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Performance comparison of low temperature and chemical absorption carbon capture processes in response to dynamic electricity demand and price profiles

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HIGHLIGHTS

- Dynamic integration of the low temperature and chemical absorption carbon capture processes with a coal-fired power plant.
- Comparison of the integrated systems with and without energy storage.
- Full utilization of wind power and optimizing its contribution to the grid.
- Minimization of the total operating cost and electricity production imbalances.
- Operational flexibility and load management of the systems with energy storage.

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ABSTRACT

Current projections to the year 2050 reveal that fossil fuels will remain the main source of energy generation. To achieve the target limits of carbon dioxide emission, set by national and international policies, carbon capture will play a key role. Modeling and optimization of various carbon capture technologies such as pre-combustion, oxy-fuel, and post-combustion, when integrated with coal-fired power plants, have been researched extensively in literature. Research on the integration of power generation with capture technologies regarding comparisons between the different schemes in response to dynamic inputs is lacking. This work provides a comparison between a low temperature carbon capture and a chemical absorption process in response to a dynamic electricity demand and price profile and in the presence of an intermittent wind power supply. The objective in this work is to meet the overall electricity demand of residential users and the carbon capture process while the total operating cost associated with the integrated system of power generation and carbon capture is minimized. This comparison includes scenarios with and without energy storage associated with each capture technology. It is observed that in both integrated systems, with and without energy storage, the overall electricity demanded by the capture process and residential users is supplied by a combination of coal and wind power. For the case without energy storage, the total operating cost and energy demand of the low temperature carbon capture, based on a similar amount of captured carbon dioxide, are 4.3% and 20.5% less than that of chemical absorption, respectively. For the scenario with energy storage, the low temperature carbon capture requires 32.34% less energy to capture similar amounts of carbon dioxide while incurring 9.09% less overall operational cost.

1. Introduction

Many countries rely on electricity generation from fossil fuels to meet a significant portion of their energy demands. In the United States, for instance, the projections from the US Energy Information Administration (EIA) show a continuing dependence of the US power sector to fossil fuels in 2050 by 56% with Clean Power Plan (CPP) regulations in place (62% without CPP), compared to 70% in 2015. Because combustion of fossil fuels generates carbon dioxide (CO_2), the power sector will remain one of the major CO_2 emitting sources in the US with 23% contribution in 2050 with CPP regulations in place (26% without CPP), compared to 26% in 2015, according to EIA Annual Energy Outlook 2017 [1]. Global and the US national CO_2 emissions will cause substantial environmental and public health issues,

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regardless of the fate of regulations such as CPP. According to reports from the US Environmental Protection Agency (EPA) [2] and Intergovernmental Panel on Climate Change (IPCC) [3], increasing concentrations of CO_2 and other greenhouse gases endanger the health and welfare of current and future generations by causing global warming, harm to agriculture and forests, climate change, and ecosystem damage.

