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Human health risks of post- and oxy-fuel combustion carbon dioxide capture technologies: Hypothetically modeled scenarios

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ABSTRACT

Carbon dioxide (CO_2) capture technology has become an available technology for ensuring reduction of greenhouse gas emissions from fossil-fuel based electricity generating plants. Since public acceptance of this technology depends critically on a reliable demonstration of its safety, it is important that the risks associated with carbon capture technology be fully understood so that standards and regulatory frameworks required for its deployment can be formulated.

The objective of this paper is to evaluate the predicted risk to human health associated with the Boundary Dam Power Station (BDPS) close to Estevan, Saskatchewan, Canada. This study aims to predict the potential instead of actual risks to human health because real data from the power plants' stacks are unavailable. Instead, the study relies on data that were entirely derived from the Life Cycle Assessment (LCA) studies (Koiwanit et al., 2014a,b; Manuilova, 2011). The risk assessment was conducted based on two tools: (i) the American Meteorological Society's Environmental Protection Agency Regulatory Model (AERMOD), and (ii) Health Canada's Air Quality Benefits Assessment Tool (AQBAT). The conventional lignite-fired electricity generation station at the BDPS is used as a reference case. This work presents the predicted risks to human health due to exposure to air pollution which has been released by the post-combustion carbon dioxide capture process, and compare the risks with those posed by the oxy-fuel CO_2 capture technology.

Nitrogen dioxide (NO_2), particulates less than 2.5 μm in diameter ($PM_{2.5}$), and sulfur dioxide (SO_2) emissions were modeled in a circular pattern of 10 degree increments with 25 zones of 100 m on each increment. This study demonstrates that the reductions in the atmospheric concentrations of NO_2, $PM_{2.5}$, and SO_2 accounted for the largest improvements in human health impacts, particularly in terms of acute respiratory, asthma symptoms, and restricted activity health outcomes. In addition, the oxy-fuel CO_2 capture system reduced emissions to the atmosphere more effectively than the post-combustion CO_2 capture technology. Therefore, the former technology's contribution to reducing air pollution is more significant than that of the latter.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) (2014), in recent decades, climate change has had a strong and widespread impact on natural systems. Recent changes in climate affect heat waves, floods, wildfires, etc. with corresponding impacts on ecosystems and human health. Emissions of carbon dioxide (CO_2), a major greenhouse gas (GHG), contribute extensively to global warming. Significant amounts of CO_2 are produced by electrical generating stations that use fossil fuels, especially coal, which are the world's primary sources of energy (Akorede et al., 2012; Aliyu et al., 2014). To ensure the reduction of CO_2 emissions, the use of an effective CO_2 capture technology is important. The existing post-combustion CO_2 capture technology and a hypothetical Canadian example of oxy-fuel combustion CO_2 capture technology are used as case studies.

A post-combustion capture system uses the traditional power plant technology, in which the fuel is combusted in air. In the post-combustion capture system, the CO_2 is absorbed by the monoethanolamine (MEA) solvent from the flue gases after combustion. The MEA solvent is used here as a proxy for the many amine chemical species available because of the abundance of information

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relating to MEA in the literature. The CO_2 rich solvent is fed to the regenerator, requiring energy to accomplish the CO_2 removal, to extract CO_2 and recover the original MEA solvent. The recovered MEA solvent is recycled for further CO_2 capture, and the CO_2 stream is purified and compressed for transportation and storage. The oxy-fuel combustion system uses the traditional power plant technology, in which the fuel is combusted in pure oxygen (O_2) (>95% volume) and a recycled flue gas stream to dilute the oxygen and provide for adequate heat transfer, instead of air. As a result, there will be a high CO_2 concentration in the resulting flue gas (Wall et al., 2009). Since very little NO_x is produced compared to the conventional air blown combustion, this helps to reduce the heat lost in the flue gas and increases boiler efficiency. However, the O_2 separation process adds an energy penalty for the power plant because additional energy is needed to separate O_2 from air. In this study, the conventional lignite-fired electricity generation station at the Boundary Dam Power Station (BDPS) in Estevan, Saskatchewan, Canada is used as a reference case. Despite their capacities for cutting GHG emissions, the post-combustion and oxy-fuel capture processes also emit some gases that can be hazardous to human health.

Risk is defined as the potential of an unwanted negative consequence or event (Elizabeth and Roy, 1998), and risk assessment is an approach used to collect and structure information so as to identify existing hazardous situations and the associated types and levels of risks to humans as well as to environmental health and safety. The public has a high expectation regarding the safety and operability of the CO_2 capture technology, and any potential liability can be an important barrier to successful implementation and wide public acceptance (Trabucchi et al., 2010; Gerstenberger et al., 2009). An additional concern is that the technology's liability is clouded by a failure to clearly define what the risk is, especially regarding human health and safety (Trabucchi et al., 2010). Hence, the objective of this study is to focus on an assessment of the predicted risks that could potentially result from application of these two CO_2 capture technologies.

