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Post-combustion carbon capture technologies: Energetic analysis and life cycle assessment

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ABSTRACT

An integrated framework focusing on the energetic analysis and environmental impacts of a CO_2 capture and storage (CCS) system is presented, in which the process simulation method and the life cycle assessment (LCA) method are integrated and applied to the CCS value chain. Three scenarios for carbon capture from post-combustion power plant – an MEA-based system, a gas separation membrane process and a hybrid membrane-cryogenic process are studied. The energy efficiency of power plant and the specific capture energy consumption for each scenario are estimated from process simulation. The environmental impacts for each scenario and the base case without CCS are assessed with LCA method. The results show that the MEA-based capture system faces the challenges of higher energy consumption, and higher environmental impact caused by solvent degradation and emissions compared to gas membrane separation processes. The hybrid membrane-cryogenic process shows a better environmental potential for CO_2 capture from flue gases due to much lower power consumption and relatively lower environmental impacts.

1. Background

CO_2 emissions from fossil based industries have contributed to the serious global warming problems. CO_2 capture and storage (CCS) has been regarded as one of the most promising options to utilize fossil fuels continuously without the significant influence to the climate change. Till now, a large number of studies have focused on the assessment of energy consumption, capture cost and environmental impacts in CCS, while most of them analyzed MEA-based capture systems which have been proven in chemical production industries, for example, process analysis and techno-economic assessment (Abu-Zahra et al., 2007; Huang et al., 2010; Husebye et al., 2011; IEA, 2006; Sanpasertparnich et al., 2010; Schach et al., 2010; Sipocz and Tobiesen, 2012) and environmental impact assessment (Nie et al., 2013; Koornneef et al., 2011, 2012; Korre et al., 2010; Pehnt and Henkel, 2009; Schreiber et al., 2009; Singh et al., 2011a,b). Research on some emerging capture technologies such as membranes, ionic liquids and metal organic frameworks (MOFs) is in progress with the aim of reducing capture energy consumption and capital investment (Favre, 2011; Figueroa et al., 2008; MacDowell et al., 2010; Zhang et al., 2012b), and shows a promising application in CO_2 capture. However, these processes are still at the lab-scale or small pilot-scale demonstration stage. In this paper, an integrated framework is proposed and used to assess the capture energy consumption and environmental impacts of the different CCS chains with conventional and emerging capture technologies, considering three post-combustion CO_2 capture technologies: an MEA-based system, a gas separation membrane process, and a hybrid membrane-cryogenic process.

Gas separation membranes have generated growing interests in recent years, as unlike MEA-based system, CO_2 capture using membrane needs no or little chemicals, requires no retrofitting for the existing power plants, have relative ease of scale-up and operation, (Ritter and Ebner, 2007; Zhao et al., 2010), and is flexible for separating gases when high purity gas streams are not vital (Powell and Qiao, 2006). At present, most of the studies on gas separation membranes focus on the membrane material selection

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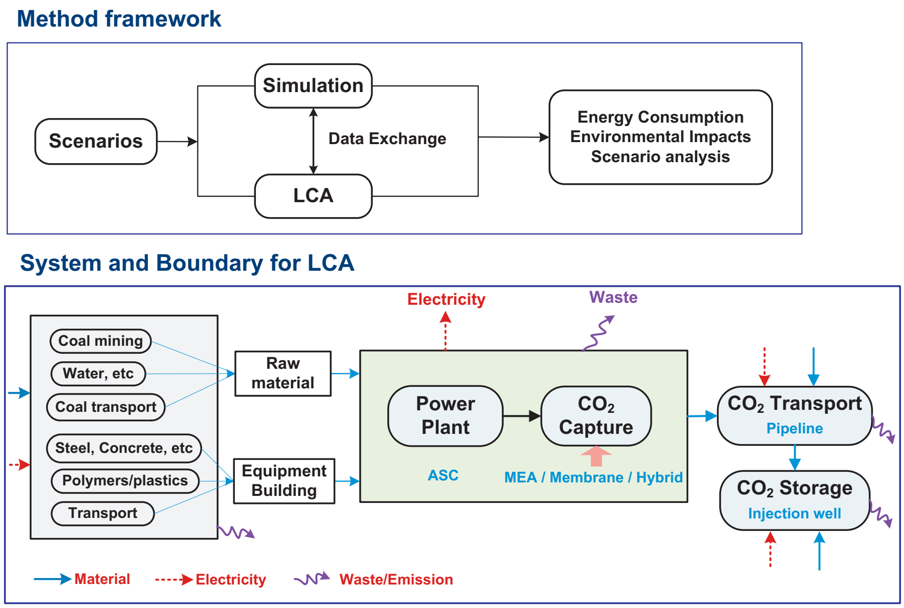

