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Life cycle human health and ecosystem quality implication of biomass-based strategies to climate change mitigation

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ABSTRACT

Exposure to air pollution claimed the lives of about seven million people worldwide in 2010, largely from combustion of solid biomass fuels. Bioenergy is an alternative renewable source which can mitigate a climate change. Little is known about the human health and ecosystem effects of bioenergy, mainly in the electricity sector. This research applied a life cycle assessment approach to examine the human health and ecosystem effects of four bioenergy pathways: direct combustion of wood biomass, direct combustion of forest residue, direct combustion of pellets, and *biomass integrated gasification and combined cycle* (BIGCC). All pathways showed some variability of impacts; therefore, no single bioenergy pathway was the best absolute option. With the exception of the slightly higher human health impact, BIGCC has the least impact for all impact categories. However, all bioenergy systems implied lower ecosystem impact but higher human health impact as compared to climate change impact. Electricity generation from wood-biomass would improve the environmental sustainability of Alberta's electricity grid system because it reduces the human health and ecosystem impacts, as compared to the existing electricity production mix of the province.

1. Introduction

Electricity production is the main contributor to GHG (greenhouse gases) emissions and their associated environmental impact [21]. Renewable energy generation sources are becoming more important as concerns over sustainable development grows. The wealth of renewable bioenergy sources in the Canadian province of Alberta is expected to significantly decarbonize its electricity grid [30]. While most renewables reduce climate change impacts, not all renewable energy sources are environmentally sustainable. 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 [18].

The net energy production of bioenergy systems is very promising. Only one unit of energy, in the form of fossil fuels, is required for BIGCC *(biomass integrated gasification combined cycle* system to produce nearly 16 units of electricity [19]. Among other bioenergy alternatives, direct-fired forest residue combustion is the best pathway for the impact indicators of net GHG emission, GOP (ground level ozone precursor), and ARP (acid rain precursor). Air emissions are released primarily from feedstock production and fuel combustion in a power plant [19,26,32]. Co-firing of biomass feedstocks with coal for electricity generation can significantly reduce GHG emissions [10,31].

Energy systems are complex and may result in shifting of impacts if their effects beyond climate change are not examined [33]. However, the focus of previous bioenergy studies has been mainly climate change [4,9,24]. Although climate change is an important sustainability issue, it could not be used as a single indicator to represent the environmental sustainability of a system [22,27]. Studies have examined the environmental impact of bioenergy production in Alberta, but these studies did not examine human health and ecosystem effects of bioenergy pathways [4,15]. Moreover, the BIGCC pathway has not been studied for the case of Alberta. Limiting the environmental evaluation to a power plant alone would partially inform the sustainability of an energy system [21]. Besides to the fuel combustion in a power plant, the feedstock production and transportation phases of bioenergy pathways should be examined for completeness.

The GHG effect of bioenergy is relatively well understood, but human health and ecosystem quality aspects of environmental sustainability remain largely unstudied [37]. The biggest challenge to bioenergy integration in Alberta's energy strategy is information

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and policy barriers [17]. Quantifying the life cycle effects of bioenergy systems can support energy strategy planning and policy making by informing potential trade-offs. This paper examines the environmental performance of bioenergy pathways for Alberta by conducting a life cycle assessment. The main objectives of this study were to (i) investigate the human health and ecosystem implications of bioenergy production, (ii) examine the main contributing substances to toxicity effects of bioenergy systems, (iii) identify impact category for which more detailed regional data is necessary, and (iv) identify important parameters and assumptions.

2. Methodology

Life cycle assessment (LCA) is a method used to evaluate the environmental impacts associated with a system from raw materials acquisition, to feedstock production, transportation, and possibly to final disposal [12,14]. It models the material and energy flows in a system in order to quantify emissions and energy use. According to [14]; the framework for LCA covers four phases, namely goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation phase.

