycle with a 2-in-1 configuration: two GE Class F (GE9371) gas turbines with the flue gas exiting into two HRSGs, which jointly supply steam to a subcritical triple pressure steam cycle. The gas turbines operate at a pressure ratio of 18, a turbine inlet temperature (TIT) of 1371 ºC and air fuel ratio (AFR) of 40.5 on mass basis at ISO ambient conditions and 100% load, with a power output at coupling of 285.5 MWe. The design parameters of the reference plant are based on the information provided in a report commissioned by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG 2012). The flue gas stream leaving each HRSG is treated in a PCC plant. The flue gas is first cooled down in a gas/gas heat exchanger and then in a direct contact cooler, entering the absorber saturated at 45 ºC. One PCC plant is considered per GT-HRSG train. The net power output of the reference NGCC power plant equipped with PCC is 777 MWe with a net thermal efficiency of 52%.

The PCC system consists of a conventional chemical absorption plant with 30 wt% monoethanolamine (MEA) aqueous solution. The process flow diagram is illustrated in Figure 3. Steam for solvent regeneration is supplied to the reboiler designed for saturated steam at 3 bar. Superheated steam is extracted from the LP superheater in the HRSG and from the IP/LP crossover, as illustrated in Figure 1 and Figure 2. The LP drum and the IP/LP crossover are designed for an operation pressure of 4 bar to overcome the pressure drop estimated at approximately 1 bar along the pipe. The steam is then suitably conditioned for reboiler use. The superheated steam is cooled in a heat exchanger and a sprayed nozzle desuperheater (Spirax Sarco, 2016) reduces the amount of residual superheat to 3 ºC using part of the reboiler condensate return. The condensate from the reboiler is pumped back to the steam cycle and it is injected in the deaerator. This option is proposed as an alternative to the configuration in the IEAGHG R&D Programme's report (IEAGHG 2012).

A detailed description of the integrated model consisting of a CCGT plant, a CO_2 capture system and a CO_2 compression train is included in Herraiz's work (2016). Design and operating parameters are provided in Appendix A.

The CCGT power plant model is built in gPROMS Model Builder (PSE, 2016) with customised models for each piece of equipment. The PCC plant and the CO_2 compression train are modelled in Aspen Plus V7.0 (Aspen Tech, 2016). The absorber is simulated with a rate-based model which includes reaction kinetics and thermodynamic equilibrium for the CO_2-H_2O-MEA system, as well as mass transfer and heat transfer phenomena (Razi, Svendsen and Bolland, 2013; Sanchez Fernandez *et al.*, 2014). The stripper column is simulated with an equilibrium model. The CO_2 recovery ratio is set to control the lean solvent CO_2 loading at which the stripper column operates and this value is selected to bring the specific heat consumption to a minimum.

The CO_2-rich gas stream leaves the condenser of the stripper column at 40 ºC and 2 bar, with a CO_2 purity of 95 vol% and is compressed up to around the critical pressure, i.e. 73.8 bar, in the compression train. It consists of three stages with intercooling and water separation between stages. Liquid phase CO_2 at 73 bar and 28 ºC is pumped up to 110 bar for transport and storage in supercritical/dense phase.

2.2 Modelling methodology for operation with SEGR

2.2.1 Combined cycle gas turbine plant operation with SEGR

In the assessment of the performance of commercially available Class F gas turbine engines with SEGR, the same GT engine as for the reference configuration is considered for all the configurations. Yet different inlet pressure, temperature and working fluid composition result in an off-design operation of a GT originally designed for air combustion with inlet air at ISO ambient conditions. The assessment procedure consists of evaluating the thermal and physical properties of the working fluid through the turbomachinery, quantifying the deviation of the actual operation point in the compressor and in the turbine from the design point, and evaluating the GT power output and thermal efficiency.

The steam cycle is specifically designed for the GT exhaust temperature and flow rate in each configuration. The same arrangement of the heat transfer banks and pressure levels as in the reference configuration are considered in all the configurations, yet heat transfer areas and steam flow rates are then evaluated for each configuration following the same design criteria. The overall effect is finally investigated in terms of combined cycle power output and thermal efficiency.

The selective CO_2 transfer (SCT) system is modelled here as a "grey box". The concept of a "grey box" implies that inlet stream variables and operating parameters with a large effect on the overall process are specified in the model. The key operating parameters are selective CO_2 transfer (SCT) efficiency, selectivity for CO_2 over other components in the flue gas, leakage levels, pressure drop and heat transfer rate or temperature pinch at the hot end. The SCT efficiency refers to the amount of CO_2 removed from the flue gas and transferred into the air stream relative to the total amount of CO_2 at the inlet of the SCT system, as indicated in Equation [1]. Initial values of these parameters are the result of a conceptual design assessment of a SCT system using a rotary wheel for adsorption with structured solid materials conducted by Herraiz (2016). Results from this conceptual design are not presented in this work. Yet a sensitivity analysis is performed in Section 5 to quantify the effect of a range of values of these parameters on the performance of the CCGT.

$$\text{SCT efficiency} = 1 - \frac{|\text{mol CO}_2|_{\text{SCT system outlet}}}{|\text{mol CO}_2|_{\text{SCT system inlet}}} \quad [1]$$

A low temperature is preferable at the inlet of the SCT system to minimise sensible heat transfer and ensure a low temperature at the GT inlet. A low temperature also enhances the CO_2 transfer capacity for certain technologies, such as adsorption. It is assumed here that the flue gas enters the SCT system saturated in moisture at 30 ºC. In SEGR in parallel, the diverted flue gas stream coming from a gas/gas heat exchanger is cooled down in a DCC, as illustrated in Figure 1. In SEGR in series, the flue gas leaving the absorber is cooled down either in the absorber water wash section or in an additional DCC downstream of the absorber column, as illustrated in Figure 2.

2.2.1.1 Gas turbine performance with SEGR

The mass flow rate swallowed by the GT compressor varies with changes in the density of the CO_2-enriched air for a fixed compressor geometry assumed here, for which the position of the variables inlet guide vanes (VIGV) is set at the corresponding angle for full load operation. The intake mass flow rate is therefore evaluated as a function of the density of the CO_2-enriched air stream at the GT compressor inlet according to the continuity equation, for constant cross section area (A) and axial flow velocity (C_x). The temperature of the air is likely to rise as it passes through the SCT system regardless the technology employed, mainly due to sensible heat transfer from the flue gas into the air stream. Euler's equation is used to evaluate the specific absolute enthalpy rise per stage and the stage efficiency in the compressor. It is also assumed that relative flow angles, axial flow velocity and mean rotor speed are constant and equal to the deign point (Herraiz, 2016).

A criterion considered in this work is to assume that the gas turbine is chocked when running at full load (Sánchez et al., 2010). The condition of chocked flow is then applied at the throat of the nozzle constituted by two consecutive blades of the first ring of stator vanes, and Equation [2] is established at the inlet section of the turbine. A reorganisation of Equation [2] leads to Equation [3], where the coefficient K_T is the turbine swallowing capacity and should remain constant for a choked turbine (Cooke, 1985).

$$\dot{m} = P_0 \cdot A \cdot \sqrt{\frac{\gamma \cdot MW}{Z \cdot R_u \cdot T_0}\left(\frac{2}{\gamma + 1}\right)^{\gamma+1/\gamma-1}} \quad [2]$$

$$K_T = \frac{\dot{m}}{P_0} \cdot \sqrt{\frac{Z \cdot T_0}{\gamma \cdot MW}\left(\frac{\gamma + 1}{2}\right)^{\gamma+1/\gamma-1}} \quad [3]$$

Variations in the working fluid composition are considered by means of the fluid properties, such as molar mass (MW), compressibility factor (Z) and the ratio of specific heats or isentropic factor (γ). Equation [3] establishes the pressure at the turbine inlet (P_0), for a given temperature (T_0) and combustion gases mass flow rate $(\dot{m})$ at the exit of the combustor. The compressor discharge pressure is evaluated considering a pressure drop through the combustor for the corresponding mass flow rates in each configuration (Walsh and Fletcher 2004). The natural gas flow rate and the cooling air flow rate, extracted from the last compression stage, are evaluated to maintain the same combustor outlet temperature (COT) and the same TIT as in the reference configuration, respectively.

The deviation on the dimensionless parameter groups for mass flow (*MF*), pressure ratio (*PR*) and rotational speed (*N*) are used to investigate the effect on the performance of the compressor and turbine of a change in the working fluid properties with SEGR and EGR, according to Equations [4], [5] and [6]. Since geometry and dimensional parameters of commercial gas turbine systems are not available in the public domain, deviations of these parameters from the design conditions are considered instead of absolute values. The physical meaning and the derivation procedure are explained in Herraiz's work (2016). The fundamental principle is that, if Mach numbers derived for the velocity components of the fluid in the blades, i.e. absolute velocity, relative velocity and rotational speed, are the same, the velocity diagrams are uniform and the Reynolds number is constant, unique flow conditions are then obtained (Dixon and Hall, 1998). Each point on the turbomachinery characteristic curve based on these dimensionless groups should therefore represent unique flow conditions and a new operational point can be identified in performance maps developed for air-based combustion (Jonshagen, Sipöcz and Genrup, 2011).

$[Ma_{c_x}]_{\mathrm{air}} = [Ma_{c_x}]_{\mathrm{SEGR}}$, then

$$MF_{\text{ deviation}} = \frac{\frac{\dot{m}_{air}}{\dot{m}_{SEGR}} \cdot \sqrt{\frac{T_{0_{\mathrm{SEGR}}}}{T_{0_{\mathrm{ref}}}}}}{\frac{P_{\mathrm{SEGR}}}{P_{\mathrm{ref}}} \cdot \sqrt{\frac{\gamma_{\mathrm{SEGR}}}{\gamma_{\mathrm{air}}} \cdot \frac{R_{\mathrm{air}}}{R_{\mathrm{SEGR}}}}} \quad [4]$$

$[Ma_U]_{\text{air}} = [Ma_U]_{\text{SEGR}}$, then

$$N_{\text{deviation}} = \sqrt{\gamma_{\text{air}} \cdot T_{0_{\text{ref}}} \cdot R_{\text{air}}} \Big/ \sqrt{\gamma_{\text{SEGR}} \cdot T_{0_{\text{SEGR}}} \cdot R_{\text{SEGR}}} \qquad [5]$$

$\left[Ma_U \cdot Ma_{C_\theta}\right]_{\text{air}} = \left[Ma_U \cdot Ma_{C_\theta}\right]_{\text{SEGR}}$, then

$$PR_{\text{deviation}} = \frac{1}{PR_{\text{ref}}} \left[\frac{\left((PR)^{\frac{\gamma-1}{\gamma}} - 1 \right)_{\text{SEGR}}}{\frac{\gamma_{\text{SEGR}} - 1}{\gamma_{\text{air}} - 1}} + 1 \right]^{\gamma_{\text{air}}/(\gamma_{\text{air}}-1)} \qquad [6]$$

2.2.1.2 Steam cycle design for SEGR

The temperature of the superheated steam entering the high pressure (HP) and intermediate pressure (IP) steam turbines is maintained at 600 ºC, which is the design value for advance steam turbines, e.g. the Siemens SST-6000 (Siemens Power Generation, 2016) GE ST-600 Series Reheat (General Electric Thermal Power Generation, 2016). The approach temperatures, which is defined as the temperature difference between HP superheated and reheated steam and flue gas entering the HP superheater and the reheater respectively, varies for each configuration depending on the GT exhaust temperature. Since the flue gas temperature does not exceed 780 ºC, the same materials are used for all the configurations (Martelli, Nord and Bolland, 2012).

