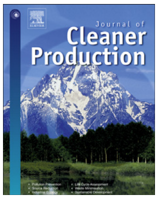
Journal of Cleaner Production 181 (2018) 271–292

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Life cycle environmental and economic analysis of pulverized coal oxy-fuel combustion combining with calcium looping process or chemical looping air separation

Yuting Tang [a, b], Fengqi You [b, *]

[a] Guangdong Province Key Laboratory of Efficient and Clean Energy Utilization, School of Electric Power, South China University of Technology, Guangzhou, 510640, China
[b] Robert Frederick Smith School of Chemical and Biomolecular Engineering, 318 Olin Hall, Cornell University, Ithaca, NY, 14853, USA

ARTICLE INFO

Article history:
Received 15 December 2017
Received in revised form
30 January 2018
Accepted 31 January 2018
Available online 5 February 2018

Keywords:
Calcium looping process
Oxy-fuel combustion
Chemical looping air separation
Multi-criteria decision making
Life cycle assessment

ABSTRACT

This paper presents multi-criteria environmental and economic analyses of pulverized coal power plants with various advanced CO_2 capture and separation (CCS) technologies, including oxy-fuel combustion (Oxy), calcium looping post-combustion capture (CaL), combination of Oxy with CaL (Oxy-CaL) and Oxy with chemical looping air separation (Oxy-CLAS). The life cycle analysis (LCA) and techno-economic analysis (TEA) are integrated with Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approaches. This methodology is applied to forecast the potential of incorporating CaL or CLAS into oxy-fuel combustion and identify the most promising CCS technology option for pulverized coal power plants from the perspectives of different stakeholders. The results show that application of CCS reduces the ecosystem quality and the human health impacts, but increases the resources use and yields an economic penalty of \$12.76~\$33.33 per ton of CO_2 avoidance. From the perspective of industry only, CCS has an unfavorable effect on the performance of the pulverized coal power plant, and the promotion in carbon price is critical for CCS to attract the support from industry. In terms of the four CCS technologies, Oxy-CLAS comprehensively performs the best, followed by Oxy. Decrement of consumption of Ca-based sorbents is critical for Oxy-CaL to outrank Oxy.

1. Introduction

Coal, one of the world's most abundant fossil fuel sources, currently meets about 28.8% of the total world primary energy demand, and 41.3% of global electricity generation (IEA, 2013). Coal will continue to dominate power production for at least the next five decades, and its share in the energy portfolio is predicted to be 34% in 2040 (U.S. Energy Information Administration, 2016). However, coal is the most carbon-intensive fossil fuel and contributes the largest share of carbon dioxide (CO_2) emissions from fuel burning (42.9%) (Erlach et al., 2011). Therefore, development of efficient, clean, and economical energy conversion systems has been an issue of international concern and a challenge for engineers and researchers (Gong and You, 2015). Incorporating CO_2 capture and separation (CCS) technologies into existing coal-fired power plants could help to address this challenge (Mukherjee et al., 2015). It is estimated that CCS may potentially contribute to 15–55% of worldwide CO_2 abatement until 2050 (IPCC, 2007).

Amine absorption is a commercially adopted CCS technology in existing coal-fired plants. However, regenerating amine absorbents such as monoethanolamine (MEA) requires a large amount of energy, thus significantly reducing the overall plant efficiency (Kursun et al., 2012). Moreover, the degradation of the amine and subsequent corrosion of the equipment increases the operation and maintenance costs (Clarens et al., 2016). There are similar concerns for other CCS technologies, such as adsorption (Chung et al., 2016), membrane (Ramasubramanian et al., 2012), and algae (Gebreslassie et al., 2013). A calcium looping post-combustion process (CaL post) based on the carbonation/calcination reaction of solid CaO particles, is found to be a promising alternative to amine absorption (Hanak et al., 2016). CaL post has several potential advantages over amine absorption such as relatively lower energy and cost penalties (Perejon et al., 2016), and the use of cheap and non-toxic sorbent (Rodríguez et al., 2012). Another promising alternative to amine

---

* Corresponding author.
E-mail address: fengqi.you@cornell.edu (F. You).

https://doi.org/10.1016/j.jclepro.2018.01.265
0959-6526/

post-combustion capture for mitigating CO_2 emissions is the oxy-fuel combustion technology (Jin et al., 2015), which has been successfully demonstrated in large-scale pilot projects (30 MW_e) (Escudero et al., 2016a). However, oxy-fuel combustion requires large amounts of oxygen, and the inclusion of conventional cryogenic air separation units (CASU) to meet this demand leads to large energy and cost penalties (Kather and Scheffknecht, 2009). Hence, there is a need for either a simpler and more energy-efficient air separation technology or a means to decrease the oxygen requirement for oxy-fuel combustion. The chemical looping air separation (CLAS) process and partial oxy-combustion are positioned to fulfill this need (Moghtaderi, 2010). In the CLAS process, an oxygen carrier releases oxygen in steam or flue gas, and the reduced oxygen carrier absorbs oxygen from air. Partial oxy-combustion is an emerging approach to reduce the pure oxygen requirement, and it can be combined with post-combustion capture process to improve the total CO_2 capture efficiency (Vega et al., 2016) These advanced CCS technologies have differences in terms of energy consumption, environmental impacts, and economic performance. Therefore, for judicious selection of CCS technologies, rigorous and systematic analyses of pulverized coal power plants with various CCS technologies need to be addressed.

