Applied Energy 138 (2015) 546–558

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Economic assessment of novel amine based CO_2 capture technologies integrated in power plants based on European Benchmarking Task Force methodology

G. Manzolini [a], E. Sanchez Fernandez [b,*], S. Rezvani [c], E. Macchi [a], E.L.V. Goetheer [b], T.J.H. Vlugt [d]

[a] Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy
[b] TNO Gas Treatment, Leeghwaterstraat 46, 2628 CA Delft, The Netherlands
[c] Ulster University, York Street Belfast, County Antrim BT15 1ED, United Kingdom
[d] TU Delft, Engineering Thermodynamics, Leeghwaterstraat 39, 2628 CB Delft, The Netherlands

HIGHLIGHTS

- Novel amine solvent applied to ASC and NGCC power plants.
- CESAR-1 (AMP and piperazine) reduces the cost of CO_2 avoided compared to MEA.
- Higher cost reduction achieved for ASC power plants.
- European common methodology description for economic benchmark studies in carbon capture.

ARTICLE INFO

Article history:
Received 21 July 2013
Received in revised form 20 April 2014
Accepted 22 April 2014
Available online 28 July 2014

Keywords:
CESAR-1 solvent
2-Amino-2-methyl-propanol
Piperazine
MEA
Post-combustion CO_2 capture (PCC)
Economic analysis

ABSTRACT

The objective of this paper is to assess the economic advantages of an innovative solvent for CO_2 capture on state-of-the-art solvents. The CESAR-1 solvent, which is an aqueous solution of 2-amino-2-methyl-propanol (AMP) and piperazine (PZ), is applied both to advanced supercritical pulverised (ASC) coal and natural gas combined cycle (NGCC) power plants with post-combustion CO_2 capture units. The methodology includes process model developments using commercial simulation programs, which determine the thermodynamic properties of the selected power plants and the performance of the CO_2 capture units. The results show that the techno-economic benefit of CESAR-1 versus MEA is more significant for ASC than that for NGCC due to a higher concentration of CO_2 in the flue gas. This follows from the fact that the switch from MEA to CESAR-1 solvents reduces the electricity cost by 4.16 €/MW h in the case of the ASC plant compared to 0.67 €/MW h in connection with the proposed NGCC plant. Based on the above figures, we can conclude that CESAR-1 reduces the cost of CO_2 avoided compared to MEA by 6 €/t CO_2 and 2 €/t CO_2 for the selected ASC and NGCC plants respectively. In view of that, the techno-economics can be improved if the CO_2 capture plant is designed to operate using the CESAR-1 absorption technology due to a reduction in the regeneration energy and the solvent recirculation rate (considering its higher CO_2 net capacity). However, the variable costs of running the capture plant are higher for the CESAR-1 solvent due to the higher cost of the amines.

1. Introduction

Within the power generation sector, post-combustion capture (PCC) is one of the options in the portfolio of CO_2 abatement technologies [1,2] that will reduce CO_2 emissions from fossil fuels. The broad number of innovations in the field, over five hundred patents have been published in the last thirty years [3], confirms the growing interest in technologies related to CO_2 capture. The current state-of-the-art in PCC is chemical absorption systems because the technology is commercially available and it has been proven at smaller scale in other fields [4]. Among the patented CO_2 capture technologies, the majority relate to solvent development, in particular amines. The major challenge facing implementation on a large scale is the high capital cost and operating cost of the technology together with an uncertain CO_2 emissions regulation. Information about the cost of CO_2 capture and storage is subjected to extensive research. There are works published in the literature assessing the

* Corresponding author.
E-mail address: eva.sanchez@processmonkey.co.uk (E. Sanchez Fernandez).

http://dx.doi.org/10.1016/j.apenergy.2014.04.066
0306-2619/

Nomenclature

AMP	2-amino-2-methyl-1-propanol
ASC	advanced supercritical power cycle
BU	bottom-up approach for capital investment estimation
CCS	carbon capture and storage
CESAR-1	amine based solvent (23% w/w AMP and 12% w/w PZ)
COE	cost of electricity (€/MW h)
DCC	direct contact cooler
DCF	discounted cash flow rate (%)
E	specific CO_2 emissions (kg/kW h)
EBTF	European Benchmarking Task Force
EPC	engineering and procurements cost (M€)
FG	flue gas
IC	indirect cost factor (%)
IGCC	integrated gasification combined cycle
MEA	monoethanolamine
NGCC	natural gas combined cycle
PC	pulverised coal
PCC	post-combustion carbon capture
PZ	piperazine
r	equipment performance rate (units depend on equipment type, e.g. for heat exchangers *r* is heat transfer area (m^2))
TD	top-down approach for capital investment estimation
TDPC	total direct plant cost (M€)
TEC	total equipment cost (M€)
TIPC	total indirect plant cost (M€)
TPC	Total plant cost (M€)