The inlet pressures to the HP and the IP steam turbines are maintained at 170 bar and 40 bar respectively. The pressure levels in the HRSG are defined to overcome the pressure drop through the steam ducts and feed water pumps discharge pressure are set in accordance. The pressure in the IP-LP crossover and the pressure in the LP drum are selected according to the steam requirements in the reboiler of the PCC plant. The LP steam turbine capacity is set for the remaining steam mass flow rate downstream of the steam extraction point.

The steam turbines have been modelled in terms of the isentropic efficiencies of the HP, IP and LP cylinders, evaluated to match the operational conditions reported in the IEAGHG R&D Programme report (IEAGHG 2012).

2.2.2 PCC optimisation for SEGR

A new-build steam cycle with dedicated steam extraction for the PCC system is considered in each configuration, with the same thermal integration between the capture plant and the power plant. The steam turbines are sized for steam extraction at nominal conditions at the design efficiency.

The capture plant is optimised for the operating conditions, i.e. flue gas CO_2 concentration and flow rate, in each configuration. Operating and design parameters are evaluated following the procedure described by Freguia and Rochelle (2003) to achieve a post-combustion CO_2 capture (PCC) efficiency in the absorber that is required to achieve a 90% overall CO_2 capture level. The overall CO_2 capture level takes into account the amount of CO_2 exiting the boundaries of the plant, and it is defined as the amount of CO_2 captured for transport and storage/utilization relative to the amount of CO_2 generated in the combustion of the natural gas, as indicated in Equation [7]. The PCC efficiency refers to the amount of CO_2 removed from the flue gas in the capture plant relative to the total amount of CO_2 in the flue gas entering the plant, as indicated in Equation [8].

$$\text{Overall } CO_2 \text{capture level} = \frac{|\text{mol } CO_2|_{\text{ to compression train}}}{|\text{mol } CO_2|_{\text{ generated in NG combustion}}} \quad [7]$$

$$\text{PCC efficiency} = 1 - \frac{|\text{mol } CO_2|_{\text{ PCC plant outlet}}}{|\text{mol } CO_2|_{\text{ PCC plant inlet}}} \quad [8]$$

For each configuration, the absorber diameter is determined for a flue gas velocity that corresponds to 80% of the velocity at the flood-point (Oexmann, Hensel and Kather, 2008). The absorber packing height is then increased for a constant diameter up to a value at which a further increase results in a marginal gain in the rich solvent CO_2 loading (< 0.2% of the previous value) and in a marginal reduction of the reboiler duty. The lean solvent loading and flow rate are then evaluated to minimise the specific reboiler duty. The conditions in the stripper are set to achieve the lean solvent loading resulting in the required PCC efficiency for each configuration. The optimisation procedure is illustrated in Appendix B for each configuration.

The benefits of SEGR on the PCC system are evaluated in terms of the reduction in both the packing volume of the absorber column and the specific reboiler duty, compared to the reference configuration of a CCGT plant with PCC and to a CCGT plant with PCC and "non-selective" EGR at 35% recirculation ratio.

3. Results

Results from the process model simulations for the investigated configurations with SEGR in parallel and SEGR in series are presented in this sections and compared with the results for an air-based CCGT with PCC and a CCGT plant with EGR and PCC operating at 35% recirculation ratio.

3.1 Selective Exhaust Gas Recirculation in Parallel

The process flow diagram for a CCGT power plant with SEGR in parallel to the PCC system is illustrated in Figure 1. A fraction of the exhaust flue gas leaving the HRSG is diverted and sent to a system where CO_2 is selectively transferred into an ambient air stream entering the GT compressor. A CO_2-enriched air is used for natural gas combustion. The non-diverted flue gas stream is treated in the PCC plant.

3.1.1 Operating framework

For an 90% overall CO_2 capture level, assumed for all the configurations, the CO_2 concentration that can be achieved in the GT exhaust flue gas is determined by the selective exhaust flue gas recirculation (SEGR) ratio, the post-combustion CO_2 capture (PCC) efficiency and the selective CO_2 transfer (SCT) efficiency. The SEGR ratio is defined as the flow rate of the diverted flue gas to the CTS over the total flue gas flow rate exiting the gas turbine, before cooling and condensation of the excess of humidity.

The CO_2 concentration increases for higher SEGR ratios and, for a wide range of recirculation ratios, the oxygen in the combustor remains above the limiting value of 17 vol% reported for GE Class F gas turbine engines with EGR (ElKady *et al.*, 2009; Evulet *et al.*, 2009), which is illustrated in Figure 4b.

Figure 4a shows the PCC efficiency that is required to capture 90% of the CO_2 generated in the combustion as a function of the SEGR ratio for a range of SCT efficiencies. For a given SCT efficiency, the PCC efficiency increases at a higher recirculation ratio. The reason is that the absolute amount of CO_2 emitted in the CO_2-depleted gas stream leaving the SCT system increases with increasing the recirculation ratio, since the flue gas CO_2 concentration is higher. A larger amount of CO_2 has therefore to be captured in the PCC plant. The SEGR ratio and the CO_2 concentration achievable in the flue gas are therefore limited by the highest efficiency that can be achieved, in practice, with each technology.

The white areas in Figure 4 indicate that a higher SCT efficiency than 85% in combination with a SEGR ratio above 40% are required to increase the flue gas CO_2 concentration beyond 6.6 vol%, achievable with EGR at 35% recirculation ratio.

The effect of SEGR in parallel on the CCGT power plant performance and the CO_2 capture process is investigated here for one configuration defined by the following operating parameters:

- SEGR in parallel (**Parallel 97/96**) operating at 70% SEGR ratio with 97% SCT efficiency and 96% PCC efficiency This configuration leads to approximately 14 vol% CO_2 in the flue gas, similar to CO_2 concentrations in flue gases from coal-fired power plants. Point A in Figure 4.

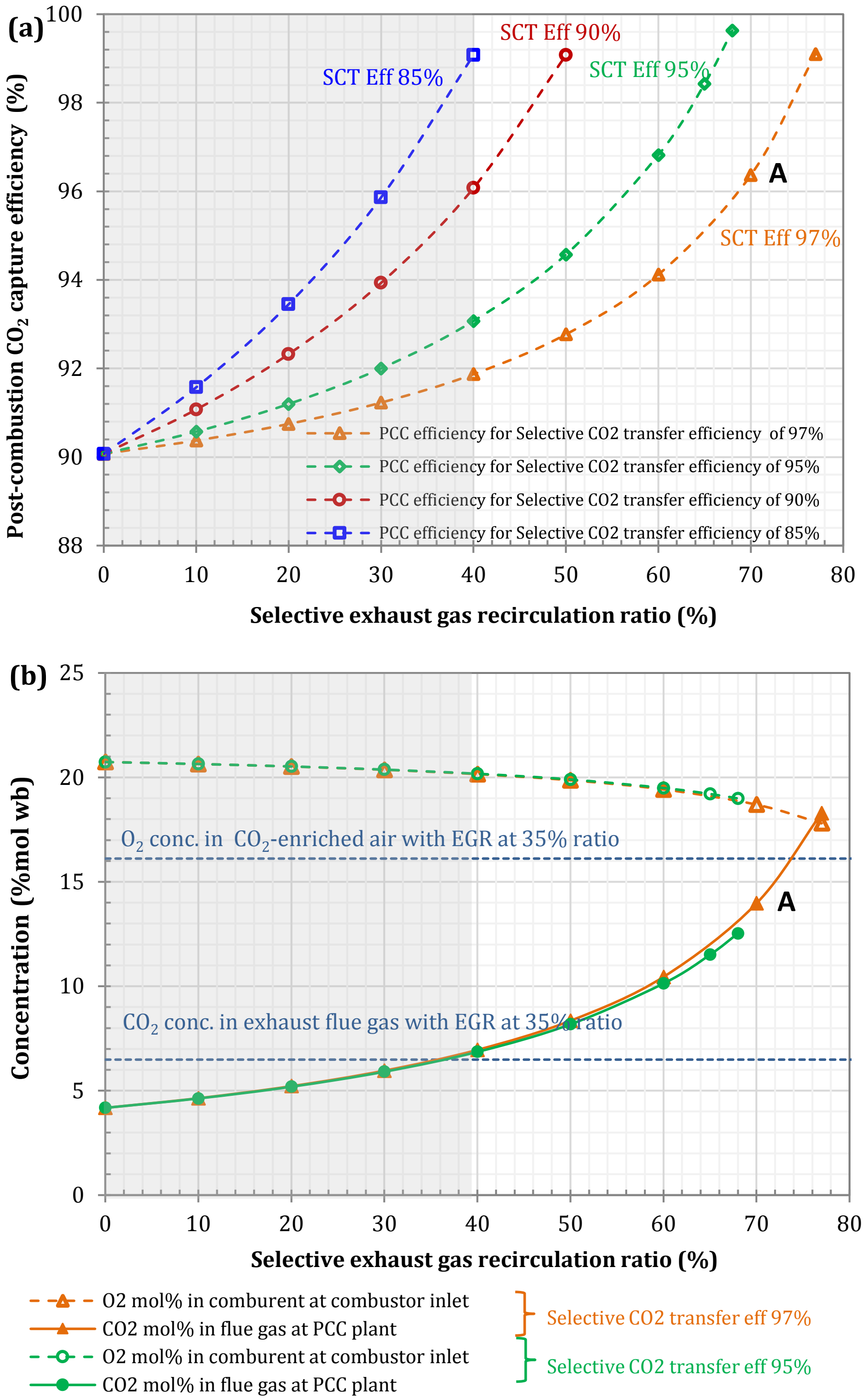


Figure 4.- (a) Sensitivity of the post-combustion CO_2 capture efficiency and **(b)** Sensitivity of CO_2 concentration in the flue gas at the inlet of the post-combustion capture system and O_2 concentration in the CO_2-enriched combustion air to the selective exhaust gas recirculation ratio, for a range of selective CO_2 transfer (SCT) efficiencies. SEGR in parallel for 90% overall CO_2 capture level.

3.1.2 Effect on the CCGT power plant

3.1.2.1 Effect on the gas turbine system

The mass flow rate swallowed by the compressor increases compared to the reference configuration for a CO_2 concentration in the CO_2-enriched air higher than 5 vol%, which is possible for SEGR ratios higher than 55%. The overall effect is an increase of the fluid density due to the high CO_2 content despite the temperature rise.

The working fluid properties which appear in the fundamental equations describing the turbomachinery performance, as explained in Section 2.2.1, are evaluated at the compressor inlet, the turbine inlet and the turbine outlet. For a higher CO_2 concentration in the working fluid, the molar mass and the density increase and the ratio of specific heats decreases. The deviation from the reference case is approximately 7%, 3.7% and 1.5%, respectively, at the compressor inlet for SEGR in parallel at 70% recirculation ratio. The increase in the mass flow rate does not significantly affect the pressure ratio in the compressor for a constant turbine swallowing capacity at choke conditions, according to Equation [3].

The dimensionless parameter groups for mass flow rate, pressure ratio and rotational speed described in Section 2.2.1, are then evaluated for the new working fluid composition and operating conditions with SEGR. The relative values referred to the design point are shown in Figure 5. The deviations are smaller than 3%, and it suggests that a high CO_2 concentration in the working fluid results in a small deviation in the compressor and the turbine performance from the design conditions. An improvement in the compressor efficiency is also expected.

