Energy 66 (2014) 550–555

Contents lists available at ScienceDirect

Energy

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

Techno-economic assessments of oxy-fuel technology for South African coal-fired power stations

B.O. Oboirien*, B.C. North, T. Kleyn

CSIR Materials Science and Manufacturing, PO Box 395, Pretoria 0001, South Africa

A R T I C L E I N F O

Article history:
Received 31 May 2013
Received in revised form
10 December 2013
Accepted 14 December 2013
Available online 10 January 2014

Keywords:
Oxy-fuel
CO_2 capture
Economic evaluation
Coal-fired power stations
South Africa

A B S T R A C T

Oxy-fuel technology is one of the potential solutions to reduce CO_2 emissions from coal-fired power plants. Although vendors offer a “retrofit package,” to the best of our knowledge there has not been a study undertaken that looks at the technical and economic viability of oxy-fuel technology for CO_2 capture for South African coal-fired power stations. This study presents a techno-economic analysis for six coal fired power stations in South Africa. Each of these power stations has a total capacity of about 3600 MW. The analysis was done using the oxy-fuel model developed by Carnegie Mellon University in the USA. The model was used to define the performance and costs of retrofitting the boilers. The results obtained showed that the CO_2 emission rate was reduced by a factor of 10 for all the plants when retrofitted to oxy-fuel combustion. Between 27 and 29% of the energy generated was used to capture CO_2. The energy loss was correlated to the coal properties. Sulphur content in the coal samples affects the energy used for flue gas cooling but did not affect the energy used for CO_2 purification and compression. The study also showed there is a need for the flue gas to be treated for NO_x and SO_x control. The total capital costs and cost of electricity for the six plants were different, resulting with the cost of electricity varying from 101$/MWh to124$/MWh.

1. Introduction

South Africa has rich coal deposits which provide 90% of the country’s electricity [1]. These coal-fired plants are located close to the coal fields [2]. Historically this has given South Africa access to cheap electricity. However, this has led to high CO_2 emissions, presently about 295 megatons per year [3]. This accounts for 80% of the total South African CO_2 emissions which are about 369 megatons per year. The South African government has committed (conditionally) to reduce its emissions by 34% in 2020 and 40% in 2040 if there sufficient funding and technology support from industrialised countries [4].

CCS (carbon capture and storage) has been recognised as an important technology to reduce CO_2 emissions significantly. Oxy-fuel technology is advantageous over other CO_2 capturing technologies since it can be successfully retrofitted into existing coal-fired power stations [5]. Oxy-coal combustion is based on burning coal in a mixture of oxygen and recycled flue gas rather than in air. This results in an exhaust gas that contains 95% of CO_2 that is ready for storage. This technology also produces less NO_x leading to lower greenhouse gas emissions into the atmosphere [6]. Technical and economical evaluation of oxy-combustion have shown it could be economic feasible for the mitigation of large scale of CO_2 reduction [7,8].

To the best of our knowledge there has not been any study undertaken that looks at the technical and economic viability of oxy-fuel technology for CO_2 capture for South African coal-fired power stations. This study presents a techno-economic analysis for six coal fired power stations in South Africa. Each of these power stations has a total capacity of about 3600 MW. The analysis was done using the oxy-fuel model developed by Carnegie Mellon University in the USA [9]. The model was used to define the performance and costs of the retrofitting the boilers.

2. Location of the coal fields and the power stations

Six power stations were chosen for this study. These pulverised coal-fired plants are located close to the coal fields. Four of the power stations are in the Mpumalanga province and the other two are in the Free State and Limpopo provinces. The Mpumalanga province accounts for 90% of the coal production in South Africa [10]. These power stations were chosen because presently they are major power stations and each has a total capacity of about

* Corresponding author. Tel.: +27 128412371, +27 731740431; fax: +27 8412135.
E-mail address: boboirien@csir.co.za (B.O. Oboirien).

0360-5442/$ – see front matter
http://dx.doi.org/10.1016/j.energy.2013.12.032

3600 MW. Each of the power plants has six units and the capacity of each unit is a 600–686 MW. They all have similar design.

These power stations are also close to the end of their expected lifetime and maybe due for retrofit or refurbishment soon. The technical and historical information of the power stations and the supplying coal fields is presented in Table 1. The elemental analysis and calorific value of coal fired in these power stations are presented in Table 2.

