Does CCS reduce power generation flexibility? A dynamic study of combined cycles with post-combustion CO_2 capture

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Abstract

To date, the deployment, integration, and utilisation of intermittent renewable energy sources, such as wind and solar power, in the global energy system has been the cornerstone of efforts to combat climate change. At the same time, it is recognised that renewable power represents only one element of the portfolio of technologies that will be required to deliver a technically feasible and financially viable energy system. In this context, carbon capture and storage (CCS) is understood to play a uniquely important role, providing significant value through flexible operation. It is therefore of vital importance that CCS technology can operate synergistically with intermittent renewable power sources, and consequently ensuring that CCS does not inhibit the flexible and dispatchable nature of thermal power plants. This work analyses the intrinsic dynamic performance of the power and CO_2 capture plants independently and as an integrated system. Since the power plant represents the fast dynamics of the system and the steam extraction is the main point of integration between the CO_2 capture and power plants, disturbances with fast dynamics are imposed on the steam extraction valve during steady state and dynamic operation of a natural gas combined cycle (NGCC) to study the effects of the integration on power generation capacity. The results demonstrate that the integration of liquid-absorbent based post-combustion CO_2 capture has negligible impact on the power generation dynamics of the NGCC.

Keywords: combined cycle gas turbine (CCGT), post-combustion CO_2 capture, amine absorption process, monoethanolamine (MEA), flexible operation, dynamic operation, dynamic modelling

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1. Introduction

Climate change mitigation is one of the greatest challenges in the 21st century. Anthropogenic greenhouse gas emissions since the industrial revolution have resulted in increasing temperatures and changes in natural and human ecosystems (IPCC, 2014). Thus, a deep decarbonization of all sectors is necessary to meet the target of not exceeding the 1.5°C temperature increase respect to pre-industrial levels (IPCC, 2018).

Among the different possibilities available to reduce the greenhouse gas emissions, carbon capture and storage (CCS) is a uniquely important technology for mitigating the CO_2 emissions associated with the energy sector and industry (IPCC, 2005, 2014). These two sectors account for more than 50% of the total global greenhouse gas emissions (IPCC, 2014; IEA, 2018a).

Renewable energy sources will also contribute significantly to reducing CO_2 emissions (IEA, 2018b). Future energy systems are expected to be characterised by a high penetration of intermittent renewable sources. This will result in additional costs associated with load balancing, additional firming capacity,

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energy storage, and interconnection capacity (Heuberger et al., 2017a,b).

Flexible dispatchable energy generation technologies such as thermal power with CCS offer a cost effective way to balance this intermittency (Heuberger et al., 2016; Kondziella and Bruckner, 2016; Montañés et al., 2016; Mac Dowell and Staffell, 2016). Consequently, thermal power plants will be exposed to cycling operation and more frequent start-ups and shut-downs (Eser et al., 2017; González-Salazar et al., 2017). Thus, to deploy CCS technology in a power market dominated by the high variability of renewable energy, it is necessary to prove its adequacy for flexible operation (Adams and Mac Dowell, 2016).

Post-combustion CO_2 capture is arguably the most mature CCS technology (IPCC, 2005; Bui et al., 2018a). Therefore, deep understanding of the dynamic performance of these capture plants integrated with thermal power plants is essential. Dynamic modelling and simulation remains the primary medium to study the interaction of these systems under transient operation due to the lack of full-scale experience (Bui et al., 2014, 2018a). Developing further detailed insight into the process dynamics could help improve the accuracy and robustness of dynamic process control and scheduling during flexible operation, plant start-up and shut-down.

The development of dynamic CO_2 capture models was extensively reviewed by Bui et al. (2014, 2018b). Whilst the vast majority of research on flexible operation of CCS focuses on modelling the dynamics of the capture plant, there are relatively few studies that model the integrated system with a thermal power plant (Lawal et al., 2012; Mac Dowell and Shah, 2013, 2015; Wellner et al., 2016; He and Ricardez-Sandoval, 2016; Mechleri et al., 2017a,b; Garðarsdóttir et al., 2017; Montañés et al., 2017b).

Lawal et al. (2012) studied the dynamic interaction between a coal-fired power plant and a post-combustion capture plant with MEA, and showed how tight control (*i.e.*, rapidly responds to minimise deviation between the controlled variable and its set-point) on the capture plant may interfere with the power output of the power plant. For a similar integrated system, Garðarsdóttir et al. (2017) found that power generation settling times are essentially independent of the integration of the capture plant. However, inadequate control strategies may result in unnecessary longer stabilization times. Both studies concluded that the dynamics of the capture plant are significantly slower than the power plant, leading to longer settling times in the absence of adequate control structures, which may affect power plant performance. Retrofitted coal power plants exhibit the same transient behaviour and the integration with the capture plant acts as steam storage that can be rapidly adjusted to meet peak power demands through the manipulation of the extraction valve (Wellner et al., 2016). Mac Dowell and Shah (2013, 2015), and Mechleri et al. (2017a,b) also developed integrated systems of coal-fired power plants with post-combustion capture plants to study the economic performance during flexible operation accounting for variations in the electricity market, although the dynamic interaction was not studied.

Commercial natural gas combined cycles integrated with full-scale post-combustion capture plants show similar transient performance. He and Ricardez-Sandoval (2016) and Montañés et al. (2017b) proved the faster dynamics of the power plant compared to the capture plant, which resulted in slow oscillations in the longer time-scales as a consequence of the interaction between both plants. The analysis of varying inputs in open-loop in the capture plant also showed the benefits that may be obtained from close-loop control and simultaneous scheduling of the power and CO_2 capture plant (He and Ricardez-Sandoval, 2016). Further, evaluation of several control structures in the capture plant showed that different control couplings may lead to distinct long term dynamics in the low-pressure steam turbine. Nevertheless, the short-term transient behaviour of the natural gas combined cycle is not affected as a result of the slow dynamic response of the post-combustion capture plant (Montañés et al., 2017b).

These studies on the full-scale transient performance of integrated systems showed that slow dynamic interactions between the thermal power plant with the post-combustion CO_2

capture plant do not affect notably their power production capacity, albeit the stabilization time is affected by the slow response of the capture plant. However, the dynamics of power generation are determined by the transient behaviour of the steam cycle, that is, by the fast dynamics of the integrated system. The decoupling of power generation capacity from the CCS process has the potential to significantly enhance the economic efficiency and the technical performance. Therefore, rapid dynamic disturbances must be analysed in order to determine whether the CO_2 capture plant limits the electricity production capabilities of the thermal power plant.

The aim of this study is to investigate the extent to which fast disturbances in the steam extraction affect the power generation capability of the integrated system. Building on previous work, a thorough analysis of the dynamics governing the thermal power plant, the post-combustion capture plant and the integrated system is included in Section 2 to understand the physical mechanisms dictating their transient operation. Section 3 describes the modelling of the natural gas combined cycle integrated with the post-combustion CO_2 capture plant and the special power generation characteristic of this type of power generation systems. Results are presented and discussed in Section 4, and the conclusions are presented in Section 5.

2. Dynamic Analysis of Thermal Power Plants Integrated with CCS

Thermal power plants and post-combustion capture plants exhibit distinct dynamic behaviour. This section identifies and evaluates the process and dominant dynamics that significantly influence thermal power plants integrated with post-combustion CO_2 capture plants, including passive elements that contribute to the dynamics but are not the main source.