The increase in the ratio of specific heats, with the increase in the CO_2 concentration, results in a decrease in the compressor outlet temperature and in an increase in the GT exhaust temperature. In the compressor, the increase in the CO_2-enriched air inlet temperature counteracts the previous effect and the reduction of the compressor outlet temperature is attenuated. The exhaust flue gas temperature entering the HRSG increases from 643 ºC, with air-based combustion, to 669 ºC, and the mass flow rate also increases from 658 kg/s to 674 kg/s, as shown in Figure 6. The overall effect is an increase of the heat available in bottoming cycle.

The higher mass flow rate through the turbomachinery results in an increase of the gas turbine net power output, e.g. by approximately 2 MW with SEGR in parallel 97/96, i.e. with 97% SCT efficiency and 96% PCC efficiency at 70% recirculation ratio, compared to the reference configuration. The CO_2-enriched air temperature at the compressor inlet of approximately 24 ºC. A higher power output could be achieved if the CO_2-enriched air entered the compressor at a lower temperature.

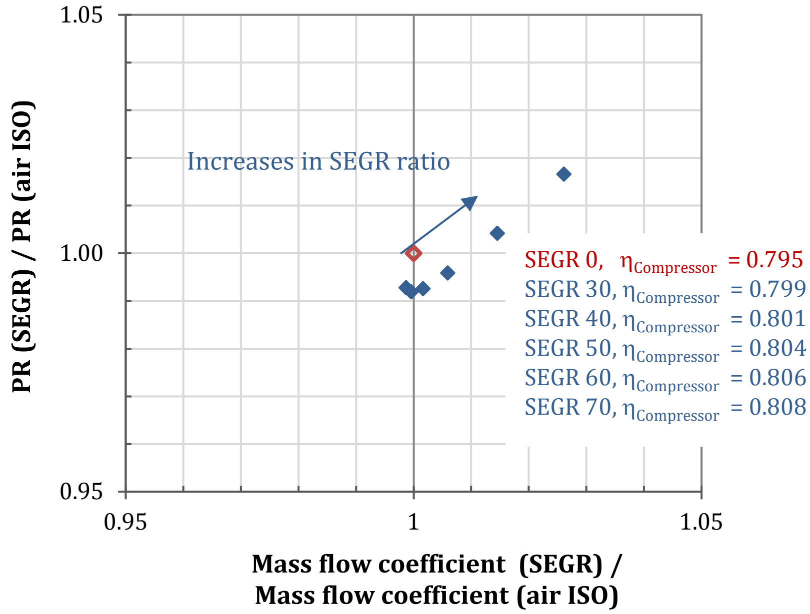


Figure 5.- Dimensionless parameter groups constituting the compressor performance curve for a range of SEGR ratios from 30% to 70%. Normalised values for the design operating point with air combustion at ISO conditions. The compressor efficiency is indicated at each recirculation ratio. Configuration: CCGT with PCC and SEGR in parallel.

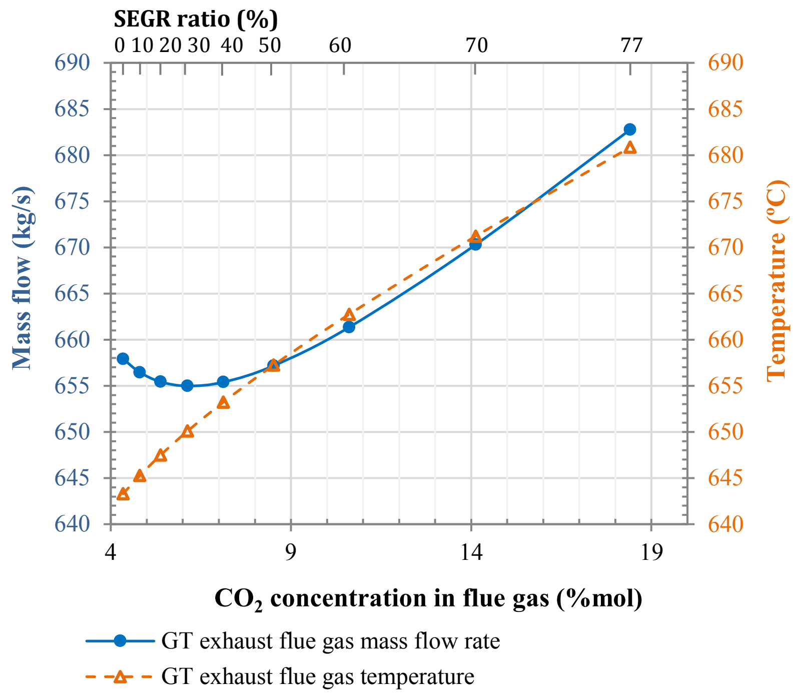


Figure 6.- Sensitivity of the gas turbine exhaust gas mass flow rate and temperature to the flue gas CO_2 concentration, for a range of SEGR ratios from 0 to 80%, increments of 10%. Configuration: CCGT with PCC and SEGR in parallel.

3.1.2.2 Effect on the steam cycle

The higher temperature and larger mass flow rate of exhaust gases results in a larger amount of heat available in the HRSG. The net power output of the steam turbines train increases by approximately 34 MW, from 256 to 290 MW, compared to the reference configuration. For further information, the temperature versus heat transfer flow rate diagram is included in Appendix C, for a configuration with SEGR in parallel 97/96. The temperatures at the high and intermediate pressure steam turbines are limited to 600 ºC and, thus, the approach temperatures increase by approximately 28 ºC, compared to the reference configuration. Yet the Rankine efficiency increases by approximately 3 %points, from 64% to 67%.

3.1.3 Effect on the PCC system

The effect on the CO_2 capture process is investigated for SEGR in parallel 97/96, i.e. operating at 70% recirculation ratio, 97% SCT efficiency and 96% PCC efficiency for 90% overall CO_2 capture level. A flue gas flow rate of 200 kg/s with 14 vol% CO_2 is treated in the absorber, which corresponds to 30% of the GT exhaust flow rate. This results in a considerably reduction of the absorber diameter. One column of 12 m diameter is required in SEGR in parallel, compared to two columns of 12 m in air-based combustion, for the same design criteria.

A 14 vol% CO_2 concentration, compared to 4.3 vol% and 6.6 vol% for air-based combustion and 35% EGR respectively, results in a larger driving force for CO_2 transfer. The equilibrium is displaced towards a higher CO_2 loading in the rich solvent, increasing the solvent capacity. The rich solvent CO_2 loading reaches a value of 0.475 mol_{CO2}/mol_{MEA} compared to 0.458 and 0.466 mol_{CO2}/mol_{MEA} for air-based combustion and 35% EGR, respectively. The lean solvent CO_2 loading that minimises the reboiler duty is 0.25 mol_{CO2}/ mol_{MEA}, compared to 0.26 mol_{CO2}/ mol_{MEA} for both air-based combustion and 35% EGR configurations. It results in an increase of the solvent capacity to 0.225 mol_{CO2} / mol_{MEA} from 0.207 and 0.198 mol_{CO2} / mol_{MEA} for air-based combustion and 35% EGR, respectively.

The relatively high CO_2 absorption efficiency of 97% results in a relatively small CO_2 partial pressure of 0.52 kPa at the top of the absorber column and, thus, a smaller driving force for CO_2 transfer, compared to 35% EGR where the CO_2 partial pressure is 0.67 kPa. This explains the small reduction of the absorber packing volume of approximately 4% compared to 35% EGR, from 2500 m^3 to 2262 m^3. A significant reduction of the absorber packing volume of 45% is, however, found when SEGR in parallel is compared to air-based combustion. The absorber sizing procedure is illustrated in Appendix B.

The relatively small CO_2 partial pressure at the top of the absorber requires a lower CO_2 loading of the lean solvent, which explains the small reduction in the reboiler duty despite the enhanced solvent capacity. The reboiler duty is around 3.56 MJ/kg_{CO2} comparing to 3.64 and 3.75 MJ/kg_{CO2} for air-based combustion and 35% EGR respectively, which corresponds to 2% and 5% reductions.

The absorber sizing procedure is illustrated in Appendix D Figure D.1 and Figure D.2, for SEGR in parallel and SEGR in series respectively. The reduction in the packing volume is indicated by the black dotted line, following the criterion of minimising both the reboiler duty and the absorber dimensions. Yet the red dotted line shows the reduction in the absorber packing volume if the design is capitalised on the basis of lower capital cost.

3.2 Selective Exhaust Gas Recirculation in Series

The process flow diagram for a CCGT power plant with SEGR in series to the PCC system is illustrated in Figure 2. The SCT system is located downstream of, and "in series" with, the PCC process. The exhaust flue gas leaving the HRSG is first treated in the PCC system where the CO_2 is partially removed. The flue gas still contains a relatively high CO_2 concentration and is then sent to the SCT system where CO_2 is transferred into the ambient air stream.

3.2.1 Operating framework

The CO_2 concentration that can be achieved in the GT exhaust flue gas is determined by the PCC efficiency and the SCT efficiency, for a 90% overall CO_2 capture level. The CO_2 concentration in the flue gas increases at a higher SCT and the oxygen level in the combustor remains above 17 vol% for a wide range of values, as illustrated in Figure 7b. The CO_2 concentration at the inlet of the SCT system is lower than at the inlet of the PCC system since the CO_2 is partially removed in the latter process.

Figure 7a shows the PCC efficiency required to achieve a 90% overall CO_2 capture level as a function of the SCT efficiency. The higher the amount of CO_2 transferred into the combustion air, the lower the efficiency required in the PCC plant.

Figure 7 indicates that a higher selective CO_2 transfer efficiency than 85% is required to further increase the exhaust flue gas CO_2 concentration above 6.6 vol%, which is the concentration achievable with EGR at 35% recirculation ratio. The required PCC efficiency is then lower than 58%.

The effect of SEGR in series on the CCGT power plant performance and the CO_2 capture process is investigated here for three configurations defined by the following operating parameters:

- SEGR in series (**Series 85/58**) operating with 85% SCT efficiency and 58% PCC efficiency. The flue gas CO_2 concentration is approximately 6 vol%, similar to the concentration achieved with EGR at 35% recirculation ratio. Point B in Figure 7.
- SEGR in series (**Series 90/48**) operating with 90% SCT efficiency and 48% PCC efficiency. The flue gas CO_2 concentration is approximately 8 vol%. Point C in Figure 7.
- SEGR in series (**Series 95/31**) operating with 95% SCT efficiency and 31% PCC efficiency. The flue gas CO_2 concentration is approximately 13 vol%, similar to the concentration in a flue gas from coal-fired power plants. Point D in Figure 7.

