Applied Energy 128 (2014) 246–253

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

Amit Thakur, Christina E. Canter, Amit Kumar [*]

*Department of Mechanical Engineering, University of Alberta, 4–9 Mechanical Engineering Building, Edmonton, Alberta T6G 2G8, Canada*

## 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.

## ARTICLE INFO

*Article history:*
Received 16 July 2013
Received in revised form 24 April 2014
Accepted 26 April 2014
Available online 20 May 2014

*Keywords:*
Life-cycle assessment
Energy input-output ratio
Forest biomass bundling
Forest biomass chipping
GHG emissions

## 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-$CO_2$eq/kW h depending on the power plant size. Option 2 ranges from 21.42 to 20.90 g-$CO_2$eq/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-$CO_2$eq/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 $CO_2$eq 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

---

[*] Corresponding author. Tel.: +1 780 492 7797; fax: +1 780 492 2200.
*E-mail address:* Amit.Kumar@ualberta.ca (A. Kumar).

http://dx.doi.org/10.1016/j.apenergy.2014.04.085
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

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-$CO_2$eq/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.

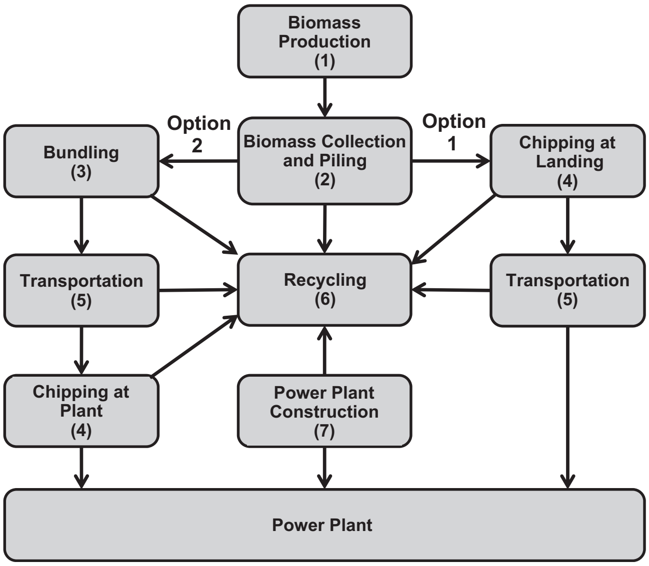

**Fig. 1.** Unit processes of power production from forest harvest residues for two different options, chipping at the power plant or the landing.

### 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

**Table 1**
Characteristics of the equipment used for the moving and processing of forest residues. (Option 1 represents chipping at the landing and Option 2 represents chipping at the power plant.)

| | Value | Unit | References |
|---|---|---|---|
| Forwarder (Option 1 and Option 2) | | | |
| Gross equipment weight | 25 | Tonne | [19] |
| Productivity | 20 | Tonne/h | [20] |
| Fuel consumption | 30 | L/h | [20] |
| Machine life | 5 | Year | [21] |
| Annual availability | 90 | % | Assumed |
| Annual operating hours | 2000 | h/year | Assumed |
| Bundler (Option 2) | | | |
| Gross equipment weight | 24.5 | Tonne | [22] |
| Fuel consumption | 11 | L/h | [23] |
| Machine life | 5 | Year | [21] |
| Annual operating hours | 2100 | h/year | [23] |
| Productivity | 40 | Bundle/h | [24] |
| Average bundle weight | 0.5 | Tonne/bundle | [23] |
| Roadside chipper (Option 1) | | | |
| Gross equipment weight | 26 | Tonne | [25] |
| Productivity | 100 | Tonne/h | [25] |
| Fuel consumption | 85 | L/h | [20,26] |
| Machine life | 5 | Year | [21,27,28] |
| Annual operating hours | 2000 | h/year | Assumed |
| Plant chipper (Option 2) | | | |
| Gross equipment weight | 37.8 | Tonne | [25] |
| Productivity | 170 | Tonne/h | [25] |
| Fuel consumption | 125 | L/h | [26] |
| Machine life | 5 | Year | [21,27,28] |
| Annual operating hours | 2000 | h/year | Assumed |
| Chip van (Option 1) | | | |
| Gross equipment weight | 60 | Tonne | [29] |
| Maximum payload capacity | 30 | Tonne | [20] |
| Fuel consumption | 40 | L/h | [30] |
| Maximum highway speed | 90 | km/h | [30] |
| Vehicle life | 10 | Year | Assumed |
| Annual availability | 90 | % | [30] |
| Log-haul truck (Option 2) | | | |
| Gross equipment weight | 60 | Tonne | [29] |
| Maximum payload capacity | 39 | Tonne | [31] |
| Fuel consumption | 40 | L/h | [30] |
| Maximum highway speed | 90 | km/h | [30] |
| Vehicle life | 10 | Year | Assumed |
| Annual availability | 90 | % | [30] |

ranging from 120 to 150 kg/m$^3$. To achieve the maximum allowable load for transportation, biomass must have a minimum bulk density of approximately 250 to 280 kg/m$^3$ [32]. By bundling residues into composite residue logs (CRL) or bundles this density can be reached. Log-haul trucks and other conventional logging equipment can be used during processing [22,23]. Operational results and performance data available for the John Deere 1490D bundler [22,23,33] were used for this analysis, with the assumption that any other bundler with the same capacity would not significantly affect the overall results. A forwarder is used to load forest residues onto the bundler. Table 1 gives the characteristics of the bundler considered in this study.

