

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



A Comparative Study of Human Health Impacts Due to Heavy Metal Emissions from a Conventional Lignite Coal-Fired Electricity Generation Station, with Post-Combustion, and Oxy-Fuel Combustion Capture Technologies

Jarotwan Koiwanit , Anastassia Manuilova ,
Christine Chan , Malcolm Wilson and
Paitoon Tontiwachwuthikul

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/63895>

Abstract

Carbon dioxide capture has become an important component for ensuring reduction of greenhouse gases in the atmosphere. Even though emission reduction technologies such as electrostatic precipitators (ESP) and flue gas desulfurization (FGD) are in place at most electricity-generating stations today, the large point source emitters of carbon dioxide (CO₂) and other emissions, such as heavy metals, to the atmosphere are still fossil fuel electricity-generating stations. When CO₂ capture is employed, these emissions can be further reduced. However, despite its important ability to reduce atmospheric emissions, the CO₂ capture technology in fact still releases some emissions through its stacks into the air. Since the safety and stability of the CO₂ capture technology are fundamental considerations for widespread social acceptance, the potential liability associated with the capture technology is cited as an important barrier to successful CO₂ capture implementation. Liability of the technology is further clouded by a failure to clearly define what is at risk, especially regarding human health and safety. This research study will focus on investigating the risks associated with human health and safety resulting from the different versions of the technology including: (i) no capture system, (ii) post-combustion, and (iii) oxy-fuel combustion CO₂ capture technology at the Boundary Dam Power Station (BDPS) in Estevan, Saskatchewan, Canada. The research objective of this study was to evaluate the risk to human health associated with the BDPS in Estevan, Saskatchewan, Canada, using the American Meteorological Society's Environmental Protection Agency Regulatory Model (AERMOD) and cancer

and non-cancer risk equations. This research presents the air dispersion modeling of the conventional lignite-fired electricity generation station at the BDPS, the inclusion of post-combustion CO₂ capture technology, and the oxy-fuel carbon dioxide capture process. The heavy metals were measured near the power plant located in Estevan, Saskatchewan. This study shows that the emissions from the three stacks posed cancer risks of less than one chance in a million (1×10^{-6}). There were only two emissions from the “no capture” scenario that caused inhalation cancer risks of more than 1×10^{-6} . In terms of non-cancer risks, the pollutant’s concentration from the three stacks was unlikely to cause any non-cancer health effects.

Keywords: carbon dioxide capture, AERMOD, air dispersion, risk, human health

1. Introduction

According to [1], in recent decades, climate change has had the strongest and most comprehensive impact to natural systems [2, 3]. Recent changes in climate affect heat waves, floods, wildfires, ecosystems and human systems. Emissions of CO₂ are known to contribute to the climate change as well. CO₂, a major greenhouse gas (GHG) which results in climate change, is mostly generated from electrical generation that uses fossil fuels (e.g., oil, coal, and natural gas, which are regarded as the world’s primary source of energy). To cope with this problem, the use of an effective CO₂ capture technology has become an important approach in ensuring the reduction CO₂ emissions. However, since additional energy is required in carbon capture systems operation, the consumption of primary materials and fuel is increased when compared to the amount used in fossil-fuel-based energy production systems without the carbon capture technology. Consequently, it is necessary to evaluate both the energy utilization of the technology and the risks of the gaseous emissions to human health. This study focuses on the latter consideration.

The objective of this study was to analyze and compare the risks to human health posed by a lignite coal-fired electricity generation station that has the following: (i) no capture system, (ii) post-combustion, and (iii) oxy-fuel combustion CO₂ capture technology at the Boundary Dam Power Station (BDPS) in Estevan, Saskatchewan, Canada. The total area in Estevan is 795.32 square kilometers with a population density of 16.3 persons per square kilometer [4]. For the post-combustion system presented in this paper, the CO₂ is absorbed by a monoethanolamine (MEA) solvent and is purified and compressed for transportation and storage. The fuel in an oxy-fuel technology is combusted in pure oxygen (O₂) (>95% volume), which results in a concentration of CO₂ that is ready for transportation and storage. However, despite its advantages in cutting greenhouse gas (GHG) emissions, post-combustion and the oxy-fuel capture processes also emit some gases through their stacks.

A comparison of the risks to human health posed by a lignite coal-fired electricity generation station that has the following: (i) no capture system, (ii) post-combustion, and (iii) oxy-fuel combustion CO₂ capture technology at the Boundary Dam Power Station (BDPS) in Estevan, Saskatchewan, Canada, will reveal whether there are health-related risks associated

with the different types of carbon capture technology. Understanding the associated risks of the technology can support formulation of the standards and regulatory frameworks required for large-scale application of the carbon capture technology [5]. In this study, the health-related risks of the three technologies are analyzed so as to shed light on the relationships between quantitative emission releases and the probability of occurrences of health effects.

This paper is organized as follows: Section 2 presents some background to the study and provides a discussion on health effects of selected power plant pollutants, Section 3 presents methods of LCA, Section 4 provides several methods for air dispersion modeling and risk assessment of post- and oxy-fuel combustion CO₂ capture processes, Section 5 discusses the results from the analysis, Section 6 gives the discussion, and Section 7 presents conclusion and discusses some direction for future work.

2. Background health effects from typical power plants

2.1. Background and related work

To assess the emissions from the stack and the environmental impacts of the carbon capture technology, three case scenarios of a typical power plant were evaluated. The three scenarios include a power plant with the following: (i) no carbon capture system, (ii) the post-combustion carbon capture system, and (iii) the oxy-fuel combustion carbon capture system. The life cycle inventory (LCI) results generated from a life cycle assessment (LCA) study were used for calculating the pollution concentrations in each grid block within the plume area [6–8]. Air dispersion modeling has been used to evaluate the concentration in each grid block. After that, the concentrations are evaluated for the possible impacts on human health. The emissions released from the tall stacks of the electricity generation plants were not deposited near the source, but further away [9, 10]. PM_{2.5} is ingested into the body via the respiratory system. Hg⁰ has the longest atmospheric life span of the various species of mercury and can be transported easily over long distances due to its insolubility in and low reactivity to water. Hg⁰ is the common mercury species in lignite [11]. Hg^p and Hg²⁺, with their high reactivity and solubility in water, can be controlled by some emission control units such as electrostatic precipitators (ESP) and wet and dry flue gas desulfurization (FGD) [10, 12]. In addition, while rainfall parameters (e.g., wind, temperature, inversions, rainfall's duration, frequency, and intensity) and precipitation near the stacks affect the deposition of wet mercury (Hg), various meteorological factors such as wind speed affect the deposition of dry Hg [12, 13]. According to [9] and [14], even though most power plants were unlikely to cause any significant non-cancer risks to human health, arsenic (As), chromium (Cr), and lead (Pb) were the primary contributors to these risks. For cancer risks, the results showed that the pollutants would not cause any carcinogenic health effects to the population [9, 14]. The studies on air dispersion and risks from coal-fired power plants are summarized in **Table 1**.

