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Modeling and optimal operation of carbon capture from the air driven by intermittent and volatile wind power

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ABSTRACT

CO_2 capture from ambient air can compensate for all CO_2 emissions to the atmosphere, ultimately reducing CO_2 concentrations on a global scale. It has been widely explored. However, additional CO_2 emits when CO_2-intensive fossil fuels are used to drive the systems of CO_2 capture from air. A replacement of conventional energy by wind energy to power existing systems of CO_2 capture from air is proposed in this paper and its technical feasibility is validated. The intermittency and volatility of wind power supply in seasonal variations are considered when wind power is used to meet the energy requirements for CO_2 capture. Energy requirements for each device in the system of CO_2 capture from air are specified and the characteristics of all devices are also analyzed. In order to investigate how flexible CO_2 capture regarding the variations in wind power supply, an optimal operation model is established. Each device in the system of CO_2 capture is considered as a separate load, thus devices are dispatched separately rather than as a whole to improve the acceptance of fluctuant wind power. The results demonstrate the feasibility of using intermittent and volatile wind power to capture CO_2 from air.

1. Introduction

Global average atmospheric CO_2, the most critical greenhouse gas, increased from 280 ppm (parts per million) by volume in pre-industrial times to a record high of 400 ppm in 2013 [1,2]. Concerns over climate change are driving innovation in technologies to control CO_2 concentration in the atmosphere [3]. CO_2 capture and storage from large stationary sources CCS (carbon capture and storage), is regarded as an effective way to address climate change and CCPPs (CO_2 capture power plants) (are established and operated in many countries [4,5]. CCS focuses on large, stationary concentrated sources, such as electrical power plants, steelworks and cement plants, which produce approximately 50% of global CO_2 emissions [6,7]. Even if all the emissions from large, stationary concentrated sources could be captured, approximately 30–50% of global CO_2 emissions from dispersed, mobile sources would still be emitted into the atmosphere [8].

Direct capture of CO_2 from air has been explored for decades. Large-scale scrubbing of CO_2 from ambient air was first suggested in the late 1990s [9], and various systems of CO_2 capture from air were proposed [10–13]. CO_2 capture processes, costs and energy requirements in published CO_2 capture studies were summarized and the total system costs were estimated again [14]. The cost was quantified to be as high as $600–1000 per ton of CO_2 or as low as $25–30 per ton of CO_2 [8,14]. The significantly expensive cost of direct capture of CO_2 from air makes it unlikely to be an economical CO_2 mitigation technology because: 1) efficiency of converting primary energy to work and second-law efficiency is low, resulting in more cost of power; 2) using carbon-intensive fossil fuel to power the systems of CO_2 capture from air will emit more CO_2 than capture, making CO_2 capture from the air infeasible, so these

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carbon-intensive power plants would need to be accompanied by decarburization technology (such as CCS), resulting in more expensive electricity [14].

It is obvious that, for any CO_2 capture strategy, the net flow of CO_2 out of the atmosphere must be positive. However, additional CO_2 emits when the systems of CO_2 capture from air are powered by fossil fuels. A potential alternative to using fossil fuels driving the systems of CO_2 capture from air is to use CO_2-free power, including wind, solar and nuclear power. Currently the published systems of CO_2 capture from air are powered by IGCC (integrated gasification combined cycle) with CCS or advanced combined cycle with CCS, and these types of carbon-neutral electricity is \$0.07/kWh [14]. Onshore wind is low cost sources of electricity available with average levelized cost of electricity by region of between \$0.06 to 0.09/kWh, and particularly, in some special areas like island and desert where the off-grid wind power without grid connection cost (accounting for 9%–14% of the total costs) have the potential to achieve optimal cost [15], the systems of CO_2 capture from air driven by such low-carbon power show much more cost-effective potential. Concentrated solar energy has been demonstrated as a viable source to provide high temperature process heat. A concentrated solar power-driven reactor was proposed to supply the thermal energy for CO_2 capture [16–18]. Thermodynamic analysis of an ideal solar–driven cycle for capturing CO_2 from air is performed [19]. Solar powered cycle for CO_2 capture addresses the effectiveness of increasing the calcinations reaction temperature. A co-location system of CO_2 capture from air powered by wind is proposed and it could capture about 75 Mt of CO_2 per year in Kerguelen plateau, a remote location with steady wind resources [8].