The bundler's productivity is an important parameter used in determining the energy use and GHG emissions of this unit process. Species of tree, moisture content, forest residue density and arrangement, size, and operator skill are critical parameters that affect the bundler's productivity [22]. To estimate energy use and emissions for this unit process, the material requirement and its percentage share in total equipment weight were assumed to be the same as in Section 2.2.1 for the forwarder and piler.

### 2.2.3. Comminution of harvesting residues

Woody biomass should be ground or chipped before it can be fired into a boiler for energy production. When forest residues are transported to the power plant in the form of CRLs, chipping is done at the plant (Option 2). In the other case the forest residues are chipped at the roadside and chips are transported to plant using chip vans (Option 1). Large-scale chippers can reduce the cost of chipping, and large-scale chipping can take place at the power plant with a stationary chipper. The largest chipper size available from Bandit Beast, 4680, was used in this analysis [25]. The maximum rated production capacity was taken for the Beast Recycler [25], and fuel consumption was estimated using a methodology provided in an earlier study [26]. For roadside chipping, a chipper with a lower capacity, the Bandit Beast 3680, was used [20]. The chipper was also accompanied by a forwarder to load either CRLs or forest residues. It was also assumed that the chipper in both scenarios operates at the maximum rated production capacity. Table 1 shows the characteristics of the chippers for both options. To estimate energy and emissions associated with equipment manufacturing for this unit process, the material requirement and its percentage share in total equipment weight were assumed to be same as in Section 2.2.1.

### 2.2.4. Biomass transportation

Transportation distances were found from the amount of biomass needed within a circular area to support a specific power plant size. First, the annual heat requirement was calculated by multiplying together the power plant size, operation days per year, and power plant capacity factor, then dividing by both generation cycle and boiler efficiencies. The annual biomass requirement was found by dividing the annual heat requirement by the higher heating value of the biomass. Next, the yearly production per unit area of the residues was divided by the dry matter of biomass to give the biomass yield. For the production per area, results for forests in Alberta using a rotation of 100 years were used, which gave 0.247 dry-tonnes/ha [34]. The harvest area is the annual biomass requirement divided by the biomass yield. It was assumed that the area would be circular, and a radius was found. Finally the transportation distance was the average radius of the circle, which was two-thirds of the overall radius, multiplied by an assumed tortuosity of 1.27 [12] that accounts for the non-linear path of the roads.

The Super B-Train chip van was considered for the transportation of the chips from the roadside to the power plant. For this analysis, a Super B-Train trailer with a combined double trailer capacity of 177 m$^3$ and a maximum payload of 45.4 tonnes for Canada was used [32]. The payload of the van is highly dependent upon the bulk density of chips being transported. It was assumed that the chips would be compacted into the van so that vehicle would reach its maximum payload capacity. Chips would also be directly fed into the chip van from the chipper. Log-haul trucks are used for transporting bundles to the power plant [31] and are accompanied by a loader for both loading and unloading CRLs. Fuel consumption for the log-haul truck was estimated from work by Harrill et al. [35]. Table 1 provides characteristics of the chip van and log-haul truck.

Many materials are used to manufacture trucks and trailers [36]. Table 2 gives the amount and percentage composition of different materials used, excluding any fluids or other materials not defined in [36]. The percentages were recalculated, assuming there would be no contribution from the two excluded categories. Parameters in this table for the tractor were used to calculate the materials used in the forwarder, bundler, chippers, chip van, and log-haul truck. The percentages for the trailer were used for the log-haul trailer. The weight of each piece of equipment was multiplied by the percentage to determine the amount of each material.

**Table 2**
Materials used for the manufacturing of trucks and trailers [36]. The percentages were recalculated by omitting fluids and the "other" category presented in [36].

| Material | Tractor (% of total weight) | Trailer (% of total weight) |
|---|---|---|
| Steel | 59.08 | 48.70 |
| Cast iron | 17.48 | 7.60 |
| Cast aluminum | 3.57 | 0.00 |
| Wrought aluminum | 3.53 | 31.20 |
| Plastic | 4.99 | 0.00 |
| Rubber | 8.28 | 12.50 |
| Copper | 1.61 | 0.00 |
| Lead | 0.82 | 0.00 |
| Glass | 0.63 | 0.00 |

### 2.2.5. Power generation plant

The size of the biomass power plant needed depends upon the availability of biomass within the region. All energy use and GHG emissions were evaluated for the optimum plant size. The impact of a change in size is discussed in subsequent sections. The plant life is assumed to be 30 years with a capacity factor of 85% [37]. A boiler efficiency of 95% and a higher heating value of biomass of 20 GJ/tonne-dry-biomass [37] are used to estimate the annual fuel requirement. The power plant construction material requirement was assumed to be same as a coal-fired power plant. The material requirements were 158,758 kg-concrete/MW, 50,721 kg-steel/MW, 419 kg-aluminum/MW, and 619 kg-iron/MW [38].