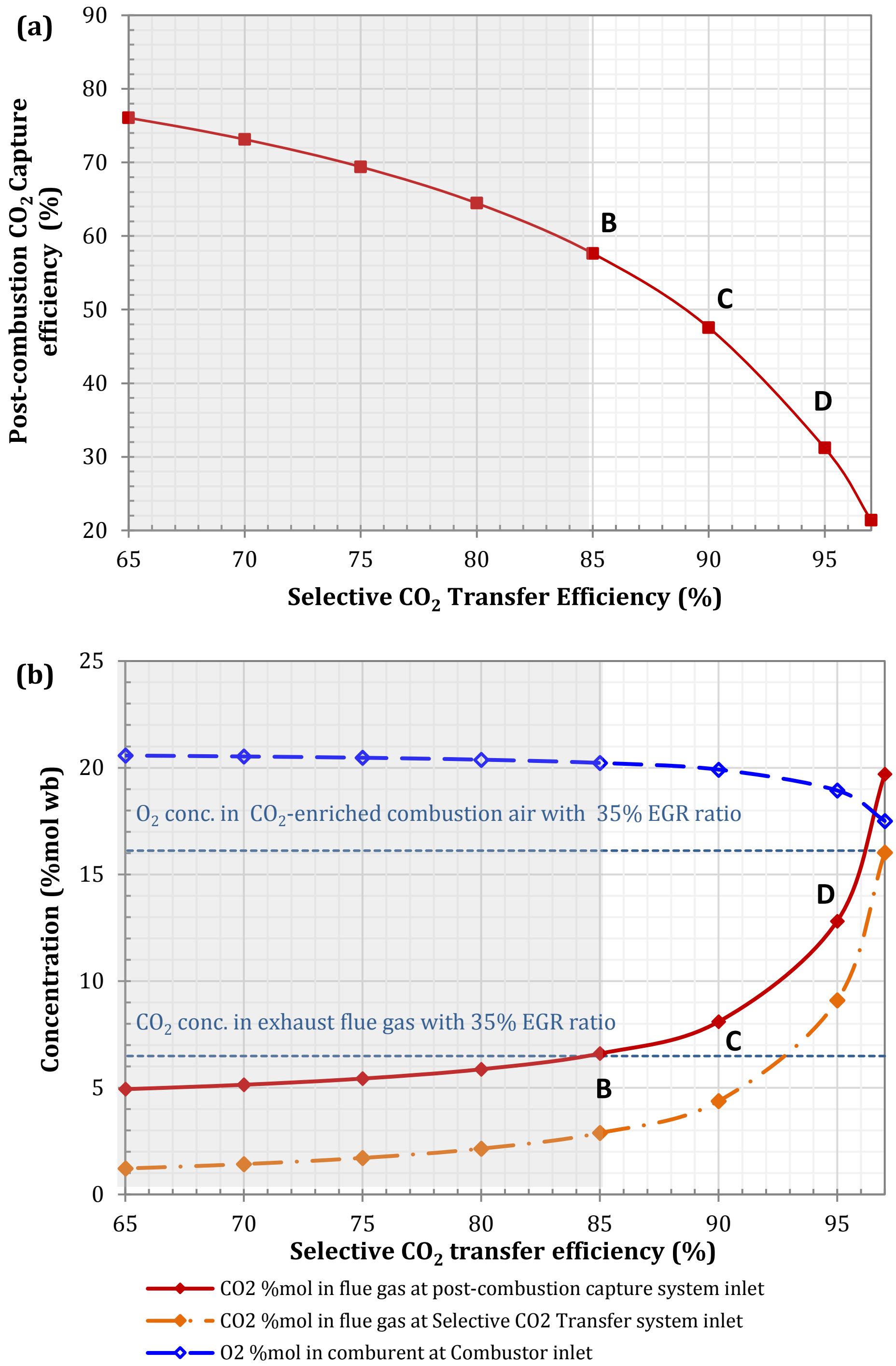


Figure 7.- (a) Sensitivity of the post-combustion CO_2 capture efficiency and **(b)** Sensitivity of CO_2 concentration, at the inlet of both the post-combustion capture system and the selective CO_2 transfer system, and O_2 concentration in the CO_2-enriched combustion air to the selective CO_2 transfer efficiency. Configuration SEGR in series at 90% overall CO_2 capture level.

3.2.2 *Effect on the CCGT power plant*

3.2.2.1 *Effect on the gas turbine system*

The mass flow rate swallowed by the compressor decreases compared to the reference configuration for the investigated configurations due to the higher compressor inlet temperature, which is detrimental for the gas turbine performance. A slightly higher temperature is expected with SEGR in series compared to SEGR in parallel, due to the smaller ratio of air to flue gas flow rate in the SCT system with SEGR in series and, thus, the likely larger sensible heat transfer rate, since the total amount of flue gases passes through the system. For SEGR in series 95/31, i.e. operating at 95% SCT efficiency and 31% PCC efficiency, the CO_2-enriched air enters the compressor at 28 ºC and the gas turbine power output decreases in approximately 4 MW, compared to the reference case.

The higher temperature at the compressor inlet results therefore in a smaller working fluid density than with SEGR in parallel for the same CO_2 concentration in the working fluid. The deviation from the reference case of the molar mass, the density and the ratio of specific heat capacities at the compressor inlet is approximately, 4.5%, 0.1% and 1% respectively for SEGR in series 95/31.

The relative values of the dimensionless parameter groups for mass flow rate, pressure ratio and rotational speed referred to the design point are represented in Figure 8. They are close to one and this suggests that a higher CO_2 concentration in the working fluid results in a small deviation for the compressor and turbine performance from the design conditions. An improvement in the compressor efficiency is also expected.

The increase in the ratio of specific heat capacities with increasing CO_2 concentration results in a decrease in the compressor outlet temperature and an increase in the turbine outlet temperature. The exhaust flue gas temperature entering the HRSG increases from the reference case only for configurations with a SCT efficiency higher than 90%, as shown in Figure 9. For those configurations, an increase in the heat available in the bottoming cycle is observed.

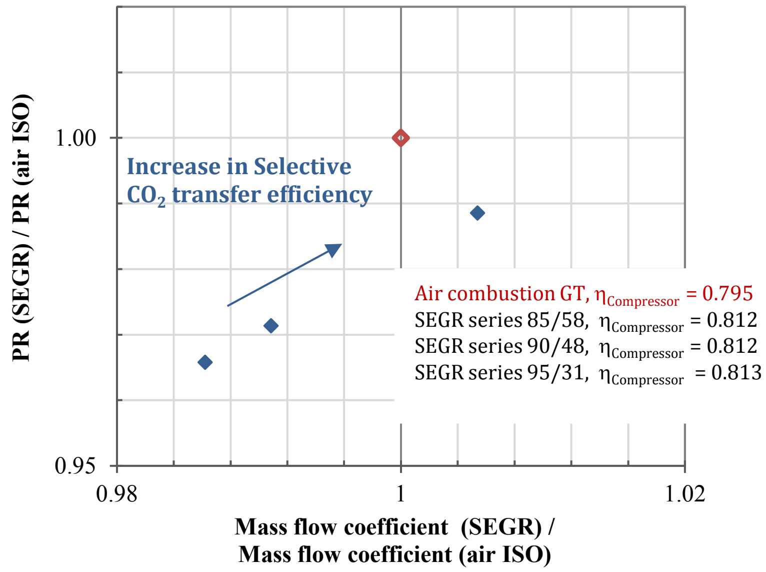


Figure 8.- Dimensionless parameter groups constituting the compressor performance curve for the configurations of SEGR in series with 85%, 90% and 95% selective CO_2 transfer efficiency. Normalised values for the design operating point with air combustion at ISO conditions. Configuration: CCGT with PCC and SEGR in series.

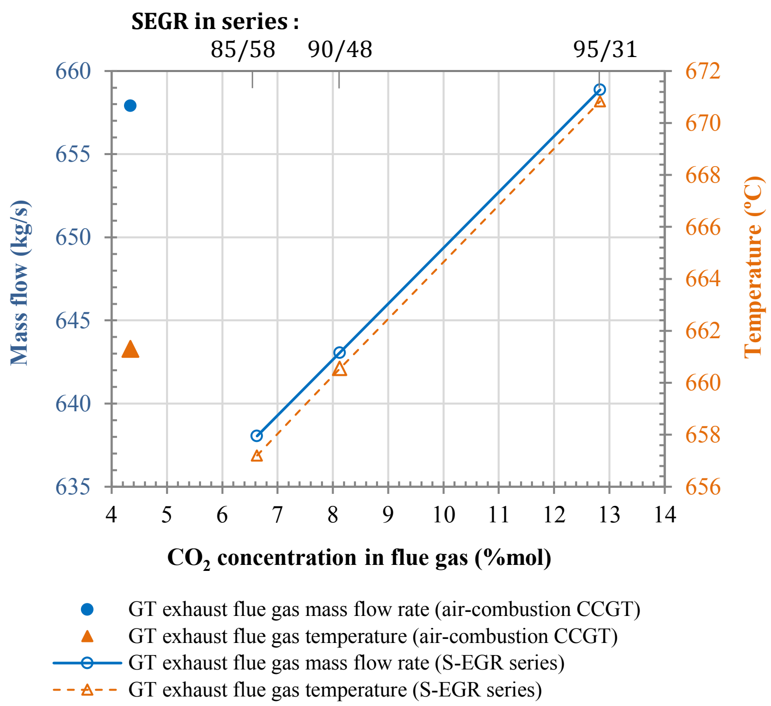


Figure 9.- Sensitivity of the gas turbine exhaust gas mass flow rate and temperature to the CO_2 concentration in the flue gas. Configuration: CCGT with PCC and SEGR in series, for 85%, 90% and 95% selective CO_2 transfer efficiency.

3.2.2.2 Effect on the steam cycle

The higher exhaust flue gas temperature leads to a larger amount of heat available in the HRSG. The steam turbine net power output increases in approximately 30 MW, from 256 MW to 286 MW, compared to the reference configuration with PCC.

The gas and water/steam temperature profile as a function of the heat transfer flow rate is shown in Appendix C, for SEGR in series 95/31. The inlet temperatures at the high and intermediate pressure steam turbines are limited to 600 ºC and, thus, the approach temperatures increase by approximately 19 ºC and 32 ºC in the respective heat transfer banks, compared to the reference configuration. Yet the Rankine efficiency increases by approximately 3% points.

3.2.3 Effect on the PCC system

For SEGR in series 85/31, the CO_2 concentration in the flue gas is 6.6 vol%, similar to the concentration for EGR at 35% recirculation ratio. The total amount of flue gas is treated in the PCC system. Yet a 58% PCC efficiency is required to achieve a 90% overall CO_2 capture level.

Two absorber columns of 12 m diameter are required. The higher CO_2 concentration and the smaller CO_2 capture efficiency, however, results in a larger driving force throughout the absorber column and the packing height significantly decreases compared to air-based combustion. The packing volume is reduced by approximately 40%, from 4190 m^3 to 2480 m^3, compared to air-based combustion.

The smaller absorber efficiency of 58%, compared to 90% in 35% EGR, leads to a higher driving force at the top of the absorber for the same CO_2 concentration at the absorber inlet of 6.6 vol%. Two absorbers of smaller height are therefore required with SEGR in series and only one higher absorber with 35% EGR. It results in a similar packing volume, 2506 m^3 for 35% EGR and 2480 m^3 for SEGR in series 85/31.

The rich solvent CO_2 loading increases from 0.458 to 0.469 mol_{CO2}/mol_{MEA}, compared to air-based combustion and it is similar to 35% EGR. The lean solvent CO_2 loading that minimises the reboiler duty is 0.28 mol_{CO2}/ mol_{MEA}, compared to 0.26 mol_{CO2}/ mol_{MEA} for both air-based combustion and 35% EGR. It results in a small reduction of the solvent working capacity, from 0.198 and 0.207 to 0.189 mol_{CO2}/ mol_{MEA}. Although a slightly larger solvent flow rate is required due to the increase in the GT exhaust flow rate, the higher CO_2 loading of the lean solvent leads to a decrease of the specific reboiler duty from 3.75 MJ/kg_{CO2}, for air-based combustion, to 3.62 MJ/kg_{CO2}, for SEGR in series, and to a similar specific reboiler duty with 35% EGR, 3.64 MJ/kg_{CO2}.

The flue gas CO_2 concentration can be further increased by operating at a higher SCT efficiency. For SEGR in series 95/31, a CO_2 concentration of approximately 13 vol% is possible, similar to the CO_2 concentration achieved for SEGR in parallel 97/96, investigated in Section 3.1.

