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Operational flexibility options in power plants with integrated post-combustion capture

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ABSTRACT

Flexibility in power plants with amine based carbon dioxide (CO_2) capture is widely recognised as a way of improving power plant revenues. Despite the prior art, its value as a way to improve power plant revenues is still unclear. Most studies are based on simplifying assumptions about the capabilities of power plants to operate at part load and to regenerate additional solvent after interim storage of solvent. This work addresses this gap by examining the operational flexibility of supercritical coal power plants with amine based CO_2 capture, using a rigorous fully integrated model. The part-load performance with capture and with additional solvent regeneration, of two coal-fired supercritical power plant configurations designed for base load operation with capture, and with the ability to fully bypass capture, is reported. With advanced integration options configuration, including boiler sliding pressure control, uncontrolled steam extraction with a floating crossover pressure, constant stripper pressure operation and compressor inlet guide vanes, a significant reduction of the electricity output penalty at part load is observed. For instance at 50% fuel input and 90% capture, the electricity output penalty reduces from 458 kWh/tCO_2 (with conventional integration options) to 345 kWh/tCO_2 (with advanced integration options), compared to a reduction from 361 kWh/tCO_2 to 342 kWh/tCO_2 at 100% fuel input and 90% capture. However, advanced integration options allow for additional solvent regeneration to a lower magnitude than conventional integration options. The latter can maintain CO_2 flow export within 10% of maximum flow across 30–78% of MCR (maximum continuous rating). For this configuration, one hour of interim solvent storage at 100% MCR is evaluated to be optimally regenerated in 4 h at 55% MCR, and 3 h at 30% MCR, providing rigorously validated useful guidelines for the increasing number of techno-economic studies on power plant flexibility, and CO_2 flow profiles for further studies on integrated CO_2 networks.

1. Introduction

Reducing carbon dioxide emissions to prevent climate change has become one of the key priorities for the energy sector. One route to achieve decarbonised electricity systems within the targets highlighted by the latest IPCC report (IPCC, 2013) will entail expanding renewable energy supply and using nuclear energy and fossil fuel plants with carbon capture and storage (CCS). Given the current installed capacity and expansion plans for electricity generation from variable renewable sources, future power systems will favour resources that provide system flexibility (ability to follow changes in variable energy plant output). In this respect, fossil fuel power plants with integrated CO_2 capture (for transportation and storage) could also play an important role in balancing low carbon electricity grids.

Post-combustion capture based on amine scrubbing is a mature technology that has been proven at small to medium scales and is the technology of choice for the first fossil fuel power plants with CO_2 capture (Boot-Handford et al., 2014). In future electricity systems, power plants with integrated amine-based post-combustion capture (here referred to as CCS power plants) are expected to operate at variable load to balance the intermittent supply from renewable sources (depending on net electricity demand) and produce low carbon intensity electricity by capturing most of the CO_2 emitted (Bruce et al., 2015). Understanding of operating flexibility is an important step in the development of amine

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scrubbing technology since they were typically designed as a base load continuous operation separation technology for natural gas treating (Kohl and Nielsen, 1997).

Flexible operation of the capture unit is widely suggested as a way to improve the economics of CCS power plants (Chalmers and Gibbins, 2007; Chalmers et al., 2009; Cohen et al., 2010, 2012; Delarue et al., 2012; Haines and Davison, 2014; Oates et al., 2014; Van der Wijk et al., 2014). For instance, the capacity to vary steam extraction levels from the power cycle to adjust both power output and capture level is a valuable option to increase/decrease power output rapidly to meet grid requirements, maintain the output of the power plant in case of a failure either in the CO_2 capture, transport or storage part of the system, generate revenue in response to price signals in the electricity spot market or generate revenue in the reserve market.

A key assumption when assessing the implications of CCS power plant flexibility is how the CO_2 capture plant is operated, which is influenced by legislation for CO_2 emissions. The CO_2 capture plant could be operated flexibly around the power plant if an annual emission tonnage is implemented instead of emission concentration limits or removal rates. Therefore, strategies for part-load operation and/or flexible operation of capture units can be classified according to their objective. There are strategies for part-load operation of the capture unit that aim to maintain the capture level, normally referred as load-following, which have been described by several authors (Kvamsdal et al., 2009; Ziaii et al., 2009; Van der Wijk et al., 2014; Brasington, 2012). Other strategies aim to provide fast power augmentation by stopping solvent regeneration temporarily (Haines and Davison, 2014) or pursue additional profitability. Capture by-pass, also referred as venting (Chalmers and Gibbins, 2007; Gibbins and Crane, 2004), consists in turning down/off the capture and compression unit and diverting the steam extracted for solvent regeneration back to the power cycle bringing it to its full net power output. When the capture unit is supplied with amine solvent storage capacity followed by delayed solvent regeneration (Chalmers and Gibbins, 2007; Gibbins and Crane, 2004), the power plant has the ability to reduce considerably the energy penalty for a set period of time and regenerate rich solvent later time.