### 2.2.6. Recycling of material

It was assumed that recyclable material used in the above-mentioned unit processes will be recovered and recycled for further use. The energy requirement and emissions are highly dependent upon collection efficiency and the type of material used. The collection efficiency was assumed to be 90% of total material used.

## 2.3. Life-cycle assessment

All material and energy use were aggregated for the entire process. Concrete, aluminum, cast iron, and steel are used in the construction of the power plant, while diesel is used for all equipment operation. Various materials were also used for vehicle construction, as discussed in previous sections. Emission factors for these materials were found from GREET 1 and 2 [39,40] and are summarized in Table 3. GREET 2 [40] contains many types of materials, so emission factors were chosen based on the best guess of material source. Emission factors included emissions for steel, cast iron, averaged plastic, rubber, and averaged cast aluminum. The energy use and emissions for recycled versions of these materials were also found from GREET 2 [40]. The emission factor for diesel was found from GREET 1 [39], specifically for heavy duty trucks.

## 2.4. Sensitivity analysis

Variables used to calculate energy consumption and GHG emissions can have either a small or large effect on the results. To determine the importance of these variables, a sensitivity analysis was performed. Parameters evaluated include the power plant life, moisture content, and equipment characteristics, which included productivity, fuel consumption, and load capacity. For the analysis, a base case was chosen. This included all of the equipment parameters discussed above and the characteristics of the power plant. The baseline moisture content was 47% on a wet basis. For the power plant size, a value of 137 MW was chosen because it is the optimum size based on cost for a power plant built in Alberta [37]. Each individual variable was both increased and decreased by 25% of its baseline value for analysis.

**Table 3**
Emission factors and production energy of materials and fuels used during the life-cycle assessment.

| Material | Emission factor (kg-$CO_2$eq/tonne) | Production energy (MJ/kg-material) | Source |
|---|---|---|---|
| Concrete | 406 | 0.24 | [40] |
| Recycled steel | 1804 | 4.8 | [40] |
| Virgin steel | 4961 | 11.52 | [40] |
| Virgin cast aluminum | 12,190 | 34.56 | [40] |
| Recycled cast aluminum | 1364 | 3.84 | [40] |
| Virgin cast iron | 1113 | 7.2 | [40] |
| Recycled cast iron | 156 | 0.41 | [40] |
| Rubber | 4180 | 11.52 | [40] |
| Plastic | 4330 | 18.24 | [40] |
| Virgin wrought aluminum | 11,334 | 155.5 | [40] |
| Copper | 2868 | 39.6 | [40] |
| Virgin lead | 882 | 27.9 | [40] |
| Glass | 1570 | 20.95 | [40] |
| Diesel | 73.98 (kg-$CO_2$eq/GJ) | | [39] |

## 3. Results and discussion

### 3.1. Life-cycle energy consumption

Fig. 2A and B shows the energy consumption for each of the unit processes in Option 1 and Option 2 respectively, presented as the percentage of thermal energy produced for varying power plant size. The thermal energy is the annual heat requirement as discussed in Section 2.2.5. The percent energy consumption for the transportation unit process increases as the size of power plant increases, but the percent energy consumption for all other unit processes remains relatively constant. This result is expected because as the size of the biomass power plant increases, the harvest residue transportation distance also increases.

The bundle transportation method for the fuel supply in Option 2 (Fig. 2B) followed the same energy consumption pattern as for Option 1 (Fig. 2A). Transportation again had the highest energy consumption for any given power plant size. A few points are worth noting at this stage. The transportation energy exhibits an overall increase in life-cycle energy consumption, but there are discontinuities at various points. The overall increase is due to the increase in plant efficiency with an increase the plant size. The efficiency increases with increasing power plant size at the values of 25%, 30%, 35%, and 40% for power plant ranges of <50 MW, 50–100 MW, 100–250 MW, and >250 MW respectively. For the discontinuities, when estimating the number of pieces of equipment operated per year, the next nearest integer was considered because this number can never be a fraction. Hence, for a range of power plants, the same number of pieces of equipment is possible. Also, when the plant efficiency increases, the amount of biomass needed to produce a specific energy decreases. A decreased biomass requirement means a smaller transportation distance and lower diesel consumption. These variables lead to the sawtooth nature of the fuel transportation curve seen in Fig. 2A and B.

Fig. 3 provides a comparison of energy consumption for both options. For all plant sizes, the method of chipping at the landing consumes less energy overall than chipping at the plant. However, as the plant size increases the difference between the two becomes smaller, suggesting that at sizes much larger than 300 MW, it would be advantageous to chip bundles at the power plant. However, this option was not considered because it is much larger than the optimum forest residue power plant size of 137 MW [37].