Compared to air-based combustion, two absorber columns with similar diameters are required, yet the packing height significantly decreases for SEGR in series. This results in a reduction of the packing volume of approximately 64%, from 4190 to 1530 m^3.

Compared to SEGR in parallel 97/96, the smaller PCC efficiency of 31%, leads to a considerably higher driving force, particularly at the top of the absorber. Two short absorber columns are required with SEGR in series and only one large with SEGR in parallel. It leads to an approximately 33% reduction of the packing volume, from 2262 to 1530 m^3.

The rich solvent CO_2 loading of 0.479 mol_{CO2}/ mol_{MEA} is higher than 0.458 mol_{CO2}/ mol_{MEA} for air-based combustion, and similar to 0.475 mol_{CO2}/ mol_{MEA} for SEGR in parallel 97/96 The lean solvent CO_2 loading that minimises the reboiler duty is higher, i.e. 0.28 mol_{CO2}/ mol_{MEA}, compared to 0.26 mol_{CO2}/ mol_{MEA} in air-based combustion and 0.25 mol_{CO2}/ mol_{MEA} in SEGR in parallel. It results in a similar solvent capacity compared to air-based combustion and in a reduction of the solvent capacity compared to SEGR in parallel, from 0.225 to 0.199 mol_{CO2}/ mol_{MEA}. Despite the larger solvent flow rate and higher contribution of the specific heat to the reboiler duty, the higher lean solvent CO_2 loading results in an overall reduction of the specific reboiler duty of approximately 6.6% and 1.9% compared to air-based combustion and SEGR in parallel respectively, from 3.64 and 3.56 MJ/kg_{CO2}, respectively, to 3.50 MJ/kg_{CO2}.

4. Comparison of the results for the integrated CCGT plant with PCC

4.1 Overall effect on the CCGT power plant

The effect of SEGR on the gas turbine system is investigated for a Class F GT engine. Results indicate a small deviation of the compressor and turbine operating point from the design point, i.e. air-based combustion with ISO ambient conditions at the GT compressor inlet.

A high CO_2 concentration in the CO_2-enriched air stream entering the GT compressor could potentially result in an increase of the gas turbine power output due to a higher gas density and, thus, a larger mass flow rate entering the compressor for a fixed position of the VIGVs. Yet an increase in the air temperature through the SCT system is likely. The overall effect is therefore a small increase or even a decrease in the CO_2-enriched air density and hence in the intake mass flow rate. Heat transfer phenomena involved in the CO_2 transfer process are therefore important when evaluating the effect of SEGR on the performance of the gas turbine engine. For the investigated configurations that result in a flue gas CO_2 concentration of 13-14 vol%, the gas turbine net power output increases by 2 MW for SEGR in parallel 97/96 and decreases by 4.5 MW for SEGR in series 95/31, due to the prevailing effect of the high temperature in the latter configuration.

The increase in the GT exhaust temperature for the investigated configurations, assuming operation at constant TIT in the GT engine, results in an increase of the heat available in the bottoming cycle and a higher steam turbine power output. Moreover, the steam specific consumption in the reboiler of the PCC system decreases. The overall effect is an increase in the steam turbines power output of 34 MW for SEGR in parallel 97/96 and of 30 MW for SEGR in series 95/31.

The combined cycle net power output increases by approximately 42 MW for SEGR in parallel 97/96 and by 18 MW for SEGR in series 95/31. This corresponds to 5.2% and 2.3% of the combined cycle net power output in each configuration. The net increase in the combined cycle power output has been evaluated considering the energy penalty due to steam extraction for the MEA scrubbing process, auxiliary power consumption in the power plant and in the capture plant, and the power consumption for CO_2 compression.

The heat input to maintain the TIT in the GT engine at the design value increases as result of the change in the thermodynamic properties of the comburent, yet the net thermal efficiency of the combined cycle increases in 0.9 %points and 0.5 %points, respectively for each configuration.

This work has provided information regarding operating conditions to conduct combustion tests (Marsh *et al.*, 2016) within the scope of the EPSRC SELECT project (SELECT, 2014). CO_2 and O_2 concentrations in the CO_2-enriched air and the equivalence ratio in the GT combustor are presented in Table 1. Flue gas composition, flow rate and temperature at the GT exhaust for the configurations compared here are also presented. Gas turbine and steam turbines power output, combined cycle power output and thermal efficiency and auxiliary power consumption for each configuration is presented in

Table 2. Relative values, compared to the reference configuration, i.e. air-based combustion CCGT plant with PCC, are illustrated in Figure 10.

Table 1.- Operating conditions and gas stream variables for the investigated configurations

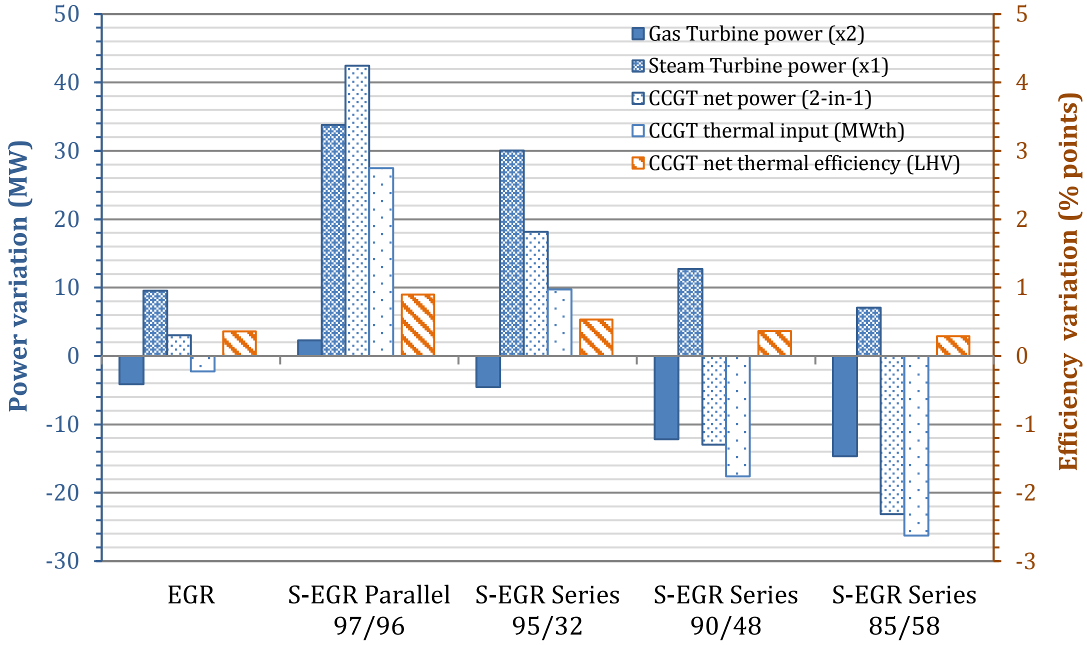
Configuration:		**Air-based combustion (reference)**	**EGR 35%**	**SEGR Parallel 97/96**	**SEGR Series 95/31**	**SEGR Series 90/48**	**SEGR Series 85/58**
Operating conditions (1)							
Recirculation ratio	%	N/A	35	70	N/A	N/A	N/A
Post-combustion CO_2 capture efficiency	%	90	90	96	31	48	58
Selective CO_2 transfer efficiency	%	90	90	97	95	90	85
CO_2-enriched air at compressor inlet							
Temperature	ºC	15	20.2	24.5	27.9	27.9	27.9
Pressure (set point)	bar	1.01	1.01	1.01	1.01	1.01	1.01
Mass flow	kg/s	642	633	653	642	627	622
CO_2 concentration	%mol	0.03	2.41	9.96	8.79	4.03	2.52
O_2 concentration	%mol	20.74	16.40	18.68	18.92	19.91	20.22
Equivalence ratio, ϕ (2)	mol/mol	0.56	0.72	0.66	0.64	0.59	0.58
Flue Gas at GT exhaust							
Temperature	ºC	643	649	671	671	661	657
Pressure (set point)	bar	1.04	1.04	1.04	1.04	1.04	1.04
Mass flow	kg/s	658	643	670	659	643	638
CO_2 concentration	%mol	4.34	6.56	14.12	12.83	8.13	6.63
H_2O concentration	%mol	9.06	9.91	9.51	9.17	8.93	8.85
O_2 concentration	%mol	11.59	7.59	9.01	9.64	10.90	11.31

Note 1: Operating parameters for 90% overall CO_2 capture

Note 2: The equivalence ratio is defined as the actual fuel to air ratio (FAR) divided by the stoichiometric fuel to air ratio for operating conditions in the combustor.

Table 2.- Power and thermal efficiency of the CCGT plant for the investigated configurations

		Air-based combustion (reference case)	**EGR 35%**	**SEGR Parallel 97/96**	**SEGR Series 95/31**	**SEGR Series 90/48**	**SEGR Series 85/58**
Gas turbine net power x 2	MWe	286	282	288	281	274	271
Gas turbines net power	MWe	572	563	576	562	547	542
GT thermal efficiency	%	38.18	37.75	37.13	37.09	37.44	37.54
Steam turbine Power x 1	MWe	256	266	290	286	269	263
Gross power	MWe	827.6	828.9	866.0	848.5	815.9	805.3
Gross thermal efficiency	%	55.50	55.55	55.80	55.96	55.82	55.76
Air fan x 2	MWe	N/A	N/A	0.75	1.07	1.13	1.15
Booster fan x 2	MWe	7.31	4.67	2.06	7.01	7.01	7.00
Booster fan for exhaust gas recycling x 2	MWe	N/A	1.28	0.99	N/A	N/A	N/A
Pumps in Steam cycle x 1	MWe	7.46	7.77	8.54	8.43	7.88	7.71
Pumps in PCC x 2	MWe	0.75	0.70	0.69	0.78	0.79	0.79
DCC pumps x 2	MWe	0.37	0.85	0.88	0.43	0.38	0.37
Compression work x 2	MWe	12.91	12.83	13.38	12.96	12.50	12.35
Net power output	**MWe**	**777.4**	**780.5**	**819.9**	**795.6**	**764.5**	**754.3**
Net thermal efficiency	**%**	**51.94**	**52.30**	**52.84**	**52.47**	**52.30**	**52.23**
Heat input	MWth	748	746	776	758	731	722
Fuel LHV	kJ/kg	46938	46938	46938	46938	46938	46938
Fuel input	kg/s	15.95	15.90	16.53	16.15	15.57	15.39



SEGR parallel: Recirculation ratio 70%, post-combustion capture efficiency 96%, selective CO_2 transfer eff. 97%.
SEGR series 95/31: post-combustion capture efficiency 31%, and selective CO_2 transfer efficiency 95%.
SEGR series 90/48: post-combustion capture efficiency 48%, and selective CO_2 transfer efficiency 90%.
SEGR series 85/58: post-combustion capture efficiency 58%, and selective CO_2 transfer efficiency 85%.

Figure 10.- CCGT net power output and net thermal efficiency variation with post-combustion carbon capture (PCC) and the operational strategies of conventional EGR, selective EGR in parallel and in series, compared to the reference case: air-based combustion CCGT with PCC.