2.1. Thermal Power Plants

As post-combustion capture plants are a cost effective technology to remove CO_2 from large-emission sources, they are a suitable complement for heavy-duty natural gas combined cycles and coal- and biomass-fired power plants (IPCC, 2005). Natural gas combined cycles rely on gas turbines to control and produce most of the power and a steam cycle that acts as a passive element, which utilizes the energy contained in the exhaust gas to generate extra power. In contrast, power generation from solid fuels, namely coal and biomass, using subcritical and supercritical power plant technology, produce electricity solely via the steam cycle, which is driven by the combustion process in the furnace.

Fig. 1 shows the different operation range of each thermal power plant. The minimum load of modern gas turbine is limited to 40% of its full load owing to the combustion stability of the fuel and the associated emissions (Alobaid et al., 2017; Eser et al., 2017). Therefore, since the gas turbine accounts for a large share of the total power capacity of natural gas combined cycles, this type of power plants cannot reduce its power generation below this limit. Conversely, coal and biomass power plants are not restricted by a gas turbine; and their minimum compliant load is around 25% of their full load (Hentschel et al., 2016). This broader operation range enhances the utilisation of coal and biomass power plants as spinning reserves.

A common characteristic of all thermal power plants is the heat transfer in the steam generator between the combustion gases and the working fluid of the Rankine cycle. In this equipment, the combustion gases flow in a counter-current or cross-flow manner through several tube bundles where energy is transferred progressively to produce the superheated steam that drives the steam turbines. Steam generators are bulky equipment whose enormous mass of metal stores large amounts of energy due to its heat capacity. This leads to slow responses in the steam cycle and hence the power generation in the steam turbines. Thus, steam generators are the main limitation during the transient operation of thermal power plants and consequently define their dominant dynamics (Alobaid et al., 2017).

Two different time-scales dictate the dynamic operation of natural gas combined cycles. Modern gas turbines are fast components that can have load ramps up to 15% per minute and whose dominant dynamics are in the order of seconds (Hentschel et al., 2016). Steam

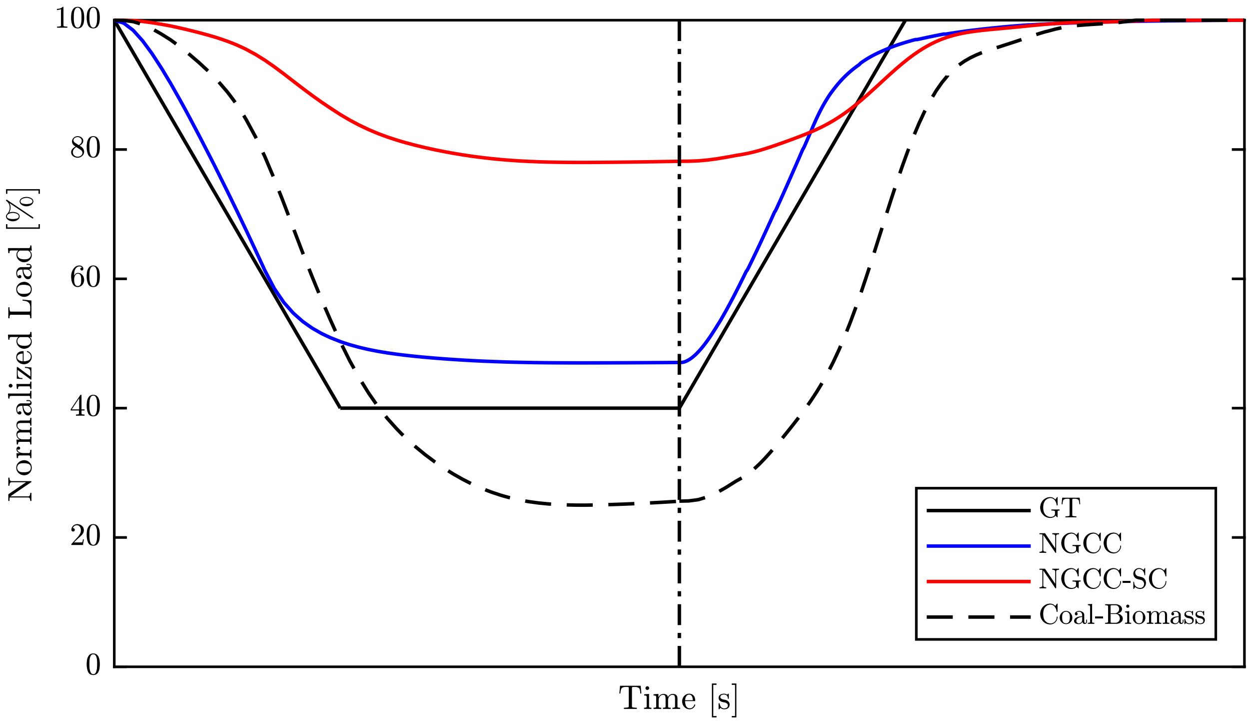


Figure 1: Generic dynamic behaviour of different thermal power plants of similar size. Maximum and minimum loads and power generation shares depend on the power plant design. The vertical line indicates the increasing load dynamic behaviour. The nomenclature is as follows. GT: Gas Turbine, NGCC: Natural Gas Combined Cycle, SC: Steam Cycle.

cycles are limited by the heat capacitance of the steam generator and thus their dominant dynamics are on the order of minutes. Fig. 1 represents the general dynamic behaviour of a natural gas combined cycle. The gas turbine drives the transient operation of the NGCC by changing its load, whilst the steam cycle determines the time required to reach steady-state (Kehlhofer et al., 2009). Nevertheless, natural gas combined cycles are able to meet the power demand before the steam cycle reaches steady-state by under- or over-shooting the gas turbine (Rúa et al., 2020). This unique ability of the gas turbine compensates for the slow transient performance of the steam cycle, enhancing the adequacy of NGCC for flexible operation.

Coal and biomass power plants do not have a gas turbine to control the power generation, thus governor valves are required at the inlet of the steam turbine to guarantee tight power control during transient operation. Fuel consumption is adjusted according to power demand to regulate the part-load performance, but this strategy cannot be applied in the time-scale of seconds owing to the heat capacitance of the steam generator and the slow response of the steam cycle (see Fig. 1). Consequently, the slow dynamics of the steam cycle dominate the transient operation of coal and biomass power plants, making them slower than modern NGCC and less suitable for flexible operation (Eser et al., 2017; González-Salazar et al., 2017).

2.2. Post-Combustion Capture Plants

Capture plants are passive systems whose operation is determined by the conditions of the gas to be treated and the steam available for the reboiler. From a dynamic operation perspective, the gas is a disturbance to which the capture plant must adapt to, whereas the steam is considered a manipulated variable. The stripper condenser pressure is also a boundary condition of the capture plant, however, this is considered constant as it is rarely modified during dynamic operation.

In a post-combustion capture plant, the fastest units are the rotating machinery (*i.e.*, blowers, compressors and pumps), as they have almost negligible dynamics with time constants in the order of a few seconds. Thus, solvent flow rates stabilize within a few minutes, depending on the size of the plant and the magnitude of the flow change (Flø et al., 2016; Montañés et al., 2018). Heat exchangers and piping lead to transport delays that do not affect the nature of the dynamics. Conversely, large vessels such as absorber and stripper sumps, reboiler hotwells or buffer tanks introduce significant inertia, which buffers and smooths the overall dynamic behaviour of the capture plant (Flø et al., 2016). Liquid hold-up in the absorber and stripper also contributes to this buffering effect, however, the effect on the solvent flow rate dynamics is small relative to that of sumps, storage tanks, *etc.* Therefore, the dynamics of the post-combustion capture plant are not governed by the mass balance but by the total volume of solvent, the volumetric capacity of the plant, and the solvent circulation time.

