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The multi-period optimisation of an amine-based CO_2 capture process integrated with a super-critical coal-fired power station for flexible operation

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ABSTRACT

In this work, we present a model of a super-critical coal-fired power plant integrated with an amine-based CO_2 capture process. We use this model to solve a multi-period dynamic optimisation problem aimed at decoupling the operation of the power plant from the efficiency penalty imposed by the CO_2 capture plant, thus providing the power plant sufficient flexibility to exploit price variation within an electricity market. We evaluate four distinct scenarios: load following, solvent storage, exhaust gas by-pass and time-varying solvent regeneration. The objective is to maximise the decarbonised power plant's short run marginal cost profitability. It is found that while the solvent storage option provides a marginal improvement of 4% in comparison to the load following scenario, the exhaust gas bypass scenario results in a profit reduction of 17% whereas the time-varying solvent regeneration option increases the profitability of the power plant by 16% in comparison to the reference scenario.

1. Introduction

Given the increasing penetration of intermittent renewable electricity generation and the essentially inflexible nature of baseload nuclear power generation, there is increasing focus on the need for decarbonised fossil fuel-fired power stations to operate in a flexible fashion as part of the low carbon energy system of the future (Mac Dowell et al., 2010; Davison, 2011; Ludig et al., 2011; Kalinin et al., 2012; Nimtz and Krautz, 2013; Domenichini et al., 2013; Oates et al., 2014; van der Wijk et al., 2014; Boot-Handford et al., 2014). It will be important that the flexible operation does not result in an increase in the overall carbon intensity of the electricity generated. In this study, we define "flexibility" as the decoupling of electricity generation from the energy penalty associated with the injection of CO_2 into a CO_2 transport grid in order to allow the power plant to take advantage of peak prices in the electricity market, whilst simultaneously maintaining a prescribed minimum average carbon intensity of the electricity generated. It is therefore useful to distinguish between the instantaneous Degree of Capture (DoC) and the Integrated Degree of Capture (IDoC). The DoC is, as usual, given by

$$\mathrm{DoC} = 100.\left(\frac{\mathrm{CO_2^{Generated}} - \mathrm{CO_2^{Emitted}}}{\mathrm{CO_2^{Generated}}}\right) \tag{1}$$

where $CO_2^{Generated}$ is the CO_2 generated by the power station and $CO_2^{Emitted}$ is the CO_2 emitted to atmosphere. In this study, the DoC is used as an interior path constraint. However, from the perspective of the dynamic operation, it is the average carbon intensity of the electricity generated by the decarbonised power plant over a given period that is of interest, and therefore we define the Integrated Degree of Capture to be:

$$\mathrm{IDoC} = \int_{t_0}^{t_f} \mathrm{DoC}dt \tag{2}$$

where t_0 and t_f are the start and end times of the period of interest. This is obviously general and can be specified to be any relevant time-period, e.g., a day, week, month or even a year. For example, in the context of UK electricity market reform, this period is a year (Maintaining, 2014; Electricity market, 2014). In this study, the IDoC is used as an end-point constraint. The recent contribution of Bui et al. (Bui et al., 2014) provides an authoritative and critical review of the current state-of-the-art of dynamic modelling of post-combustion CO_2 capture processes. In particular, they noted

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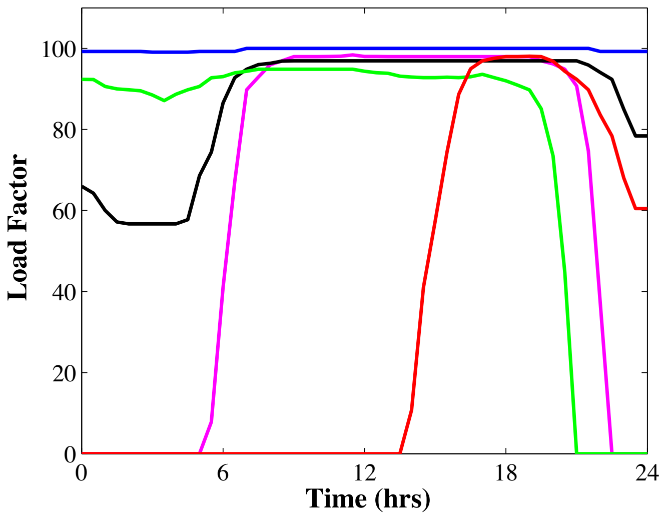

Fig. 1. Data from Elexon (Balancing, 2014) was used to identify five typical modes of behaviour for coal-fired power plants in the UK in 2012. The continuous blue curve represents a "baseload" plant, the continuous magenta curve represents a "peaking plant", the continuous green curve represents a "switch-off" plant, the continuous red curve represents a "switch-on" plant and finally the continuous black curve represents a "load following" plant. In this work, we are interested in the behaviour of the load following plant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

