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The search for most cost-effective way of achieving environmental sustainability status in electricity generation: Environmental life cycle cost analysis of energy scenarios

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A B S T R A C T

Over 80% of Alberta's electricity supply comes from fossil fuels; coal fired plants made up 43%. Alberta has announced its *climate leadership plan*, in which it is going to end electricity from coal and move towards sustainable power production. All categories of renewable energy sources, including bioenergy are expected to significantly contribute to the transition and transformation of Alberta's fossil-intensive electricity. As Alberta searches for measures to phasing out coal power plants, understanding the environmental and economic impact of alternatives can support decision-making. The main purpose of this research was to determine a cost-effective way of achieving environmental sustainability status in electricity generation. An environmental life cycle costing approach was applied to compare three biomass-based alternative scenarios, which represented energy transition and transformation in Alberta's electricity sector, with the prevailing scenario of coal-fired energy.

All alternative energy scenarios showed environmental life cycle improvement from 47 to 92% for global warming, 46–90% for human health, and 47–91% for ecosystem impacts, when compared to a reference coal-fired generation scenario. On the other hand, the coal-fired electricity generation scenario demonstrated approximately 63–83% lower life cycle cost impact than alternative scenarios. The life cycle cost of wood biomass-based alternatives demonstrated 83–87% and 22–45% lower than the maximum and minimum average historical electricity generation cost for Alberta, respectively. Bioenergy can support the transition and transformation of coal power plants to a more sustainable power production.

1. Introduction

Searching for cost effective and environmental friendly energy source has become more critical with the increasing concern of sustainability. Sustainability is a process for improving development over a sustained period of time, while maintaining the resilience of economic, social, and environmental systems (Munasinghe and Cutler, 2004). Alberta has announced its climate leadership plan, in which it is going to end electricity from coal and move towards sustainable power production. All categories of renewable energy sources, including bioenergy are expected to significantly contribute to phasing out Alberta's electricity from coal. As Alberta searches for measures to phasing out coal power plants, understanding the environmental and economic impact of biomass-based alternatives can support decision-making.

Bioenergy is becoming vital as a renewable energy source for decarbonizing a fossil-intensive electricity grid system (Weldemichael and Assefa, 2016). Previous research has compared the environmental and economic impacts of bioenergy systems to coal-fired electricity (Basu et al., 2011; De and Assadi, 2009; Hoffmann et al., 2012). The results indicated that coal-fired electricity generating system has the lowest levelized cost (LCOE); however, it poses the highest environmental damage. The prospect for transitions and transformations in the electricity sector draws interest toward biomass as a renewable resource for addressing sustainability. However, the integrated economic and environmental impact of bioenergy alternatives for Alberta has not been studied. On the other hand, assessment based on a levelized cost of

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electricity and a conventional financial accounting method can't inform sustainability. While LCOE is a convenient measure of the overall competitiveness of alternative products, the results can't be used to imply economic sustainability. To this effect, a code of practice for environmental life cycle costing (LCC) has been proposed by the *Society of Environmental Toxicology and Chemistry* (SETAC) to asses the economic sustainability of products (Swarr et al., 2011). To the authors knowledge, this study is the first to apply the framework for LCC in order to determine a cost-effective and environmentally friendly solution in electricity generation. Additionally, the traditional economic impact assessment methods do not address the complete life cycle. The life cycle evaluation of energy systems at power plant alone may oversimplify the sustainability of a product. The upstream and downstream stages of a product affect its economic sustainability (Hunkeler et al., 2008). This study conducted a complete assessment by including important life cycle stages namely, feedstock production and transportation stages, and the internalized cost of external effects throughout the product supply chain.

Alberta's GHG emission has significantly increased by 47% since 1990, primarily due to the increase in the production of fossil fuel resources. Following Saskatchewan, Alberta has much higher emissions per capita than the rest of provinces. Alberta generated 35.7% of Canada's total emissions, while it represented only 11.2% of Canada's population (Weldu and Assefa, 2016). Over 80% of Alberta's electricity supply comes from fossil fuels; coal fired plants made up 43% (Alberta Energy, 2016). As a result, Alberta has announced its *climate leadership plan*, in which it is going to end electricity from coal and move towards sustainable power production. As Alberta searches for measures to phasing out coal power plants, understanding the environmental and economic impact of alternatives can support decision-making. In addition, the lack of an economic impact assessment, within the framework of environmental impact assessment method, has limited the significance of environmental life cycle assessment (LCA) results for decision-making (Swarr et al., 2011). Evaluating the synergies between the environmental and economic considerations of electricity generation supports sustainability and sound policy-making (Zamagni et al., 2012). The objective of this study was to determine a most cost-effective way of achieving environmental sustainability status in electricity generation, and to contribute knowledge and validate the utility of the LCC framework for economic sustainability assessment of products.