4.2 Comparison of the effect on the post-combustion capture system

SEGR significantly increases the CO_2 concentration in the flue gas entering the PCC plant to approximately 14 vol%, compared to 6.6 vol% with "non-selective" EGR at 35% recirculation ratio. A high CO_2 concentration in the gas phase enhances the CO_2 absorption rate due to an increase in the driving force for mass transfer and the displacement of the thermodynamic equilibrium towards high CO_2 loadings in the solvent. The effects on the PCC capture system are evaluated in terms of the reduction in both the absorber packing volume and the specific reboiler duty for SEGR in parallel and SEGR in series, as described in Table 1. Results are compared in Figure 11, considering an air-based combustion CCGT plant with PCC as the reference case. Table 3 summarises the design and operating parameters for the 30 wt% MEA absorption plant.

SEGR in parallel additionally results in a reduction of the flow rate of the gas treated in the absorber, compared to 35% EGR. Yet a higher PCC efficiency is required to achieve 90% overall CO_2 capture level with increasing the fraction of the flue gas diverted to the SCT system, for a given SCT efficiency. It results in a larger driving force at the bottom of the absorber which becomes significantly smaller towards the top of the absorber, as illustrated in Figure 12. Thus, a small CO_2 loading in the lean solvent is required. The diameter of the absorber column is significantly smaller, yet a higher packing section for absorption is required, compared to air-based combustion and 35% EGR.

SEGR in parallel 97/96 operating at 70% recirculation ratio leads to a reduction of 46% in packing volume and 5% in specific reboiler duty, compared to air-based combustion, and of 10% in packing volume and 2% in specific reboiler duty, compared to 35% EGR.

Figure 12 illustrate the driving force for CO_2 transfer at the top of the absorber for all the configurations. The CO_2 partial pressure in the flue gas and the CO_2 partial pressure in equilibrium with the lean solvent CO_2 loading are presented in Table 4.

SEGR in series requires a relatively small efficiency in the PCC process to achieve 90% overall CO_2 capture level, which results in a higher driving force through the absorber and particularly at the top, as illustrated in Figure 12. Two absorber columns are required with a considerably smaller packing height, which results in a smaller packing volume compared to air-based combustion and EGR at 35% recirculation ratio.

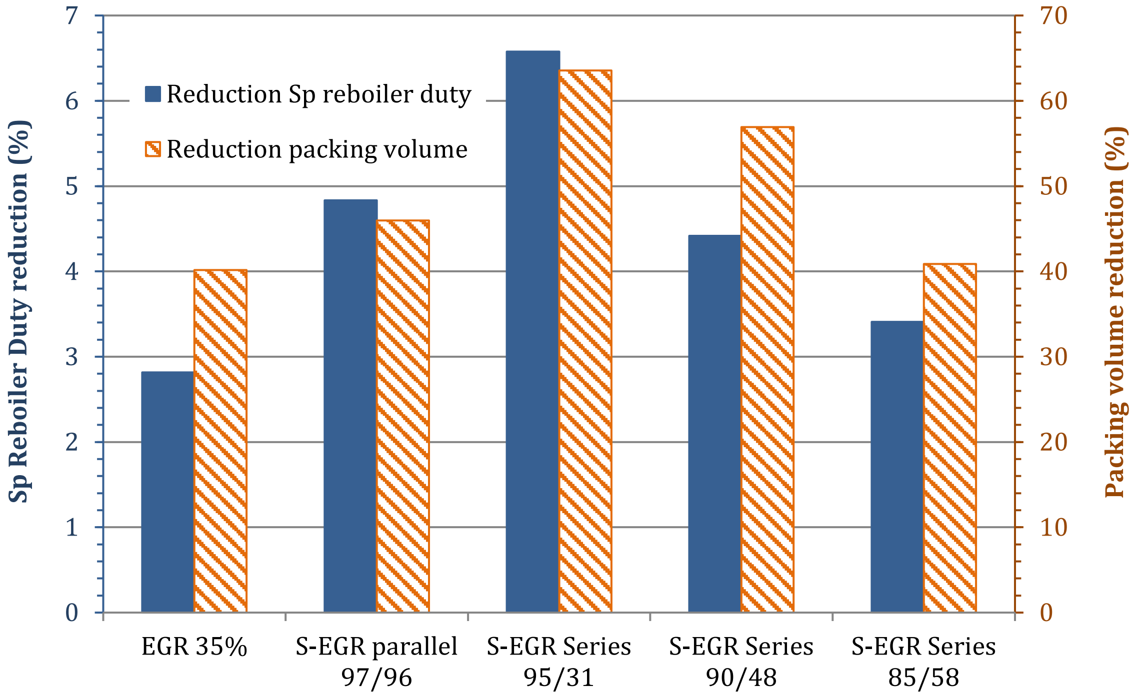
SEGR in series 95/31 results in a reduction of 64% in packing volume and 6.6% in specific reboiler duty compared to air-based configuration, of 40% in packing volume and 3.9% in specific reboiler duty compared to 35% EGR, and of 33% in packing volume and 2% in specific reboiler duty, compared to SEGR in parallel 97/96 with a similar CO_2 concentration in the flue gas of approximately 13-14 vol%.

It must be noted that, EGR and SEGR requires a slightly higher thermal input to maintain the TIT in the GT at the design value. For 90% overall CO_2 capture level, the absolute amount of CO_2 removed in the PCC system slightly increases as indicated in Table 3.

Table 3.- Design and operating parameters of the CO_2 capture process based on chemical absorption with 30 wt% MEA aqueous solution

Configuration/ Case		Air-based combustion (reference case)	EGR 35%	SEGR Parallel 97/96	SEGR Series 95/31	SEGR Series 90/48	SEGR Series 85/58
PCC efficiency	**%**	**90**	**90**	**96**	**31**	**48**	**58**
Absorber (per GT-HRSG-PCC train)							
Absorber efficiency	%	90	90	96	31	48	58
Flue gas BOTTOM							
Mass flow rate	kg/s	658	418	200	659	642	637
CO_2 conc.	vol%	4.21	6.65	14.00	12.89	8.15	6.64
Flue gas TOP							
Mass flow rate	kg/s	622	382	161	599	585	581
CO_2 conc.	vol%	0.43	0.70	0.59	8.8	4.67	3.08
Temperature	ºC	54	58.4	66	55	55	55
Lean solvent loading	mol_{CO2}/ mol_{MEA}	0.26	0.26	0.25	0.28	0.28	0.28
Rich solvent loading	mol_{CO2}/ mol_{MEA}	0.458	0.466	0.479	0.472	0.469	0.467
Solvent capacity	mol_{CO2}/ mol_{MEA}	0.198	0.207	0.225	0.189	0.192	0.199
Lean solvent molar flow rate	mol/s	886	851	808	942	947	969
Liquid / Gas ratio	kg/kg	1.35	2.05	3.99	1.38	1.42	1.44
Environmental							
Emissions MEA	mg/Nm^3	<1.53	<1.53	<2.22	<0.14	<0.14	<0.14
Structural parameters							
No. Absorbers	--	2	1	1	2	2	2
Packing diameter	m	12	14	12	12	12	12
Packing height	m	19	17	20	11	8	7
Packing Total Vol.	**m^3**	**4187**	**2506**	**2262**	**1526**	**1804**	**2476**
Stripper							
Stripper pressure	bar	1.84	1.84	1.82	1.92	1.89	1.89
Steam specific consumption	kg/ kg_{CO2}	1.71	1.66	1.62	1.59	1.62	1.65
Specific Reboiler Duty	**MJ/ kg_{CO2}**	**3.75**	**3.64**	**3.56**	**3.50**	**3.58**	**3.62**
CO_2 to pipeline	kg/s	76.5	76.89	80.12	78.3	75.53	74.64

Note: PCC system is optimised for an overall CO_2 capture level 90%. The reboiler operates at 133 ºC and 2.95 bar and it is designed for a pinch temperature of 13 ºC.



SEGR paralle 97/96l: Selective recirculation ratio 70%, PCC efficiency 96%, selective CO_2 transfer efficiency 97%.
SEGR series 85/58: post-combustion capture efficiency 58%, and selective CO_2 transfer efficiency 85%.
SEGR series 90/48: post-combustion capture efficiency 48%, and selective CO_2 transfer efficiency 90%.
SEGR series 95/31: post-combustion capture efficiency 31%, and selective CO_2 transfer efficiency 95%.

Figure 11.- Specific reboiler duty and packing volume reduction for a CCGT plant with Post-combustion Carbon Capture for the configurations: 30% exhaust gas recirculation, selective exhaust gas recirculation in parallel and in series, compared to the reference case: air-based combustion CCGT with PCC.

Table 4.- CO_2 partial pressure and driving forces at the top of the absorber of the PCC

Configuration/ Case		**Air-based combustion (reference case)**	**EGR 35%**	**SEGR Parallel 97/96**	**SEGR Series 95/31**	**SEGR Series 90/48**	**SEGR Series 85/58**
P CO_2 (Absorber TOP)	kPa	0.436	0.719	0.528	8.913	4.467	2.938
P $CO_{2\ equilibrium}$ (1)	kPa	0.090	0.135	0.241	0.128	0.122	0.118
P CO_2 – P $CO_{2\ equilibrium}$	kPa	0.345	0.585	0.287	8.786	4.345	2.819
Lean solvent loading	mol_{CO2}/ mol_{MEA}	0.26	0.26	0.25	0.28	0.28	0.28

Note 1: Vapor liquid equilibrium curves fitted from data (Dugas, 2009; Aronu *et al.*, 2011; Oexmann, 2011)

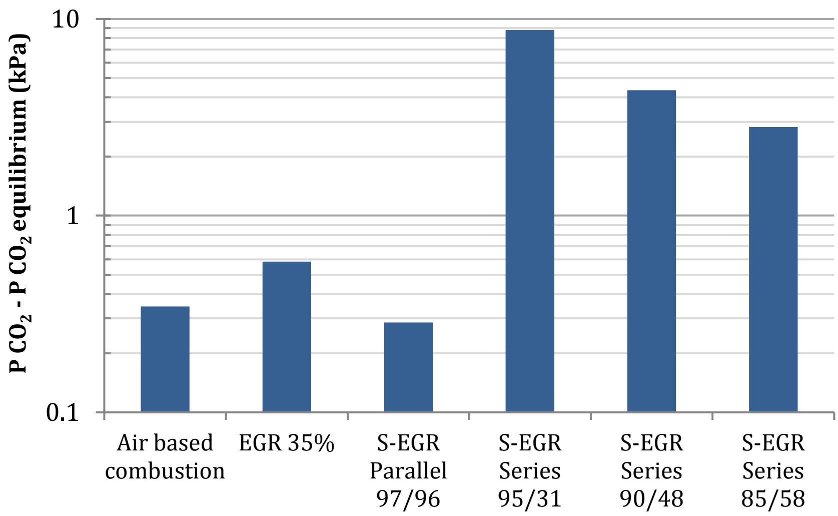


Figure 12.- Driving force for CO_2 transfer at the top of the absorber.

The operation and capital cost benefits of SEGR on the PCC system have to be balanced against the additional costs associated to the CO_2 transfer system. The performance analysis and the design of the CO_2 transfer process are not presented in this work. A detailed techno-economic analysis for a specific CO_2 transfer technology appears therefore necessary to fully assess the advantages of SEGR over EGR.

The largest reduction in the absorber packing volume is observed for SEGR in series 95/31. This reduction is higher than for SEGR in parallel 97/96 for a similar flue gas CO_2 concentration at the inlet of the PCC process. It has to be noted that the design and the operation of the SCT system is likely more challenging for SEGR in series than for SEGR in parallel, since the CO_2 concentration in the flue gas is smaller in the former configuration where the CO_2 is partially removed upstream of the SCT system. CO_2 concentrations in the diverted flue gas stream entering the CO_2 transfer system are illustrated in Figure 7.