Countries around the world have implemented policies aimed to reduce carbon dioxide emissions from different sources [4,5]. Among all carbon emission sources, coal fired power plants contributed 42% of all CO_2 emissions in 2012 [6]. As a significant contributor to carbon dioxide emissions, CO_2 from coal-fired power plants must be mitigated to meet carbon dioxide standards defined by policy. The problem of reducing carbon dioxide emissions from coal-fired power plants has been addressed and documented in literature. Pre-combustion [7–9], oxy-fuel [10,11], and post-combustion [6,12–26] carbon capture processes have been researched to reduce carbon dioxide emissions from coal-fired power plants. Extensive research has been conducted on modeling and improving individual carbon capture schemes [27–30], but lacks much regarding comparison between the different schemes in response to dynamic inputs [31]. For instance, [32] considered the techno-economic study of two super critical circulating fluidized bed (CFB) power plants when integrated with oxy-combustion and Ethanolamine (MEA)-based post-combustion processes to separate CO_2. This study compared the operating and capital costs, cost of electricity, and CO_2 penalty when generating a constant power output. Dynamic investigation of each integrated system was also limited to start-up and shutdown procedures. Net efficiency comparison was also considered between oxy-fuel, pre- and post-combustion-based carbon capture technologies when coupled with Integrated Gasification Combined Cycle (IGCC) plants [33]. The pre-combustion process considered in this analysis was based on hot gas clean-up, membrane-enhanced CO conversion, and CO_2 condensation while the combination of calcination - carbonation loops, hot gas clean-up, and oxygen membranes constituted the post-combustion capture process. This comparison was also based on constant inputs to the power plant to generate a time-invariant power output. Other studies also compared the techno-economic performance of different integrated systems, consisting of various configurations of thermal power plants and post-combustion, precombustion, and oxy-fuel combustion technologies, to produce time-invariant power output [34–42]. With the increasing penetration of renewable sources into the power grid, however, thermal power plants experience a significant increase in the number of load ramps to compensate for the intermittent behavior of renewable sources [43–46]. It is, thus, critical to investigate the performance of integrated systems of thermal power plants and carbon capture in response to dynamic circumstances that they may experience. This work compares the dynamic performance of a coal-fired power plant equipped with a novel low temperature carbon capture (LTCC) process with that of a conventional chemical absorption process, when both hybrid systems are subject to time-of-day electricity prices, dynamic electricity demand, and intermittent wind power. The LTCC process considered in this work is a novel technology that has an external cooling loop and requires less energy than most traditional capture processes at similar capture rates. The second capture process is an amine-based chemical absorption system, which is a relatively mature technology. Comparison of the techno-economic performance of the LTCC process with chemical absorption, to produce time-variant power output, and in response to dynamic inputs, is considered for the first time in this paper. This work also provides an optimization framework and demonstrates the benefits of using dynamic optimization principles in finding the optimum power dispatch schedule as well as the optimum operating point of the carbon capture process that results in minimum operational costs while the integrated system is exposed to an intermittent renewable source, a dynamic electricity demand profile, and time-of-day prices of electricity. This optimization framework is modular and can be easily modified and used for similar systems in many industries to optimize the operation of the system in response to the anticipated transient circumstances that occur in the system. In this work, two scenarios are considered for carbon capture plants. In the first scenario, carbon capture technologies operate without energy storage in an inflexible operation configuration. In the second scenario, energy storage is incorporated into the model that allow for flexible operation of the capture plant. The comparison results show that while both systems are able to meet the total electricity demand, the LTCC process has lower total operational costs than chemical absorption. Additionally, the low temperature carbon capture consumes less energy per unit of CO_2 captured.

The remainder of this paper is divided into five sections; in Section 2, integration of the coal-fired power plant with each of the carbon capture technologies is briefly reviewed. Section 3 discusses the common assumptions made in each system and the modeling and optimization frameworks used to describe each technology are also presented. Then, Section 4 presents the simulation results for both systems with and without energy storage. Finally, Section 5 provides a conclusion of the main achievements in this paper as well as a summary of the shortcomings of each model and directions for future work.

2. Description of carbon capture plants

This section provides an overview of integration of the two capture technologies with a base power plant for inflexible and flexible operations.

2.1. Low temperature carbon capture

Low temperature carbon capture separates carbon dioxide by cooling down the power plant flue gases to the desublimation temperature of CO_2. Solid CO_2 is then separated from the remaining flue gases by filtration and liquefied by using the heat available from other streams in the process. Once liquefied, CO_2 is pressurized and transported to the pipeline for other applications such as enhanced oil recovery and fertilizer production. The series of processes that the CO_2-containing streams go through, as described above, are shown in Fig. 1 as a box entitled as “LTCC process”. More details about the LTCC process are available in [47–49]. The cooling medium for the LTCC process is provided by two refrigeration cycles (internal and external). The internal refrigeration cycle uses CF_4 as the refrigerant while liquefied natural gas (LNG) is used in the external cycle. A mixed refrigerant cycle is also utilized to produce LNG in the LNG/mixed refrigerant recuperator [50–52].

In the inflexible operation of the LTCC process, a constant amount of natural gas is circulated to the LNG production facility and the flow rate changes to meet the peak refrigerant demand. In the flexible scenario of the LTCC process, natural gas could be imported from the pipeline and the rate of LNG production can be adjusted according to the volatile electricity price and demand. This is possible because an insulated tank is utilized in the flexible scenario and LNG is produced in excess and stored in the tank during periods with low electricity prices. When electricity is more expensive, LNG is retrieved from the tank to meet the refrigerant demand of the LTCC process. A bypass stream is also used in the flexible scenario to continuously meet the LNG demand of the LTCC process, either partially or completely (according to the electricity price). It should also be noted that the LTCC process and LNG production facilities can operate separately from each other that is a direct result of energy storage. In both scenarios of the LTCC process, the electricity demand of the mixed refrigerant compressor is directly related to the rate of LNG production. Additionally, LNG vaporizes at the outlet of the capture plant in both scenarios and it produces a two-phase stream (95–97% vapor fraction) [47–49]. This stream reaches ambient temperatures by transferring heat in the LNG/mixed refrigerant recuperator, followed by a pressurization step in the natural gas