Study	Country	Air dispersion and risk methods	Technology/power plant	Results
	Taiwan	ISCST	- 550 MW coal-fired power plant with ESP, FGD, and SCR - 10 stacks	- The average gaseous Hg (Hg^0 and Hg^{2+}) was 2.59–4.12 ng/m ³ - The average particulate Hg (Hg^p) was 105–182 pg/m ³ - The majority of the Hg from the stacks was in gaseous form, so the particulate form was very low - The maximum concentration of total Hg was from downwind site D (10 km from the plant) - The lowest concentration of total Hg was from upwind site A (11 km from the plant)
Lee and Keener Table [12]	USA	AERMOD and ISCST3	- 2 coal-fired power plants - 4 stacks for each plant	- The average annual atmospheric mercury concentration was 0.014–0.085 ng/m ³ depending on each power plant and air dispersion modeling - The average annual dry Hg deposition was 3.62–6.25 $\mu\text{g}/\text{m}^2$ depending on each power plant and air dispersion modeling - The average annual dry Hg deposition was 0.35–13.73 $\mu\text{g}/\text{m}^2$ depending on each power plant and air dispersion modeling - Wet Hg deposition is influenced by rainfall parameters and precipitation near the stacks - Dry Hg deposition depends on meteorological factors - There were similar trends of Hg deposition between these two power plants
Mokhtar et al.	Malaysia	AERMOD and quality health	- 700 MW coal-fired power plant	- The predicted atmospheric As, Cd, Cr, and

Study	Country	Air dispersion and risk methods	Technology/power plant	Results
Table [14]		risk assessment (QHRA)	with ESP and FGD - 3 power plants	<p>Pb concentrations were 1.84×10^{-4}, 2.3×10^{-5}, 5.38×10^{-4}, $1.73 \times 10^{-4} \mu\text{g}/\text{m}^3$</p> <p>- Hazard quotient (HQ) values of all pollutants concentration were less than one. This showed that the pollutants concentration were unlikely to cause any non-cancer risks to human health</p> <p>- For cancer risks, the results showed that the pollutants would not cause any carcinogenic health effects to the population which are at 1 km away from the power plants</p>
French et al. Table [9]	U.S.	Screening assessment	426 coal-fired and 137 oil-fired power plants	<p>- Cancer risks: 424 of the 426 coal-fired plants did not pose any risks. As and Cr were the primary contributors to these risks</p> <p>- Non-cancer risks: None of the emissions posed these risks</p> <p>- Hg emitted during coal-fired power generation is a potential concern since it is a persistent emission which contributes to the Hg levels especially in freshwater fish. Moreover, the emission mostly does not become deposited near the source but further away</p>

Table 1. Summary of air dispersion studies on coal-fired power plants.

2.2. Health effects of typical power plant pollutants

Emissions from a typical coal-fired electricity-generating station without carbon capture technology include secondary aerosols such as heavy metals, nitrogen oxides (NO_x), sulfur dioxide (SO₂), and non-methane volatile organic compounds (NMVOC), which pose risk to human health [15]. The emissions constitute air pollution and can be hazardous to human health [3]. Health effects of selected power plant pollutants are summarized and shown in **Table 2**.

Substances	Human toxicity		Limit value		Typical exposure within the plume	Comments
	Acute (short-term effects)	Chronic (long-term effects)	TWA (the 8-hour time-weighted average (TWA) limit	STEL (short term)/C ceiling	Emission factors (kg/mg coal)	
Sulfur dioxide (SO ₂)	Lung irritant, triggers asthma, low birthweight in infants	Reduces lung function, associated with premature death	5000 ppm	15,000 ppm	2300	Contributes to acid rain and poor visibility
Nitrogen oxides (NO _x)	Changes lung function, increases respiratory illness in children	Increases sensitivity to respiratory illnesses and causes permanent damage of lung	2 ppm	5 ppm	0.054	Forms ozone smog and acid rain. Ozone is associated with asthma, reduced lung function, adverse birth outcomes, and allergen sensitization
Nitrogen dioxide (NO ₂)	Affect health exposure mortality	Decreased lung function in children, perhaps adults	N/A	N/A	4.25	–
Carbon monoxide (CO)	Increase frequency and severity of angina, headaches, exacerbation of cardiovascular pulmonary dysfunction	Decrease work capacity in healthy adults, decrease alertness, flulike symptom in healthy adults, asphyxiation	N/A	1 ppm	N/A	–
Particulate matter (PM)	Asthma attacks, heart rate variability, heart attacks	Cardiovascular disease, lung inflammation, premature death, decreased lung function	25 ppm	100 ppm	N/A	Fine-particle pollution from power plants is estimated to cut short the lives of 30,000 Americans each year
Hydrogen chloride (HCl)	Inhalation causes coughing, hoarseness, chest pain, and inflammation of respiratory tract	Chronic occupational exposure is associated with gastritis, chronic lung inflammation, skin inflammation	N/A	N/A	0.308	–

Substances	Human toxicity		Limit value		Typical exposure within the plume	Comments
Hydrogen fluoride (HF)	Inhalation causes severe respiratory damage, severe irritation, and pulmonary edema	–	N/A	2 ppm	0.6	Very high exposures through drinking water or air can cause skeletal fluorosis
Arsenic (As)	Ingestion and inhalation affect the gastrointestinal system and central nervous system	Known human carcinogen with high potency. Inhalation causes lung cancer; ingestion causes lung, skin, bladder, and liver cancer. The kidney is affected following chronic inhalation and oral exposure	N/A	2 ppm	0.075	–
Cadmium (Cd)	Bronchial and pulmonary irritation, long-lasting impairment of lung function	Human carcinogen of medium potency, kidney injury, chronic inhalation, and oral exposure	0.01 mg/m ³	N/A	0.000205	Other effects noted from chronic inhalation exposure are bronchiolitis and emphysema
Lead (Pb)	Abdominal (stomach) pain, seizures	Kidney injury, decrements in renal function, anemia, paralysis, nervous system issues, and loss of cognitive ability	0.01 mg/m ³	N/A	0.0000255	–
Antimony (Sb)	Gastrointestinal symptoms (vomiting, diarrhea, abdominal pain, and ulcers)	Hemolysis with abdominal and back pain	0.05 mg/m ³	N/A	0.00021	Acute inhalation is related to irritation of the respiratory tract and impaired pulmonary function
Barium (Ba)	Vomiting, perioral paresthesias, diarrhea, paralysis, hypertension, and cardiac dysrhythmias	Baritosis (coughing, wheezing, nasal irritation), kidney damage	0.5 mg/m ³	N/A	0.000009	The health effects depend on the dose, water solubility, and route of exposure

