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Life cycle human health and ecotoxicological impacts assessment of electricity production from wood biomass compared to coal fuel

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HIGHLIGHTS

- We compared the human health and ecotoxicological impact of bioenergy with coal fuel.
- Respiratory effect is a concern to electricity production from wood biomass.
- Bioenergy systems significantly reduced both human health and ecosystem quality.
- Bioenergy can assist Alberta's Climate Leadership plan to end electricity from coal.

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ABSTRACT

Analyzing human health and ecotoxicological impacts is crucial in the development of sustainable energy products and technologies. In this research, the human health and ecotoxicological impacts of electricity production from wood biomass were compared to coal fuel. Four bioenergy pathways based on forest residue, round wood chips, and wood pellet feedstocks were compared to direct-fired coal combustion pathway using a novel life cycle assessment approach. Bioenergy pathways significantly reduced both human health and ecosystem quality, when compared to coal fuel combustion. The reduction in toxicity ranged from 89 to 95% for carcinogenics, 68–81% for non carcinogenics, and 66–76% for ecotoxicity impacts, when compared to coal-fired electricity. Use of forest residue feedstock is the absolute option to reduce both human toxicity and ecotoxicity impacts. On the other hand, the respiratory effect of coal fuel was lower by approximately 60–72%, when compared to bioenergy pathways. The respiratory effects impact of all energy pathways is primarily a result of fuel combustion at power plant. Improvements in power plant efficiency, silviculture management, and reduced transport distance have the potential to reduce the respiratory effects of bioenergy systems. Bioenergy can assist Alberta's Climate Leadership plan in the production of sustainable electricity.

1. Introduction

Analyzing human health and ecotoxicological impacts is of central importance in the development of sustainable energy products and technologies [1]. It is imperative that climate mitigation strategies in the electricity sector take into consideration protection against toxicity because actions should not shift the risks from one impact to another [2]. Renewable bioenergy is an alternative source for climate change mitigation; however, it could also possibly have other negative impacts. Significant amount of pollutants that are harmful to human health and ecosystems can be emitted from the combustion of both biomass and coal fuels [3]. Low-level exposure to toxic chemicals present in power plant effluent or used as agriculture inputs are responsible for more chronic health impacts, and can damage ecosystem quality [4].

Generally, bioenergy can reduce the negative environmental impacts from existing coal power plants [5–7]. The presence of potentially toxic elements is a concern for using coal fuel for energy production [8]. The mono-combustion and co-firing of biomass with coal showed human toxicity and ecosystem benefits, when compared with coal-fired electricity generation system [9,10]. Arteaga-Pérez et al. [7] compared the life cycle toxicity impacts of co-firing untreated pine pellets and torrefied-pretreated pine pellets with coal fuel-based electricity. Results show that the co-firing of coal and pellets instead of pure coal leads to a reduction in acidification, eutrophication, global warming,

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photochemical oxidation, human toxicity, and ecotoxicity impacts. Specific policies that promote the generation of energy from renewable sources rather than from fossil fuels, can reduce GHG (greenhouse gas) emissions as well as result in benefits to human health [11]. However, there may be unintended increased impacts when using biomass from an intensely cultivated source [12]. The use of biomass for power generation raises potential occupational health and safety concerns [13].

Studies have examined the environmental impact of bioenergy production in Alberta [14–16]. Those studies focused on GHG emission, however, they may have overlooked the impact in other areas. Moreover, limiting the environmental evaluation to a power plant alone would partially inform the sustainability of an energy system (Meier et al., 2005). Besides to the fuel combustion in a power plant, the feedstock production and transportation life cycle stages of bioenergy pathways should be examined for completeness. The life cycle human health and ecotoxicological effects of energy systems depend on the type of feedstock, energy conversion technology, forest management system, emission control standards, energy pathway, geography, and modeling assumptions. We are not aware of any single life cycle human health and ecotoxicological research conducted, nor have we found a representative study, which examined the life cycle toxicity impacts of a coal-fired energy pathway for Alberta. In addition, the toxicity impact of certain bioenergy pathways, including biomass integrated gasification combined cycle (BIGCC), and the processes and substances that contribute most to toxicity impact remain largely unstudied.

