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Energy penalty estimates for CO_2 capture: Comparison between fuel types and capture-combustion modes

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ABSTRACT

Carbon capture from power plants holds the key to any significant reduction in CO_2 emissions. This work considers the energy penalty related to CO_2 capture from coal, natural gas and fuel oil-based power plants. We evaluate the minimum thermodynamic work for CO_2 capture, and then estimate achievable targets. All the three modes of capture-combustion: pre-combustion, post-combustion, and oxy combustion, are considered. The low CO_2 concentration in natural gas-based power plants translates into the highest capture energy per ton of CO_2. However, the lowest energy penalty of 10% is obtained with pre-combustion capture in natural gas-based power plants (versus 17% for coal-based power plants). The highest energy penalty of about 20% is found for oxy combustion capture from coal-based power plants. In general, pre-combustion capture seems to provide the lowest energy penalties.

1. Introduction

The tremendous scale of CO_2 emissions and the associated global warming present an urgent environmental challenge [1,2]. The first and necessary step in mitigating CO_2 emissions is CO_2 capture, before any subsequent sequestration or utilization. The largest stationary source of CO_2 emissions worldwide are power plants, followed by refineries, steel and cement production, and petrochemical plants [3,4]. Hence, these are the main sources where carbon capture and storage/utilization (CCS/U) is expected to be applied in the coming years. In this work we evaluate the energy penalty for CO_2 capture from power plants for different fuel types: coal, natural gas and fuel oil.

Different aspects of CO_2 capture from power plants have been studied and the literature is vast. Many studies focus on a particular CO_2 capture technology (e.g., absorption, adsorption, membrane, etc.), while others focus on a particular type of power plant (e.g., coal). Instead, we present a comprehensive technology-agnostic study based on the thermodynamic minimum separation energy. In the context of this study, we first review general works that present a thermodynamic analysis or report energy penalties for different capture modes in power plants.

Hammond and Akwe [5] reported an exergy and economic analysis to evaluate the effect of CO_2 capture for NGCC (natural gas combined cycle) plants. In their study, 90% capture was considered using a commercial amine process. A significant energy penalty of 21% was determined, as well as a concomitant increase in the power generation cost. The study by Davison [6] is one of few to consider the three different types of combustion capture, namely pre-combustion, post-combustion, and oxy combustion. In this study, performance, cost and emissions data are presented for coal and natural gas-fired power plants. Davison reported lower estimated costs of CO_2 capture and compression for coal-based power plants than for natural gas-based power plants. The lowest electricity generation cost was found for pre-combustion capture. Rubin et al. [7] also evaluated the CO_2 capture cost for three major fossil fuel power plant types – pulverized coal, NGCC and IGCC (integrated gasification combined cycle) systems using coal. A modified definition of energy penalty was introduced in their study, namely, the increase in plant energy input per unit of product or output. This measure directly determines the increase in

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resource consumption, environmental burden and economic cost associated with producing an additional amount of electricity. According to this measure, pulverized coal-fired plants with CO_2 capture are found to require 31% more coal per kWh than reference plants without capture.

House et al. [8] calculated the thermodynamic work required for the various steps of post-combustion CCS (carbon capture and storage) from pulverized coal-fired power plants. They concluded that an energy penalty of 40% could be easily achieved, while an energy penalty of 29% is proposed as a reasonable target. Bhown and Freeman [9] calculated the theoretical minimum energy required for post-combustion capture from a coal-fired power plant. For 100% capture, the minimum energy penalty for a flue gas stream with 13% CO_2 is 5.1% of the electrical energy generated by the power plant. Strube and Manfrida [10] studied the effect of capture on plant performance for a pulverized coal power plant with post-combustion CO_2 capture, an IGCC and an oxy-fuel power plant with cryogenic CO_2 capture. They concluded that the IGCC shows the highest efficiency and the lowest energy penalty. However, the captured CO_2 for this option also had the lowest purity, and required further treatment. On the other hand, low energy efficiency was reported for oxy combustion due to the high energy requirement for air separation.

Manzolini et al. [11] studied the integration of a SEWGS (Sorption Enhanced Water Gas Shift) reactor for carbon capture in NGCC. They performed simulation studies on different configurations of SEWGS and three reference cases for electricity production, namely, without carbon capture, with post-combustion carbon capture by MEA (monoethanolamine) and with pre-combustion carbon capture by MDEA (N-methyldiethanolamine). Comparison in terms of net electric efficiency and CO_2 avoided indicated that SEWGS achieves a lower efficiency penalty (7.5%) than MEA (8.4%) and MDEA (8%). Cormos [12] studied pre-combustion capture applied to an IGCC plant, and evaluated the technical, economic and environmental performance of the plant with and without CCS. He reported an energy penalty in terms of net plant efficiency of 7.0–9.5% with CCS. Li and Liang [13] performed an Aspen Plus simulation of a retrofitted 1000 MW pulverized coal-fired power plant in China, and reported an energy penalty of 8.6% for 90% capture and 6% for 50% capture. The retrofitted plant simulated in this study comprised of the conventional power generation system together with a post-combustion unit and additional equipment.