When comparing the unit processes between the two options, power plant construction, fuel collection and piling, and recycling

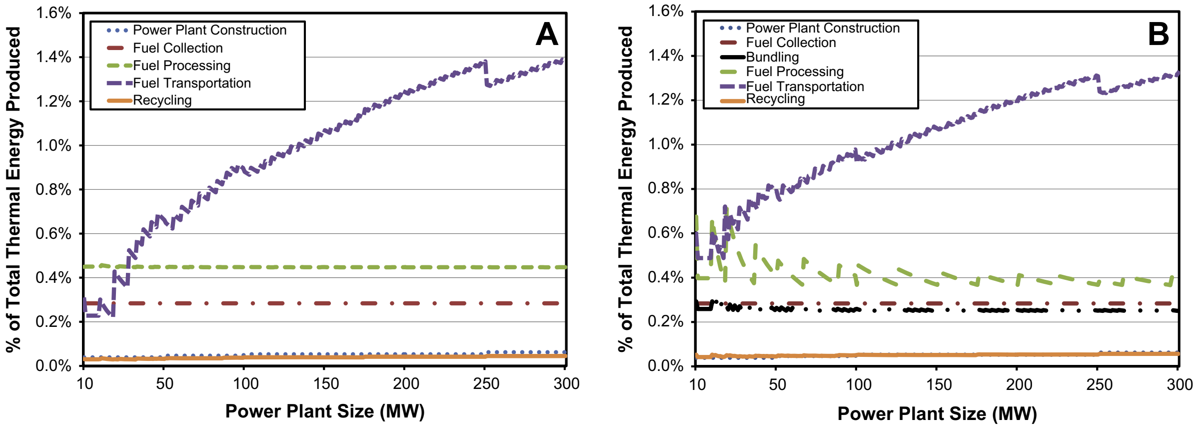

**Fig. 2.** Energy consumption profile for varying power plant sizes for (A) Option 1 (chipping at the landing) and (B) Option 2 (chipping at the plant). The energy is presented as the amount of thermal energy required divided by the amount of thermal energy produced.

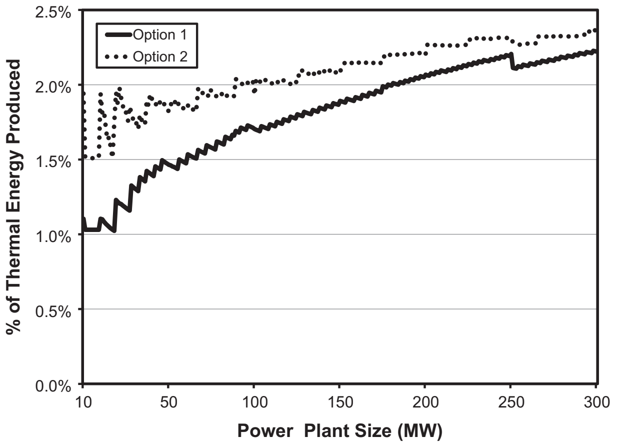

**Fig. 3.** Comparison of the net energy consumption profile for both options. Option 1 considers chipping at the landing and Option 2 at the power plant.

are the same. Hence energy consumption remained the same in these areas for a given power plant size. The energy consumption in the chipping process between the two options was approximately the same (≈0.01%) for all power plant sizes. Bundling is an additional process needed in Option 2 but not in Option 1. Additional energy due to this unit process was approximately 0.29%. The difference between the energy consumption for transportation between the two options decreases as the plant size increases, with Option 1 initially being lower than Option 2. The values are equal at approximately 200 MW, after which Option 2 becomes lower than Option 1.

### 3.2. Life-cycle emissions

Fig. 4A and B shows the GHG emissions (g-$CO_2$/kW h) for Option 1 and Option 2, respectively, as a function of power plant size. Most of the energy is consumed as diesel fuel during equipment operation. Hence, more energy consumption means more $CO_2$ emissions. For each option, the emissions (g-$CO_2$/kW h) during transportation increase with increasing plant size, which is to be expected. A few points are worth noting at this stage. For a plant size less than 250 MW, there is a stepwise decrease in life-cycle emissions for fuel collection and fuel processing (as shown in Fig. 4A and B). This stepwise decrease is due to the increase in plant efficiency with increasing plant size, as discussed earlier. Plant efficiency affects the GHG emission results in the same way as the energy consumption in Section 3.1. When the number of pieces of equipment operated per year for a given unit process is estimated, the next nearest integer is considered because this number can never be fractional. Hence, for a range of power plants the same number of pieces of equipment is possible. These variables lead to the saw-tooth nature of the curve, as shown in Fig. 4A and B.