3. Methodology

The performance of the retrofit plants was evaluated using the IECM (Integrated Environmental Control Model, Version 8.1). It was developed by the by Carnegie Mellon University and it is a free software [9]. The model calculates mass and energy flows across various units such as ASU (oxygen generator), flue recycle unit and other plant components. Key parameters such as total CO_2 captured and net power outputs were obtained. These were used to calculate the COE (cost of electricity) and the COA (cost of CO_2 avoidance). Technical documentation of some of the correlations used in the calculations of performance and cost model can be found in Rao et al. [11]. This model also been used to model coal fired power stations by different researchers [12–14].

In this study, the economic analysis was only based on CO_2 Capture and CO_2 compression. The cost associated with transport and storage was excluded because research on possible storage sites is still on-going [15]. In this study, two different types of plant configuration were investigated.

- Oxy-combustion with NO_x, and SO_x treatment
- Oxy-combustion without NO_x and SO_x treatment

In the model the NO_x treatment was done using the SCR process (selective catalytic reduction). Nitrogen oxides in the flue gas are removed by reduction of NO_x by ammonia to Nitrogen and water. The reduction occurs in the presence of a catalyst. The process chemistry is shown in Equation (1) below:

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

The performance model of is given below:

$$SV = \frac{3600C(r_e)a}{-\ln(1-\eta_{NO_x})} \quad (1)$$

where

SV = space velocity
C = constant representing catalyst activity for a given operating condition (temperature, inlet NO_x concentration)
Re = exit molar ratio of NH_3 to NO_x at SCR reactor outlet
a = constant
η_{NO_x} = NO_x removal efficiency

For SO_x treatment – The wet flue gas desulphurisation process was used and the Performance mode is given below Equation (2):

Table 1
Technical and historical information of power plants.

Power station	Matla	Duhva	Kendal	Tutuka	Matimba	Lethabo
Capacity (MW)	3600	3600	4116	3654	3990	3708
Date Commissioned	1980	1983	1988	1985	1985	1985
Coal field	Highveld	Witbank	Witbank	Highveld	Waterberg	Sasolburg
Location of Mine	M.Langa	M.Langa	M.Langa	M.Langa	Limpopo	Free State
Colliery	Matla	Duhva	Leeufontien	New Denmark	Grootegeluk	New Vaal

Table 2
Elemental analysis of power station coal samples.

Coal samples	Matla	Duhva	Leeufontien	New Denmark	Grootegeluk	New Vaal
Carbon (%) ad	50.66	58.70	68.69	52.08	51.96	42.58
Hydrogen (%) ad	2.65	3.33	3.48	2.80	3.15	2.19
Nitrogen (%) ad	1.07	1.27	1.49	1.40	0.99	0.89
Sulphur (%)ad	0.74	1.10	0.36	1.25	1.58	0.69
Oxygen (%) ad	7.97	3.14	7.98	7.71	5.85	7.54
Calorific value (MJ/kg) ad	18.60	21.10	25.28	19.95	19.80	15.07

$$\eta_{SO_2} = 1 - \exp\left(-\frac{kg^*a^*P^*V}{G}\right) \quad (2)$$

where

a = interfacial mass transfer per unit volume
V = scrubber volume
P = total pressure in scrubber
G = molar gas flow rate
kg = molar gas flow rate

The model calculations have been added to the paper and can be found on page 5. Full details of model calculations can be found from Technical documentation of ICEM model by Berkenpas et al. [16] and accessed on this link http://www.cmu.edu/epp/iecm/iecm_doc.html.

3.1. Economic analysis

The cost of electricity was calculated using the framework provided in the IECM Model [11] and was done by dividing the total annual cost of the plant by the net electricity output in Equation (3).

$$COE = \frac{TRR}{MW_{net} \times H} \quad (3)$$

where,

TRR = Total annual revenue requirement ($/yr)
MWnet = Net Power generation capacity (MW)
H = Annual hours of operation (h/yr) (6575 h was used in this work).

While the cost of CO_2 avoidance is calculated in Equation 2

$$COA = \frac{(COE)\text{with capture} - (COE)\text{without capture}}{(CO_2/kWh)\text{without capture} - (CO_2/kWh)\text{with capture}} \quad (4)$$

3.2. Key assumptions for the six power plants

Capture efficiency is 90%
Excess oxygen required for complete combustion 5%