Substances	Human toxicity		Limit value		Typical exposure within the plume	Comments
Chromium (Cr)	High exposure to chromium VI may result in damage to the kidneys, gastrointestinal bleeding, and internal bleeding	Known human carcinogen of high potency	0.5 mg/m ³	N/A	N/A	Chronic effects from industrial exposures are inflammation of the respiratory tract, effects on the kidneys, liver, and gastrointestinal tract
Beryllium (Be)	Erythema and edema of the lung mucosa. This will produce pneumonitis	Chronic beryllium disease or berylliosis	0.5 mg/m ³	N/A	0.0000395	The effects of beryllium vary depending on the concentration of the substance in the air and the duration of the air exposure
Copper (Cu)	Nausea, vomiting, abdominal pain, anemia	Symptoms of liver toxicity such as Wilson's disease, jaundice, and swelling	0.002 mg/m ³	0.01 mg/m ³	0.0000105	–
Cobalt (Co)	Allergic contact dermatitis	Asthma, carcinogenicity	1 mg/m ³	N/A	N/A	Two routes that cobalt can be absorbed: (1) oral and (2) pulmonary routes
Molybdenum (Mo)	–	A gout-like illness, higher serum uric acid levels, carcinogenicity	0.02 mg/m ³	N/A	0.00005	–
Manganese (Mn)	–	Parkinson's disease, clumsiness, tremors, speech disturbances, psychological disturbances, cough, bronchitis, lung disease	0.5 mg/m ³	N/A	N/A	No reports of human effects following acute effects to manganese are available
Selenium (Se)	Producing coughing, nosebleeds, dyspnea, bronchial spasms, bronchitis, and chemical pneumonia	Alkali disease (hair loss, erosion of the joints of the bones, anemia, etc.), cardiovascular disease	0.2 mg/m ³	N/A	0.000245	–

Substances	Human toxicity		Limit value		Typical exposure within the plume	Comments
	(lung irritation caused by toxins, gases, etc.)					
Nickel (Ni)	Skin rash, eczema	Asthma attacks, chronic bronchitis, reduced lung function, lung, and nasal sinus cancer (>10 mg nickel/m ³)	0.1 mg/m ³	N/A	0.00065	People can be exposed to nickel by breathing air and drinking water
Vanadium (V)	Cough, sputum, difficulty in breathing, ear, nose, and throat irritation, headache, palpitation	Cardiovascular disease	0.05 mg/m ³	N/A	0.00014	–
Mercury (Hg)	Inhalation exposure to elemental mercury results in central nervous system effects and effects on gastrointestinal tract and respiratory system	Methyl mercury ingestion causes developmental effects. Infants born to women who ingested methylmercury may perform poorly on neurobehavioral tests	0.2 mg/m ³	N/A	N/A	The major effect from chronic exposure to inorganic mercury is kidney damage
Volatile organic compounds (VOCs)	Irritation, neurotoxic effects, hepatotoxic effects, headache, nausea, irritation of eyes, respiratory system, drowsiness, fatigue	Asthmatic symptom, cancer	0.025 mg/m ³	N/A	0.0000415	–

Table 2. Health effects of typical coal-fired power plant pollutants (modified from Refs. Table [16–21]).

3. Methods of life cycle assessment (LCA)

LCA is a methodology that studies the whole life cycle of a product, often called the cradle-to-grave approach, in which complex systems are broken down into elementary flows. The life cycle assessment consists of four main stages: goal and scope definition, LCI analysis, life cycle impact assessment (LCIA), and interpretation. The phase of defining the goal and scope of an LCA study is important for it is at this stage that the requirements are set. The requirements determine the methodology, which can directly affect the results. The second phase of the LCA

involves construction of a flow model and an inventory analysis so as to provide inventory data for supporting the goal and scope defining in the study. The LCI model is generally shown as a flowchart; and LCI modeling consists of the construction of the flowchart, data collection, and the calculation procedure [22]. The third phase of LCIA aims to specify the environmental consequences in the inventory analysis process. This phase is normally applied to translate the environmental load, inputs, and outputs, based on the inventory results, into environmental impacts such as acidification, global warming potential, and ozone depletion. The last stage of an LCA is the interpretation of outcomes. At this stage, the main objectives include reaching conclusions and preparing recommendations for action. The conclusion should also be consistent with the goal and scope of the study.

The study focuses on using the emission outputs from the LCI step for calculating the emission concentration using air dispersion modeling. Then, the results are used to generate the cancer and non-cancer risks. All unit processes in each scenario of the carbon capture technology are modeled using engineering equations incorporated in a Microsoft® Excel spreadsheet.

4. Methods of air dispersion modeling and risk assessment of post- and oxy-fuel combustion CO₂ capture technologies

4.1. The selected technological boundaries

To assess health-related risks due to heavy metals, three scenarios are compared, which include (i) the conventional lignite-fired electricity generation station without CO₂ capture, (ii) the amine post-combustion CO₂ capture system, and (iii) the oxy-fuel combustion CO₂ capture

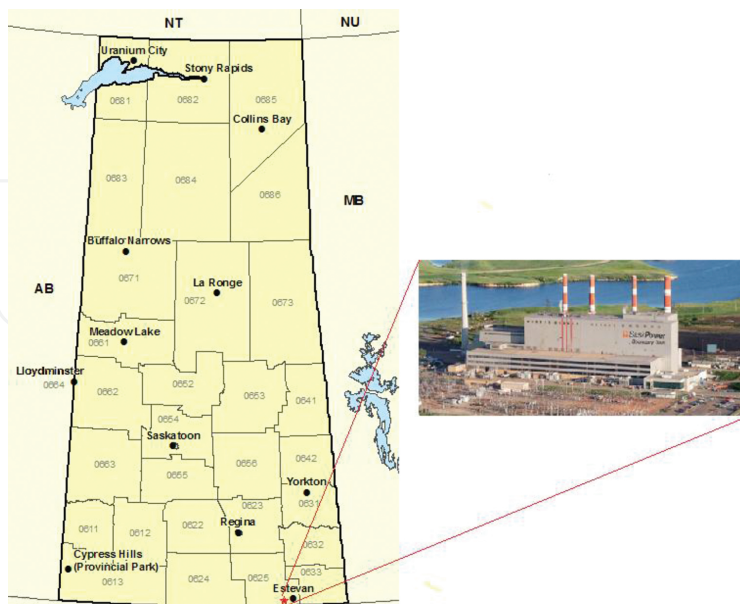


Figure 1. Boundary Dam Power Station (BDPS) in Estevan, Saskatchewan, Canada.

system. The lignite-fired electricity generation station at the BDPS in Estevan, Saskatchewan, Canada, was used in this study; the BDPS is shown in **Figure 1** [23, 24].