Chemical and thermal equilibrium in the absorber and stripper columns also affect the transient behaviour but has a minor influence on the stabilisation time of the capture plant. (Flø et al., 2016; Tait et al., 2016; Montañés et al., 2017a, 2018). During open-loop operation, changes in flue gas flow rate primarily impacts the absorption section, affecting the CO_2 capture rate and shifting the temperature profile as a result of the difference in released energy from the exothermic chemical reactions (Kvamsdal and Rochelle, 2008; Bui et al., 2016; Tait et al., 2016; Montañés et al., 2018). Both changes are dominated by the chemical and thermal inertia within the absorber as the stabilization times of the absorber temperature profile and CO_2 capture rate are larger than the rise time of the flue gas flow rate (Montañés et al., 2018).

For a given solvent flow rate, moderate changes to the exhaust gas flow rate have a minor effect on the rich CO_2 loading of the solvent (Lawal et al., 2010; Flø et al., 2016; Bui et al., 2016; Montañés et al., 2017a, 2018; Bui et al., 2018b). However, sufficiently large variations in the feed gas CO_2 concentration or mass flow rate may lead to more pronounced effects on rich solvent loading. Changes in flue gas flow rate only affect the absorption section and the solvent loading, but the effect of these changes on the overall stabilization time of the entire capture plant is essentially negligible.

The steam flow rate to the reboiler is an important process parameter. Sufficiently large changes to the steam flow rate will vary the temperature in the reboiler, and consequently the operating conditions of the stripper column. Assuming the other process conditions remain constant or are not adequately adapted, this would result in changes to the lean CO_2 loading exiting the stripper. (Lawal et al., 2010; Garðarsdóttir et al., 2015; Flø et al., 2016; Montañés et al., 2017a; Bui et al., 2020). This change in lean loading affects the amount of CO_2 the solvent can absorb, which in turn influences the energy released during the absorption reaction, the absorber column temperature profile and the CO_2 capture rate. These operation changes are expected to result in different rich loadings, which will affect the stripper transient conditions (Lawal et al., 2010; Flø et al., 2016; Bui et al., 2016; Montañés et al., 2017a, 2018).

Slow and long dynamics can limit the rate of transient behaviour and increase solvent circulation time. There is a combination of factors that contribute to slow dynamics, these include (i) total volume of solvent stored or held-up in the capture plant, (ii) size of the vessels in the system which impacts residence time, and (iii) transport delay introduced by the heat exchangers and piping. There is also an observable inter-column interaction between the stripper and absorber conditions. In a plant with slow dynamics (*e.g.*, owing to larger total liquid hold-up), changes to the solvent flow rate lead to slow variation of the rich and lean solvent loading. Thus, the slow interaction between the absorber and stripper columns due to the large liquid volumes (*e.g.*, long solvent circulation time or slow transient behaviour) is the main bottleneck, slowing the response time during flexible operation of post-combustion capture plants.

2.3. Thermal Power Plants Integrated with Post-Combustion Capture Plants

Several process configurations to integrate the power and capture plants have been studied (Botero et al., 2009; Lucquiaud et al., 2009; Jordal et al., 2012; Jonshagen et al., 2012; Mac Dowell and Shah, 2014), with steam extraction from the crossover between the intermediate- and low-pressure (IP-LP) steam turbines being the preferred option (Lawal et al., 2012; Montañés et al., 2017b; Garðarsdóttir et al., 2017). In this integration approach the steam extracted from the steam turbine may be mixed with low-pressure superheated steam in NGCC, and temperature is controlled by evaporative spray cooling with pressurized water from the intermediate-pressure economizer (Montañés et al., 2017b). In contrast, temperature control in coal or biomass power plants is achieved by using feedwater downstream the condenser (Fernandez et al., 2016; Garðarsdóttir et al., 2017).

Steam availability at the IP-LP crossover does not limit the dynamic operation of integrated system. This is largely due to the steam requirements of the CO_2 capture plant being small compared the large amount of steam produced in the Rankine cycle of the thermal power plant (Jordal et al., 2012; Rezazadeh et al., 2015). As a result, steam can always be extracted by modifying the opening of the steam extraction valve. This equipment can move from fully open to fully closed in seconds and thus their dynamics are negligible compared to those governing the thermal power plant and post-combustion capture plant.

System integration also includes the cooling and compression of the exhaust gas leaving the heat-recovery steam generation. From the perspective of dynamic operability, treatment of this flue gas is not a major concern due to the fast the dynamics of the blowers utilized to overcome the absorber column pressure drop, and hence do not limit the capture plant process dynamics. The direct contact cooler only introduces time delays. Ideally, the equipment integrating the thermal power plant with the post-combustion capture plant should not slow the overall transient operation of the integrated system. However, this coupling may lead to interactions between both plants that can affect their dynamics.

As different time-scales govern the dynamic operation of thermal power plants and post-combustion capture plants, system integration must consider the distinctively different process dynamics. Whilst heat capacitance in the steam generator limits the transient behaviour of thermal power plants to an order of minutes, typically 10-20 minutes for power plants of several hundred MW, the large solvent volumes and long circulation time in the CO_2 capture plant might lead to stabilization times in the order of hours (Lawal et al., 2012; Montañés et al., 2017b; Garðarsdóttir et al., 2017).

The power demand defines the operation of the power plant and hence the mass flow rate of the exhaust gas. Whereas changes in the flue gas conditions do not affect the performance of the thermal power plant, such changes are a disturbance for the capture plant, which must adapt its operation to meet the CO_2 capture targets. This may lead to different steam extraction rates that also modify the operating conditions in the power plant. If steam extraction variation occurs at a slow dynamics scale, *i.e.*, the time-scale defined by the capture plant, small fluctuations and longer stabilization times are obtained in the power generation of the low-pressure steam turbine (Lawal et al., 2012; Garðarsdóttir et al., 2017; Montañés et al., 2017b). However, this type of interaction between both plants is not critical as the thermal power plants are faster than the slow-dynamic time-scales of the CO_2 capture plant. Furthermore, steam extraction does not significantly influence the load of the power plant. On the contrary, steam extraction in the fast dynamic time-scale occurs simultaneously with the change of power plant load and may lead to dynamic interactions that compromise the power generation capacity of the system. Therefore, it is important to address this possible issue by studying the dynamic interaction between the thermal power plant and the CCS system in the fast dynamics time-scale, which are addressed in Sections 3 and 4.

3. Dynamic Modelling

In this study, a physics-based model of a 615 MW NGCC integrated with a 30 wt% MEA-based post-combustion capture process was used to study the dynamic interaction of NGCC integrated with absorption CO_2 capture Montañés et al. (2017b). Triple pressure steam cycles with reheat are the most efficient and common configuration of modern natural gas combined cycles (Alobaid et al., 2017; Kehlhofer et al., 2009). GT PRO (Thermoflow, 2014) was utilized to design the natural gas combined cycle as it provides detailed information about the geometry of the plant. Full-physics dynamic modelling was carried out in the Modelica-based (Modelica Association, 2019) software Dymola (Dassault Systemes, 2016) using the specialized Thermal Power library (Modelon, 2015).