Jenni et al. [14] discussed expert assessments of the range of likely energy penalties for coal-based power plants in 2025, considering six capture technologies for three different policy scenarios. In this study, the energy penalty is defined as the fractional decrease in output per unit input. It was found that a scenario of worldwide carbon pricing could lead to a 1–10% decrease in the mean energy penalty across all technologies, and a scenario of increased US government funding in research and development could lead to a 6–14% decrease in the mean energy penalty. Pre-combustion capture was found to show the smallest improvement in energy penalty from R&D funding and carbon pricing, while post-combustion capture with membranes and other approaches were expected to show the largest improvement. Kuramochi et al. [15] evaluated the techno-economic prospects of CO_2 capture from distributed energy systems. Their findings show that in the near term (2020–2025), the energy penalty for CO_2 capture ranges from 23 to 30% for coal-fired plants and from 10 to 28% for natural gas-fired plants. The latter energy penalty might reduce to 4–9% beyond 2030. Goto et al. [16] reviewed previous studies on the efficiency penalty for post-combustion CO_2 capture from coal-fired power plants. In this study, the efficiency penalty was defined as the net decrease in the power output of a power plant caused by the implementation of CO_2 capture and compression. Efficiency penalties of about 10% were obtained, irrespective of the type of power plant and the type of coal. However, the choice of CO_2 capture technology (chemical absorption, adsorption, membrane, etc.) was found to influence the efficiency penalty reduction significantly (for e.g., novel membranes could lower the efficiency penalty by 5% or more).

Tola and Pettinau [17] reported a techno-economic analysis for coal combustion and gasification. Three coal-fired power plant technologies were compared: (1) USC (ultra-supercritical) plants with conventional flue gas treatment, (2) USC plants with SNOX technology for combined removal of sulphur and nitrogen oxides, and (3) pre-combustion IGCC plants. Detailed process simulations showed that, without CCS, USC is more efficient than IGCC. However, after the implementation of CCS, IGCC becomes more efficient than USC. Cormos [18] reported a techno-economic analysis for a coal-based power plant with calcium looping as the capture method. The reported energy penalty of 5–7.5% for combustion based power plants with calcium looping is lower than for gasification-based power plants with calcium looping and for post-combustion capture with gas–liquid absorption.

More recently, Basavaraja and Jayanti [19] compared four gas-fired power plants with carbon capture: two based on pressurized oxy combustion and two based on chemical looping combustion. Detailed energy and thermodynamic analyses yielded net efficiencies in the range of 31–52% for the four plants. They concluded that chemical looping combustion plants should be preferred as they can accommodate CCS with only 2% loss in thermal efficiency. Supekar and Skerlos [20] examined the thermal efficiency penalties for pulverized coal power plants with post-combustion CO_2 capture. They concluded that contrary to previously lower reported values, capture can decrease the plant thermal efficiency by as much as of 11–23%.

The majority of power plants currently use coal as the primary fuel source, though there has been a recent growth in the number of natural gas-based power plants. The above studies have individually considered one or a few particular aspects of carbon capture from power plants with the performance evaluated in terms of energetics, economics and/or efficiencies. In this work we report a comprehensive study comparing the most common fuel types (coal, natural gas and fuel oil) and the three capture modes (pre, post, and oxy combustion). Results compare the capture energy and the corresponding energy penalties for the various scenarios. The energy penalties are based on the thermodynamic minimum separation energy and a heuristic scaling factor to determine technologically achievable energy penalties. Different from previous studies, our results do not depend on a particular choice of separation technology or process implementation.

2. CCC (Carbon capture and concentration)

Carbon capture and concentration (CCC) is imperative for subsequent sequestration/utilization of CO_2. The energy required to run a capture process is known as the energy penalty. The energy penalty gives an indication of the amount of energy that needs to be spent for carbon capture in relation to the energy generated by the plant. In other words, it is the relative increase in energy input or the relative decrease in electric power output of a power plant with capture compared to the same power plant without capture. More specifically, Bhown and Freeman [9] define the energy penalty as the energy required to capture a ton of CO_2 divided by the electrical energy generated by the power plant per ton of CO_2 emitted.

Energy penalty is perhaps the most objective consideration for the acceptability of a proposed capture technology. However, given the scale of CO_2 emissions, the footprint and capital costs of a capture plant are also critical. The footprint is particularly