The three technologies are compared. These technologies include the following: (i) the conventional lignite-fired electricity generation station without CO₂ capture, (ii) the lignite coal-fired electricity-generating unit with an amine-based post-combustion capture system, and (iii) the oxy-fuel combustion CO₂ capture system. Each technology is described as follows. The conventional lignite-fired electricity generation station consists of (i) unit 3 at the BDPS, which generates 150 MW and is a tangentially fired subcritical boiler, and (ii) a dry ESP unit. The lignite coal-fired electricity-generating unit with an amine post-combustion capture system consists of the following: (i) unit 3 at the BDPS, which generates 150 MW and is a tangentially fired subcritical boiler, (ii) a dry ESP unit, (iii) a wet FGD unit, and (iv) a CO₂ capture and compression unit. The oxy-fuel combustion CO₂ capture system consists of the following: (i) an air separation unit (ASU) for cryogenic distillation, which is often commercially used for air separation, (ii) unit 3 at the BDPS, which generates 150 MW and is a tangentially fired subcritical boiler, (iii) a dry ESP unit, (iv) a wet FGD unit, and (v) a CO₂ purification and compression unit.

The oxy-fuel combustion CO₂ capture technology model is described in [6]. The post-combustion CO₂ capture technology model is presented in [8].

4.2. System boundary

The studied system is located at the BDPS unit 3 in Estevan, Saskatchewan, Canada. From this location, the emissions of heavy metals are predicted to occur in a circular pattern of 10 degrees increments with 25 points of 100 m on each increment. Each direction has 25 distances starting from 100 m and increases every 100 m. The location of the stack at the BDPS unit 3 is set as an origin of the emissions and designated as (0.0, 0.0).

4.3. Modeling air dispersion and risk

Since the objective of this study is to evaluate the risk to humans posed by the conventional coal-fired power plant, the post-combustion, and oxygen-based combustion systems specific to Saskatchewan, Canada, the evaluation was conducted using methodologies for assessing air pollution dispersion, cancer, and non-cancer risks. Two options were considered for implementing the air pollution dispersion methodology: AERMOD and CALPUFF. AERMOD is a steady-state Gaussian plume dispersion model, which is designed to predict near-field (<50 km) impacts [25]. The model aims to estimate and calculate how the pollutions, which are emitted from a source, can disperse in the atmosphere and travel across a receptor grid [26]. By contrast, CALPUFF is a non-steady-state meteorological and air quality modeling system, which can be applied to measure air quality from tens to hundreds of kilometers [27, 28]. The model consists of preprocessing and post-processing programs that can be categorized into three main components: (1) a meteorological model, (2) an air dispersion model, and (3) post-processing packages for the meteorological, concentration, and deposition data output [29]. Both AERMOD and CALPUFF were developed by the US EPA. Since the Government of

Saskatchewan provides the meteorological data specific to Estevan required in the AERMOD model, and AERMOD has been widely used for predicting near-field impacts of chemical pollutants, the AERMOD model is suitable because this study aims to evaluate the risks to health that people who live near the power station face.

Due to the limited available data on the heavy metals, the equations for calculating cancer and non-cancer risks from [30, 31] were chosen as the most appropriate tools for conducting the risk analysis.

4.3.1. Modeling air dispersion

As previously stated, AERMOD is a steady-state Gaussian plume dispersion model, which is designed to predict near-field (or less than 50 km) impacts in both simple and complex terrains as shown in **Figure 2** [25, 32]. The model recognizes the manner in which the pollutants emitted from a source are dispersed in the atmosphere and travel across a receptor grid [26].

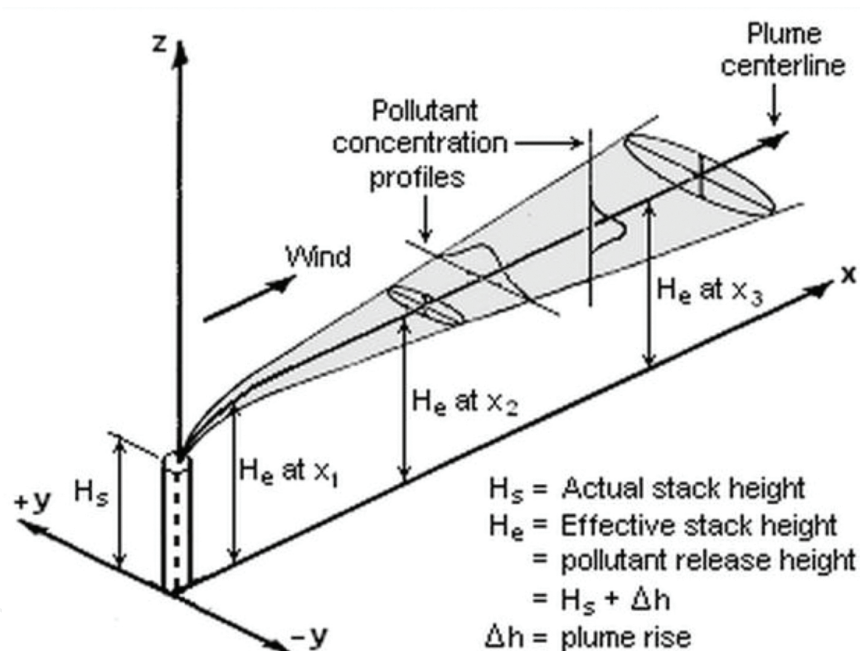


Figure 2. Steady-state Gaussian plume dispersion model in AERMOD [32].

The main data requirements for AERMOD include AERMET, or meteorological data in Estevan, emission rates released from the selected stack, stack height, exit temperature and velocity of the selected emission, and inside stack diameter. The sources of data consist of (i) the meteorological dataset specific to Estevan required in the AERMOD model, which has been provided by the Government of Saskatchewan (www.environment.gov.sk.ca); (ii) the stack data for the “no capture” and “post-combustion” scenario provided by the Saskatchewan Power Corporation (SaskPower) and the dataset of the oxy-fuel combustion generated using the IECM software version 8.0.2 (Trademark of Carnegie Mellon University, USA), and

(iii) the emission rates from the power plant obtained from the LCA studies of a conventional coal-fired power plant, a post-combustion, and an oxy-fuel combustion CO₂ capture processes [6–8]. The meteorological data from years 2003–2007 were used for the AERMOD modeling due to the limitations in available data. The stack data and emission rates are summarized in **Table 3**.