Fig. 5 shows the overall GHG emissions (g-$CO_2$/kW h) for both fuel supply options. It can be concluded from this figure that the gap between the two options is higher for smaller plants (<100 MW), and this gap reduces with increasing plant size. If only transportation is compared for both fuel transport options, Option 1 (chipping at the landing) emits less $CO_2$ per unit power generated compared to Option 2 (chipping at the plant) for smaller plant sizes. For this unit process, the estimated emissions of $CO_2$ per unit power output are approximately the same at 150 MW for both options. Transportation emissions for plant sizes greater than 150 MW are smaller for Option 2 than Option 1. This is the only reason for the gap in the reduction of emissions of $CO_2$ per unit for larger plant sizes. For other unit processes like fuel collection, processing, etc., the emissions (g$CO_2$/kW h) are higher for smaller plants (<100 MW) and remain constant for larger plants.

### 3.3. Comparison to other studies

Studies have been done evaluating the energy use and GHG emissions for harvesting, processing, and transporting forest residues in the United Kingdom [41], Finland [17], and Sweden [42]. The first paper [41] evaluated chipping either at the landing or the power plant for specific types of residues included whole tree thinning, roundwood, and brash bundles. That study found that chipping at the power plant resulted in fewer GHG emissions than chipping at the landing, which is contradictory to our study. The reason for this contradiction may be that all of their forest residues were bundled, regardless of chipping location. In our study, bundling only occurs if chipping takes place at the power plant.

The results of the Finland study [17] are similar to ours. The authors of that study reported that 2–3% of the energy produced was needed during production, which is similar to our range of 1.1–3.1% for both options. Also, more fuel was consumed for chipping at the plant than at the landing, which is the same as the result from our study. The GHG emissions of their processes for chipping at the roadside or chipping at the plant were 4.3 and 7.5 g-$CO_2$/kW h, respectively. Our study included power plant construction and recycling, while the Finland study did not. Not including emissions from these steps, our values are more than

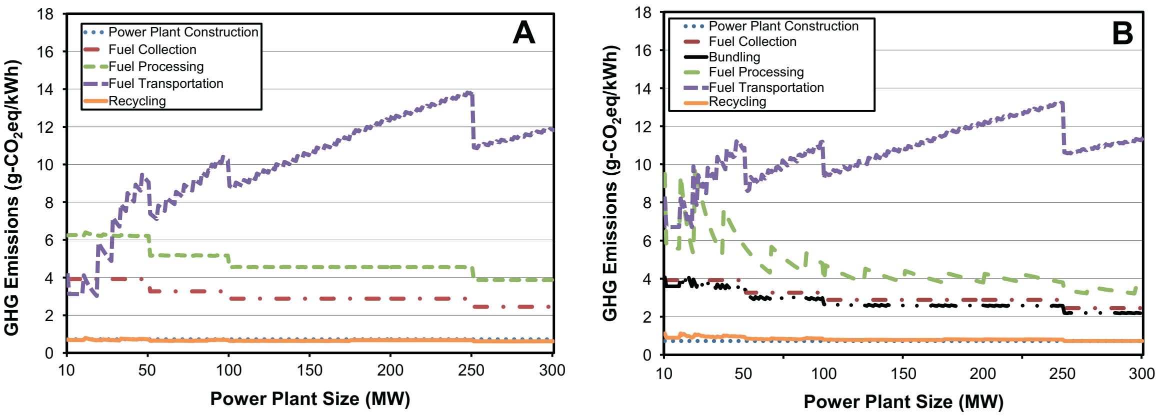

**Fig. 4.** GHG emissions profile for (A) Option 1 (chipping at the landing) and (B) Option 2 (chipping at the plant) based on power plant size.

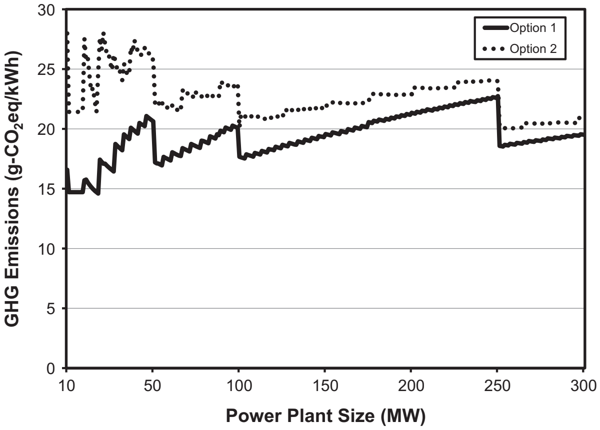

**Fig. 5.** Comparison of total GHG emissions for Option 1 (chipping at the landing) and Option 2 (chipping at the power plant).