2.1. Goal and scope definition (GSD)

This LCA study examines the life cycle environmental impact of direct-fired RW (round wood chips) combustion, direct-fired FR (forest wood residue) combustion, direct-fired PL (pellets) combustion, and BIGCC systems for the case of Alberta using a functional unit of 1 kWh. Biomass for the power plant was assumed to be a mix of spruce and pine woods that were harvested from Alberta's sustainably managed forest. All of the life cycle activities from resource extraction, production, and feedstock transportation, to the use of the feedstock in the power plant were included. The energy and material flows of all processes necessary to operate the power plant are included in the assessment. Grid electricity distribution and use were not included in the system boundary since they are identical for all pathways and do not affect the overall outcome. The core system studied consists of the production of biomass as a dedicated feedstock crop, its transportation to the power plant, and electricity generation to the grid. Upstream processes required for the operation of these sections are also included from gate to gate. The biomass was assumed to be supplied to the plant as FR, RW, or PL forms. Transportation of the biomass and other materials is by lorry. Primary road construction was not accounted for FR supply because road is constructed primarily for RW extraction. The environmental impact categories examined were global warming, acidification, eutrophication, ecotoxicity, carcinogenics, non-carcinogenics, respiratory effects, ozone depletion, and smog. Human health effect is indicated based on carcinogenics, non-carcinogenics, and respiratory effects impact categories. Ecosystem quality, on the other hand is represented by acidification, eutrophication, and ecotoxicity impact categories. Climate change is indicated by the global warming effect. Because the impact categories of ozone depletion and smog have significance on human health, ecosystem, and climate change impacts, they are discussed independently. The use of specific regionalized impact assessment method provides more accurate result [32]. Unlike to many jurisdictions, Alberta has not developed its own regional life cycle impact assessment method. The *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI) life cycle impact assessment method has been developed for the North American region [3]. Thus, TRACI/US-Canadian 2008 was used to calculate the environmental impacts of energy pathways. The TRACI/US-Canadian 2008 is a midpoint oriented life cycle impact assessment method for characterisation of human and ecotoxicological impacts in LCA. In this research, we identify impact category for which more detailed regional data is necessary by comparing the substance contribution result obtained using TRACI with ReCiPe and IMPACT 2002+ impact assessment methods. Environmental impact category results are difficult to understand because they involve different units and different scales. Therefore, further aggregation of results is needed through weighting [14]. Using a weighting step, impact category results are aggregated into a single index. On the other hand, the main objective of this study is to examine the human health and ecosystem implications of alternative bioenergy pathways. However, TRACI does not quantify environmental impacts at damage level or end point. Therefore, this objective was addressed by including a weighting evaluation using ReCiPe and IMPACT 2002+ impact assessment methods [13].

A sensitivity analysis was conducted to minimize the impact of incorporating assumptions. Primary data and Alberta specific settings were used to represent the elementary flows of the core bioenergy system. The systems studied were the generation of electricity based on DF (direct-fired) biomass combustion and biomass gasification technologies.

2.2. Life cycle inventory analysis and modeling assumptions

The LCI (life cycle inventory) phase is the compilation and quantification of elementary flows to and from the product system throughout its life cycle. The SimaPro software package was used to track the material and energy flows among unit processes within a system. Except for some intermediate unit processes, the emissions and material or energy use of most unit process were constructed manually from primary data, and entered into SimaPro. The main parameters and data sources considered for analysis of the energy pathways was documented (see Table A of the Supplementary material: A). The *Base Case* for energy pathways indicates the characteristics of initial modeling assumptions made before conducting a sensitivity analysis of parameters and methods. The process flow diagram for tracking the energy and material uses for electricity production is drawn as shown in Fig. 1.

2.2.1. Base case feedstock production

Forest stands remove large amounts of CO_2 from the atmosphere during early growth and release a similar amount of CO_2 after their growth rate is saturated. This analysis considers a continuous supply of biomass from Alberta's sustainably managed forest units and an equal rate of biomass growth for each year was throughout the life time of the plant operations. As a result, the average net biogenic CO_2 emission was assumed to be zero [20]. Silviculture through the application of recommended fertilizer in Alberta soil would increase the yield by 15% [34–36]. For the base case analysis, the yield of biomass was estimated to be 34 dry ton/ha for RW chips. Around 15% of the biomass harvest is collected in Alberta as FR [30]. Thus, the yield for FR was estimated to be 7.2 dry ton/ha.

In this study, we assumed that biomass feedstock was collected from the *Peace River North-West* region of Alberta radially to the preprocessing plant. Transportation distances were found from the amount of biomass needed to support the specific power plant size. It was assumed that the area would be circular, and a radius was found. Primary road network is used to transport the round wood chip to the biomass preprocessing plant. The ratio of actual distance travelled to the line of sight distance is defined as the tortuosity factor, and the extent of biomass share across the harvesting area is determined by the geometric factor measure. The transportation distance was the average radius of the circle, which was two-thirds