Full-scale post-combustion capture plants are designed based on the flue gas CO_2 concentration and conditions (i.e., flow rate, temperature, pressure), the required CO_2 capture rate, the maximum pressure drops in the absorber and stripper columns, column flooding limits and a reasonable balance between capital and operational costs (Jordal et al., 2012; Dutta et al., 2017). For the natural gas combined cycle considered in this work, a capture plant with two absorber columns in parallel and one stripper for a nominal 90% CO_2 capture rate was found to meet these requirements (Montañés et al., 2017b). A dual absorber process topology was selected due to the limits in column sizing and construction (Dutta et al., 2017).

Integration of the power and capture plants was achieved by extracting steam from the crossover between the intermediate- and low-pressure steam turbines (see Section 2.3). Thus, the low-pressure section of the steam turbine was designed for nominal conditions where steam is extracted to achieve a 90% capture rate. Fig. 2 represents the layout of the natural gas combined cycle integrated with the post-combustion capture plant. Details on the design data, performance indicators, modelling assumptions and validation results are presented in the work by Montañés et al. (2017b).

The design of the power plant steam cycle includes the extraction of steam for the CO_2 capture plant. Consequently, the power generation distribution between the different turbines in this power plant differs from modern NGCC without a capture plant. Fig. 3 represents the power generation distribution at different gas turbine loads. The gas turbine produces the majority of the power as in any combined cycle without steam extraction, however, the contribution to the overall power generation of the low-pressure section of the steam turbine is halved due to the steam extraction (Jordal et al., 2012; Rezazadeh et al., 2015). Therefore, the contribution of the low pressure section in electricity production and in the steam cycle diminishes as a result of the integration with the post-combustion capture system. The high- and intermediate-pressure steam turbines contribute similarly as in NGCCs without steam extraction. This leads to larger power generation from the intermediate-pressure section because of the similar inlet temperature owing to the reheating and its larger pressure ratio.

4. Results and Discussion: Dynamics of a NGCC with CO_2 Capture

The dynamics of the natural gas combined cycle occur in shorter time scales compared to the overall transient operation of the integrated system. Thus, to study whether the steam extraction coupling affects the power generation capacity in different dynamic operation scenarios, the variations in the opening of the extraction valve must be faster than the dominant dynamics of the thermal power part (see Section 2). A damping sine signal was hence superimposed on the extraction valve opening to ensure fast dynamics in the interface between the NGCC and the capture plant (Ljung, 1987). This signal was characterized by an offset of 0.69 and an amplitude of 0.29, with a natural and damping frequencies of 0.01 and 0.001 Hz, respectively. These values ensure that variations in the steam extraction occur faster than the dominant dynamics of the NGCC. Albeit highly oscillating valve movements do not occur in practice during open loop operation (*i.e.*, no feedback control), these values generate a signal that provides sufficient variation in steam extraction from the IP-LP crossover valve. This will give insight into the transient effects of variations in steam extraction on power generation.

Two different scenarios were considered to analyse the integration effect on the power generation during both steady-state and transient operation of the power plant. In the case where the NGCC is at steady-state, the damping sine in the valve opening drives the dynamics of the system. In contrast, when there is a load change in the power plant, the dynamics are dictated by simultaneous changes occurring at the gas turbine and the steam extraction. Varying gas turbine loads directly affect power production. Secondly, steam cycle performance is influenced by change in exhaust gas conditions (*e.g.*, temperature and mass flow rate), and variations in steam extraction.

As optimal operation of the integrated system is not the main objective of this work, the NGCC only had a regulatory control layer, which regulates the steam temperature at the steam turbine inlet, levels in drums and condenser, and the pressures in the deaerator and the low-pressure drum. In the post-combustion capture plant, the levels in the large vessels were exclusively controlled, fixing the solvent flow rate to nominal conditions. Details of the implementation of this control structure are included in the work by Montañés et al. (2017b).

4.1. Effect of Steam Extraction During Steady State Operation of the NGCC

In this study, a sinusoidal signal was imposed in the steam extraction valve during steady state operation of the NGCC to observe the effect of disturbances in the interface of the integrated system. The power generation distribution was analysed in the NGCC, whilst key performance indicators of the capture plant such the carbon capture ratio and the reboiler temperature were investigated.

4.1.1. Power Generation Performance

Several part-loads during steady state operation are considered in order to cover a wide op-

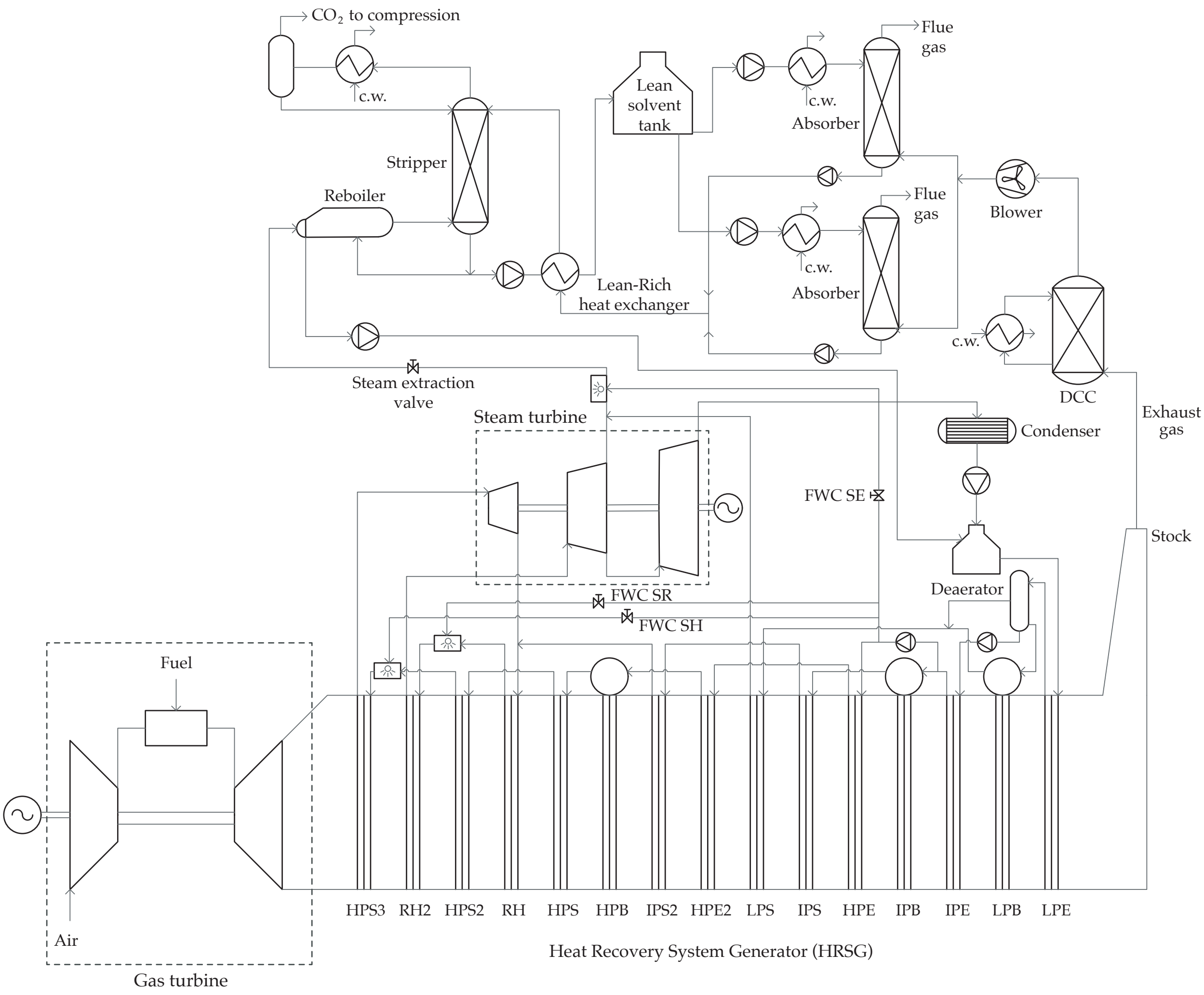


Figure 2: Process diagram of the natural gas combined cycle integrated with the post-combustion capture plant.The nomenclature is as follows. E: Economizer, B: Boiler, S: Superheater, R: Reheater P: Presure, L: Low, I: Intermediate, H: High, FWC: Feed-water cooling, RS: Reheated steam, SS: Superheated steam, SE: steam extraction, DCC: Direct contact cooler.