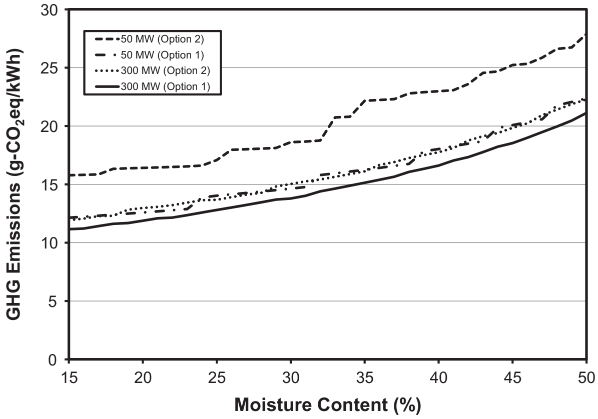

**Fig. 6.** Effect of moisture content on life-cycle emissions for both Option 1 (chipping at the landing) and Option 2 (chipping at the power plant).

twice as high, ranging from 13.3 to 19.8 g-CO$_2$/kW h, depending on option and power plant size. The Swedish study [42] evaluated five different scenarios, all of which included chipping after transportation. One scenario is similar to our Option 2, which includes collection of residues, baling, transporting, chipping at the facility, and combustion. Their energy use per amount of fuel produced was approximately 8% higher, but it is not clear why this is. For their results, the baling of residues used more energy than transportation, which is contradictory to our study and which probably explains the increase in energy.

### 3.4. Effect of moisture content

Moisture content impacts the life-cycle energy consumption and emissions for both options considered in this study by changing the heating value of the biomass, which in turn affects the harvest area required to achieve a particular energy production. The results presented above were based on a harvesting residue moisture content of 47% (wet basis). This is the average moisture content of roadside logging residues in Alberta [20]. The GHG emissions for two power plant sizes, 50 and 300 MW, at varying moisture contents of 15–50% are presented in Fig. 6. Some results are worth noting. For a given moisture content, an increase in power plant size shows a decrease in overall emissions (g-CO$_2$/kW h). For a given plant size, higher moisture content results in higher emissions per unit of electricity generation. The same results were also found for energy consumption. For both power plant sizes, graphs for Option 1 lie below those for Option 2. This is because, as mentioned above, higher emissions were found with Option 2 than with Option 1. For the 50 MW power plant, emissions are 30% higher with Option 2 than Option 1 at 15% moisture content. This difference falls to 25% at 50% moisture content. For the 300 MW power plant, the trend is the same but at lower values. The difference is 7% at 15% moisture content and 6% at 50%. This happens because for a larger power plant size, there are fewer emissions with Option 2 than with Option 1 due to an increase in the efficiency of the processing equipment.

### 3.5. Sensitivity analyses

Sensitivity analyses for Option 1 and Option 2 are presented in Table 4. Results are presented for a 137 MW power plant. The GHG emissions and energy required both show a 25% increase and decrease for parameters above the reported baseline parameters in the table. For Option 1, the biggest changes to both emissions and energy come from changing the plant lifetime and the moisture content, with the largest change from the latter. There is a greater change from increasing the moisture content than from decreasing it. Changes to the load capacity and fuel consumption during chip transportation also have a greater than 10% effect on both parameters. However, changes to the productivities and fuel consumptions of the forwarder and chipper have only a minor effect. Results for Option 2 are similar to those for Option 1. The effect of the plant lifetime is similar, but the moisture content

**Table 4**
Sensitivity analysis for Option 1 (chipping at the landing) and Option 2 (chipping at the plant), with a base case defined as a 137 MW power plant, a plant lifetime of 30 years, and a forest residue moisture content of 47%.

| | Baseline value | GHG emissions (% change) | | Energy required (% change) | |
|---|---|---|---|---|---|
| | | +25% | −25% | +25% | −25% |
| *Option 1* | | | | | |
| Baseline GHG emissions (g-$CO_2$eq/kW h) | 18.83 | | | | |
| Baseline energy required (% of thermal produced) | 1.82% | | | | |
| Plant lifetime (years) | 30 | −1.1% | 1.9% | 24.0% | −24.0% |
| Moisture content (%) | 47% | 40.9% | −21.7% | 41.7% | −22.1% |
| Harvesting | | | | | |
| Forwarder: | | | | | |
| Productivity (tonne/h) | 20 | −3.2% | 5.4% | −3.2% | 5.4% |
| Fuel consumption (L/h) | 13 | 3.6% | −3.6% | 3.7% | −3.7% |
| Processing | | | | | |
| Chipping at the landing: | | | | | |
| Productivity (tonne/h) | 90 | −4.2% | 7. 0% | −4.3% | 7.2% |
| Fuel consumption (L/h) | 85 | 5.2% | −5.2% | 5.4% | −5.4% |
| Transportation | | | | | |
| Chip transportation: | | | | | |
| Load capacity (tonnes/trip) | 30 | −10.1% | 18.5% | −10.3% | 19.0% |
| Fuel consumption (L/h) | 40 | 12.8% | −12.8% | 13.1% | −13.1% |
| *Option 2* | | | | | |
| Baseline GHG emissions (g-$CO_2$eq/kW h) | 21.7 | | | | |
| Baseline energy required (% of thermal produced) | 2.09% | | | | |
| Plant lifetime (years) | 30 | −0.9% | 2.0% | 24.1% | −23.9% |
| Moisture content (%) | 47% | 37.5% | −20.7% | 38.0% | −21.0% |
| Harvesting | | | | | |
| Forwarder: | | | | | |
| Productivity (tonne/h) | 20 | −2.7% | 4.4% | −2.7% | 4.5% |
| Fuel consumption (L/h) | 13 | 3.1% | −3.1% | 3.2% | −3.2% |
| Bundler: | | | | | |
| Productivity (bundles/h) | 40 | −2.6% | 3.9% | −2.6% | 3.8% |
| Fuel consumption (L/h) | 11 | 2.7% | −2.7% | 2.8% | −2.8% |
| Processing | | | | | |
| Chipping at the plant: | | | | | |
| Productivity (tonne/h) | 170 | −3.3% | 6.6% | −3.3% | 6.5% |
| Fuel consumption (L/h) | 125 | 3.9% | −3.9% | 4.0% | −4.0% |
| Transportation | | | | | |
| Bundle transportation: | | | | | |
| Load capacity (tonnes/trip) | 39 | −7.3% | 11.5% | −7.5% | 11.8% |
| Fuel consumption (L/h) | 40 | 8.8% | −8.8% | 9.1% | −9.1% |