Moreover, with SEGR in parallel at a large PCC efficiency, the temperature of the CO_2-depleted gas leaving the absorber packing section is relatively high due to the significantly higher ratio of the solvent flow rate over the gas flow rate (L/G), compared to air-based combustion, EGR at 35% recirculation ratio and SEGR in series.

The temperature profiles of the liquid and the gas in the absorber column are presented in Figure 13. The temperature increases due to the heat of adsorption reaching a maximum, i.e. temperature bulge, close to the top of the absorption section. The temperature then decreases due to the cooling effect of the lean solvent and the water vaporization. The amount of evaporated water is smaller at higher L/G ratios and so is the cooling effect (Kvamsdal, Haugen and Svendsen, 2011). The CO_2-depleted gas leaves the absorption section at approximately 65 ºC in SEGR in parallel and at approximately 55-60 ºC in the other configurations. A higher water wash section is therefore required in SEGR in parallel to cool the CO_2-depleted gas to 45 ºC and reduce MEA emissions to a similar level. The packing of the water wash section has not been considered in the results reported in Table 3 since less expensive random packing can be used. The same effect of the L/G ratio on the temperature profiles is also found in the experimental data from the test campaign of the CO_2 capture pilot plant at Esbjerg power station, as part of the "CO_2 Enhanced Separation and Recovery" (CESAR) project, performed to optimise the flow rate of the lean solution to the absorber with respect to a minimal reboiler duty (Abu Zahra, 2009; Oexmann, 2011). From this observation, it can be suggested that intercooling at the top section of the absorber can improve the absorber performance for SEGR in parallel by reducing the temperature bulge and thus displacing the thermodynamic equilibrium (Zhang *et al.*, 2016).

It is also important to note that other solvents may benefit more from the increase in the CO_2 partial pressure achieved with SEGR, for instance, solvents with slower absorption kinetic rates, higher CO_2 absorption capacity and smaller enthalpy of absorption, such as tertiary amines, e.g. methyldiethanolamine (MDEA), or hindered amines, e.g. 2-amino-2-methyl-1-propanol (AMP) (Ma'mun *et al.*, 2005). A small increase in the rich solvent CO_2 loading is observed for 30 wt% MEA when the CO_2 partial pressure increases from 4 kPa to 14 kPa, indicating that the thermodynamic equilibrium is limiting the enhancement effect. A higher CO_2 partial pressure would lead to faster absorption kinetic rates when it is the limiting factor for CO_2 transfer, higher enhancement factors and higher mass transfer rates in the liquid boundary layer.

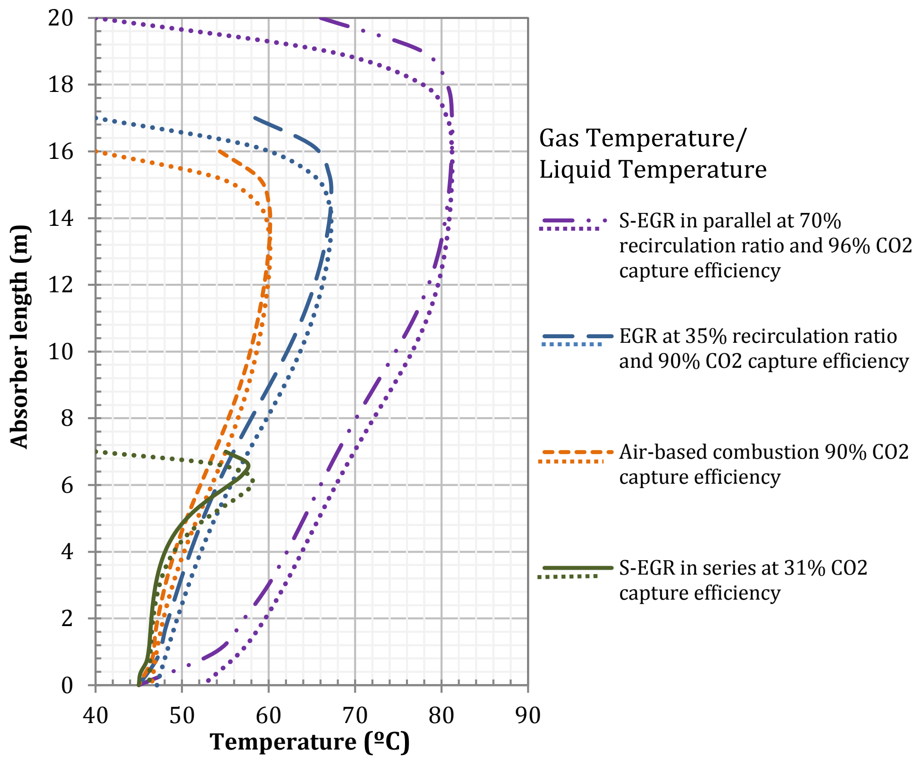


Figure 13.- Temperature profile of the gas phase (continuous and dashed lines) and the liquid phase (dotted lines) in the absorber for the configurations with: air-based combustion with 90% CO_2 absorption efficiency, 35% EGR with 90% CO_2 absorption efficiency, SEGR in parallel at 70% recirculation ratio and 96% CO_2 absorption efficiency, and for SEGR in at 31%, 48% and 58% CO_2 absorption efficiencies.

5. Sensitivity analysis to operating parameters in the Selective CO_2 Transfer system

The Selective CO_2 Transfer (SCT) system is modelled in previous sections as a "grey box" in which key operating parameters, such as CO_2 selectivity, leakage levels, thermal flow rate and pressure drop are input data. Initial values are the result of a conceptual design assessment using rotary adsorption for selective CO_2 transfer, which was conducted by Herraiz (2016). The effect of a variation of these parameters from design values on flue gas CO_2 concentrations and/or power outputs is conducted here to provide guidance on the minimum requirements for CO_2 transfer technologies. Results are shown here for the configuration with SEGR in parallel at 70% recirculation ratio. Similar results were observed for SEGR in series.

5.1 Selectivity to CO_2 over other components in the flue gas

A high CO_2 selectivity over other components in the flue gas is desired for SEGR applications. Oxygen and water vapour are however likely to be transferred along with CO_2, either in a competitive or non-competitive mechanism, due to the difference in partial pressure between a flue gas entering the system saturated in moisture at 30 ºC and the ambient air, i.e. 4.5 vol% H_2O compared to 1 vol% and 9.8 vol% O_2 compared to 21 vol%.

A sensitivity analysis of the O_2 concentration in the comburent and the CO_2 concentration in the flue gas entering the absorber to the amount of oxygen transfer from air into flue gas (x-axis) and to the amount of water vapour transferred from the flue gas into air (parameter), is shown in Figure 14. The amount transferred for each component is expressed as a percentage of the inlet flow rate of the component flow rate.

The oxygen concentration in the CO_2-enriched air decreases with increasing either the amount of oxygen transferred from air into flue gas or the amount of water transferred from flue gas into air, since a larger amount of intake air is replaced by the water vapour. The effect of oxygen transfer on the concentration is larger, since the oxygen concentration in air is considerably larger. A 10% of the O_2 transfer would reduce the oxygen concentration by around 1 wt%. The flue gas CO_2 concentration increases with increasing the amount of water vapor transferred, since the excess of humidity condenses in the direct contact cooler upstream of the absorber.

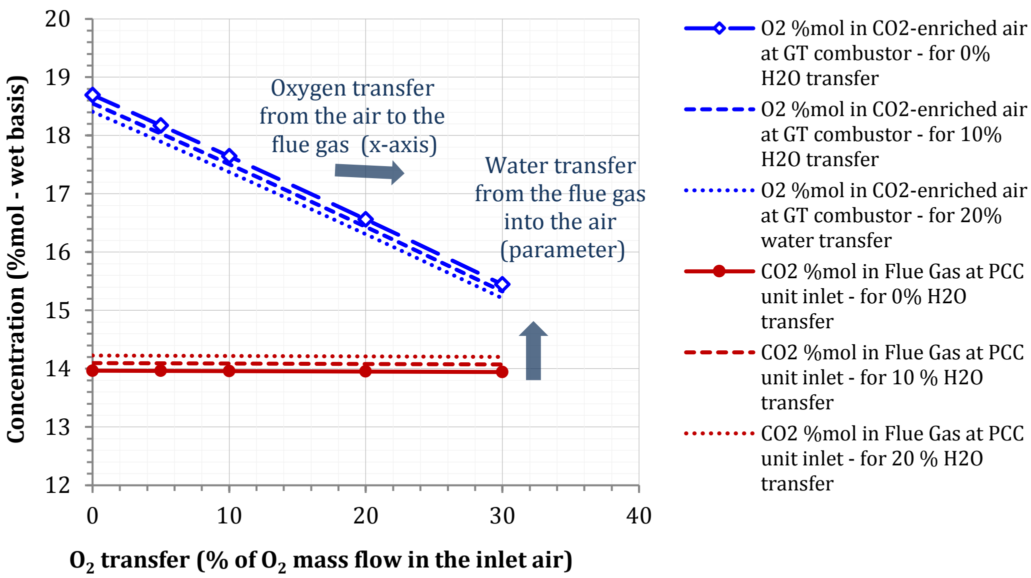


Figure 14.- Sensitivity of the flue gas CO_2 concentration and the comburent O_2 concentration to the O_2 transfer level from the air into the flue gas, for a range of water vapour transfer levels from the flue gas into the air. Configuration: SEGR in parallel with a recirculation ratio of 70%, a selective CO_2 transfer efficiency of 97% and a post-combustion capture efficiency of 96.7%.

5.2 Heat transfer

The compressor inlet temperature is a critical parameter in the assessment of the gas turbine performance with SEGR and it has a large effect on the power output and exhaust gases flow rate and temperature. For the design of the SEGR system, it is therefore important to understand the heat transfer mechanisms and heat generation/consumptions. For CO_2 adsorption, for example, the CO_2-enriched air temperature leaving the system results from an energy balance that considers the contribution of the enthalpy for CO_2 desorption and the sensible heat transfer, as the solid material acts as a heat storage medium in the adsorption/desorption cycles. In practice, the technologies proposed for SEGR applications are likely to benefit from lower flue gas temperature. It is for instance the case for rotary adsorption proposed in Herraiz's work (2016). The flue gas stream is cooled down to 30 ºC in a direct contact cooler.

Figure 15 shows the sensitivity of the gas turbine power output and thermal efficiency to the CO_2-enriched air temperature at the compressor inlet. The air temperature increases from 15 ºC (ISO ambient conditions) to 16.5 ºC due to the compression in the air fan and a further increase of 8 ºC through the SCT system is assumed here. A higher temperature rise results in a larger reduction of the gas turbine power output. For an ideal system with no heat transfer/generation, SEGR would increase the gas turbine power output by approximately 13 MW, compared to the power output in the reference configuration (red dot), due to the higher CO_2-concentration and density of the working fluid. It is indicated by the green dotted line in Figure 15.