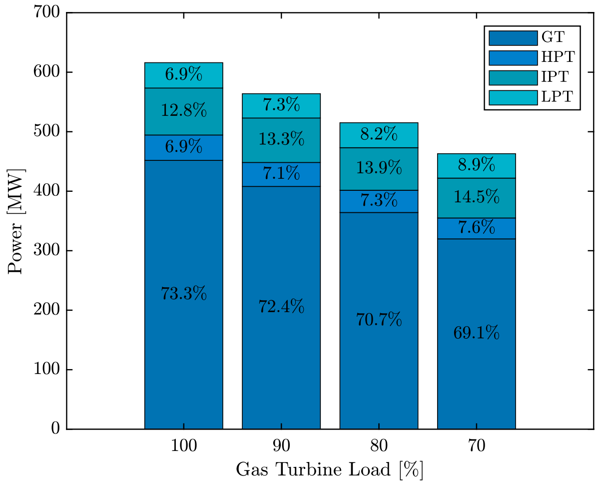


Figure 3: Power distribution of the natural gas combined cycle with CCS at different gas turbine loads.

erational range of the NGCC integrated with post-combustion CO_2 capture. Fig. 4 represents the variation in mechanical power production in the NGCC and the different steam turbine sections due to variation in steam extraction from the IP-LP crossover. The opening of the steam extraction valve defines the mass flow rate of working fluid available for expansion, which appears to have the greatest impact on the low pressure section in Fig. 4d. The valve opening also alters the intermediate and low pressure sections of the steam cycle, leading to deviations in power generation by the intermediate-pressure section of the steam turbine, albeit to a lesser extent compared to the low-pressure counterpart.

The variation in power generation by the intermediate- and low-pressure steam turbines has a negligible impact on the total power produced by the NGCC. The reasons for this effect is the gas turbine generates most of the total power and the average contribution from the IP and LP steam turbine sections is 20% (see Fig. 3). Therefore, the variations induced by the steam extraction valve in the NGCC power generation during steady-state operation are negligible and can be easily compensated by the power controllers included in the gas turbine. Fig. 4a demonstrates how the variation in steam extraction only creates a small disturbances in the total power generation.

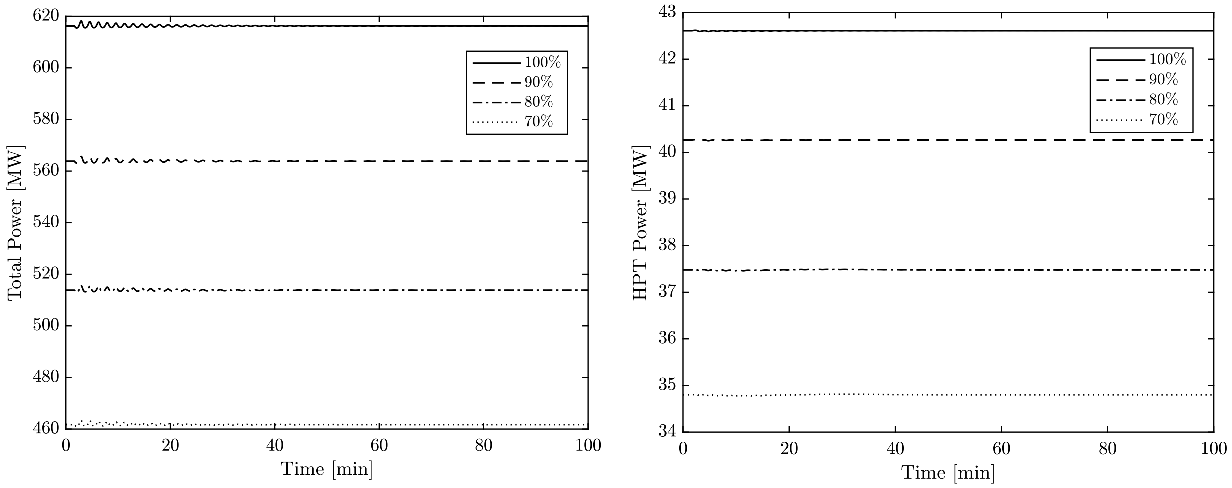
4.1.2. CO_2 Capture Performance

Steam extraction dictates the steam flow rate to the reboiler of the post-combustion capture plant, thereby influencing the CO_2 capture performance. Fig. 5 illustrates the effect of steam flow rate on reboiler temperature, lean loading and CO_2 capture rate. The steam flow rate has an insignificant effect on the transient behaviour of the reboiler temperature, where variation is less than 0.2 °C (shown in Fig. 5d). Therefore, the operating conditions within the stripper column are relatively unaffected and the solvent lean loading (Fig. 5b) only deviates slightly from its steady-state value. This results in almost constant CO_2 capture ratios, defined as the ratio of CO_2 product over CO_2 in the feed flue gas (see Fig. 5a).

Fig. 5 shows how the effect of large fluctuations in steam mass flow rate (Fig. 5c) is dampened in the CO_2 capture system (described in Section 2.2). The dampening effect observed in these results are in line with previous dynamic operation studies discussed in Section 2.2. As steam flow rate fluctuates, the transfer of heat is limited by the heat capacitance of the equipment and fluid. Consequently, the change in reboiler temperature is dampened (Fig. 5d), that is, very little fluctuation observed. Hence, there is minor variation in the degree of solvent regeneration, which leads to limited change in lean loading (Fig. 5b). This contributes to the “smoothing” of the CO_2 capture ratio trend (Fig. 5a). Similarly, the volume of solvent hold-up in the plant (buffer/storage tanks, column sumps) also has a role in buffering variations in the system. Therefore, having large liquid vessels that limit the transient behaviour during slow disturbances are advantageous during fast disturbances as they buffer the dynamics and prevent departure from steady state set-points of the CO_2 capture process. However, this only occurs if the initial and final state of the disturbed variable are similar, otherwise the time required to reach a new steady-state is dictated by the large liquid hold-ups and the transport delays in the capture plant.