change is slightly lower. All other values show a less than 10% change except for decreasing the load capacity during bundle transportation to the power plant.

Plant lifetime is a variable that cannot be changed easily, but moisture content can be decreased by allowing the residues to dry at the roadside [41]. One effect of adding this step to dry the wood is a change in the overall area required to meet a specific power plant size, which in turn would affect transportation distances, thereby changing fuel consumption during harvesting and processing. Allowing the residues to dry at the roadside would decrease the transportation distance required. Reducing the moisture content would also raise the lower heating value of the biomass [32], which would affect operations at the power plant. To reduce energy consumption and emissions, focus should be placed on transportation to ensure that the chip vans and log-haul trucks are hauling the maximum amount of material and operating at the highest fuel consumption.

## 4. Conclusion

Forest residues can provide an almost carbon neutral energy source that has lower GHG emissions than fossil fuels and requires very little energy for processing and growth compared to what is produced. Forest residues can be chipped at the landing or at the power plant. Results for both methods show that only fuel transportation, as a percentage of total energy produced, increases with increasing power plant size. All other parameters remain relatively constant. The same trend is seen in the GHG emissions. When comparing both chipping options, for smaller power plant sizes less energy is needed and lower GHG emissions are produced when chipping takes place at the landing. Larger power plants would benefit from chipping at the plant. While a larger size may not be possible at an individual plant, multiple plants could be built near each other. These results are most dependent on the plant lifetime and the moisture content of the residues, the latter of which affects the residue transportation distance and heating value.

## References

[1] Bracmort K. Is biopower carbon neutral? In: Congressional Research Service. 2013 January Report No.: R41603. Available from: <http://www.fas.org/sgp/crs/misc/R41603.pdf>.

[2] Kumar A, Flynn P, Sokhansanj S. Biopower generation in British Columbia: an opportunity for greenhouse gas mitigation. In: EIC Climate Change Technology, 2006 IEEE; 2006. p. 1–10.

[3] Royo J, Sebastián F, Garcia-Galindo D, Gómez M, Diaz M. Large-scale analysis of GHG (greenhouse gas) reduction by means of biomass co-firing at country scale: application to the Spanish case. Energy 2012;48:255–67.

[4] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32:1543–59.

[5] Parliamentary Office of Science and Technology. Carbon footprint of electricity generation; 2011. Available from: <http://www.parliament.uk/documents/post/postpn268.pdf>.

[6] Heller MC, Keoleian GA, Mann MK, Volk TA. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renew Energy 2004;29:1023–42.

[7] Cameco Corporation. Comparison of lifecycle greenhouse gas emissions of various electricity generation sources; 2010. Available from: <http://www.cameco.com/common/pdf/uranium_101/Cameco_-_Corporation_Report_on_GHG_Emissions_nov_2010.pdf>.

[8] Jambeck J, Weitz K, Solo-Gabriele H, Townsend T, Thorneloe S. CCA-treated wood disposed in landfills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal. Waste Manage 2007;27:S21–8.

[9] Carpenter A, Jambeck JR, Gardner K, Weitz K. Life cycle assessment of end-of-life management options for construction and demolition debris. J Ind Ecol 2012;17(3):396–406.

[10] Environment Canada. In: National inventory report: greenhouse gas sources and sinks in Canada Part 1. Canada's 2013 UNFCCC Submission; 2013. p. 171–97.

[11] Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, et al. Forest carbon sinks in the northern hemisphere. Ecol Appl 2002;12:891–9.

[12] Sarkar S, Kumar A, Sultana A. Biofuels and biochemicals production from forest biomass in Western Canada. Energy 2011;36:6251–62.

[13] Government of Alberta. Forest industry competitiveness: current facts & statistics; 2010. Available from: <http://www.esrd.alberta.ca/lands-forests/forest-business/documents/ForestIndustryCompetitiveness-AlbertaBiomassOpportunitiesMarch2010.pdf>.

[14] Valente C, Hillring BG, Solberg B. Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. Scand J Forest Res 2011;26:429–36.

