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ANALYSIS

Carbon capture and coal consumption: Implications of energy penalties and large scale deployment

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ABSTRACT

Carbon capture and storage (CCS) can limit carbon emissions from coal power stations, but unfortunately decreases the net efficiency of such power plants. This study examines the link between capture technology and coal consumption for large scale CCS deployment. Estimates of the efficiency reduction (i.e., the energy penalty, EP) are assembled for three main technologies. Pre-combustion CCS is most efficient (EP = 18.9 ± 3.9%), oxy-fuel combustion CCS is intermediate (EP = 21.4 ± 5.3%), and post-combustion CCS is least efficient (EP = 24.8 ± 7.5%). Published CCS scenarios are compiled and their associated coal uses are calculated using the obtained EPs under different technology pathways. Coal consumption using CCS can be up to 31% higher compared to equal non-CCS cases, leading to several scenarios exceeding projected coal production in resource constrained studies.

1. Introduction

1.1. Background

The start of the industrial revolution led rapidly to an increase in demand for combustible fuels to feed the new technology that was the steam engine. Eventually, firewood and charcoal could not keep pace with this growing demand and society turned to coal. The emerging industries of the United Kingdom, Germany and the USA spearheaded a rapid growth of coal production in the 19th century with other nations following close behind leading to coal's dominance as an energy source for the industrialized nations. Ever since, coal has remained vital in the modern world and now fuels the rise of China and other emerging actors in the globalized economy [1,2]. However, depletion of available coal resources and questions regarding the long-term longevity of coal production trends have been raised [3]. In recent decades a clear desire to reduce environmental impact has also been highlighted in public debate. Issues such as landscape modification, smog and particulates, acidification, water contamination, and release of Hg and other pollutants have long been connected to coal [4–6]. Furthermore, coal has been identified as a major source of anthropogenic greenhouse gases (GHG), primarily carbon dioxide. This has shifted the focus towards more environmental concern in coal energy utilization, paving the road for clean coal technology development.

Clean coal technologies are a collection of technologies capable of mitigating the environmental impact of coal use. Historically, the primary focus was on sulphur dioxide and particulates, since it is an important factor at the root of acid rain. A more recent focus has been on carbon dioxide due to its impact on anthropogenic global warming. *Carbon Capture and Storage* (CCS) is the latest branch of clean coal technologies and provides a means to significantly reduce CO_2-emission from coal combustion. Important intergovernmental and research organizations such as the International Energy Agency (IEA) and the International Institute for Applied System Analysis (IIASA) recognize the potential of CCS and this technology is included in many scenarios for future energy systems.

The use of CCS brings about several challenges when compared to ordinary coal combustion. One of the most significant issues is the additional energy requirement for the capture process. This is called the *energy penalty* (EP) and can result in a substantial drop in plant efficiency and electricity output. Essentially, this makes a CCS-plant use more coal compared to a conventional coal-fired plant to produce the same amount of net heat and electricity available for consumers.

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Future large scale deployment of coal power with CCS and the intrinsic resource limitations of coal introduce several strategic issues that require attention in development and deployment of CCS technologies, and increased coal consumption for carbon capture adds complexity to this problem. Several studies [3,7,8] aim to projecting future coal production while other studies aim to describe future energy systems with CCS [9–11]. The literature however is deficient in investigations regarding the connection and consistency between available resources and implied resource demand amongst such scenarios.

1.2. Aim of study

The aim of this study is to quantify and discuss the link between carbon capture technologies and coal consumption in the context of available coal resources and likely long-term production pathways. This is done in four steps. Firstly, energy penalties (EPs) are reviewed for three main CCS technology options: pre-combustion, oxy-fuel combustion and post-combustion. Descriptive statistics for estimated EPs found in the literature are derived and presented. Secondly, published CCS scenarios are reviewed with respect to the projected amount of CCS deployment and assumed EPs. Thirdly, EPs found in the literature are used in three CCS deployment scenarios, each with three different technology combinations, described here as technology pathways. For each scenario and technology pathway the associated coal consumption is estimated and compared with an equivalent net energy output coal scenario without capture technology. Lastly, resource constrained outlooks for coal production are compiled and compared with the implied coal consumption for different CCS scenarios. Strategic issues raised by the additional coal requirements of CCS are then discussed.