2. Methodology and approach

An integrated life cycle assessment and life cycle costing approach was applied to compare three biomass-based alternative electricity generation pathways, which represented energy transition and transformation scenario, with the prevailing scenario of coal-fired energy pathway. The three alternative scenarios are modeled to represent the anticipated transition and transformation in Alberta's electricity sector. The integrated approach uses system boundaries and functional unit equivalent to that of LCA. The ultimate results are portfolio presentations of the LCC integrated with key environmental life cycle impacts.

2.1. Environmental modeling

Life cycle assessment method was used to evaluate the environmental impacts associated with the product system (ISO, 2006).

2.1.1. Goal and scope definition (GSD)

Pellet substitution and co-firing of pellet with coal are the quicker options for integrating biomass to existing coal-fired power plants as they require only minor retrofitting (Ruhul Kabir and Kumar, 2012). Direct co-firing is the simplest and most widely applied technology for co-firing biomass (Fernando, 2012). It involves firing the coal and biomass in the same boiler. Direct co-firing with separate feed systems for coal and pellet was considered for analysis. This LCA includes all of the life cycle activities from resource extraction and feedstock production, transportation, to the production of electricity, and any necessary waste disposal.

Alberta has announced its *climate leadership plan*, in which it is going to end electricity from coal and move towards sustainable power production after 2030. Using a functional unit of 1 kWh, this study quantifies the impact of four electricity generation scenarios for the case of Alberta. Three biomass-based alternative scenarios, which represented energy transition and transformation, were compared with the prevailing scenario of coal-fired energy. Scenario 1 represents the prevailing scenario of direct fired mono-combustion of coal in a pulverized boiler. Scenario 2 represented energy transformation of the coal plant using a direct fired mono-combustion of pellet. On the other hand, Scenarios 3 and 4 represented energy transition in coal power plants. For Scenario 3, the power plant would use coal fuel until 2030, and switches to the use of pellet from 2031 up to the end of the economic life time of the power plant. In contrast, Scenario 4 operates co-firing of pellet and coal until 2030, and switches to a total use of pellet beginning from 2031 up to the end of the economic life time of the power plant. In a pulverized boiler, the coal or pellet are burnt as a fine powder suspension in an open furnace. The IMPACTWorld + impact assessment method was used to quantify the impacts on human health, ecosystem, and climate change.

2.1.2. Environmental life cycle inventory

The life cycle inventory phase (LCI) is the compilation and quantification of elementary flows to and from the product system throughout its life cycle. The process flow diagram for energy pathways was drawn, as shown in Fig. 1. The main parameters and data sources considered for the environmental modeling was compiled (see Tables A1 and A2 of the Supplementary material: A).

2.1.2.1. Feedstock production

2.1.2.1.1. Pellet 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 study considers a continuous supply of biomass from Alberta's sustainably managed forest units of *Division No. 13* and *Division No. 14 West* region of Alberta. An equal rate of biomass growth for each year was assumed throughout the life time of the plant operations; therefore, the average net biogenic CO_2 emission was assumed to be zero (Marland and Schlamadinger, 1997). Silviculture through the application of recommended fertilizer in Alberta soil would increase the yield by 15% (Yang and Bella, 1986). Nitrogen, phosphorus, and copper nutrients are most often responsible for limiting biomass yields in Alberta (AAFRD, 2004). These nutrients were assumed to be supplied by fertilizers. Glyphosate herbicide is necessary for the proper growth and survival of young trees (Thompson and Pitt, 2011). In this analysis, the yield of biomass was estimated to be 34 dry ton/ha for RW chips (Weldemichael and Assefa, 2016). Pellet is formed by an extrusion process, using a piston press, where finely ground biomass material is forced through round cross-sectional dies and cut to a desired length. Processes involved with biomass feedstock production are silviculture, felling, skidding, road construction, biomass preparation, and pelletization. An average life cycle biomass feed requirement at the plant gate was calculated in bone dry ton by accounting pre-haul and post-haul losses. Assuming the harvest area will be circular in shape; therefore, the preprocessing plant would be located