[15] Lindholm EL, Berg S, Hansson PA. Energy efficiency and the environmental impact of harvesting stumps and logging residues. Eur J Forest Res 2010;129:1223–35.

[16] Climate Change Solutions. Canada – sustainable forest biomass supply chains; 2007. Available from: <http://www.canbio.ca/upload/documents/sustainableforestsupplychainsoct192007.pdf>.

[17] Wihersaari M. Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass Bioenergy 2005;28:435–43.

[18] Timberjack: A John Deere Company. Green forest machines for sustainable development. Available from: <http://www.deere.com/en_US/compinfo/media/pdf/envtsafety/env/TJ_YMPESITE_USA_2final.pdf>.

[19] Cesco Used Equipment. CAT 322L excavator. Available from: <http://www.cescoused.com/images/specs/734.pdf>.

[20] MacDonald AJ. Processing roadside harvesting residues with a horizontal grinder in northern Alberta. Advantage 2009;11(12).

[21] Brinker RW, Kinard J, Rummer R, Lanford B. Machine rates for selected forest harvesting machines; 2002. Available from: <http://www.srs.fs.usda.gov/pubs/ja/ja_rummer020.pdf?>.

[22] Forest Operations Research Unit. Forest residues bundling project: new technology for residue removal; 2004. Available from: <http://www.fs.fed.us/woodybiomass/strategy/bundling/documents/bundler_report_final.pdf>.

[23] Mitchell D. Bundling logging residues with a modified John Deere slash bundler. In: Proceedings of the international conference on woody biomass utilization, Starkville, MS, Madison, WI; 2009 August 4–5. p. 58–63.

[24] Schmidt M. 1490D Eco III energy harvester. In: Proceedings of the international conference on woody biomass utilization. Starkville, MS, Madison, WI; 2009 August 4–5.

[25] Bandit Industries Inc. Beast recycler; 2007. Available from: <http://www.icuee.com/Documents/VTS/Brochure/fpC9JD7ne7/Beast-WinterSpring07.pdf>.

[26] Klvac R, Skoupy A. Characteristic fuel consumption and exhaust emissions in fully mechanized logging operations. J Forest Res 2009;14:328–34.

[27] Morey RV, Kaliyan N, Tiffany DG, Schmidt DR. A biomass supply logistics system. In: Proceedings of the ASABE annual international meetin, Reno, NV; 2009 June 21–24. p. 1–13.

[28] Westbrook MD, Greene WD, Izlar RL. Utilizing forest biomass by adding a small chipper to a tree-length southern pine harvesting operation. South J Appl Forest 2007;31(4):165–9.

[29] Transport Canada. Operating costs of trucks in Canada. In: Report No.: T8080-05-0242; 2005. Available from: <http://www.tc.gc.ca/media/documents/policy/oc_2005_e.pdf>.

[30] University of New Brunswick. On/Off highway 8-axle B-train chip van machine information summary. Available from: <http://www.unb.ca/standint/nbcc/machine/transport/tlsimp_b.html>.

[31] Johansson J, Liss J, Gullberg T, Björheden R. Transport and handling of forest energy bundles—advantages and problems. Biomass Bioenergy 2006;30:334–41.

[32] Angus-Hankin C, Stokes B, Twaddle A. The transportation of fuelwood from forest to facility. Biomass Bioenergy 1995;9:191–203.

[33] Patterson DW, Pelkki MH, Steele PH. Productivity of the John Deere slash bundler in removing in-forest residues from pine harvest sites in the mid-South: four case studies. Forest Prod J 2008;58(7–8):31–6.

[34] Kumar A, Sarkar S. Techno-economic assessment of biomass conversion to charcoal for carbon sequestration. In: 2009 July report for Alberta innovates – Energy and Environmental Solutions (EES) and cenovus energy. Available from: <http://www.ai-ees.ca/media/6900/techno-economic_assessment_of_biomass.pdf>.

[35] Harrill H, Han H, Pan F. Combining slash bundling with in-woods grinding operations. In: Proceedings of the council on forest engineering (COFE) conference, Lake Tahoe, CA; 2009 June 15–18. p. 1–4.

[36] Gaines L, Stodolsky F, Roy C, Eberhardt J. Life-cycle analysis for heavy vehicles. In: Proceedings of the air & waste management association annual meeting, San Diego, CA; 1998 June. p. 1–16.

[37] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass Bioenergy 2003;24:445–64.

[38] Spath PL, Mann MK, Kerr DR. Life cycle assessment of coal -fired power production. In: 1999 June Report No.: NREL/TP-570-25119.

[39] Wang M. GREET 1. Argonne, IL: Argonne National Laboratory; 2012.

[40] Wang M, Burnham A, Wu Y. GREET 2. Argonne, IL: Argonne National Laboratory; 2012.

[41] Whittaker C, Mortimer N, Murphy R, Matthews R. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass Bioenergy 2011;35:4581–94.

[42] Forsberg G. Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. Biomass Bioenergy 2000;19:17–30.