Greek letters

α	specific equipment cost as a function of equipment performance rate (M€)
β	factor accounting for owner's cost and contingency (%)

Subscripts

i	indicates the attributes of a plant component (e.g. efficiency, heat rate)
j	indicates a specific equipment piece

economics of fossil fuel based plants with amine based PCC performed by agencies and independent authors [5–11]. A recent work by Finkenrath [12] summarised and aligned the economic evaluation of fossil fuel based power plants with carbon capture and storage (CCS). The original values from Finkenrath [12] have been calibrated to match the assumptions of this work (values in €, 2008). The calculated average of the specific investment cost for ASC plants without capture is about 1398 €/kW (based on bituminous coal) with an increase of 60% when CO_2 capture is applied. The increase is due to both higher capital investment costs and lower net power outputs. The resulting cost of electricity increases from 48 €/MW h for no capture case to 71 €/MW h with capture resulting in a cost of CO_2 avoided of 36 €/t CO_2. The specific costs of NGCC are significantly lower and equal to 674 €/kW without capture which increases to 1204 €/kW for a capture case. The determined cost of electricity is 48 €/MW h and 59 €/MW h for no capture and with capture respectively. This corresponds to a CO_2 avoidance cost of 44 €/t CO_2. The cost of electricity increase in the first industrial scale CO_2 capture plant installed in China confirmed the figures above shown. In this particular case, the cost of electricity increase was quoted equal to 29% [13]. As a basis for comparison, the cost of CO_2 avoided for renewable energies is in the range of 80–250 €/t CO_2 [14], making CCS a competitive technology from an economic perspective, when carbon abatement is required. All the costs described correspond to the state-of-the art chemical absorption process based on monoethanolamine (MEA).

One important research area to improve PCC performance is the development of novel solvents that require less energy for regeneration and, therefore, lead to lower operating costs than that of the state-of-the-art technology [15–17]. In this respect, a tertiary or hindered amine is, generally mixed with a primary or secondary amine in order to retain much of the reactivity of the primary amine but with low regeneration energy similar to those of tertiary amines [18]. Besides thermal energy for regeneration, other aspects that are crucial to consider in solvent development are solvent volatility, solvent degradation and solvent price [19–21]. The vast majority of economic assessments do not clarify the possible contribution of these solvent characteristics to the operating costs at an early stage in solvent development. There are also issues regarding the reporting of capture costs. As highlighted in the recent work by Rubin [22], there are differences in methodology, measures for cost estimates and underlying assumptions that are not always explicit in the published cost estimates. When assessing the potential of a new technology, as compared to an already published evaluation of a state-of-the-art technology, these issues are likely to influence the final evaluation of the new technology leading to a certain degree of confusion.

This paper examines the economic performances of two amine solvents for PCC integrated within two different fossil fuel based power plants. The innovative solvent named CESAR-1, which is an aqueous solution of 2-amino-2-methyl-propanol (AMP) and piperazine (PZ) [23], is compared to MEA, which has been used as a reference baseline. For both cases, advanced supercritical (ASC) pulverized coal and natural gas combined cycle (NGCC) technologies have been selected for the economic analysis of PCC based on the mentioned solvents. The economic assessment is based on the thermodynamic assessment presented in our previous work [24], which established the potential of the innovative CESAR-1 solvent. The power plant efficiency, the capture plant design and the solvent replenishment cost have been determined by process simulation and estimated degradation rates. Compared to the MEA baseline, CESAR-1 reduces the efficiency penalty points related to CO_2 capture by 2% in the NGCC case and by 6% in the ASC case.

The parameters adopted as terms of comparison are the impact of CO_2 capture on Cost of Electricity [€/MW h] and the CO_2 avoidance cost [€/t_{CO2}] (cost to avoid the emission of a unit of CO_2 in the atmosphere). The economic assessment is performed through a clear and detailed approach in line with the best practice guidelines of the European Benchmarking Taskforce (EBTF) [25], which was created by the European commission to unify the modelling methodologies and to align both technical and economic assumptions taken in benchmarking studies of this type, within European projects involved in CCS [26–28]. Finally, for the total plant cost assessment, two different methodologies have been adopted to determine the influence of the method on the results: top-down (TD) and bottom-up approach (BU). In the TD approach, the power plant specific costs were defined and agreed upon in joint effort by the European power plant companies supporting the study (as in the method of Abu-Zahra et al. [29]). In the BU approach, the cost was estimated by economic models (as in the method of Manzolini