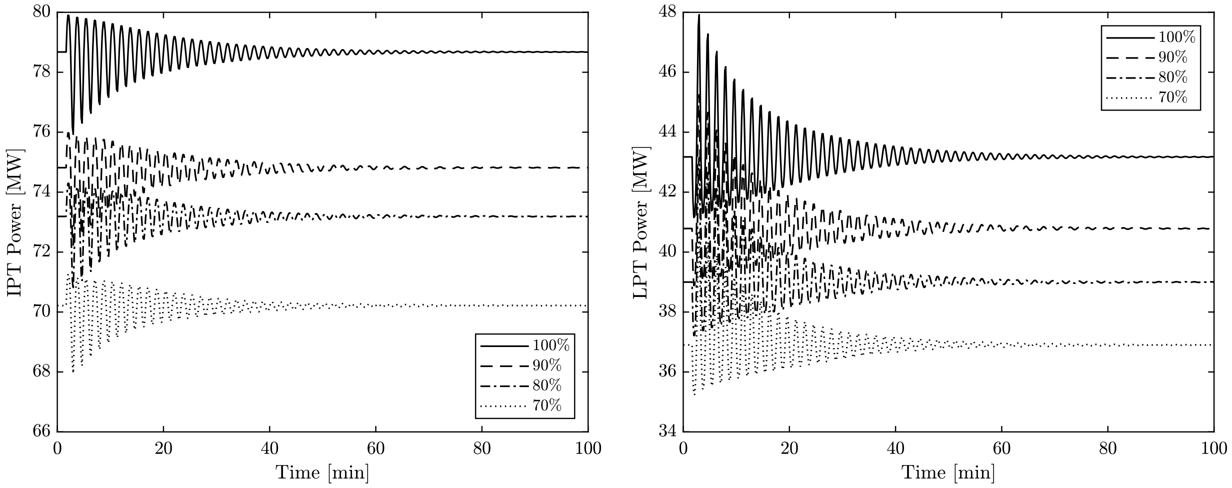
4.2. Effect of Steam Extraction During Dynamic Operation of the NGCC

In this case, the disturbance in the steam extraction valve was imposed simultaneously



(a) Total power generation of the natural gas combined cycle.

(b) Power generation of the high-pressure steam turbine.



(c) Power generation of the intermediate-pressure steam turbine.

(d) Power generation of the low-pressure steam turbine.

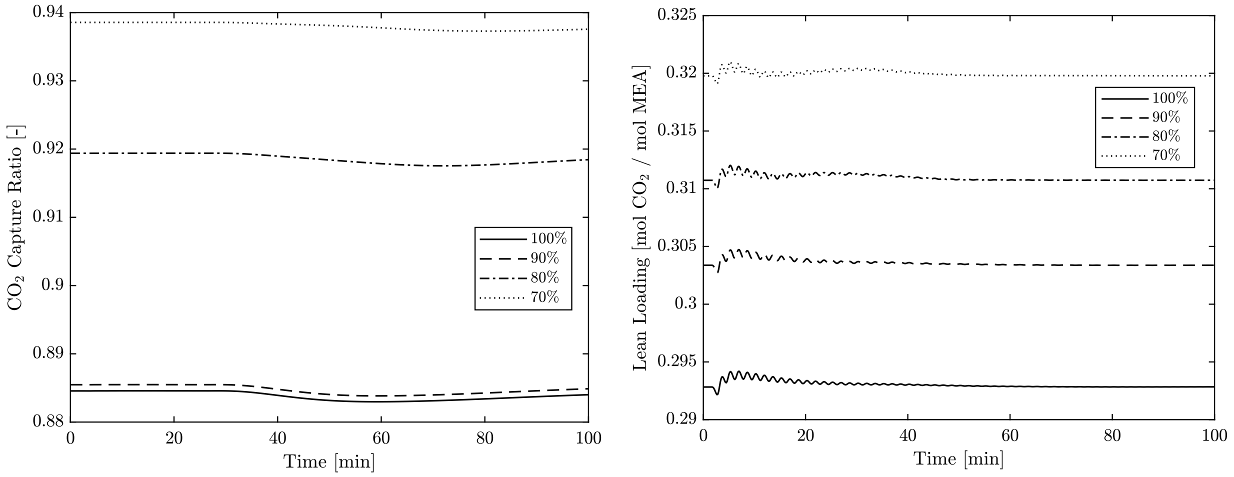
Figure 4: Variation in power generation in the natural gas combined cycle and the steam turbine sections (HP, IP and LP) due to the fluctuation in the steam extracted from the IP-LP crossover at different gas turbine loads.

with a change of load in the gas turbine. The same parameters, i.e. power generation distribution and key performance indicators, were analysed in the NGCC and CO_2 capture plant, respectively.

4.2.1. Power Generation Performance

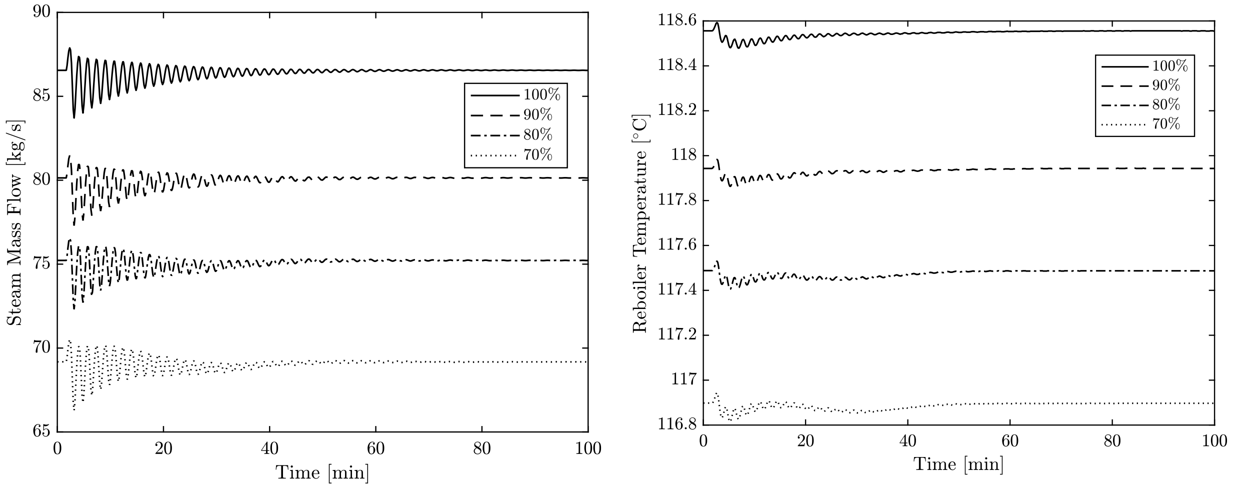
The damping sine signal in the steam extraction valve was implemented during a gas turbine load change from 100% to 70%. This demonstrates the effect of fast variations in the steam extraction during transient operation of the NGCC. Fig. 6 represents the power generation profile of the overall power plant and of each section of the steam turbine. Fig. 7 shows key process variables of the CO_2 capture plant during the transient operation of the power plant with varying steam extraction. Figs. 6 and 7 show performance with fast dynamic fluctuations in the steam extraction valve (black line), and without fluctuations (red line).

During transient operation, the change in gas turbine load dictates power generation (Fig. 6a). This is because the oscillations generated by the steam extraction valve have a negligible effect on power generation in NGCC plants. This occurs regardless of the fluctuations in the IP and LP steam turbines, represented in Figs. 6c and 6d respectively, due to the low contribution of these units to the total power production (see Fig. 3). As steam



(a) CO$_2$ capture ratio.

(b) Lean solvent CO$_2$ concentration.



(c) Steam mass flow rate.

(d) Reboiler temperature.