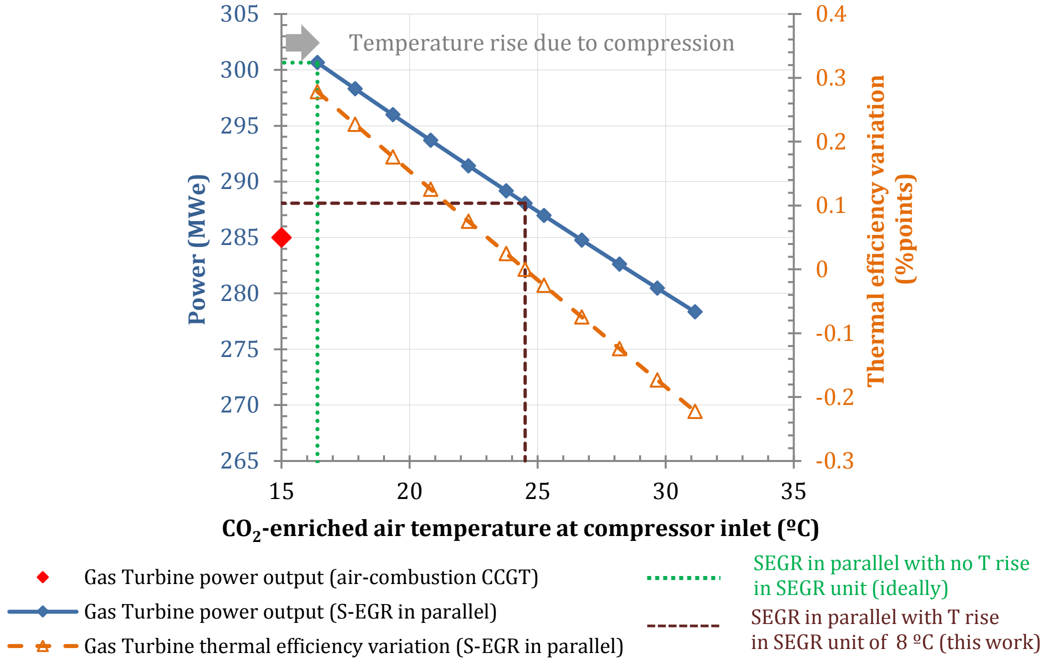


Figure 15.- Sensitivity of the gas turbine power output and thermal efficiency to the CO_2-enriched air temperature at the inlet of the compressor. Configuration: parallel SEGR with a recirculation ratio of 70%, a selective transfer efficiency of 97% and a post-combustion capture efficiency of 96.7%.

5.3 Pressure drop

An air fan and a booster fan are used to overcome pressure drop in the air and the diverted flue gas pathways through the SCT system, as shown in the process flow diagrams in Figure 1 and Figure 2. As an alternative, additional stages in a compressor are considered to replace the air fan.

Figure 16 shows a sensitivity analysis of the gas turbine power output to the pressure drop on the CO_2 transfer system for two configurations: with an air fan and without an air fan. With an air fan, the gas turbine power output decreases compared to the reference case due to the temperature rise in the fan, yet the power output penalty is smaller than in the configuration without an air fan. Despite the higher efficiency of the gas turbine compressor compared to a fan, the temperature is higher at the compressor inlet. An increase in the pressure drop of 1 kPa (10 mbar) results in a penalty of approximately 2 MW with an air fan and of 4.5 MW without an air fan.

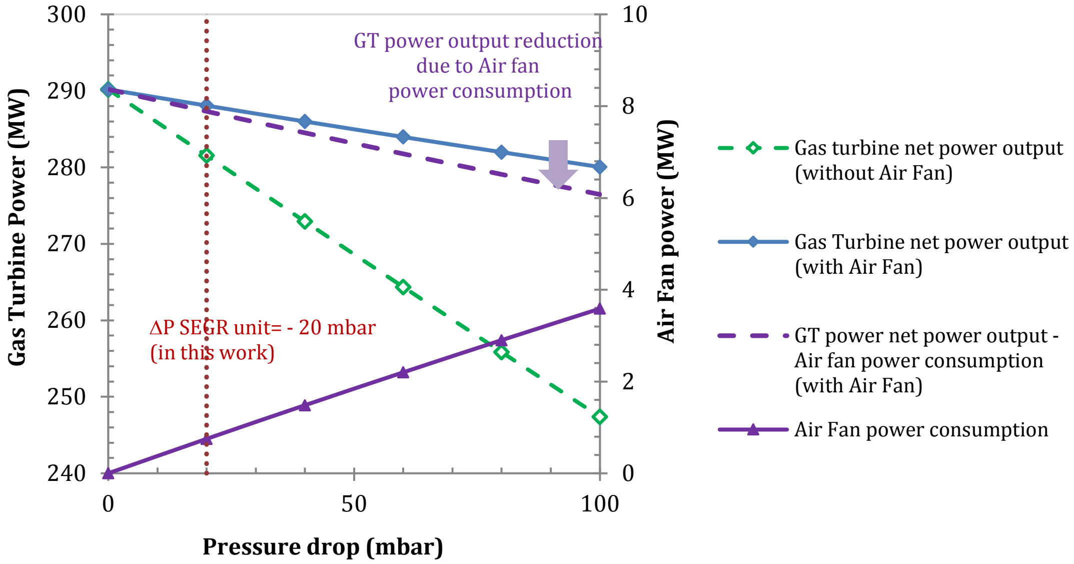


Figure 16.- Sensitivity of the gas turbine power output and air fan power consumption to the pressure drop in the air side of the selective CO_2 transfer device for the configuration in parallel with and without an air fan. Configuration: parallel SEGR with a recirculation ratio of 70%, a selective transfer efficiency of 97% and a post-combustion capture

6. Conclusions

- This work shows that SEGR operated either in parallel or in series with a PCC process significantly increase the CO_2 concentration in the exhaust flue gas of a CCGT power plant, maintaining oxygen levels in the combustor at approximately 19 vol%. The CO_2 concentration is limited by the highest efficiency that can be achieved in practice with the technologies used for CO_2 capture and for selective CO_2 transfer.
  - A CO_2 concentration of 14 vol% is possible at the inlet of the PCC system with SEGR in parallel 97/96, operating at 70% SEGR ratio with 96% PCC efficiency and 97% SCT efficiency.
  - A CO_2 concentration of 13 vol% is possible at the inlet of the PCC system with SEGR in series 95/31, operating with 95% SCT efficiency and 31% PCC efficiency.
- The assessment of the performance of a CCGT plant with SEGR leads to the following conclusions:
  - A small deviation on the compressor and the turbine behaviour of a Class F gas turbine engine, i.e. GE 9F-class, with SEGR from the design point, i.e. air-based combustion ISO ambient conditions, is expected for a range of CO_2 concentrations up to 9-10 vol% in the CO_2-enriched air stream entering the gas turbine compressor. This range is the equivalent to 13-14 vol% CO_2 in the GT exhaust flue gas.
  - For both configurations, SEGR in parallel and SEGR in series, the GT power output could increase by approximately 15 MW, equivalent to 5% of the GT net power output, as result of the higher density of a CO_2-enriched air compared to ambient air at the same temperature. Yet, a likely temperature rise through the selective CO_2 transfer system results in a marginal increase in the gas turbine power output with SEGR in parallel, or even in a reduction in the power output with SEGR in series, for the operating parameters described above.
  - The variation of the thermal and physical properties of the working fluid in the gas turbine is considerably small compared to the reference configuration. Yet, the smaller ratio of specific heats at high CO_2 concentrations leads to a higher GT exhaust temperature and heat available in the bottoming cycle. Consequently, the steam turbine power output increases by approximately 34 MW and 30 MW.
  - The overall effect is an increase of the CCGT net power output by approximately 42 MW and 18 MW, respectively for SEGR in parallel and SEGR in series operating at the conditions indicated above. This corresponds to 5.2% and 2.3% of the CCGT net power output respectively. The net thermal efficiency of the combined cycle increases by 0.55 %point and 0.83 %point, despite of the fact that the heat input increases by 27 MWth for SEGR in parallel and by 8 MWth for SEGR in series in order to maintain the TIT at the design value of 1371 ºC.

- Regarding the benefits of SEGR for the PCC system:
    - SEGR in parallel reduces the flow rate of the flue gas stream entering the absorber in the PCC plant, e.g. by 70% at 70% recirculation ratio, in addition to increasing the CO_2 concentration. The PCC efficiency, required to achieve 90% overall CO_2 capture level, increases with increasing the fraction of the flue gas diverted to the selective CO_2 transfer system, for a given SCT efficiency. The absorber diameter is smaller. Yet a higher packing section for absorption is necessary compared to air-based combustion and 35% EGR.
    - SEGR in series requires a considerably lower PCC efficiency than 90% to achieve a 90% overall CO_2 capture level. The total amount of GT exhaust gases is treated and similar absorber diameter as in air-based combustion is required. Yet the height of the absorption packing section is considerably smaller compared to both air-based combustion and 35% EGR.

  This work evaluates quantitatively the effect of SEGR on the PCC process in terms of reduction in packing volume and in specific reboiler duty for the configurations that results in 13-14 vol% CO_2 concentration in the GT exhaust gases:
    - SEGR in parallel 97/96 results in a reduction of 46% in packing volume and 5% in specific reboiler duty, compared to air-based combustion, and of 10% in packing volume and 2% in specific reboiler duty, compared to 35% EGR.
    - SEGR in series 95/31 results in a reduction of 64% in packing volume and 6.6% in specific reboiler duty, compared to air-based configuration, of 40% in packing volume and 3.9% in specific reboiler duty compared to 35% EGR, and of 33% in packing volume and 2% in specific reboiler duty, compared to SEGR in parallel 97/96 for a similar flue gas CO_2 concentration of approximately 13-14 vol%.
- A better performance of the CCGT plant is found with SEGR in parallel 97/96, since this configuration results in a higher power output and thermal efficiency, compared to SEGR in series 95/31. Yet the latter configuration results in a higher reduction in absorber size. The selection of either SEGR in parallel or SEGR in series however depends on the technology used for selective CO_2 transfer. An optimisation produce should be focused on minimising cost of the overall system and, it should therefore include a detailed design of the SCT system.
- On selecting a technology for SEGR applications, the pressure drop and the heat transfer rate have a large effect on the GT power output and the power plant performance. It is therefore important to minimise the pressure drop, the temperature increase at the GT compressor inlet and the oxygen leakage levels to avoid gas turbine derating. It is found that a 1kPa pressure drop or a temperature rise of 1.5 °C results in approximately 2MW decrease in the GT power output.

Nomenclature

Acronyms

CAPEX	Capital expenditures
CCC	Committee on Climate Change
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
COT	Combustor outlet temperature
DCC	Direct contact cooler
FAR	Fuel to air ratio
GT	Gas Turbine
HHV	Higher heating value
HP	High pressure
HRSG	Heat recovery steam generator
IP	Intermediate pressure
LHV	Lower heating value
LP	Low pressure
MEA	Monoethanolamine
NGCC	Natural gas combined cycle
OPEX	Operational expenditures
PC	Pulverized coal
PCC	Post-combustion CO_2 capture
SCT	Selective CO_2 transfer
SEGR	Selective exhaust gas recirculation
TIT	Turbine inlet temperature
UHC	Unburned hydrocarbons

Symbols

A	Cross section (m^2)
C_θ	Tangential component of the gas absolute velocity (m/s)
K_T	Turbine swallowing capacity
N	Rotor angular speed (rpm)
$\dot{m}$	Mass flow rate (kg s^{-1})
Ma	Match number
MW	Molar mass (kg mol^{-1})

P	Pressure (bar)
PR	Pressure ratio
R_u	Universal gas constant (8.314 J mol^{-1} K^{-1})
T	Temperature (K)
U	Rotor linear speed (m s^{-1})
y	Mass fraction (kg kg^{-1})
Z	Compressibility factor
Greek letters	
γ	Specific heat ratio, $\gamma = C_p/C_v$
ϕ	Equivalence ratio, $\phi = [FAR\ ]_{actual}/[FAR\ ]_{stoichiometric}$
Subscripts	
des	Design
ref	Reference
g	Flue gas
0	Stagnation or total properties

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