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Life-cycle energy and emission analysis of power generation from forest biomass

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HIGHLIGHTS

- This paper evaluated the energy use and GHG emissions for forest harvest residues.
- Two chipping scenarios were compared for power plant sizes from 10 to 300 MW.
- Feedstock transportation to power plant highest energy use and GHG emissions.
- Chipping at landing used less energy and GHG emissions than chipping at power plant.
- Results were most sensitive to biomass moisture content and power plant lifetime.

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ABSTRACT

Forest harvest residues, which include limbs, branches, and tree tops, have the potential to generate energy. This paper uses a life-cycle assessment to determine the energy input-to-output ratios for each unit operation in the use of these residues for power generation. Two preparation options for obtaining the biomass were evaluated. For Option 1, the forest residues were chipped at the landing, while for Option 2 they were bundled and chipped at the power plant. Energy use and greenhouse gas (GHG) emissions were found for power plants sizes ranging from 10 to 300 MW. For power plants with capacities greater than 30 MW, the transportation of either bundles or woodchips to the power plant used the most energy, especially at larger power plant sizes. Option 1 used less energy than Option 2 for all power plant sizes, with the difference between the two becoming smaller for larger power plants. For the life-cycle GHG emissions, Option 1 ranges from 14.71 to 19.51 g-CO_2eq/kW h depending on the power plant size. Option 2 ranges from 21.42 to 20.90 g-CO_2eq/kW h. The results are not linear and are close to equal at larger power plant sizes. The GHG emissions increase with increasing moisture content. For a 300 MW power plant with chipping at the landing, the GHG emissions range from 11.17 to 22.24 g-CO_2eq/kW h for moisture contents from 15% to 50%. The sensitivity analysis showed both energy use and GHG emissions are most sensitive to moisture content and then plant lifetime. For the equipment, both the energy use and GHG emissions are most sensitive to changes in the fuel consumption and load capacity of the chip van and the log-haul truck used to transport either bundles or wood chips to the power plant.

1. Introduction

Forest biomass for energy generation is considered nearly carbon neutral [1,2] because the amount of CO_2 released during combustion is nearly the same as taken up by the tree during growth. Some GHGs are emitted during the transportation and processing of forest harvesting residues, but they are substantially lower than the total GHG emissions in the production of energy from fossil fuels. Several studies are available for life-cycle emissions for biomass-based power generation [3–9]. However, these analyses were mostly based on agricultural biomass production or construction/demolition wood waste. The amount of GHGs emitted depends upon the type of biomass and the way it is burned [7].

In 2011, Canada emitted 702 million tonnes of CO_2eq GHGs [10]. Of this, the western province of Alberta had the largest emissions [10], which were driven by the petroleum industry. A sink for some of these GHGs is the 404 million ha of forests and woodlands located in the country [10,11]. These plants and trees make up approximately 20% of all the forests and woodlands in the world. In Canada approximately 250 million m^3 of the forest is allowed to be harvested for wood products [12]. British Columbia has the

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highest average harvest at approximately 67 million m^3, followed by Quebec at 16 million m^3, then Alberta at 14 million m^3. Residues left from the harvesting of these trees can provide biomass that can be used to produce bioenergy [13].

In cut-to-length tree harvesting, trees are dragged to the roadside so that the roundwood can be taken out. The removal of the roundwood generates logging residues in the form of tops, limbs, and branches, which are called forest harvest residues. Forest harvest residues collection, piling, processing, and transportation are the key unit processes in which an energy input is required before biomass reaches the boiler. Logging residues (wood chips) have low bulk density and energy content, resulting in low energy per truckload of wood chips transported. To increase the bulk density and transport the maximum allowable load, logging residues are bundled and transported to the power plant for chipping, where a high productivity chipper can be used. Some studies have analyzed GHG emissions and energy input–output ratios for forest biomass bundling in Scandinavian countries [14,15].

Western Canada, which includes Alberta and British Columbia, provides opportunities to use these forest residues for energy generation. In British Columbia, 87 million m^3 of roundwood is harvested per year [16]. Twenty-five percent or 11.6 million bone dry tonnes end up as harvest residues, for which 80% is available at roadsides for easy collection. In Alberta, approximately 23.5 million m^3 of roundwood is harvested per year. Residues constitute ten percent or 1.04 million bone dry tonnes, of which 95% is available at the roadside. Currently residues are burned to prevent wildfires [12]. There is concern that using forest residues removes nutrients used for forest growth that would otherwise return to the soil. To help maintain the forest soil nutrients, ash can be returned back to the forest floor after the biomass is used for energy [17]. Adding this step in the forest biomass to energy generation process is negligible for both the energy balance and GHG emissions and keeps the forest nutrients in balance. Because the nutrient system is maintained and the residues are considered a waste by their burning, the forest harvest residues can be considered to be a good source for bioenergy production.