Previous studies mainly focused on kinetics and thermodynamics analysis, since thermodynamic constraints could derail any form of direct capture of CO_2 from air [20]. However, the output of wind turbines is determined by wind speed whose magnitude and direction have the characteristics of randomness, instability and intermittency, making wind power supply intermittent and volatile. The abundant wind energy may have to be curtailed because real-time balance between load and generation must be maintained, and electricity cannot be economically stored on a large scale [21]. Wind energy curtailed in these cases is called wind power curtailment. Curtailment of wind power generation is becoming common worldwide as wind power development expands across the country, so CO_2-free wind power is put forward to power the systems of CO_2 capture from air. However, the intermittency and volatility of wind power supply are neglected when they are used to meet the energy requirements for capturing CO_2 from air. It is unreasonable to ignore the intermittency and volatility, which, fortunately, are acceptable by the systems of CO_2 capture from air to some extent.

In this paper, conventional fossil energy is replaced by wind energy to power the published systems of CO_2 capture from air. The intermittency and volatility of wind power supply is taken into consideration when validating the technical feasibility of powering CO_2 capture system. The key technical challenges for this system are to specify the energy requirements of each device, such as continuity, stability, and the acceptable limit of power fluctuation rate. Through optimizing the decomposition of intermittent and volatile wind power, energy requirements of devices are met, and the system of CO_2 capture from air is enhanced to capture the maximum CO_2.

The remainder of this paper is organized as follows. Wind power-driven system of CO_2 capture from the air is designed and its load characteristics are analyzed in Section 2. An optimal operation model is established in Section 3. The optimization results for a numerical case study are described in Section 4. The conclusions are provided in Section 5.

2. The system of CO_2 capture from air and its load models

2.1. Schematic of wind power-driven CO_2 capture system

Previous researches have outlined specific technologies for direct capture of CO_2 from air. In this paper, the system of wind power-driven CO_2 capture from air is designed on the basis of existing CO_2 capture systems. The energy requirements for the system are all supplied by intermittent and volatile wind power. The most commonly proposed technology for direct capture of CO_2 from air is known as “wet scrubbing”. Overall of the system is shown schematically in Fig. 1 [10,22]. The yellow lines in Fig. 1 represent the energy flow. The system includes two processes: air contact and regeneration cycle. The chemical reactions of the representative system of CO_2 capture from air are presented in Table 1 [10].

- *Air-contactor:* In the contactor, NaOH (sodium hydroxide solution), popularly called “caustic soda”, is brought into contactor with atmospheric air. CO_2 is absorbed by alkaline NaOH solution, forming Na_2CO_3 (sodium carbonate). This carbonate solution is then sent to *Regeneration cycle.* The gas feed in the schematic is ambient air and gas let out is the air with lower CO_2 concentration.
- *Regeneration cycle:* CaO (Lime) and water are added into slaker, producing $Ca(OH)_2$ (calcium hydroxide). It is then sent to causticizer and reacts with Na_2CO_3 solution, producing solid $CaCO_3$ (calcium carbonate) and NaOH. $CaCO_3$ is collected and sent to the calciner while NaOH is sent back to the *Air-contactor.* The calciner heats $CaCO_3$ until CO_2 is driven off and CaO is reformed. CO_2 is captured, purified and compressed for sequestration. As shown in Fig. 1, sodium hydroxide and lime are regenerated during the process.

2.2. Specification for each device

Researchers have carried out energy analyses on systems of CO_2 capture from air [10,14,23]. The system includes contactor, causticizer, slaker, calciner, kiln, and compressor. Reactions (air contacting, causticization, evaporation, calcinations, CO_2 purification and CO_2 compression) are performed among these devices. The energy requirements for the system include both thermal and kinetic (usually supplied by power motors). An extremely slow decay exists in the system of CO_2 capture from air when the pump is shut down or the fan stops running. The system could capture about 80% of what it would normally capture after the pump had been out of work for 10 min [24]. Regarding the intermittency and volatility of wind power, it is essential to analyze the energy requirements of each device. The energy requirements for separate devices are listed in Table 2, including energy required, energy types, acceptable active power fluctuation rate, electrical replacement and the proportion of energy required for each device.

2.3. Load characteristics of the system of CO_2 capture from air

In order to illustrate the acceptance of power fluctuation of each device, active power fluctuation rate of wind power output is introduced [25]. δ represents the wind power fluctuation rate during time period (t, t+1) and can be calculated by: