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Cost and performance of some carbon capture technology options for producing different quality CO_2 product streams

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This paper is dedicated to the memory of our friend and colleague, Dr. Robert M. Woolley, who made a significant input to the CO_2QUEST project and whose expertise, commitment and great humour will never be forgotten.

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ABSTRACT

A techno-economic assessment of power plants with CO_2 capture technologies with a focus on process scenarios that deliver different grades of CO_2 product purity is presented. The three leading CO_2 capture technologies are considered, namely; oxyfuel combustion, pre-combustion and post-combustion capture. The study uses a combination of process simulation of flue gas cleaning processes, modelling with a power plant cost and performance calculator and literature values of key performance criteria in order to evaluate the performance, cost and CO_2 product purity of the considered CO_2 capture options. For oxyfuel combustion capture plants, three raw CO_2 flue gas processing strategies of compression and dehydration only, double flash system purification and distillation purification are considered. Analysis of pre-combustion capture options is based on integrated gasification combined cycle plants using physical solvent systems for capturing CO_2 and sulfur species via three routes; co-capture of sulfur impurities with the CO_2 stream using Selexol™ solvent, separate capture of CO_2 and sulfur impurities using Selexol™, and Rectisol® solvent systems for separate capture of sulfur impurities and CO_2. Analysis of post-combustion capture plants was made with and without some conventional pollution control devices. The results highlight the wide variation in CO_2 product purity for different oxyfuel combustion capture scenarios and the wide cost variation for the pre-combustion capture scenarios. The post-combustion capture plant with conventional pollution control devices offers high CO_2 purity (99.99 mol%) for average cost of considered technologies. The calculations performed will be of use in further analyses of whole chain CCS for the safe and economic capture, transport and storage of CO_2.

1. Introduction

CO_2 Capture and Storage (CCS) technologies will produce CO_2 product streams that are expected to contain a range of impurities at certain levels depending on the technology type and several other factors. The impact of these impurities on the safe and economic transportation and storage of CO_2 is a fundamentally important issue that must be addressed prior to wide scale deployment of CCS (CO_2QUEST, 2015). The ultimate composition of the CO_2 streams captured from fossil fuel power plants or other CO_2 intensive industries and transported to storage sites using high pressure pipelines will be governed by safety, environmental and economic considerations. Even though from a technological perspective, very high purity CO_2 from fossil fuel-fired power plant flue gas is achievable, it may not be required for some transport and storage applications, and so the associated increase in cost in achieving high purity levels may be avoided. Conversely, the extent to which impurities can be co-disposed along with CO_2 in capture streams is currently uncertain in terms of its technical feasibility and acceptability. Impurities in CO_2 mixtures can potentially cause problems with compression, as well as corrosion issues for pipeline transport. Economic viability and acceptability in terms of the risks to health and the environment are also crucial factors. Pipeline operators and CO_2 end users may impose regulations that limit impurities concentrations that are accepted, therefore further purification will become necessary. Some previous studies have assumed that impurities can be co-captured for co-disposal

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while others assume flue gas purification is necessary. Therefore, it is important to determine the optimal balance between purification costs and the transport and storage requirements. This study presents a cost benefit analysis in relation to product purity in CO_2 capture systems to enable the evaluation of the economic viability of co-capture scenarios in full chain CCS systems.

Impurities in CO_2 captured from combustion-based power generation with CCS can arise in a number of ways and include major and minor fuel oxidation products (e.g., H_2O, SOx, NOx, Hg), air related impurities (N_2, O_2 and Ar) and process fluids, such as solvents (e.g. monoethanolamine (MEA) and Selexol™) used for capture (Porter et al., 2015). CO_2 impurities are known to have a number of mainly detrimental impacts on the downstream transport and storage CCS chain elements. CO_2 impurity impacts can be classified into chemical (e.g. those caused by SO_2), physical impacts (e.g. those caused by N_2) and toxic/ecotoxic effects (e.g those caused by mercury) (Farret, 2015). The numerous types of impacts of impurities on transport and storage in CCS have been outlined in two reports by the IEAGHG (2004a,b, 2011) and further studies by the National Energy Technology Laboratory (NETL) (Matuszewski and Woods, 2012) and the Dynamis project (de Visser et al., 2008) which have provided recommended impurity limits for CO_2 stream components in studies of CO_2 capture utilisation and storage systems. Limits are suggested based upon a number of different factors and these quality guidelines may serve as a basis for conceptual studies.

Of the different capture technologies, oxyfuel combustion is known to have the widest possible range of CO_2 purity, being dependent mostly on the selection of the CO_2 purification strategy (e.g. compression and dehydration only, "double flash" phase separation, or cryogenic distillation). Detailed modelling of these processes has been reported in work performed by Mitsui Babcock, Alstom and Air Products for the IEAGHG (Dillon et al., 2005) with costs and CO_2 product quality reported. Further process simulation studies have aimed to optimise these processes (Posch and Haider, 2012) and have analysed the impact of impurities on the purification requirements (Li et al., 2009). The highest concentration impurities from oxyfuel combustion capture are O_2, N_2 and Ar, but SOx and Hg may also be present at certain levels posing corrosion concerns.