2. Review of capture technologies and energy penalties

2.1. Carbon capture technologies

There are three main technology categories for capturing CO_2 in coal-fired power plants: *pre-combustion, oxy-fuel combustion,* and *post-combustion* capture. According to Rubin et al. [12], in all three capture methods, the capture process accounts for roughly 60% of the energy penalty, the compression of CO_2 30% and electricity for pumps and fans 10%. However, the three categories differ in how the CO_2 is captured, which fuel is combusted and when in the electricity generation process the capture takes place. A brief overview of the different approaches is therefore necessary to better understand the energy penalty.

2.1.1. Pre-combustion capture

In pre-combustion capture, the CO_2 is separated and collected before the combustion of the fuel. One way of doing this is by employing an integrated gasification combustion cycle (IGCC). An *air separation unit* (ASU) delivers oxygen used by the gasification process. Synthesis gas (syngas), a mixture of primarily CO and H_2, is produced from which CO_2 is recovered after shift reaction. After capture, the remaining H_2 is burned in a gas turbine to produce electricity and heat. Together with excess heat from the gasifier, a heat recovery steam generator (HRSG) produces steam for an additional steam turbine. Compared with post-combustion and oxy-fuel, IGCC is a more complicated technology. Fig. 1 shows a basic IGCC configuration.

2.1.2. Oxy-fuel combustion

This technology aims to increase the CO_2 concentration in the flue gases by reducing the N_2 in the gas used for combustion [13]. Coal is combusted in pure oxygen, derived from an air separation unit, to produce electricity. Some of the generated electricity will be used to compress the CO_2 and power the ASU and auxiliary equipment like pumps. Around 70% of the flue gas, which contains mostly CO_2 and water, is recycled to the furnace. This is done to control the combustion temperature and prevent damage to heat exchangers and other components [14]. Fig. 2 shows the working principle of an oxy-fuel coal power plant.

2.1.3. Post-combustion capture

Post-combustion techniques feature CO_2 separation and treatment after the coal is combusted by working with the flue gasses. Fig. 3 displays a basic setup of a post combustion capture power plant. Steam is required for regenerating solvents and electricity is required to compress the CO_2. Before CO_2-capturing, flue gasses have to go through a cleanup-process to remove sulphur, nitrous oxides, ashes, and other compounds that could interfere with the capture process.

2.1.4. Retrofitting of existing coal plants

CCS technology can be applied to existing coal-fired power plants with variable ease. Post-combustion systems can be installed without interfering too much with existing plant setup. No major alterations have to be made to the boiler, but the steam cycle of modern plants must be reconfigured so that low pressure steam can be extracted and used in the solvent regeneration [15]. Post-combustion appears to be the most likely technology choice for retrofitting.

New plant construction is the main focus for oxy-fuel combustion, although it can be used to retrofit existing plants [14]. Oxy-fuel combustion capture requires an ASU and a reconstruction of the flue gas system to enable flue gas recycling. The flue gas recycling must be built

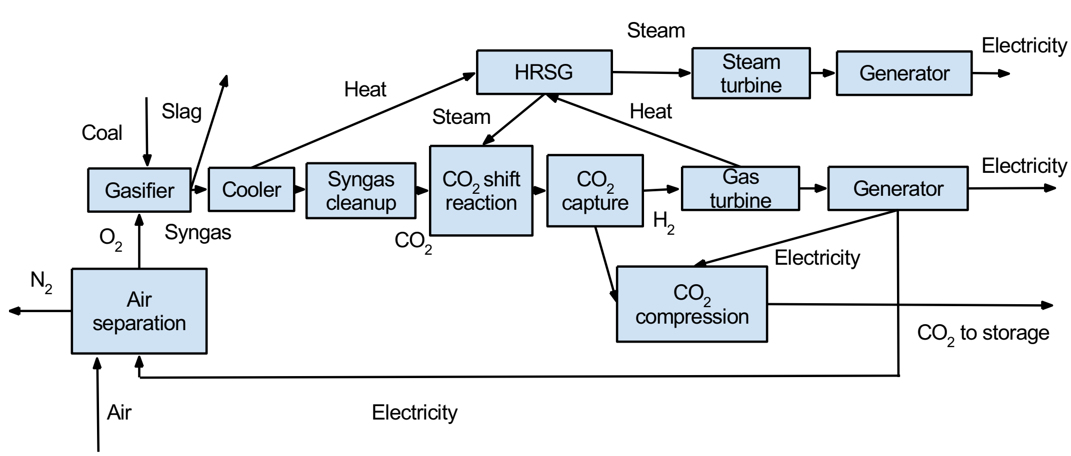

Fig. 1. Overview of a pre-combustion capture coal power plant. The figure shows the most important components of the plant and electricity, steam and gas flows.