While amine is an effective solvent that has been used in post-combustion carbon capture, using amine can result in solvent loss due to: (i) degradation, (ii) vaporization, (iii) mechanical losses, and (iv) aerosol (mist) formation (Mertens et al., 2013). These losses, degradation and vaporization in particular, can lead to unwanted contamination of the treated off-gas leaving the absorber column to the air, particularly if the capture plant is not operated efficiently. The off-gas being discharged from the capture system, while lean in CO_2, can contain toxic substances such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) (Koiwanit et al., 2014c). Various amine degradation products, particularly volatile ones such as ammonia (NH_3), aldehydes, and ketones, can also be carried over from the absorber to contaminate the off-gas stream and pose immediate hazard to human health and the environment (Thitakamol et al., 2007). In addition, the amine solvent used in the system can produce nitrosamines and nitramines, which potentially pose a cancer risk (Korre et al., 2015). However, this study adopted the AQBAT software package for health risk evaluation, and the software only considers the pollutants of $PM_{2.5}$, NO_2, SO_2, O_3, and CO. Thus, the risks to human health derived from the emissions of the degradation products of the amine solvent mentioned earlier cannot be calculated.

To evaluate the concentration in each grid block within the plume area for each type of atmospheric emission from the stack, modeling of the dispersion of contaminants in the air has been conducted. The impacts or damages vary depending on the exposure of the population per unit of emission, the atmospheric conditions, the distances traveled by the pollutants, the types of fuel, and the control technology involved (Levy et al., 2009). According to Preiss et al. (2013) and French et al. (1997), the emissions released from the tall stacks of an electricity generation plant have higher impacts for people who live between 100 km and 200 km from the plant because the emissions from the tall stacks tend not to deposit near the source, but further away. Since the only population base within a reasonable distance of the stack, particularly within the avenues of the primary wind directions, resides in Estevan, hence, it is important to take account of what is happening to this population base. It is also true that the population in Estevan has an exceptionally high rate of asthma (The University of Saskatchewan Airways Research Group, 2012).

NO_x and sulphur dioxide (SO_2) make up the majority of emissions which potentially pose risk to human health (Preiss et al., 2013; Senior et al., 2013). In addition, particulates less than 2.5 μm in diameter ($PM_{2.5}$) and mercury (Hg) emitted during coal-fired power generation are of concern. In terms of mercury, it is true that high levels of airborne elemental mercury (as in an occupational setting) could be acutely hazardous, but not ambient levels, which are orders of magnitude lower. Even though much of the mercury found in lignite is elemental (Srivastava et al., 2006), the concern with mercury from power plants is not airborne elemental mercury but rather methylmercury, which is formed when the mercury is deposited on land and is taken up into fish. There is no observational evidence that mercury "as liquid micro-droplets" (elemental mercury aerosols) occur at sea level, nor at any atmospheric elevation below about 5 km (Murphy et al., 2006). And there have never been reports of mercury aerosols in the Arctic regions (Cole et al., 2013), where temperatures should bring about their formation. However, the mechanisms for homogeneous-phase nucleation of mercury compounds are still relatively unexplored (Ariya et al., 2015).

The amine-based post-combustion system also emits amines, formaldehyde, nitrosamines, and nitramines, which have been predicted to have potential adverse health impacts (Gjernes et al., 2013; Nielsen et al., 2012). While amines were detected in the air, its concentration was below any reliable detection limit, and there were no detectable amounts of nitramines or nitrosamines (Gjernes et al., 2013). As such, the risks posed by these chemicals are considered to be minimal and will not be discussed further in this study. The cancer risk of the amount of formaldehyde released from the post-combustion system is at a level which merits concern (Nielsen et al., 2012). For the most part, however, there are no carcinogenic and non-carcinogenic health effects to populations that are 1 km away from the power plants (Mokhtar et al., 2013). Some studies on risks related to coal-fired power plants are summarized in Table 1.

This paper is organized as follows. Section 2 presents several methods for air dispersion modeling and risk assessment of post- and oxy-fuel combustion CO_2 capture processes. Section 3 discusses the results from the analysis; Section 4 gives the discussion on health outcomes posed by the selected CO_2 capture systems and concerns rising from the comparison; and Section 5 presents the conclusion and discusses some directions for future work.

2. Methods of air dispersion modeling and risk assessment of oxy-fuel and post combustion CO_2 capture

2.1. Modeling air dispersion and risk

Since the objective of this study is to evaluate the predicted risks posed to human health by post-combustion and oxygen-based combustion capture systems specific to Saskatchewan, Canada, the assessment of air pollution dispersion and risk was conducted using methodologies that are suited for the Canadian environment. The choice of air pollution dispersion methodology was made between the American Meteorological Society's Environmental Protection Agency Regulatory Model (AERMOD) and CALPUFF. AERMOD and