Coal-fired power plant	BDPS unit 3 (without CO ₂ capture)	BDPS unit 3 (with oxy-fuel combustion CO ₂ capture)	BDPS unit 3 (with post-combustion CO ₂ capture)
Stack height (m)	91.44	91.44	91.44
Stack diameter (m)	4.27	4.27	4.27
Exit gas velocity (m/sec)	18.1	15.09	18.1
Exhaust gas temperature (K)	436.15	310.93	436.15
Mercury (Hg)	0.001902781	–	0.001675417
Antimony (Sb)	0.000170833	1.70833E-06	3.41667E-06
Arsenic (As)	0.002041667	0.000018375	0.00003675
Barium (Ba)	0.000541667	5.41667E-06	1.08333E-05
Beryllium (Be)	6.66667E-05	3.33333E-07	6.66667E-07
Cadmium (Cd)	0.000170833	3.41667E-06	6.83333E-06
Chromium (Cr)	0.002458333	0.0000295	0.000059
Cobalt (Co)	0.0002875	0.000002875	0.00000575
Copper (Cu)	0.000958333	2.97083E-05	5.94167E-05
Lead (Pb)	0.00125	0.0000125	0.000025
Manganese (Mn)	0.000179167	1.25417E-06	2.50833E-06
Molybdenum (Mo)	0.001583333	1.58333E-05	3.16667E-05
Nickel (Ni)	0.002416667	3.38333E-05	6.76667E-05
Selenium (Se)	0.017083333	0.0007175	0.001435
Vanadium (V)	0.003666667	2.93333E-05	5.86667E-05

Table 3. Stack features and emission rates.

A comparison of the three scenarios revealed that the higher temperatures, which cause more atmospheric lift, occur with the stacks in the “no capture” and the “post-combustion capture” scenarios. However, the flow velocity in the “post-combustion capture” scenario should have been slightly lowered because of the pressure drop in the unit processes. This study used the same flow velocity both in the “no capture” and the “post-combustion capture” scenarios because this study has adopted the data on the exhaust gas velocity and temperature from SaskPower, which was the only source of data available. The “oxy-fuel combustion” scenario showed lower exhaust gas velocity and temperatures due to the recycling of the flue gas and

the CO₂ compression and purification unit. The data on exit gas velocity was obtained from the SaskPower Web site for the “no capture” and “post-combustion” scenarios, while the oxy-fuel combustion data were results taken from IECM modeling.

4.3.2. Analysis of cancer and non-cancer risks analysis

The risk calculation involves an estimation of the cancer and non-cancer risks related to heavy metals, which can become inhaled contaminants. The emission data for the “no capture” and the two “capture” scenarios are taken from the LCI results in [6–8]. Based on the data, the emission concentrations on the ground were generated using AERMOD, and then, the data were used for evaluating the cancer and non-cancer risks. The equations recommended for estimating cancer and non-cancer risks are taken from [30, 31].

4.3.2.1. Long-term cancer risk

While cancer risks can be associated with both inhalation and ingestion, this study only took the risk related to inhalation into consideration. The unacceptable cancer risk is the risk higher than 1,000,000 [9, 33]. In other words, a cancer risk which is higher than 0.000001 will cause carcinogenic effects, which is an undesirable outcome. The unit risk factor (URF) data were taken from the toxicity values for inhalation exposure shown on the New Jersey Department of Environmental Protection Web site (www.nj.gov). The cancer risk via the inhalation pathway can be calculated with the following equation:

$$\text{Cancer risk} = \text{EC} * \text{URF} \quad (4.1)$$

where EC = Exposure air concentration ($\mu\text{g}/\text{m}^3$) and URF = Unit risk factor ($\mu\text{g}/\text{m}^3$)⁻¹.

4.3.2.2. Long- and short-terms non-cancer risk

The exposure to non-cancer risk due to direct inhalation can be estimated using the hazard quotient (HQ) approach, which involves a ratio for estimating chronic dose/exposure level to the reference concentration (RfC), an estimated daily concentration of emissions in the air [30, 34]. There are two main types of RfC values associated with long-term and short-term effects. The RfC data were taken from the toxicity values for inhalation exposure shown on the New Jersey Department of Environmental Protection Web site (www.nj.gov). HQ values equal to or less than one are referred to as having little or no adverse effect [34]. By contrast, a HQ value that exceeds one implies that the emissions have reached a level of concern [35]. However, since the HQ is not a probability of risk, it does not matter how large the HQ value is, only whether or not the HQ value exceeds one [34]. For example, a quotient of 0.01 does not mean that there is a one in a hundred chance that the effect will occur. The HQ value is calculated using the following equation.

$$\text{HQ} = \text{EC} / \text{RfC} \quad (4.2)$$

where HQ = Hazard quotient (unitless), EC = Exposure air concentration ($\mu\text{g}/\text{m}^3$), and RfC = Reference concentration ($\mu\text{g}/\text{m}^3$).

5. Results

5.1. Results from AERMOD

The study examined the air dispersion modeling of the “no capture” and the two “capture” scenarios. For cancer and non-cancer risks, the maximum 24-hour and 1-hour average concentration values of heavy metals were used for long-term and short-term exposures, respectively. The maximum 24-hour concentration values generated from AERMOD of the “no capture,” “post-combustion CO₂ capture,” and “oxy-fuel combustion CO₂ capture” scenarios are shown in **Table 4**. For short-term effects, the maximum 1-hour concentration values generated from AERMOD of the “no capture,” “post-combustion CO₂ capture,” and “oxy-fuel combustion CO₂ capture” scenarios are shown in **Table 5**. It can be seen from the two tables that the maximum 24-hour and 1-hour average concentrations of the heavy metals of the “no capture” scenario, respectively, show the highest concentrations compared to the other two scenarios. This shows that when the CO₂ capture technologies are applied, lower concentrations of Hg and heavy metals will be emitted into the air. These emissions are captured by the pollution control units provided in the CO₂ capture technologies, and distribution in the atmosphere is controlled by parameters such as the stack height, exhaust gas temperature, and exit gas velocity, as shown in **Table 3**.

Substances	Concentrations		
	No capture	Oxy-fuel combustion	Post-combustion
Hg	4.72E-02	0	4.15E-02
As	5.06E-02	1.08E-03	9.1E-04
Ba	1.34E-02	3.2E-04	2.7E-04
Be	1.65E-03	2.0E-05	2.0E-05
Cd	4.24E-03	2.0E-04	1.7E-04
Cr	6.1E-02	1.73E-03	1.46E-03
Co	7.14E-03	1.7E-04	1.4E-04
Cu	2.37E-02	1.74E-03	1.47E-03
Pb	3.10E-02	7.3E-04	6.2E-04
Ni	5.99E-02	1.99E-03	1.68E-03
Se	4.23E-01	4.21E-02	3.56E-02
V	9.1E-02	1.72E-03	1.46E-03

Table 4. The maximum 24-hour average concentrations of the heavy metals of the “no capture” and the two “capture” scenarios in 2003–2007 ($\mu\text{g}/\text{m}^3$).