This study uses a life-cycle assessment to evaluate the energy input and GHG emissions for two pathways of biomass used for electricity production in Western Canada. The first pathway (Option 1) involves residue collection, piling, chipping at the roadside (landing), and transportation of the chips to the power plant. The second pathway (Option 2) involves residue collection, piling, bundling of slash, transportation of the bundles to the power plant, and chipping at plant. This study considers a maximum unit size of 300 MW for biomass-based electricity generation. A comparative analysis for net energy input over the 30-years life of plant for both the options is presented, along with the life-cycle GHG emissions, which are given in g-CO_2eq/kWh. This study also analyzes the effect of power plant size and biomass moisture content on the above-mentioned parameters. Finally, a sensitivity analysis was done to show which variables have the greatest effect on energy use and GHG emissions.

2. Life-cycle assessment of biomass power generation

2.1. Goal and scope

In this study, a life-cycle assessment (LCA) of power generation using forest harvesting residues was carried out. The study presents results for two pathways, Option 1 and Option 2, of fuel supply in Western Canada. The unit processes involved in the production steps considered for power generation and the system boundary are shown in Fig. 1. Biomass production, collection, and piling operations are common to each option. The other unit processes involved in Option 1 are biomass processing (chipping at landing), chip transportation, power plant construction, and recycling of materials. The other unit processes involved in Option 2 are bundling, bundle transportation, chipping at the plant, power plant construction, and recycling of material. The number inside the bracket for each unit process is arbitrarily assigned to each unit process. For unit process 1 (biomass collection), energy consumption and GHG emissions are taken from a detailed literature review. For all other unit operations, energy consumption and GHG emissions are estimated. No credits are taken for sequestration of carbon dioxide during tree growth.

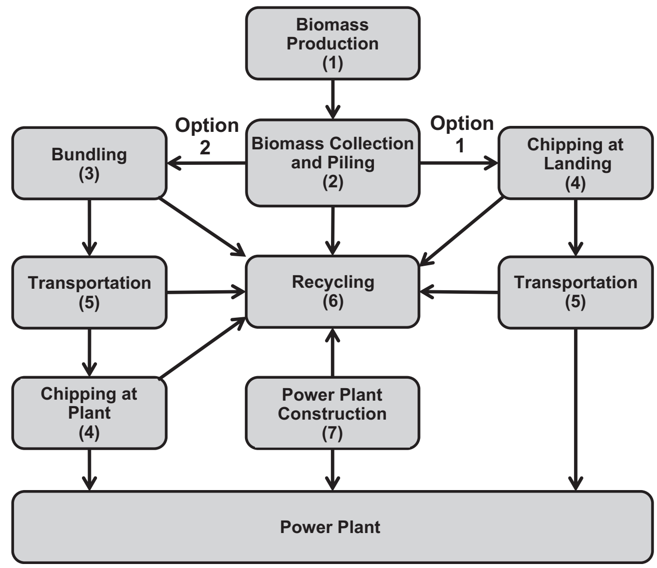

Fig. 1. Unit processes of power production from forest harvest residues for two different options, chipping at the power plant or the landing.

2.2. Life-cycle inventory

2.2.1. Biomass collection and piling

Logging slash is dispersed at the landing site of tree-length harvesting. One way of dealing with the slash is to collect and pile it before a chipping or bundling operation. Normally, a forwarder is used for collection and piling. For this analysis, the Caterpillar 322L excavator is used, with the assumption that a different excavator with similar capacity will not significantly affect the overall results. Table 1 shows the input parameters used in this study for all the equipment used to move and process forest residues. Information on bundling, chipping, and transportation equipment is presented in later sections.

Timberjack, a John Deere company, has conducted life-cycle assessments for several forestry machines. One study presented by this company states that 92.4% and 91.8% of material, for harvesters and forwarders respectively, can be recycled [18]. The same study also mentions that steel, cast iron, and tires are the main materials used in manufacturing and their contributions to the total weight of the machine are 65.5%, 11.2%, and 12.8%, respectively. In this study only these three materials and their percentage contributions in the total equipment weight are considered to estimate lifetime energy and emissions from the unit processes. Minor changes in percentage contributions are possible but these would not change the overall results.

2.2.2. Bundling of harvesting residues

Wood fuel has a lower heating value than do fossil fuels. Apart from the lower heating value, biomass has a low bulk density