This flexible strategy is associated with an increase in plant revenues when electricity prices are high and/or from balancing services (Chalmers and Gibbins, 2007; Chalmers et al., 2009; Cohen et al., 2010, 2012; Delarue et al., 2012; Gibbins and Crane, 2004; Oates et al., 2014). However, profitability is highly dependent on the differential in electricity prices and the amount of wind generation in the electricity system considered. Brasington (2012) showed that flexibility with amine solvent storage does not increase profitability under the set of electricity price spreads that were considered. Patiño-Echeverri and Hoppock (2012) showed that flexibility with amine storage may be marginally cost-effective for retrofitted plants by taking advantage of arbitrage opportunities present in electricity markets with large price differentials.

Van der Wijk et al. (2014) recently carried out a comprehensive study integrating a capture unit with an electricity system model of the North West part of Europe, including revenue from some ancillary services. By comparing the revenues of different options for flexible CCS power plants to a non-flexible counterfactual they showed that the main benefit of flexible CCS is an increase in reserve capacity. They also concluded that solvent storage could be a viable option independent of the carbon price if solvent can be regenerated during hours of low demand, when the plant generator operates regularly at part-load when it is displaced by wind generation. The work of Oates et al. (2014) concluded that solvent storage could be used for capital cost gain by undersizing the regenerator to smooth out compressed CO_2 flow throughout the day.

Mac Dowell and Shah (2013, 2015) have proposed a flexible solvent regeneration strategy. Using a multi-period design approach, they show that, with perfect foreknowledge of electricity prices and a specific set of electricity price distribution, time varying solvent regeneration approach has the potential to generate electricity that has, on average, a lower carbon dioxide intensity and to be more profitable than the options of either capture bypass or solvent storage (Mac Dowell and Shah, 2014).

Despite this prior art, the value of flexibility strategies in CCS power plants is still unclear, and conclusions from various authors are sometimes contradictory, perhaps due to the complexity of the networks and systems involved. The assumptions about part-load performance and the capabilities of the plant when operated with solvent storage and delayed solvent regeneration have a large influence on the outcome of flexibility studies. Besides the influence of the selected assumptions, which is not always reported transparently, most of the previous studies simplify parts of the systems involved in power generation and capturing and compressing CO_2. For instance, the performance of the capture unit is simplified (Lucquiaud et al., 2007), the interface between the power cycle and the capture is not described (Van der Wijk et al., 2014) or is simplified (Ziaii et al., 2009), the effects on compression power of changes in the volumetric flow rate of CO_2 at part-load are not included (Van der Wijk et al., 2014), or they focus on the operation of one part of the system only (Kvamsdal et al., 2009). This work builds on these studies and examines the full implications of important parameters, such as power plant efficiency at part-load and impact of additional solvent regeneration on overall efficiency. Parameters related to flexible operation such as capture level, availability of steam extraction and steam pressure, compressor efficiency, are included to evaluate the extent of the sensitivity of the value of flexibility to these parameters.

In addition, future CCS power plants, beyond initial demonstration from a single source to a single CO_2 sink, will have to operate within the constraints of a second network, namely the downstream CO_2 transport and storage system. The latter presents its own constraints on variations in CO_2 flow and conditions, CO_2 phase change, injection rates and gas composition. CCS power plant flexibility may become valuable to control CO_2 flows, possibly independently of electricity generation, to meet the requirements of transport networks or storage sites by adjusting compressed CO_2 flow in response to signals from the transport network and storage operators.

This study contributes to the existing literature on CCS power plant flexibility by providing an engineering analysis of part load and flexible operation of CCS power plants using a rigorous fully integrated modelling approach of the CCS power plant system. The part-load operation of a supercritical coal power plant is evaluated taking into account the main factors that influence the performance of capture units integrated into flexible power plants:

(1) Power plant part load strategy,
(2) Power plant and capture unit integration philosophy,
(3) Capture unit configuration and operation strategy, and
(4) Compression unit operation.

For this purpose, a detailed model is used to characterise the operating envelope, the performance and the corresponding CO_2 output of supercritical coal power plants with post-combustion capture for a range of loads, varying from 20% to 100% of the power plant maximum continuous rating (MCR), with or without voluntary by-pass of the capture unit. The performance of two power plant configurations is evaluated. The first configuration illustrates the case of a CCS power plant designed with limited consideration for part-load operation and flexibility, with the exception of oversizing the low pressure turbine, which is a minimum requirement