Energy Policy 63 (2013) 168–180

Contents lists available at ScienceDirect

Energy Policy

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

Assessment of selected CCS technologies in electricity and synthetic fuel production for CO_2 mitigation in South Africa

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HIGHLIGHTS

- Analysis of costs of implementing CCS at IGCC, USC, CTL, GTL plants in South Africa.
- Analysis of the life cycle emissions and GHG abatement costs for 2025 and 2040.
- Generating costs of for IGCC plants are lowest whereas those of GTL are the highest.
- The highest potential in mitigating GHG (84%) was found for IGCC plants.
- The GHG abatement costs are lowest for the IGCC with CCS (170 ZAR/t CO_{2eq} in 2025).

ARTICLE INFO

Article history:
Received 20 August 2012
Accepted 9 August 2013
Available online 30 August 2013

Keywords:
CCS
CO_2 mitigation
LCA
Abatement costs

ABSTRACT

One of the actions proposed to reduce greenhouse gas (GHG) emissions in South Africa (SA) is to install carbon capture and storage (CCS) at new energy-producing plants. This paper aims to evaluate the costs and GHG emissions of implementing CCS at a coal-fired integrated gasification combined cycle (IGCC) power plant, at a coal fired ultra-supercritical (USC) power plant, at a synthetic fuel coal-to-liquid (CTL) plant and at a gas-to-liquid (GTL) plant for SA. The approach for comparing of these CCS applications is based on a combination of a techno-economic analysis with a life-cycle assessment. As expected, the generating costs in plants with CCS are higher than without CCS for all case studies. GHG-abatement costs in 2040 are shown to be the lowest for the IGCC power plant at 173 ZAR_{07}/t CO_{2eq}, followed by the USC power plant at 227 ZAR_{07}/t CO_{2eq}. These costs are considerably higher for the CTL and GTL plants. The results show that from an economic perspective, CCS might be an attractive option for CO_2 mitigation in SA especially for the electricity sector. However, a prerequisite for the implementation of CCS is that the technology reaches commercial scale for the investigated options and is socially accepted.

1. Introduction

South Africa holds extensive coal deposits estimated to be the eighth largest in the world. According to EIA and DoE estimates, 33 billion metric tonnes of coal, or about 730 EJ, were proven in 2008 (EIA, 2011; DOE, 2012), which are relatively easy and cheaply to mine. The country has, therefore, established an energy sector based mainly on coal-fired power plants and coal liquefaction. In 2008, 71% of primary energy supply in South Africa (IEA, 2009; DOE, 2008) and about 93% of (gross) electricity generation was coal based (Eskom, 2011). With total GHG emissions of about 337 Mt carbon dioxide equivalent (CO_{2eq}) in 2008, South Africa accounts for about 38% of the African GHG emissions and contributes more than 1% of the world's total carbon emissions (IEA, 2010a). As a consequence, South Africa generates the same order of magnitude of yearly specific GHG emissions at 9.0 t CO_2/capita as countries such as Italy at 9.7 t CO_2/capita and France at 8.7 t CO_2/capita (World Resources Institute, 2011). Furthermore, South Africa generates five times more CO_2 emissions per unit of gross domestic product (1.72 kg/$\$_{2007}$ GDP) than Germany (0.34 kg/$\$_{2007}$) (IEA, 2007).

In 2007, South Africa initiated a process to develop CO_2 mitigation scenarios to respond to increasing atmospheric CO_2 emissions in the context of the United Nations Framework Convention on Climate Change (UNFCCC). This process involved devising so-called Long Term Mitigation Scenarios (LTMS) (Winkler, 2007). One of its key objectives was to develop ambitious but realistic scenarios to support government policy to combat climate change. One of the proposed actions was to install carbon capture and storage (CCS)

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0301-4215/$ - see front matter
http://dx.doi.org/10.1016/j.enpol.2013.08.038

technology which offers the possibility of reducing GHG emissions (specifically of CO_2) significantly by storing it in geological formations.

Large industrial processes such as coal-to-liquid (CTL) or gas-to-liquid (GTL) plants are especially suitable for the application of this technology because they produce large amounts of highly concentrated CO_2 which can be instantly compressed for pipeline transportation to the storage. Moreover, coal-fired power plants, which are the backbone of the South African energy supply and major emitters of CO_2, might also be suitable for CCS application.

To store CO_2 permanently in a supercritical state above 80 bar, it has to be transferred to a suitable sink (IEA, 2008b). There are four primary options for the geological storage of CO_2: depleted gas and oil fields, coal beds with CO_2-enhanced methane recovery, usage of the CO_2 for enhanced oil recovery, and deep saline aquifers (porous rock formations confined by layers of rock containing brackish water) (IEA, 2008b; Fischedick et al., 2007).

Today, first CCS projects have been applied worldwide, predominantly for enhanced oil recovery. Among the actively operating eight "large-scale" CCS sites (with a minimum capacity of 0.8 Mt CO_2/a for coal power plants or 0.4 Mt CO_2/a for other industries), six are located in North America using enhanced hydrocarbon storage by injecting CO_2 into existing oil fields to maintain production capacities (Global CCS Institute, 2013). Furthermore, two CCS projects are located in Norway. There, the CO_2 in natural gas streams is separated and re-injected into an offshore deep saline formation (Global CCS Institute, 2013). Except for one project in the USA, all other current large-scale CCS projects are using the pre-combustion technology to capture the CO_2 (Global CCS Institute, 2013).