Several publications address the life cycle assessments (LCA) and/or techno-economic analyses (TEA) of coal power plants with different CCS technologies (Korre et al., 2010; Pehnt and Henkel, 2009; Singh et al., 2011a). Most of them have evaluated MEA post-combustion capture and oxy-fuel combustion with CASU technologies (Iribarren et al., 2013; Joris Koornneef, 2012; Korre et al., 2010; Nie et al., 2011; Pehnt and Henkel, 2009; Singh et al., 2011b), while a smaller number of studies have considered CaL post-combustion capture technologies (Clarens et al., 2016; Hurst et al., 2012; Petrescu et al., 2017). To the best of our knowledge, there is no existing literature addressing the environmental and economic analysis of oxy-fuel combustion with CLAS (Oxy-CLAS) and the combination of partial oxy-fuel combustion and the CaL post-combustion capture process (Oxy-CaL) from the whole life cycle perspective.

Multi-criteria decision-making (MCDM) is a powerful methodology for decision makers to identify the best option from a set of alternatives (Deveci et al., 2015). MCDM methods take various criteria into account (Lerche et al., 2017), allowing stakeholders to participate in decision-making processes and yielding comprehensive results (Mardani et al., 2016). MCDM approaches have been used to assess complexity of CCS and reveal the interconnection among complexity factors (Sara et al., 2015), and to identify and evaluate the main non-technical factors affecting the CCS chain (Jakobsen et al., 2013). MCDM approaches have also been used to compare a power plant using MEA post-combustion capture with the uncontrolled release of CO_2 (Fozer et al., 2017). However, to the best of our knowledge, there is no systematic MCDM analysis of other CCS options for pulverized coal-fired power plants that accounts for economic and environmental performance from the life cycle perspective.

This paper presents multi-criteria environmental and economic analyses of pulverized coal-fired power plants with and without four CCS technologies. The economic and environmental potentials of incorporating CCS in pulverized coal-fired power plants are systematically investigated by an MCDM methodology. The MCDM methodology combines LCA and TEA with Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approaches. The aforementioned CCS technologies, namely, conventional oxy-fuel combustion with CASU (Oxy), CaL post, Oxy-CaL and Oxy-CLAS, are systematically compared by the MCDM methodology to evaluate the economic and environmental potentials of incorporating CaL and CLAS in oxy-fuel combustion and identify the most promising CCS technology option. Moreover, the order preference of CCS technologies is analyzed from the perspectives of local government, industry, residents, and an 'egalitarian' perspective in which all indicators are weighted equally, respectively.

The major novelties of this work are summarized as follows:

- Comparative LCA studies of a pulverized coal power plant with Oxy, CaL post, Oxy-CaL and Oxy-CLAS technologies using comprehensive environmental impact categories.
- TEA of a pulverized coal power plant with Oxy, CaL post, Oxy-CaL and Oxy-CLAS technologies, respectively.
- Comprehensive comparison of novel CCS technology alternatives for pulverized coal power plants from different stakeholders' perspectives using MCDM.

The rest of this paper is organized as follows. First, Section 2 introduces an existing conventional coal-fired power plant and retrofitted power plants with CCS units. Next, Section 3 describes the LCA, TEA, AHP, and TOPSIS approaches. The proposed methodologies are then applied to coal-fired power plants with four CCS technologies in Section 4, and the results are compared with the conventional pulverized coal power plant without CCS. Conclusions are provided in the end.

2. Process and systems description

Plants operating with a steam pressure >221 MPa and steam temperature >374 °C are super-critical (SC) power plants (Basu and Debnath, 2014). Compared with subcritical power plants, they are typically more energy efficient and more environmental friendly (Basu and Debnath, 2014). SC technology is well-developed and adopted by increasingly more industrial coal-fired power plants (Tan, 2012). Therefore, a SC pulverized coal power plant is chosen as the research subject in this work. This conventional power plant without CCS is defined as a baseline (Case 1). Four cases using different CCS technologies are considered:

Case 2: SC pulverized coal power plant retrofitted for oxy-fuel combustion using conventional cryogenic air separation units (Oxy).
Case 3: SC pulverized coal power plant with calcium looping for post combustion capture (CaL post)
Case 4: SC pulverized coal power plant with a novel CO_2 capture system by integrating partial oxy-fuel combustion with the calcium looping process (Oxy-CaL)
Case 5: SC pulverized coal power plant retrofitted for oxy-fuel combustion using chemical looping air separation with Cu-based oxygen carriers (Oxy-CLAS)

The retrofitted SC power plants for Oxy, CaL post and Oxy-CaL and Oxy-CLAS are shown in Fig. 1. Schematic diagram of the CLAS and CASU processes are shown in Fig. 2. The main technical parameters are shown in Table 1.

Pittsburgh No. 8 coal, which is typical high volatile bituminous coal, is considered in this paper. The composition of Pittsburgh No. 8 coal is listed in Table 2 (U.S. National Energy Technology Laboratory, 2012).

2.1. *Description of case 1 (without CCS)*

The base case considers a conventional power plant consisting of a pulverized coal boiler with an air preheater and fuel gas treatment systems, including a selective catalytic reduction (SCR) denitrification device, a cold side electrostatic precipitator (ESP)