Fig. 1. Integrated method and system boundary of LCA.

and functionalization, membrane preparation and characterization (Aaron and Tsouris, 2005; Powell and Qiao, 2006; Scholes et al., 2008), and membrane process analysis (Bounaceur et al., 2006; He et al., 2009; Hussain and Hagg, 2010; Merkel et al., 2010; Van Der Sluijs et al., 1992; Zhao et al., 2010, 2008). For instance, the parametric studies and the systematic energy analysis of a single stage membrane process (Bounaceur et al., 2006; Zhao et al., 2008), the energetic and economic analyses of multi-stage membrane processes (Zhao et al., 2010), the influences of membrane parameters and process configurations on the energy consumption and cost considering a real industrial process (Merkel et al., 2010), the process feasibility of post-combustion of the real flue gas by facilitated transport membrane based on process simulation and cost estimations (Hussain and Hagg, 2010) as well as the process feasibility analysis of hollow fiber carbon membranes for CO_2 capture from flue gases (He and Hagg, 2011, 2013). These contributions are important for understanding the feasibilities of CO_2 capture with membrane technologies; however, the assessment results are not directly comparable as different authors use different membranes and process parameters, membrane models, process configuration and assumptions. To the best of our knowledge, there are no studies focusing on the environment impacts of membrane technologies, thus no quantitative results can be referred to understand their environmental benefits and concerns.

In our previous work (Zhang et al., 2013), we conducted the analysis for parametric influence, capture cost and exergy efficiency of the post-combustion membrane based carbon capture process. As for environmental issues, it has been shown in literature that a CCS system with an MEA-based capture method though can achieve a significant reduction of CO_2 emissions but have multiple environmental trade-offs (Koornneef et al., 2011, 2012; Korre et al., 2010; Pehnt and Henkel, 2009; Schreiber et al., 2009; Singh et al., 2011a,b). Although there are no MEA degradation and solvent losses in a membrane process, the preparation and replacement of membrane might cause additional environmental impacts. Thus, assessing systematically the energy consumption and environmental impacts of membrane capture technologies is important.

In this study, we evaluate the energy consumption and environmental impacts of three different post-combustion capture technologies, i.e., an MEA-based system, a gas separation membrane process, and a hybrid membrane-cryogenic process, using energetic analysis and life cycle assessment (LCA) method. At first, the capture process for each scenario is designed and simulated on the basis of engineering heuristics and judgment to determine the relevant operating parameters, and then the process simulation and optimization are performed to obtain the detailed energy and mass flows, as well as the parameters of all unit operations involved in the whole system. Based on the simulation results and process configuration of the CCS system, the LCA method is applied to evaluate the environmental impacts of the system considering the complete life cycle from resource mining to CO_2 injection.

2. Methodology

The concept of the integrated method and the system boundary of CCS involved in this study are shown in Fig. 1. The main motivation of this work is to investigate the performance of energy consumption and environmental impacts in a designed system framework with process simulation and life cycle assessment. The system boundary for LCA will cover the CCS value chain from resource extraction, pre-treatment, distribution and transport, infrastructure, electricity generation (advanced super critical boiler and turbine), CO_2 capture (three capture technologies: an MEA-based system, a two-stage membrane system and a hybrid membrane/cryogenic process), CO_2 transport (pipeline) and storage. The detailed descriptions are given as follows.

2.1. Process models

The power plant is based on an advanced super critical boiler and turbine delivering 819 MWe (gross) without carbon capture. When the auxiliary power is taken into account, the net power output is 754.3 MWe, yielding a net cycle efficiency of 45.5%. The models involved in the power plant and the flue gas composition as well as the parameters are from the literature (Anantharaman et al., 2011).

For the MEA-based capture process, the mechanism of CO_2 absorption in an amine solution using an absorption column is quite complex, and there are many references about the chemical reactions and vapor–liquid equilibrium involved in this system (Aaron and Tsouris, 2005; MacDowell et al., 2010). It is a typical electrolyte thermodynamic system and the amines property package in Aspen Plus® is often used to model the absorption and desorption