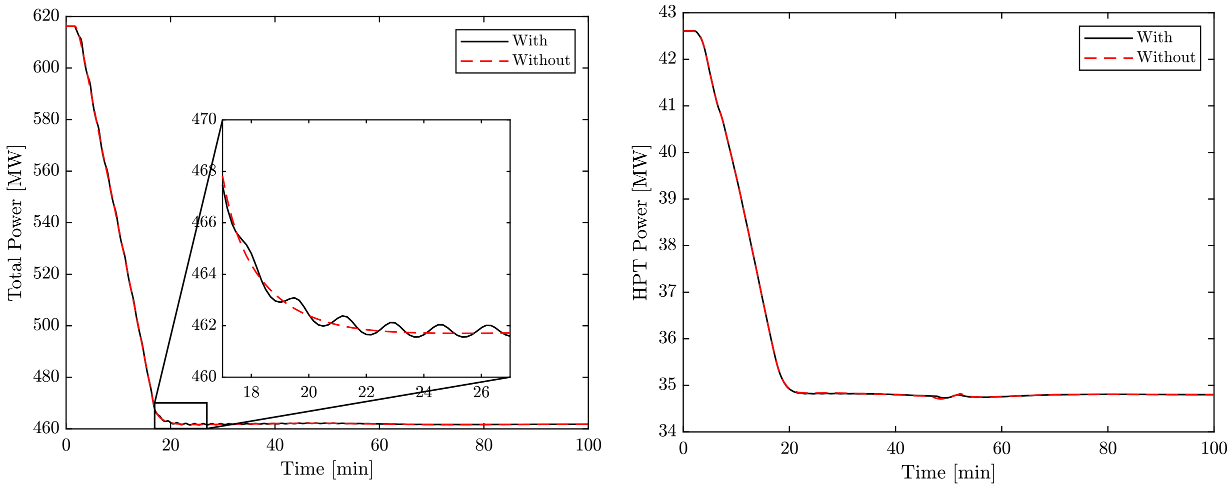
Figure 5: Dynamic behaviour of key process variables in the post-combustion capture plant during steady-state operation of the natural gas combined cycle. Transient operation is driven by opening variations of the steam extraction valve.

extraction does not have a notable effect on the total power generation, the NGCC power plant may operate independently of the capture plant without any penalty on its dynamic performance.

4.2.2. CO$_2$ Capture Performance

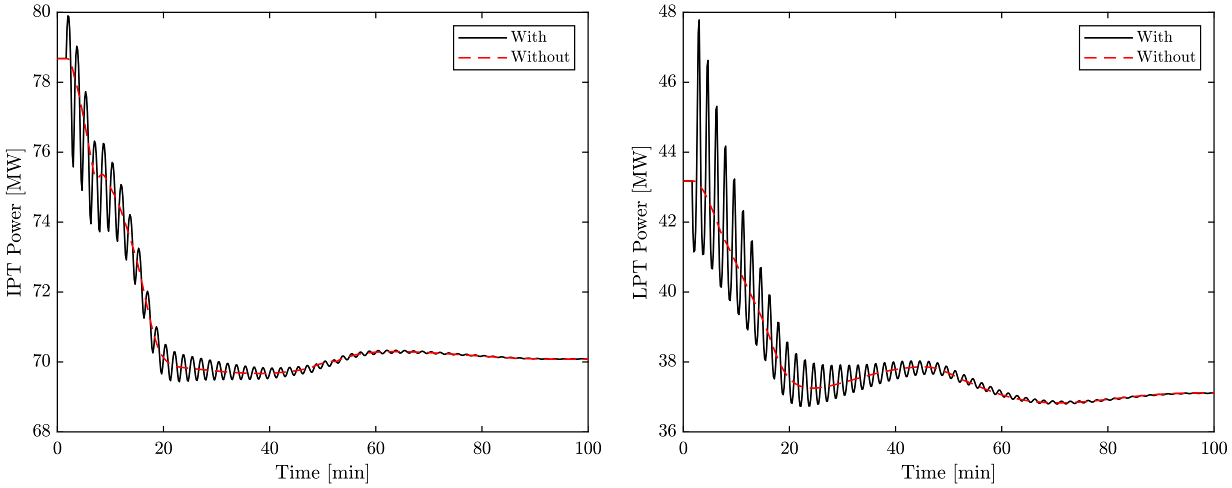
The transient behaviour of the CO$_2$ capture process is governed by the variation in flue gas conditions due to changes in gas turbine load and the steam flow rate fed to the reboiler, which depends on the steam availability in the power plant and the opening of the steam extraction valve. The gas turbine load determines steam availability for extraction at the IP-LP crossover valve, and hence dictates the dynamic performance of the reboiler and stripper. The scenario without fast dynamic fluctuations in steam extraction is represented by the red line in Fig. 7, whereas the behaviour with fast valve fluctuations is shown by the black line.

For a given steam extraction valve opening, the decrease in steam availability that arises from the change in gas turbine load results in less steam extraction (Fig. 7c), which leads to more pronounced variations in the reboiler temperature and lean loading. Unlike the fast disturbances of imposed fluctuations in the opening of the steam extraction valve, the gas turbine load change disturbance is slower. There is sufficient time for heat transfer from the steam to the reboiler fluid, thus reboiler temperature follows the same trajectory as the



(a) Total power generation of the natural gas combined cycle.

(b) Power generation of the high-pressure steam turbine.



(c) Power generation of the intermediate-pressure steam turbine.

(d) Power generation of the low-pressure steam turbine.

Figure 6: Power generation dynamic behaviour during a gas turbine load change from 100% to 70% with and without fast dynamic fluctuations in the steam extraction valve.

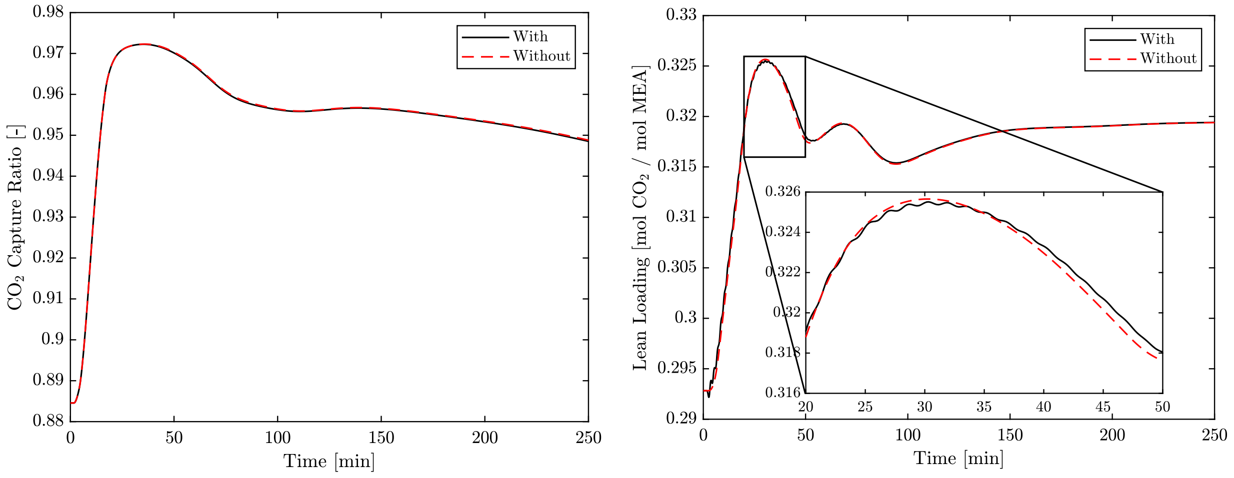
steam flow rate. Similarly, as the reboiler temperature dictates the degree of solvent regeneration, lean loading has the same trend. The variation in reboiler temperature and lean loading have an apparent effect on the CO_2 capture ratio.