The novelties of this research are numerous. First, the human health and ecotoxicological impacts of energy systems is a scarcely analyzed, yet controversial sustainability issue that needs consideration [17]. Health and ecosystems have been missing dimensions in most climate policies and low carbon energy strategies. Thus, this research introduces new perspectives to the human health and toxicity challenges of developing sustainable energy products. Second, although human health and ecotoxicology is a rapidly growing area of research, quantitative studies remain rare, mainly in the electricity sector [18,19]. Exposure to air pollution claimed the lives of about seven million people worldwide in 2010, largely from the combustion of solid biomass fuels for cooking and heating in households [20]. The degradation of ecosystem services is a significant barrier to achieving *millennium development goals* [21]. Thus, this research informs policy-makers about the human health and ecotoxicological implications of alternative bioenergy sources. Third, this research elucidates the significance of utilizing a representative data and supply-chain for accurate energy decision-making. The coal-fired electricity production system has been modelled for Alberta in *Ecoinvent 3* of the SimaPro database. However, the dataset in this coal life cycle inventory was simply extrapolated from models, which were developed for other jurisdictions. This model does not represent the actual setting for Alberta in terms of fuel type, supply chain, power plant technology, emission standards, and other requirements such as land reclamation. Whereas no bioenergy model was developed in *Ecoinvent 3* for Alberta. Therefore, this study provides insight to policy-makers regarding the guiding measures that are required to ensure sustainable bioenergy production by accounting for important processes, considering multiple energy pathways, and conducting of a comprehensive LCA that represent Alberta's actual condition. Fourth, the use of specific regionalized impact assessment method provides more accurate result. Unlike to many jurisdictions, Alberta has not developed its own specific life cycle impact assessment method. An IMPACT World+ impact assessment method was developed in response to the need of regionalized impact assessment covering the whole world. This method offers generic characterization factors (CFs) representing average conditions for a specific area that do not account for the spatial variability of impacts. This research for the first time tests a novel life cycle impact assessment method called the *IMPACTWorld+* and compares it with the *North American Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI/US-Canadian 2008) method to examine the utility of the method for a wide region.

The prospect of ending electricity from coal through Alberta's Climate Leadership Plan raises a concern that transformations in the electricity sector should not shift the impacts from one impact category to another. The main objectives of this study were to (i) compare the human health and ecotoxicological impacts per functional unit of 1 kW h electricity production, (ii) identify the processes and substances that contribute most to both human health and ecotoxicological impacts, and (iii) identify the changes required across the supply chain to ensure sustainable bioenergy production.

2. Methodology

A life cycle assessment (LCA) method is used to evaluate the environmental impact associated with electricity production from wood biomass to coal fuel throughout its life cycle. The framework for LCA covers four phases, namely goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation phase [22]. A toxicity footprint analysis is conducted in order to assess the chemical impacts that a product may have on human beings and ecosystems [1].

2.1. Goal and scope definition (GSD)

This study compared the life cycle human health and ecotoxicological impacts of biomass and coal fuels per a functional unit of 1 kW h electricity production for the case of Alberta. Direct-fired coal (DF Coal) combustion in a pulverized boiler was compared to four alternative energy pathways for biomass-based electricity: combustion of direct-fired round wood chips (DF RW), combustion of direct-fired forest wood residue (DF FR) in a stoker grate, combustion of direct-fired pellets (DF PL) in a pulverized boiler, and BIGCC. All of the life cycle activities from resource extraction to the use of the feedstock in the power plant were included. However, grid electricity distribution and use were not included in the system boundary since they are identical for all pathways. The system studied consists of the production of feedstock (i.e., biomass or coal), its transportation to the power plant, and electricity generation to the grid. Upstream processes required for the operation of these subsystems are also included from gate to gate. Data for energy and material flow was collected from various government website sources, power plant reports, and literature representing Alberta's specific condition.

The environmental impact categories of respiratory effects, carcinogenics, non carcinogenics, and ecotoxicity were examined using a TRACI/US-Canadian 2008 impact assessment method. The TRACI/US-Canadian 2008 is a midpoint oriented life cycle impact assessment method for characterisation of human and ecotoxicological impacts in LCA. Additionally, an IMPACT World+ life cycle impact assessment method was used to compare the results for environmental impacts with a TRACI/US-Canadian 2008. IMPACT World+ is a novel method which was developed in response to the need of regionalized impact assessment covering the whole world.

2.2. Life cycle inventory analysis

The SimaPro software package was used to track the material and energy flows among unit processes within a system. The