So far, South African researchers discussed the current status of CCS, its potential, and financing as well as governance issues (Beck et al., 2011; Mwakasonda and Winkler, 2005). The *Atlas of Geological Storage of Carbon Dioxide in South Africa* (Council for Geoscience, 2010) identified potential CO_2 storage sites in the country. Furthermore, a roadmap was drawn to indicate milestones for a commercial CCS roll-out. According to this roadmap, the first test injections are planned for 2016 and commercial operation is scheduled for 2025 (Council for Geoscience, 2010). Román (2011) discussed the current CCS policies of developing countries such as Brazil, India and South Africa and analysed GHG mitigation targets and aspects such as environmental, economic and social development objectives related to the large-scale deployment of CCS. Social benefits of CCS were in detail investigated by Mwakasonda and Winkler (2005) and found to be low in South Africa. Among other concerns, they point out that the application of CCS will probable increase the cost of service provision, e.g. for electricity, and thus be of a major threat especially for lower income parts of the society. Furthermore, they pointed out a first cost estimate for CCS application in South Africa based on international figures. Almendra et al. (2011) point out that the main barriers in the development of commercial scale CCS projects can be seen in minimal incentives as their overall costs are higher than projects without CCS but that CO_2 emissions do not cause direct costs to the emitters (Almendra et al., 2011). However, all these analyses are mainly qualitative rather than quantitative. Zapp et al. (2012) gives an overview on the most recently conducted studies using Life Cycle Assessment (LCA) to investigate the introduction of CCS. They identified that plant efficiency, capture efficiency and fuel origin have a significant impact on the LCA results.

To evaluate the costs and GHG emissions of CCS implementation in South Africa, this paper provides a quantitative assessment of selected CCS technology options at the most promising locations in the country Four technology options are investigated: a new coal-fired power plant at the existing coal-fired power plant site Majuba based on either integrated gasification combined cycle (IGCC) or an ultra-supercritical (USC) configuration, a CTL plant with an output of 80,000 bbl/day in Limpopo and a GTL plant with an output of 45,000 bbl/day at Secunda assuming natural gas supply via pipeline from Mozambique (see also Kearney, 2013; ICF International, 2012; True, 2012). The liquid fuel plants are both based on the Fischer–Tropsch process. For each of these sites, this paper evaluates in detail consequences of adopting CCS for

- the additional costs of implementing the technology (disaggregated in terms of the plant, the carbon dioxide transport and the storage),
- the life-cycle GHG emissions (LCA),
- the GHG emission mitigation potential and
- the GHG abatement costs.

The additional costs and differential LCA based GHG emissions as a result of upgrading the plants with CCS technology are calculated as well as the corresponding efficiency loss, additional electricity requirement and other components. Furthermore, the costs and LCA-based GHG emissions for the CO_2 transportation via pipeline to the most promising CO_2 storage site are analysed by calculating the necessary pipeline diameter, length and the corresponding pressure drop along it.

All costs in this work are given in South African Rands in real terms for a base year of 2007, as ZAR_{07} (1 ZAR_{07} corresponds to 9.66 $€_{07}$).

2. CCS installation and storage potential in South Africa

In this section, CCS installation at advanced coal fired power plants (Section 2.1) and synthetic fuel plants (Section 2.2) are analysed techno-economically due to their high CO_2 abatement potential. Moreover, the CO_2 storage potential (Section 2.3) in South Africa is presented.

2.1. Advanced coal-fired power plants

A combined-cycle power system consists of a gas turbine and a steam turbine, which operate together to increase overall efficiency by using the excess heat of the gas turbine for steam generation. In an integrated gasification combined cycle system, the solid fuel (mostly coal) is gasified before the combustion process. This synthetic gas (syngas) is treated to remove especially sulphur and particulates. The treated gas is then combusted in a gas turbine and the steam cycle is driven by the heat from exhaust gases (IEA, 2008a).

The IGCC systems are considered to be cleaner and more efficient with an electric efficiency of about 40–43% than conventional (pulverised) coal-fired power plants with about 35–39% (IEA, 2008a). Owing to the relatively low additional energy requirement, an IGCC plant is considered to be suitable for CO_2 capture (Spliethoff, 2010). In the IGCC system, CO_2 can be captured after gasification and before combustion. It is, therefore, called a pre-combustion capture system. In the CO_2 capture process, the CO in the syngas is converted to H_2 and CO_2 via a shift reaction. The resulting CO_2 is removed from the rest of the gas (Spliethoff, 2010).

Ultra-supercritical power plants overheat the steam above the critical point of water (about 22 MPa and 647 K) which allows for higher pressures and temperatures and, thus, increases the plant efficiency. However, the increased temperature requires durable materials especially in the turbines. Possible materials to handle that high temperatures like nickel based alloys are under further development (Weitzel, 2011). Advanced USC power plants with a turbine inlet temperature of 700 °C and above are estimated to be