Substances	Concentrations		
	No capture	Oxy-fuel combustion	Post-combustion
Hg	4.16E-01	0	3.66E-01
As	4.47E-01	8.43E-03	8.05E-03
Ba	1.18E-01	2.48E-03	2.37E-03
Be	1.46E-02	1.5E-04	1.5E-04
Cd	3.74E-02	1.57E-03	1.5E-03
Cr	5.38E-01	1.35E-02	1.29E-02
Co	6.29E-02	1.32E-03	1.26E-03
Cu	2.09E-01	1.36E-02	1.3E-02
Pb	2.73E-01	5.73E-03	5.47E-03
Ni	5.29E-01	1.55E-02	1.48E-02
Se	3.74	3.29E-01	3.14E-01
V	8.02E-01	1.34E-02	1.28E-02

Table 5. The maximum 1-hour average concentrations of the heavy metals of the “no capture” and the two “capture” scenarios in 2003–2007 ($\mu\text{g}/\text{m}^3$).

The oxy-fuel combustion system gives out less emission at a lower flow velocity, so the emissions fall on the ground closer to the stack and there are less emissions further away. By contrast, the post-combustion system gives out higher emissions at a higher velocity, which enables the emissions to travel further away; the higher temperature of the flue gas also causes atmospheric lift of the emissions. As a result, the emissions are more evenly distributed over a wider area further away from the stack, and their concentrations are lower.

5.2. Results from cancer and non-cancer risks related to heavy metals

The missing inhalation URF and RfC values limit the calculations of cancer and non-cancer risks for some metals. Cancer and non-cancer risk results are shown in **Table 6** and **Table 7**, respectively. **Table 6** indicates that the emissions from the stack in each of the three scenarios pose cancer risks of less than one chance in a million (1×10^{-6}). However, there are two emissions, which include As and Cr, from the “no capture” scenario that pose cancer risks due to inhalation with a chance greater than 1×10^{-6} . In terms of non-cancer risks, the inhalation exposures are estimated by the HQ value, a ratio to estimate chronic dose/exposure level to RfC, an estimated daily concentration of emissions in air. The results shown in **Table 7** display that all HQ values are less than one. When the HQ values are less than one, this indicates that pollutant concentrations from the three stacks are unlikely to correlate with any non-cancer-related health concerns.

Substances	Inhalation unit risk factor (URF) ($\mu\text{g}/\text{m}^3$) ⁻¹	Cancer risk		
		No capture	Oxy-fuel combustion	Post-combustion
Hg	–	–	–	–
As	4.3E-03	1.45E-06	3.09E-08	2.61E-08
Ba	–	–	–	–
Be	2.4-E03	2.64E-08	3.20E-10	3.20E-10
Cd	4.2E-03	1.18E-07	5.6E-09	4.76E-09
Cr	1.2E-02	4.88E-06	1.38E-07	1.16E-07
Co	9E-03	4.28E-07	1.02E-08	8.4E-09
Cu	–	–	–	–
Pb	1.2E-05	2.48E-09	5.84E-11	4.96E-11
Ni	–	–	–	–
Se	–	–	–	–
V	–	–	–	–

Table 6. Cancer risks of heavy metals.

Substances	Long term			Short term		
	RfC ($\mu\text{g}/\text{m}^3$)	Non-cancer risk		RfC ($\mu\text{g}/\text{m}^3$)	Non-cancer risk	
		No capture	Oxy-fuel combustion		No capture	Oxy-fuel combustion
Hg	0.3	1.05E-030	9.24E-04	–	–	–
As	0.015	2.25E-024.8E-04	4.04E-04	0.2	1.49E-022.81E-04	2.68E-04
Ba	–	–	–	0.5	1.58E-033.31E-05	3.16E-05
Be	0.4	5.5E-04 6.67E-06	6.67E-06	–	–	–
Cd	0.02	1.41E-036.67E-05	5.56E-05	–	–	–
Cr	–	–	–	–	–	–
Co	0.006	7.93E-031.88E-04	1.55E-04	–	–	–
Cu	–	–	–	100	1.39E-059.09E-07	8.67E-07
Pb	–	–	–	0.1	1.82E-023.82E-04	3.65E-04
Ni	0.05	7.99E-032.65E-04	2.24E-04	6	5.87E-041.72E-05	1.65E-05
Se	20	1.41E-041.40E-05	1.18E-05	–	–	–
V	0.1	6.06E-031.14E-04	9.73E-05	–	–	–

Table 7. Long- and short-term inhalation exposures of heavy metals.

6. Discussion

The carbon capture technology is one of the most widely discussed solutions for cutting GHG emissions which are mostly generated from electrical generation that uses fossil fuels (e.g., oil, coal, and natural gas, which are regarded as the world's primary source of energy). According to [36], fossil fuels will be continuously used to supply energy globally for at least the next few decades, especially with the recent development of shale gas in many regions of the world. In this scenario, without a proper control technique, the CO₂ atmospheric emissions will continue to increase and pose an even more serious threat to people and the environment. To cope with this problem, the adoption and use of an effective CO₂ capture technology have become an important approach in ensuring the reduction CO₂ emissions. Consequently, it is important to conduct risk assessment to ensure safety of the carbon capture technology. Understanding those risks can support the formulation of standards and regulatory frameworks required for large-scale application of the carbon capture technology [5]. Greater emissions of carbon dioxide poses hazards to human health because inhaling concentrations of CO₂ emissions around 3–5% will pose risks to human health [37]. Inhaling concentration higher than 15% can be fatal. The health, safety, and environmental (HSE) risk of the fossil-fuel-based electrical generation system can be determined to a large extent by both the total amount of CO₂ lost and the maximum rate of CO₂ lost in the system [2]. The health-related damage associated with emissions from coal-fired electricity-generating plants can vary, depending on a number of factors including the facilities, the function of the plant, the site, and population characteristics [38].