In contrast, fast dynamic fluctuations in the steam extraction do not disrupt the transient behaviour of the plant as the main process variables follow the same trajectory as in the scenario without fluctuations (red and black lines in Fig. 7). Thus, steam availability in the steam cycle has a more pronounced affect on the dynamic response of the CO_2 capture plant than the opening of the steam extraction valve.

Similar to the steady-state operation results, a smoothing effect of the fast fluctuations in steam extraction was observed during dynamic operation. Due to the fluctuations in the steam valve being so rapid, which subsequently results in equally rapid steam flow rate fluctuations, there is insufficient time for heat to transfer from the steam to the reboiler fluid. Thus, the reboiler temperature, lean loading and CO_2 capture rate are practically the same with and without steam valve fluctuations.

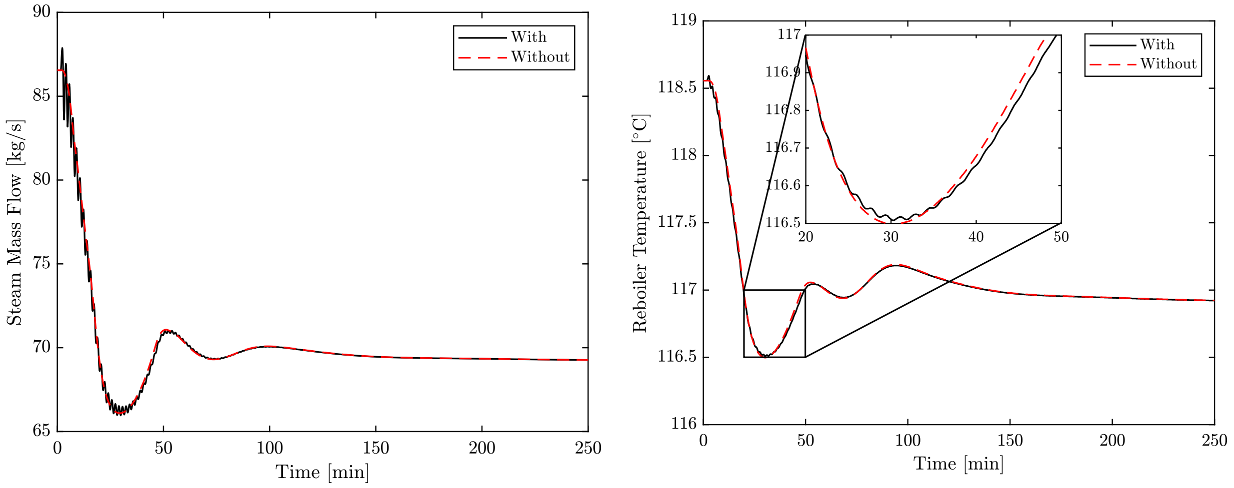
5. Conclusions

There are essentially two ways to integrate post-combustion CO_2 capture with thermal power plants. The first simply connects the



(a) CO$_2$ capture ratio.

(b) Lean solvent CO$_2$ concentration.



(c) Steam mass flow rate.

(d) Reboiler temperature.

Figure 7: Dynamic behaviour of key process variables in the post-combustion capture plant during a gas turbine load change from 100% to 70% with and without fast dynamic fluctuations in the steam extraction valve.

exhaust gas with the capture process, and the energy required for solvent regeneration is supplied externally. Whilst this does present the challenge of mitigating any emissions associated with providing that energy, it does entirely avoid imposing constraints on the operability of the power plant - this form of CCS is an entirely “end of pipe” solution. The second, more commonly discussed, option involves the extraction of steam from between the intermediate and low pressure steam turbines. This avoids the challenge of having to mitigate additional emissions, but has led to concerns as to the effect this strategy might have on the operability of the power plant, since these two plants operate in two different transient timescales. This work seeks to address this challenge by analysing the effect of disturbances on power generation capacity, specifically disturbances with faster dynamics than the dominant dynamics of the power plant.

Transient power generation was assessed during steady-state and dynamic operation of the power plant by modifying the valve opening for steam extraction in the short time-scales defined by the power plant. Since the gas turbine generates most of the total power, fluctuations in the steam extraction valve have no impact on the power generation capacity. In steady-state power plant operation, the total power generation remains unaltered with small fluctuations around the steady-state value that are easily compensated for with small adjustments in the gas turbine. During transient operation of the power plant, the change of load in the gas turbine drives the dynamic behaviour of the

NGCC. Hence, disturbances in steam extraction can be regarded as noise around the transient value dictated by the gas turbine load.

Different behaviour may be expected from power plants where the steam cycle generates most of the power, *e.g.* coal-fired power plants. Valve opening fluctuations in this type of power plants might lead to larger variations in the total power generation since larger steam mass flow rates are required in the steam turbine. Therefore, steam extraction from power plants dominated by the steam cycle performance has greater influence on power generation, and may add value to the flexible performance of NGCCs. However, this behaviour is yet to be demonstrated by dynamic studies.

The transient behaviour of the capture plant was similar to the power plant since its dynamics is dominated by the operating conditions in the gas turbine and steam cycle. A change in gas turbine load results in different flue gas flow rate and steam availability, thereby influencing the performance of the capture plant. The varying steam extraction only leads to small fluctuations, with the trends following the same trajectory as the profile of the scenario varying valve opening variations. These small fluctuations disturb the process and are smoothed along the capture plant. This effect is demonstrated by the disturbance starting as significant fluctuations in steam flow rate, which dampen to become smaller fluctuations in reboiler temperature and lean loading, then finally resulting in a smooth CO_2 capture ratio profile. The dampening effect is attributed to the heat capacitance of the system and the buffering of the disturbance in the large liquid hold-ups. Thus, the large vessels of the capture plant are advantageous for small, fast variations as they buffer disturbances, avoiding departure from steady-state conditions. This phenomena occurs at both steady and dynamic operation of the NGCC.

These results highlight the benefits and disadvantages of having large liquid hold-ups in the capture plant. Large storage vessels allow the buffering of the fast variations in the process variables. However, these vessels also lead to slow transients, increasing the time to reach a new steady state to several hours, which will potentially limit the flexibility of the capture plant. This suggests that the post-combustion capture plants can be operated optimally and independently of the power plant. Imposing tight controls on specific variables to minimize the difference between a value and its set-point a could limit the flexibility of the integrated system. Instead, the capture plant should aim at finding a new optimal operation point given the boundary conditions imposed by the power plant. This is because any changes in steam extraction to achieve optimal operating conditions would not affect power plant performance, as shown in this work. Therefore, the decarbonisation of an NGCC via post-combustion CO_2 capture does not appear to impose any limitation on the flexibility or operability of the underlying power plant in terms of power generation.

Therefore, one key research challenge is to develop control strategies and operation protocols that enable optimal operation of the capture plant that is essentially independent from the operation of the power plant rather than load following mode with fixed capture ratios (Sahraei and Ricardez-Sandoval, 2014; Bankole et al., 2018; Decardi-Nelson et al., 2018). This may lead to improvements in the financial viability of the CCS project as steam extraction fluctuations have no impact on power generation. The development of process control structures designed for flexible operation and dynamic conditions will be an important area of future research (Åkesson et al., 2012; Hauger et al., 2019). Finally, the development of reliable start-up and shut-down protocols for CCS-equipped power plants so as to avoid increasing the carbon intensity of these assets is a priority.

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