The level of CO_2 purity derived from pre-combustion capture in Integrated Gasification Combined Cycle (IGCC) plants has a narrower range as compared to oxyfuel combustion capture. Potentially problematic impurities from pre-combustion capture are H_2S, due to corrosion issues when mixed with water, and H_2 which can lead to increased pumping costs and reduced storage capacity. Process factors that have a large influence on the CO_2 purity in pre-combustion capture include the choice of solvent and the CO_2 capture process configuration and, in particular, the decision whether to remove sulfur species simultaneously with CO_2 (co-capture scenario) or to remove them in a separate stream for possible further processing (separate capture scenario). The potential benefits of co-capturing impurities in pre-combustion gasification systems have been investigated in a report published by the IEAGHG (2004a,b), resulting in cost savings relative to CO_2-only capture for Selexol™ solvent systems. Ordorica-Garcia et al. (2006) have performed detailed process system simulation studies of IGCC systems with glycol solvents with plants that co-capture impurities showing substantial techno-economic advantages over separate capture plants due to their decreased energy penalty and lower capital costs. Further work by Padurean et al. (2012) has compared the techno-economics of the use of different solvents in IGCC at different levels of CO_2 capture, concluding that Selexol™ is the more energy efficient solvent when compared to the others investigated such as Rectisol®.

Post-combustion capture generally has low levels of impurities, with dried CO_2 purity usually reported in excess of 99% (E.C., 2011; CO_2PIPETRANS, 2008) and impurities are less of an issue, N_2, water and O_2 are the main impurities of highest concentration. Estimates for the efficiency penalty typically range between 8 and 16% points for pulverised coal plants with post-combustion capture units (Goto et al., 2013). Techno-economic studies often aim to find the optimal configuration for the process (Rao and Rubin, 2006; Schach et al., 2010). Lee et al. (2009) estimated the impurities included in the CO_2 stream from a post-combustion capture control unit with different combinations of air pollution control devices and different flue gas compositions, concluding that plants employing Flue Gas Desulfurisation (FGD) systems followed by absorption using monoethanolamine are the most favourable in terms of minimising the impacts from CO_2 impurities in geological storage.

Comparative techno-economic assessments of CO_2 capture technologies as applied to fossil fuel power plants have been performed by a number of authors (Rubin et al., 2005, 2007; Ekström et al., 2009; Parsons Brinckerhoff, 2012), including those that incorporate a significant portion of biomass in the fuel input (Al-Qayim et al., 2015; Catalanotti et al., 2014). However, to our knowledge, there has been no published study of a cross-comparative cost-benefit analysis for producing CO_2 product streams of different quality from the three leading capture technologies of oxyfuel combustion capture, pre-combustion capture and post-combustion.

The purpose of this paper is to develop an understanding of the dependence of capture cost on the required purity level. A scenario-based cost analysis is presented for the three capture technologies of oxyfuel combustion capture, pre-combustion capture and post-combustion capture with respect to impurities removal and variation. The scenarios include different power plant configurations and options for CO_2 purification. The performance of the different scenarios with respect to mass and energy balances, energy production and CO_2 purity is assessed. To account for the many factors that affect the power output, cost of electricity, emissions and cost of CCS at combustion based power plants, we have used the Integrated Environmental Control Model (IECM) to perform techno-economic calculations. The IECM was selected because it provides ready built in process performance models for a range of combustion based power generation and CO_2 capture technologies and therefore extends the scope of this study to a large range of scenarios. The IECM model cases have been supplemented in some areas where necessary using calculations performed using a process systems simulator and with information gathered from a detailed literature survey. The engineering cost models are applied to calculate capital costs in addition to operational and maintenance costs; these costs are then used to calculate the cost of electricity and other techno-economic indicators for each of the technologies and scenarios considered. Finally, the costs of each scenario and different CO_2 purity levels are compared and discussed.

2. Analysis of oxyfuel combustion carbon capture with respect to cost and CO_2 impurities

2.1. Modelling methods and assumptions

Currently, one of the leading technologies for CO_2 capture from coal fired power plants is oxy-combustion capture. This capture method comprises of an ASU to produce a high purity oxygen stream which is mixed with recycled flue gas, providing an oxidation environment in which to burn the fuel that is low in nitrogen but has similar characteristics to those encountered in air combustion. The flue gas produced by oxyfuel combustion will vary in purity, and still requires dehydration, further purification and compression in order to be suitable for transport and storage. The latter is performed by means of a CO_2 compression and purification unit