Different studies focus on different kinds of risks associated with the process of carbon capture such as (1) cancer and non-cancer risks; (2) population exposure per unit of emissions, which is associated with atmospheric condition, the population size, and their proximities to the emissions; (3) social and mental impacts; and (4) accidents and deaths [9, 14, 15, 39–42]. According to [9], among the emissions from coal-fired electricity-generating plants, As and Cr were the main contributors to cancer risks, and HCl, Mn, HF, and Hg contributed to the non-cancer risks. The coal combustion process can also release many toxic elements, which include As, Hg, Cd, Pb, Se, and Zn, and among these, Hg is of the most concern [15]. According to [43], the population in Estevan has an exceptionally high rate of asthma. In [44], the study compares the human health risks associated with SO₂, NO₂, and PM_{2.5} of the oxy-fuel carbon dioxide capture with those from the post-combustion CO₂ capture technology, and the study reveals that the oxy-fuel system posed fewer human health risks because this technology captures more emissions. In [44], the study fills the gap in research because none of the past studies emphasize the human health impacts due to heavy metals associated with the BDPS in Estevan, Saskatchewan, Canada. This study produces useful data on human health risk and help decision makers quantify the impact of different CO₂ capture technologies. From a practical perspective, the study provides support for efforts aimed at improving the air quality in the Estevan region.

7. Conclusion

Since the coal-fired electricity generation plant is widely regarded as a significant source of air pollution, the adoption of the carbon capture technology is a potential solution for reducing emissions. However, the carbon capture technology requires additional energy for its operation which results in lowering the overall efficiency of the electricity-generating plant. More fossil fuel per unit of electricity generated is needed to compensate for the lost capacity, but the higher requirement also necessitates a higher level of emissions and resource consumption. Since safety of the carbon capture technology is an important public concern, a risk analysis of the carbon capture technology was conducted. While risk is normally defined as the potential of an unwanted negative consequence or event [17], risk analysis is a tool used to form, structure, and collect information to identify existing hazardous situations and report potential problems or the type and level of the environmental health and safety risk [36].

This study focuses on examining the health impacts of the conventional coal-fired generation station without CO₂ capture, with post-combustion and oxy-fuel combustion CO₂ capture technologies. The study analyzed the cancer and non-cancer risks to human health based on the data of air pollutants from heavy metals obtained from the LCA models [6–8]. The risks associated with these pollutants are calculated for the three CO₂ capture scenarios of (i) “no capture,” (ii) “post-combustion CO₂ capture,” and (iii) “oxy-fuel combustion CO₂ capture.”

7.1. Summary of air dispersion modeling

The maximum 24-hour and 1-hour average concentration values of Hg and heavy metals are used for assessing the long-term and short-term exposures, respectively. The results show that, in the “no capture” scenario, the maximum 24-hour and 1-hour average concentrations of the Hg and heavy metals, respectively, show the highest concentrations compared to the two “capture” scenarios. This shows that these emissions are captured by the pollution control units of the CO₂ capture technologies and the less concentrated Hg and heavy metals consequently will be emitted into the air. The air dispersion modeling, which generates emission concentrations, depends not only on the amount of emissions but also on other parameters such as the stack height, exhaust gas temperature, and exit gas velocity. Compared to the post-combustion system, the oxy-fuel combustion system gives out less emission at a lower flow velocity, so the emissions fall on the ground closer to the stack. As a result, there are less emissions further away.

7.2. Summary of risk analysis

The analysis results shown in **Table 6** indicate that the emissions from the three stacks generally posed cancer risks of less than one chance in a million (1×10^{-6}). However, there are emissions from two elements in the “no capture” scenario that pose cancer risks of more than 1×10^{-6} ; As and Cr are the primary contributors to these risks. In terms of non-cancer risks, the results show that all HQ values are less than one. This indicates that the pollutant concentration from the three stacks will not cause any non-cancer health issues.

A limitation in the cancer and non-cancer risks calculation is that data on URF and RfC associated with some types of heavy metals are not available. In future studies, this limitation can be addressed. Generally, it can be concluded that for electricity generation with carbon capture, even though there are increases in adverse health impacts associated with soil and water pollution, the broad distribution of health impacts associated with atmospheric pollutants is significantly reduced. We believe the benefits to human health outweigh the negative of increased emissions.

Acknowledgements

We would like to acknowledge the financial support to the first author from the Networks of Centres of Excellence of Canada–Carbon Management Canada (CMC–NCE), the Government of Saskatchewan, and the Faculty of Graduate Studies and Research of University of Regina. We are also grateful for the financial support from the Canada Research Chair Program to the research project.

Author details

Jarotwan Koiwanit¹, Anastassia Manuilova², Christine Chan^{1*}, Malcolm Wilson² and Paitoon Tontiwachwuthikul¹

*Address all correspondence to: chanchristine888@gmail.com

1 Faculty of Engineering and Applied Science, University of Regina, Saskatchewan, Canada

2 ArticCan Energy Services, Regina, Saskatchewan, Canada

References

- [1] IPCC. Summary for policymakers in climate change 2014: Impacts, adaptation, and vulnerability. New York, USA: Intergovernmental Panel on Climate Change; 2014.
- [2] Gerstenberger M, Nicol A, Stenhouse M, Berryman K, Stirling M, Webb T, Smith W. Modularised logic tree risk assessment method for carbon capture and storage projects. *Energy Procedia*. 2009; 1(1): 2495–2502.
- [3] Trabucchi C, Donlan M, Wade S. A multi-disciplinary framework to monetize financial consequences arising from CCS projects and motivate effective financial responsibility. *International Journal of Greenhouse Gas Control*. 2010; 4(2): 388–395.

- [4] Statistics Canada. Census agglomeration of Estevan, Saskatchewan. 2015 [Internet]. Available from: <https://www12.statcan.gc.ca/census-recensement/2011/as-sa/fogs-spg/Facts-cma-eng.cfm?LANG=Eng&GK=CMA&GC=750>. Accessed on 30 August 2015.
- [5] Damen K, Faaij A, Turkenburg W. Health, safety and environmental risks of underground CO₂ sequestration. (No. NWS-E-2003-30). Netherlands: Copernicus Institute for Sustainable Development and Innovation; 2003.
- [6] Koiwanit J, Manuilova A, Chan C, Wilson M, Tontiwachwuthikul P. A life cycle assessment study of a hypothetical Canadian oxy-fuel combustion carbon dioxide capture process. *International Journal of Greenhouse Gas Control*. 2014; 28: 257–274.
- [7] Koiwanit J, Piewkhaow L, Zhou Q, Manuilova A, Chan C W, Wilson M, Tontiwachwuthikul P. A life cycle assessment study of a Canadian post-combustion carbon dioxide capture process system. *The International Journal of Life Cycle Assessment*. 2014; 19(2): 357–369.
- [8] Manuilova A. Evaluation of environmental performance of carbon capture and storage project in Canada using life cycle assessment methodology [thesis]. Regina: University of Regina; 2011.
- [9] French C, Peters W, Maxwell B, Rice G, Colli A, Bullock R, Cole J, Heath E, Turner J, Hetes B, Brown D C, Goldin D, Behling H, Loomis D, Nelson C. Assessment of health risks due to hazardous air pollutant emissions from electric utilities. *Drug and Chemical Toxicology*. 1997; 20(4): 375–386.
- [10] Wu Y, Rahmaningrum D, Lai Y, Tu L, Lee S, Wang L, Chang-chien G. (Mercury emissions from a coal-fired power plant and their impact on the nearby environment. *Aerosol and Air Quality Research*. 2012; 12: 643–650.
- [11] Srivastava R K, Hutson N, Martin B, Princiotta F, Staudt J. Control of mercury emissions from coal-fired electric utility boilers. *Environmental Science & Technology*. 2006; 40(5): 1385–1393.
- [12] Lee S, Keener T C. Dispersion modeling of mercury emissions from coal-fired power plants at Coshocton and Manchester, Ohio. *Ohio Journal of Science*. 2008; 108(4): 65–69.
- [13] Tudose T, Moldovan F. Characteristics of heavy rainfall parameters in the north-western Romania. *Aerul și Apa: Componente ale Mediului*. 2011; 91–98.
- [14] Mokhtar M M, Hassim M H, Taiba M R, Lim S Z, Sahani M. Health risk assessment in coal-fired power plant in Malaysia. In: *Proceedings of the 6th International Conference on Process Systems Engineering (PSE ASIA)*; 2013. p. 147–152.
- [15] Castleden W M, Shearman D, Crisp G, Finch P. The mining and burning of coal: effects on health and the environment. *The Medical Journal of Australia*. 2011; 195(6): 333–335.