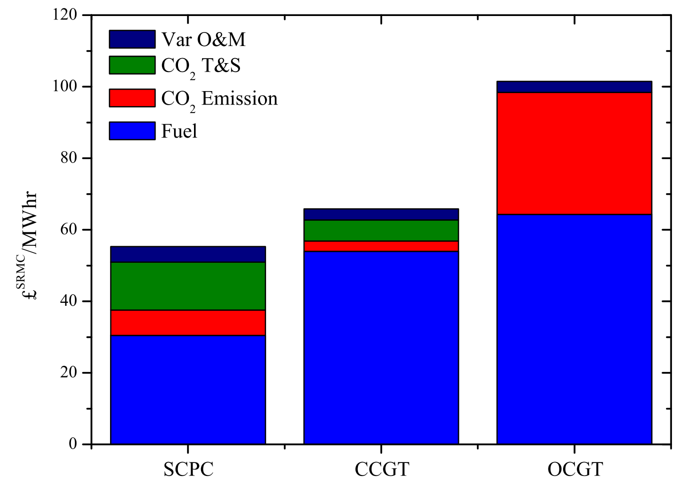

Fig. 2. Calculated electricity prices for a SCPC, CCGT and OCGT using Eq. (3) and the data presented in Table 1. We note that we are assuming that OCGTs will operate in an unabated fashion, thus they are subject to a significant cost associated with their CO_2 emissions.

that flexible operation of PCC may involve the variation of the CO_2 capture rate in accordance with trends in the electricity market, reducing the PCC energy impost during crucial periods. In this context, the main suggestions for flexible operation have included solvent storage (Gibbins and Crane, 2004; Cohen et al., 2011), or CO_2 capture bypass (also known as exhaust gas venting) (Rao and Rubin, 2006; Cohen et al., 2011). A further point made by Bui et al. (Bui et al., 2014) is that despite the fact that there are numerous contributions in the literature wherein detailed dynamic models of post-combustion CO_2 capture have been presented (see for example (Lawal et al., 2009, 2010, 2012; Gaspar and Cormos, 2011, 2012; Harun et al., 2012; Mac Dowell et al., 2013; Mac Dowell and Shah, 2013; Saimpert et al., 2013) and references therein), the majority of these studies have focused on the steady state operation of the capture plant, while the optimisation of processes for dynamic operation is typically overlooked. This is of particular importance as power plants in a given energy system do not all operate in the same way. For example, as illustrated in Fig. 1, in 2012 there were five distinct types of load factor exhibited by coal-fired power plants based in the UK (Balancing, 2014).

The way in which these five different plant types operate are significantly different. It is therefore probable that each would adapt significantly different designs and operation strategies for their decarbonisation. Further, in a diverse, low carbon energy system, there will be a greater premium associated with the ability of a power plant to operate in a load following manner. Thus, we will focus solely on the "load following" plant in the remainder of this study.

1.1. Energy system of the 2030s

In this study, we are considering the design and operation of a super-critical coal-fired power plant integrated with post-combustion CO_2 capture process using 30 wt% monoethanolamine (MEA) in aqueous solution as a solvent. We envision that this kind of generator will be situated in the mid-merit/peak market with baseload electricity generation provided by inflexible nuclear power. We consider that peak energy demand is met by a combination of fossil-fuels and renewable generators. We assume that fossil fuel derived electricity will be provided by super-critical pulverised coal (SCPC), combined cycle gas turbines (CCGT) and open cycle gas turbines (OCGT). Clearly, each of these generators have different short run marginal costs (SRMC). Data from the UK's Department of Energy and Climate Change (DECC) (DECC, 2012; Update short, 2011) were used to specify fossil fuel prices, $£_{Fuel}^{MWhr}$, and carbon prices, $£_{Tonne}^{CO_2}$. Similarly, data from the Joint Research Centre of the European Commission (Vatapoulos et al., 2012) was used to specify a range of probable generator efficiencies, η_{Plant} and carbon intensities, $CI_{MWhr}^{Tonnes\ \ CO_2}$. Using these data, we calculate possible short run marginal cost (SRMC) prices for SCPC, CCGT and OCGT in the 2030s using Eq. (3):

$$\frac{£^{\mathrm{SRMC}}}{\mathrm{MWhr}} = \frac{£_{\mathrm{Fuel}}^{\mathrm{MWhr}}}{\eta_{\mathrm{Plant}}} + (£_{Tonne}^{CO_2} . CI_{\mathrm{MWhr}}^{\mathrm{Tonnes\ \ CO_2}}) + £_{VarO\&M} + £_{T\&S}^{CO_2}. \qquad (3)$$

where $£^{\mathrm{SRMC}}$ is the SRMC cost of the electricity generated by a given plant which includes the variable operating and maintenance costs, $£_{VarO\&M}$ and also the fixed cost of CO_2 transport and storage $£_{T\&S}^{CO_2}$. For convenience, these values are provided in Table 1.

Using the data in Table 1 in Eq. (3), the calculated SRMC for each generator is illustrated in Fig. 2. We note that these numbers are within 15% of previously reported costs (Electricity, 2012; Foy et al., 2013), providing some confidence in the usefulness of the scenarios considered in this work.

On the basis of Fig. 2, we hypothesise that over-night (off-peak) electricity prices will be set by SCPC plants, day-time prices will be set by CCGT plants with morning and evening peaks serviced by OCGT plants. This hypothesis is illustrated in Fig. 3:

Fig. 3 also serves to illustrate the multi-period concept applied to 24 h. As can be observed, there are 6 distinct periods of operation; 2 peak periods and 4 off-peak periods. As pointed out by Bui et al. (Bui et al., 2014), there is a knowledge gap associated with how a decarbonised plant will operate to exploit the differential between peak and off-peak electricity prices. It is the aim of this paper to address this gap by quantifying the extent to which different modes of operation can decouple the operation of the solvent regeneration process from that of the power plant, thus allowing the power plant to act in a profit maximising manner whilst concurrently maintaining a low average carbon intensity of the electricity which it generates. We achieve this by applying Grossmann and Sargent's (Grossmann and Sargent, 1979) theory for the optimum design of multipurpose chemical plants to the integrated design and