- [16] CDC. Fourth national report on human exposure to environmental chemicals. Atlanta, GA, USA: Centers for Disease Control and Prevention; 2009.
- [17] Elizabeth L A, Roy E A. Risk assessment and indoor air quality. New York, USA: Lewis Publishers; 1998.
- [18] Hu H. (2002). Human health and heavy metals exposure. In: McCally M, editor. Life support: The environment and human health; MIT Press. Cambridge, Massachusetts. 2002. p. 65–82.
- [19] Keating M. Cradle to grave: the environmental impacts from coal. Boston, MA, USA: Clean Air Task Force; 2001.
- [20] NH DES. Copper: health information summary. Concord, NH, USA: New Hampshire Department of Environmental Services; 2013.
- [21] US EPA. Selenium compounds. 2000. [Internet]. Available from:<http://www.epa.gov/ttnatw01/hlthef/selenium.html>. Accessed on 15 August 2013.
- [22] Baumann H, Tillman A. The hitch hiker's guide to LCA. An orientation in life cycle assessment methodology and application. United States of America: Studentlitteratur; 2004.
- [23] Beacon news group Canada. SaskPower launches world's largest carbon capture project. Edmonton Beacon; 2014.
- [24] Environment Canada. Forecast regions - Saskatchewan. 2013. [Internet]. Available from: <http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=CE708E88-1>. Accessed on 21 November 2014.
- [25] US EPA. Summary of public comments: 10th conference on air quality modeling. (No. EPA - HQ - OAQ - 2012 - 0056). U.S.: US EPA, Washington, DC; 2012.
- [26] Heckel P F, LeMasters G K. The use of AERMOD air pollution dispersion models to estimate residential ambient concentrations of elemental mercury. *Water, Air, & Soil Pollution*. 2011; 219(1–4): 377–388.
- [27] Hoeksema G, Onder K, Unrau G. A comparison of Aermოდ and Calpuff models for regulatory dispersion modelling in the alberta oil sands region. *Air and Waste Management Association Annual Meeting Conference and Exhibition*. 2011; 3: 2035–2044.
- [28] US EPA. CALPUFF modeling system. 2013. [Internet]. Available from: http://www.epa.gov/scram001/dispersion_prefrec.htm. Accessed on 4 April 2014.
- [29] Scire J S, Strimaitis D G, Yamartino R J. A user's guide for the CALPUFF dispersion model. Concord, MA, USA: Earth Tech, Inc; 2000.
- [30] US EPA. Chapter 7: Characterizing risk and hazard. Human health risk assessment protocol (pp. 7-1-7-15). 2005; US EPA, Washington, DC.

- [31] US EPA. Risk assessment guidance for superfund. volume I: Human health evaluation manual: (Part F, supplemental guidance for inhalation risk assessment). (No. EPA-540-R-070-002). Washington, DC: US EPA; 2009.
- [32] Beychok M. Air pollution dispersion modeling; 2012. Available from: <http://www.eoearth.org/view/article/169860/> [Accessed 2014-11-21].
- [33] ATSDR. Public health assessment guidance manual (2005 update): Appendix F: Derivation of comparison values [Internet]; 2005. Available from: <http://www.atsdr.cdc.gov/hac/PHAManual/appf.html> [Accessed: 2014-12-15].
- [34] US EPA. Ecological risk assessment step 2 [Internet]; 2011. Available from: <http://www.epa.gov/R5Super/ecology/erasteps/erastep2.html> [Accessed: 2014-12-15].
- [35] Kincaid L E, Davis G A, Meline J. Cleaner technologies substitutes assessment – A methodology and resource guide. Washington, DC: US EPA; 1997.
- [36] Suebsiri J. A model of carbon capture and storage with demonstration of global warming potential and fossil fuel resource use efficiency [thesis]. Regina: University of Regina; 2010.
- [37] Lilliestam J, Bielicki J M, Patt A G. Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): Potentials, costs, risks, and barriers. *Energy Policy*. 2012; 47: 447–455.
- [38] Levy J I, Baxter L K, Schwartz J. Uncertainty and variability in health-related damages from coal-fired power plants in the United States. *Risk Analysis*. 2009; 29(7): 1000–1014.
- [39] Gjernes E, Helgesen L I, Maree Y. Health and environmental impact of amine based post combustion CO₂ capture. *Energy Procedia*. 2013; 37: 735–742.
- [40] Nielsen C J, Herrmann H, Weller C. Atmospheric chemistry and environmental impact of the use of amines in carbon capture and storage (CCS). *Chemical Society Reviews*, 2012; 41(19): 6684–6704.
- [41] Preiss P, Roos J, Friedrich R. Assessment of health impacts of coal fired power stations in Germany. Stuttgart, Germany: Institute for Energy Economics and the Rational Use of Energy (IER); 2013.
- [42] Senior C L, Morris W, Lewandowski T A. Emissions and risks associated with oxyfuel combustion: state of the science and critical data gaps. *Journal of the Air & Waste Management Association*. 2013; 63(7): 832–843.
- [43] The University of Saskatchewan Airways Research Group. The impact of airborne environmental contaminants on respiratory public health in Saskatchewan; 2012. Unpublished manuscript.
- [44] Koiwanit J. Evaluation of environmental performance of hypothetical Canadian oxy-fuel combustion carbon capture with risk and cost analyses [thesis]. Regina: University of Regina; 2015.

